

RESULTS

Experiments in-situ

WP 2, experiments after intervention

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Contents

Contents	2
Summary	3
1. Introduction.....	5
Relation with other programs	6
2. Measurement method	7
Outcome parameters	9
3. Results after intervention.....	12
Summary room and system characteristics	12
Summary indoor and outdoor conditions	12
Summary results of measurements	13
4. Comparison before and after the intervention.....	17
Summary results of measurements	17
5. Conclusions.....	23
6. Appendices	24
6.1 Annex A, results classroom 1	27
6.2 Annex B, results classroom 2 (intervention A).....	45
6.3 Annex B, results classroom 2 (intervention B).....	62
6.4 Annex B, results classroom 2 (intervention C).....	79
6.5 Annex C, results classroom 3 (intervention A).....	96
6.6 Annex C, results classroom 3 (intervention B)	112
6.7 Annex D, results classroom 4	130
6.8 Annex E, results classroom 5	146
6.9 Annex F, results classroom 6	165
6.10 Annex G, results classroom 7	183
6.11 Annex H, results classroom 8	201

Deliverable Work package 2

Summary

This report presents the outcomes of Work Package 2 (WP2) within the CLAIRE project, which investigates ventilation properties in primary schools and long-term care facilities. The primary aim is to enhance understanding of aerosol behavior under various ventilation systems and develop simplified methods to assess ventilation performance. The report focuses on measurements conducted before and after interventions of the ventilation system in eight primary school classrooms, with a comparison to earlier results from the 'before intervention' measurements.

The methodology involved selecting representative classrooms and determining critical measurement positions based on room geometry, ventilation system typology, and user behavior. Measurements included particle concentration dynamics, the air velocity from three directions, and ventilation efficiency. Key outcome parameters were:

- 100-fold increase time: Time for particle concentration to rise significantly.
- 100-fold recovery time: Time for particle concentration to decrease after emission stops.
- t_{delay} : Time delay between emission and detection at measurement points.
- Local Air Changes per Hour ($\text{ACH}_{\text{local}}$): Proxy for ventilation rate.

Measurements were conducted under realistic operational conditions, though without children and teachers in the classroom, with interventions including system replacements, control adjustments, airflow rate changes, and the use of mobile air cleaners.

In the measurements after intervention, all eight classrooms transitioned from predominantly natural ventilation systems to mechanical supply and exhaust systems. The results of classroom 3 are shown, however, the intervention malfunctioned during measurements. Therefore, average values are also presented excluding classroom 3. The interventions led to notable improvements in air quality performance:

- 100-fold recovery time decreased significantly, with average values dropping from 181 minutes before intervention to 59 minutes after. This indicates faster removal of airborne particles and improved ventilation efficiency.
- Local ACH increased from an average of 2.6 to 6.0, reflecting enhanced air exchange rates.
- t_{delay} values became more consistent across measurement points, suggesting more uniform airflow distribution.
- Airflow measurements showed higher velocities and clearer flow patterns post-intervention, especially in classrooms with well-positioned supply and exhaust grills.

Two classrooms (classroom 2 and 3) were also tested with mobile air cleaners. While these devices improved recovery times, mechanical ventilation systems proved more effective overall in particle removal.

The comparison between the before and after intervention measurements reveals several key insights:

1. Improved Recovery Times and Ventilation Rates;
Phase 2 interventions resulted in shorter recovery times and higher $\text{ACH}_{\text{local}}$ values compared to phase 1. This demonstrates the effectiveness of mechanical ventilation systems in flushing airborne contaminants and maintaining cleaner indoor air.

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2. More Controlled Particle Dispersion;

Interestingly, the 100-fold increase time was longer in five of the eight classrooms after intervention. This could indicate that particles took longer to reach certain areas, likely due to improved air flow control and reduced spread. While this may seem counterintuitive, it reflects a more localized and efficient ventilation strategy that limits widespread dispersion of contaminants.

Additionally, the variation in measurement results across different positions within classrooms was reduced in the after-intervention measurements, indicating more homogeneous air distribution. This consistency is important for ensuring that all occupants benefit equally from improved air quality.

The after-intervention measurements confirm that upgrading to mechanical ventilation systems significantly enhances indoor air quality in primary school classrooms. These systems not only improve particle removal efficiency but also create more uniform airflow patterns, reducing exposure risks. Compared to the before intervention measurements, the measurements after interventions led to better performance across all outcome parameters, supporting the continued implementation of mechanical ventilation and targeted air cleaning strategies in educational environments.

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1. Introduction

Work package 2 “ventilation properties” has two main objectives:

- Moving beyond the state of the art in understanding the behavior of aerosol particles under different types of ventilation systems and realistic operational circumstances;
- Develop more sophisticated model-based understanding of effects, interactions and sensitivities, as well as methodologies.

A smaller “Industrial research” component is also involved, as functional requirements for the assessment method to be developed are informed by end-user and industry needs, expectations and competencies.

This report describes the assessment of ventilation efficiency at critical positions and recovery time in test environments, Figure 1. This report concerns the measurements both before the intervention and after the intervention at 8 primary schools. Furthermore, measurements before the intervention were conducted in 2 rooms of a long-term care facility, but it was not possible to measure after the intervention since this implementation was cancelled. Therefore, the results of these measurements are not included in this report.

The approach for this deliverable consists of four steps:

1. Selection of primary schools and long-term care facilities where an intervention of the ventilation system will take place in the near future. The ventilation systems are classified in consultation with the various trade associations. A number of criteria apply here, including:
 - a) Typology of the ventilation system to include the widest possible number of typical systems
 - b) Rooms where air cleaning techniques will be applied in due course (WP 3)
 - c) Ventilation systems to be adjusted/improved at the second half of 2023.
2. Determining the basic data of each ventilation system such as type, positions, air volumes, type of grilles and position, air velocity, etc.
3. Determining the critical positions for measurements. The locations where people are mostly present will be used as “critical positions”. The results of the measurements as well as the characteristics of the system will be translated into a simplified method for assessing ventilation performance in confined environments.
4. Measuring ventilation efficiency and recovery time at the critical positions.

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1) Existing ventilation system and room typologies (Basic ventilation)			Outcome: • Amount of fresh (outdoor)air • Ventilation efficiency based on 100-fold recovery time at six positions simultaneously, emission sequential at max 6 positions • Vector of the air flow (direction and speed) • Temperature and RH
Interventions			
2) Adaption of existing ventilation system	3) Use of mobile air cleaners	4) Adaption of existing ventilation system + use of mobile air cleaners (if possible)	
n = 10			

Figure 1. Summary of the approach for working program 2.

The CLAIRE project is powered by Health~Holland, Top Sector Life Sciences & Health, through its Public-Private Partnership (PPP) Allowance program under project number LSHM22032. Health~Holland is the trade name of the Dutch Top Sector Life Sciences & Health. Health~Holland is one of ten top sectors set up by the Ministry of Economic Affairs to harness Dutch innovation potential for a substantial contribution to global societal challenges.



For more about Health~Holland, visit [Health~Holland](https://www.health-holland.nl)

Relation with other programs

WP2 of CLAIRE has a strong relationship with the P³Venti program; both are coordinated by TNO. It also has a relationship with the Mitigation Strategies for Airborne Infection Control (MIST) project funded by NWO.

WP2 of CLAIRE relates in particular to P³Venti program lines 1 “Analysis usage and interaction” and 3 “Experiments in a practical setting under operational conditions”. While CLAIRE focuses on primary schools and long-term care facilities, P³Venti focuses exclusively on long-term care facilities. Therefore the CLAIRE project focused mostly on primary schools, with approximately 80% of pilots being schools. The MIST project started at the end of 2022 with a duration of 4 years. In this project, more fundamental research will be performed regarding the behavior of aerosols, pathogens, ventilation systems and air purification in a number of use cases, resulting in strategies to reduce transmission. As TNO and TU/e both participate in all three of the programs/projects, they will ensure good inter-program synergy.

2. Measurement method

The measurement method has been described in the report of phase 1 as well.¹ The aim of WP2 is to evaluate the performance of ventilation systems in relation to airborne (bio)contaminants, considering the exposure from varying source locations, and in a simple way without the use of complex measurements. A derived aim is to determine the ventilation performance for various ventilation systems and mitigation measures.

Inclusion criteria for primary schools and long-term care facilities:

- Room typology must include common (living) rooms in long term care facilities (exclusion of patient rooms) and classrooms in primary schools.
- The room must be representative of the sector (primary schools and long-term care facilities). This means representative in use (so interactions around living/dining room), and less so in terms of spatial properties (volume, etc.) ;
- Mix of different ventilation systems in each sector;
- All situations must comply with the ventilation requirements that applied according to Bouwbesluit during building year.
- Permission to generate particles (no people present).

In the selected pilot locations (8), the following characteristics of the location, system and use are determined and noted:

- Geometry of the space;
- Typology of the ventilation system;
- Type, position, and airflow rates through individual supply grilles;
- Amount of supply air;
- Usage type (interactions between people, number of people present in the room, use of the existing (ventilation) facilities; based on interviews).

Step 1: Selecting the rooms

Selection of ventilation systems and pilot location and determination of the basic ventilation system data.

Step 2: Determination of the critical positions for measurements in all selected locations (rooms)

Based on expert opinion the 6 distinct locations in the room were identified based on the position of both the furniture and the ventilation system in the room, the expected behavior of the users. The results of the measurements as well as the characteristics of the system will be translated into a simplified method for assessing ventilation performance in confined environments.

¹ A. de Lange, R. Traversari, R10059 Results experiments in-situ (2024)

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Step 3: Measuring the ventilation efficiency and recovery time at the critical positions

The measurement protocol, consisting of particle concentration measurements at six critical positions, was applied uniformly across all selected rooms. In cases where deviations from the protocol occurred, these are explicitly noted in the results section and appendices.

1. Determine the amount of supply and extract air from the room per grill with a pressureless airflow meter (except for natural ventilation, with natural ventilation, the air volume could not be easily measured),
2. Measure the recovery time simultaneously at the 6 critical positions; do this with the emission (source) of particles at 2 different locations in succession. These locations were representative (realistic) emission locations in the room e.g. position of the teacher and students. The measuring procedure is shown in Figure 2:
 - 1) measure the baseline concentration,
 - 2) start the emission for 10 minutes. 10 minutes was chosen due to time restrictions, a steady state concentration has not been reached at this point in time.
 - 3) stop emitting and measure the decay in concentration.
3. Measure the air velocity from three different directions (at 7-8 different heights (between 0.13 and 3.08 m) on a grid of 1.0 m x 1.0 m and close to the walls (approximately 0.2 m). The velocity was measured at each point for 30 seconds at 1 Hz.
4. If possible, (non-destructively) measure the concentration in or at the exhaust duct to calculate the contaminant removal effectiveness.

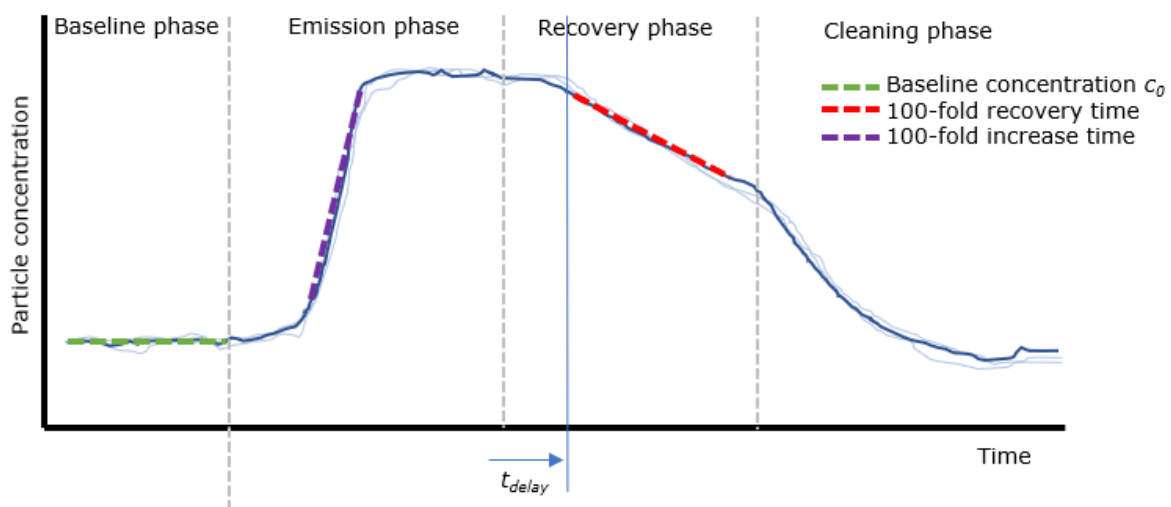


Figure 2. Particle concentration measurements.

Step 4: Implement air cleaners, or, if applicable, a ventilation system adapted within the framework of the specific benefit for ventilation in schools (Subsidieregeling ventilatie scholen, SUVIS).

The measurements described in step 1 are carried out as much as possible before and after a certain intervention (adjusting the air treatment system or applying an air cleaner). It is most effective to select locations where the ventilation system will be modified within the duration of the project. In this way, a before and after measurement can be performed. An air cleaner can be applied relatively easily and it would be preferable if the effect of an air cleaner can be determined both before and after adjusting the ventilation system. This way, multiple interventions can be considered at one location. The position of the air cleaner in the room is also an important parameter.

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Step 5: Determination of the ventilation efficiency and recovery time at the critical positions with the interventions.

See step 4.

Step 6: Evaluation of the outcome variables before and after the intervention.

The outcome variables that will be compared between the situation before and after the intervention are the 100-fold increase time, t_{delay} , 100-fold recovery time and the local ventilation rate as a proxy for the exposure to virus particles.

Step 7: Development of a simplified (proxy) method for assessing ventilation performance in confined environments

A comprehensive overview of the theoretical framework is given in the report of phase 1. This section will elaborate on the measurement methods used in phase 2.

Outcome parameters

Additional outcome variables are defined that focus on dynamic behavior of systems. In order to address the research questions, a data analysis has been conducted. Initially, particle concentrations during the entire measurement cycle were examined to subsequently answer the more in-depth research questions. The following outcome measures were used:

t_{delay}

After the start of emission of particles from a source, an increase in particle concentration at the measurement points occurs after a certain time delay (t_{delay}). This time between the start of emission and the increase in particle concentration depends on the distance between the source and the measurement point, as well as on the airflow pattern in the room (velocity and direction). In other words, it represents the "path" that the emitted particles travel before being detected at the measurement point. This variable, t_{delay} , indicates how quickly pollution spreads through a space to specific measurement points which is a function of the flow pattern resulting from ventilation.

It can also be determined as the time between the cessation of emission and the attainment of the maximum concentration at the respective measurement point. During the analysis for this research, t_{delay} is calculated as the time difference between the end of the emission and when the particle concentration starts to decrease.

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100-fold recovery time

The 100-fold recovery time was defined in section 4.2.1 and is calculated through:

$c_t = c_0 \cdot e^{-\frac{Q \cdot t}{V}}$	(Equation 8)
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Where:

c_t is the concentration at time t per m^3

c_0 is the initial concentration per m^3

Q is the amount of clean supply air in m^3/s

V is the volume of the room in m^3

t is the time in seconds after the initial concentration is present

(local) Air changes per hour (ACH_{local})

ACH and ventilation rates are often used as indicators to denote the amount of ventilation in a space. It refers to the number of times per hour that the total air volume in the space is replaced. It is determined at the measurement points based on the 100-fold recovery time and is then referred to as the *local* air exchange rate. A long 100-fold recovery time leads to a low local air exchange rate. The local air exchange rate is calculated based on the 100-fold recovery time using the equation:

$C_t = C_0 \times e^{-t \cdot \frac{Q}{V}}$	(Equation 9)
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Where:

C_t is the concentration at time t ,

C_0 is the initial concentration,

Q is the supplied air quantity per unit of time,

V is the volume of the space.

Q divided by V is defined as the air exchange rate. With a known 100-fold recovery time, the local air exchange rate at position x is then:

$Local\ ACH = \frac{Q}{V} = \frac{-\ln\left(\frac{C_{t,x}}{C_{0,x}}\right)}{t_x} = \frac{4,6}{t_x}$	(Equation 10)
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Where:

t_x is the 100-fold recovery time at position x .

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100-fold increase time

The 100-fold increase time at a certain location in the space is defined as the time needed to increase a concentration of emitted particles by a factor of 100. After particle emission from a source, an increase in particle concentration at the measurement points occurs after a certain time delay. This increase can have the character of a step response or a very gradual increase. A step response-like increase (short 100-fold increase time) indicates that the particle concentration arrives at the measurement positions as a front with a relatively sharp delineation. A gradual profile (long 100-fold increase time), on the other hand, indicates a calm (gradual) increase. The maximum increase (maximum slope in the logarithmic concentration vs time graph) is used to determine the 100-fold increase time.

3. Results after intervention

A total of 10 locations were visited and measured. The locations comprise 8 elementary schools and 2 long-term health care facilities. At the 2 long term health care facilities no intervention was implemented, therefore this location is excluded from this report. The detailed results are shown in annex A to H. The results presented in the upcoming chapters present the situation both without any intervention and after the intervention to optimize the ventilation system to compare these 2 measurements. Interventions are defined as modifications of the ventilation in the classroom by modification of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and/or exhaust, balanced ventilation system),
- Adjustment of controls: new control system, e.g. based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of airflow rate: the airflow rates are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

After the intervention was implemented, all 8 locations had replaced their ventilation system with a ventilation system with mechanical supply and exhaust. At two locations, the use of an mobile air cleaner was also tested.

Summary room and system characteristics

The characteristics of the rooms and the ventilation system for primary schools are presented in Table 1 (Appendices). From these tables, it is evident that the vast majority of the experiments before the intervention was conducted with natural ventilation systems. This is because the design was to perform measurements before and after the intervention. In the case of primary schools, it is logical that systems where an intervention will be carried out are generally not the better-performing systems. It is also noticeable that during the measurements carried out the ventilation facilities were used as intended, but that this is different from the systems used in practical situations. As a result, the performance of the systems should not be compared to each other. However, after the post-measurement, the effect of the intervention can be visualized by comparing the results before and after the intervention. At two locations, two or three different post-measurements were executed since measurements were also done with a mobile air cleaner at a representative setting.

Summary indoor and outdoor conditions

The indoor and outdoor conditions during the measurements for primary schools are presented in Table 2. When comparing indoor and outdoor conditions, six of the eight primary schools experienced a cooler indoor air temperature after the intervention than before. The average indoor temperature difference before and after the intervention ranged from 1.3 to 8.4 degrees Celsius, while the outdoor temperature difference varied between 0.0 and 11.1 degrees Celsius.

Deliverable Work package 2

In seven schools, the outdoor relative humidity was higher after the intervention, leading to an increase in indoor relative humidity in most cases. Wind velocity and direction were particularly relevant before the intervention, as natural ventilation systems relied heavily on outdoor conditions.

Summary results of measurements

In this section, the summarized results of the phase 2 measurements are presented. The results for each location are shown in Appendix A through H. Per outcome parameter, 100-fold increase time, 100-fold recovery time, t_{delay} and $\text{ACH}_{\text{local}}$, a figure with the results of all locations is presented.

The 100-fold increase time shows that after intervention, the range is between 1- 937 minutes (Figure 3). Especially classroom three shows a wide spread in particle concentrations, this was caused by an inconsistent working ventilation system. Based on our findings this new system was adapted and the imperfections have been corrected so that the system functions properly. However, it was not possible to re-measure the system after these adjustments. In Figure 3, the values are truncated to 300 minutes for readability. Values above 300 minutes are considered extreme. The 100-fold increase time measures how quickly the particle concentration rises at a specific location in a room. A shorter increase time indicates a rapid increase in particle concentration, whereas a longer increase time suggests that fewer particles are reaching that position. This can occur for several reasons: the distance between the emitter and the particle counter may be large, the particle counter may be located at a position with a low-airflow "dead zone," or the ventilation system may remove particles from the air before they reach the particle counter. In the appendices, Figure 12 shows the maximum particle concentrations per classroom, per measurement location. It shows the critical locations in which the particle concentrations are high (red). The figure shows that higher particle concentrations are noted for emitter location 2. In classrooms 2, 3, 5, 7 and 8 specific locations show increased particle concentrations. In classrooms 3 and 8 there are also lower particle concentrations at specific locations, resulting in a wide particle concentration range.

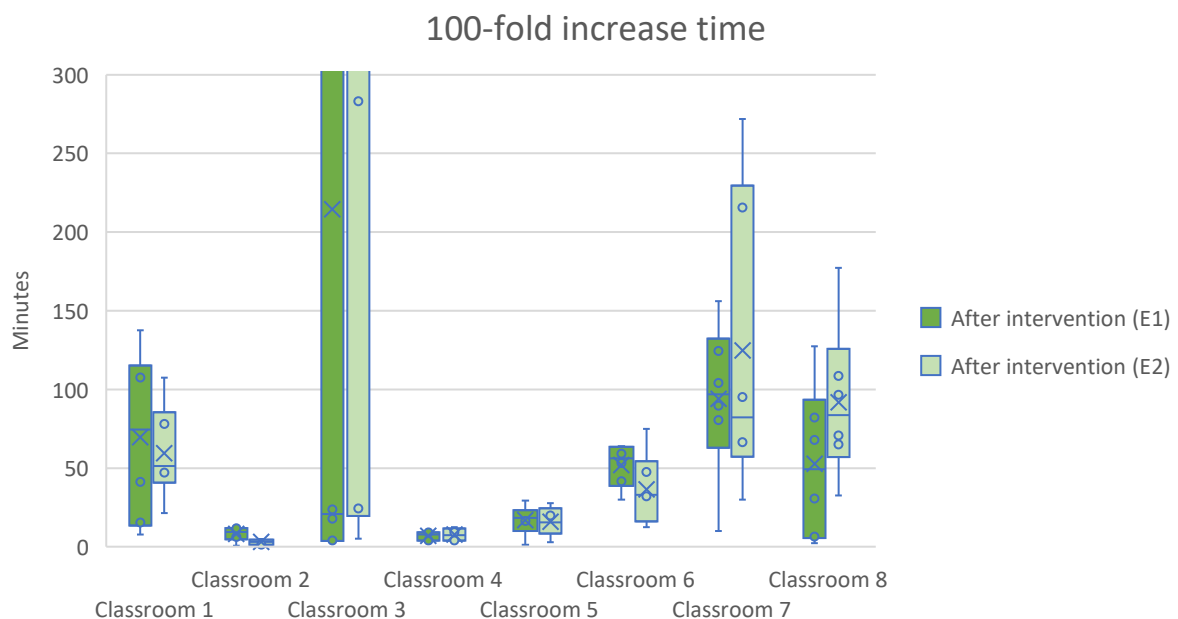


Figure 3. Boxplot of the 100-fold increase time in primary schools at 8 classrooms for the different locations of emission (E1 and E2).

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The 100-fold recovery time is a measure of the ability of a ventilation system to flush the space and remove particles and other airborne contaminants. The longer the recovery time, the more time a system needs to remove contaminants. The 100-fold recovery time has a direct relationship with the local air exchange rate. Figure 4 shows the 100-fold recovery time for the 8 classrooms. In Figure 4, the values are truncated to 100 minutes for readability. Values above 100 minutes are considered extreme. The classrooms, with exception of classroom 3 (E2), have recovery times within the range 20-80 minutes. Classrooms 3 and 4 show a larger spread than the other classrooms.

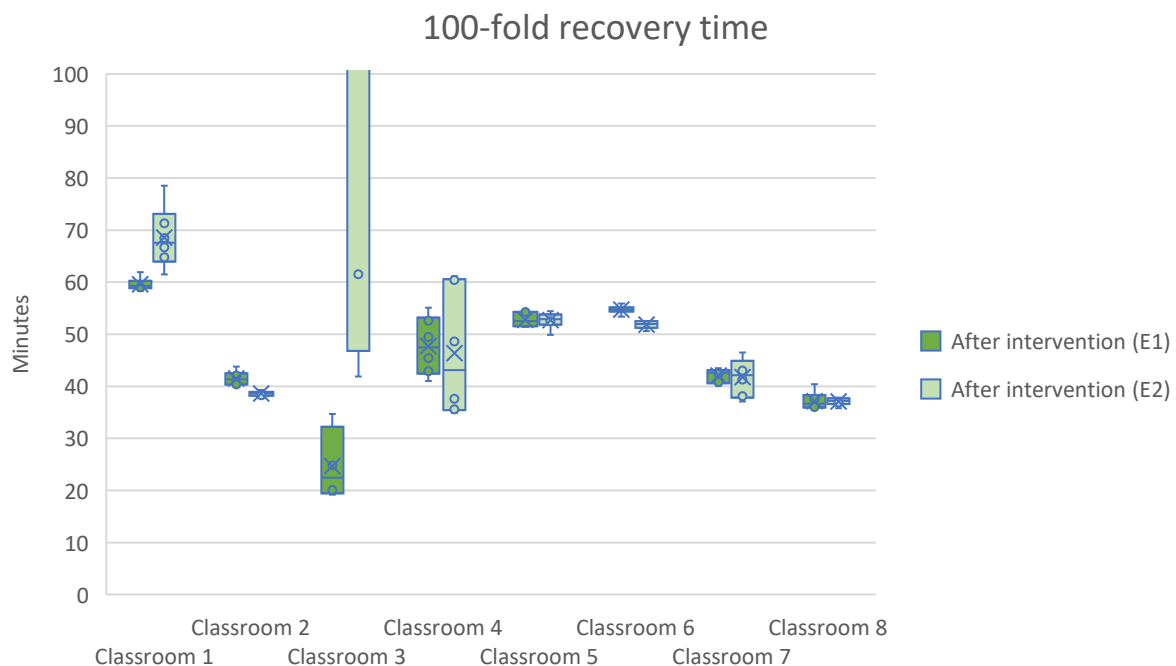


Figure 4. Boxplot of the 100-fold recovery time in primary schools at 8 classrooms for the different locations of emission (E1 and E2).

The time it takes for emissions to become visible at the measurement locations after the start of emission (t_{Delay}) depends on airflow and the distance between the emission point and the measurement point. A long t_{Delay} indicates either that the distance between the emission and measurement point is large, and it takes a long time for the particles to reach the measurement point, and/or the air velocity is low or even opposite to the direction from emission to the measurement point. This variable is represented for primary schools in Figure 5. The median of t_{Delay} falls between 1 and 8 minutes. However, also extreme values were observed, up to 14 minutes for classroom 3. The lower limit is generally around 0.5 minute. This t_{Delay} shows higher values for E2 than E1. Also this parameter shows the malfunction of ventilation system 3.

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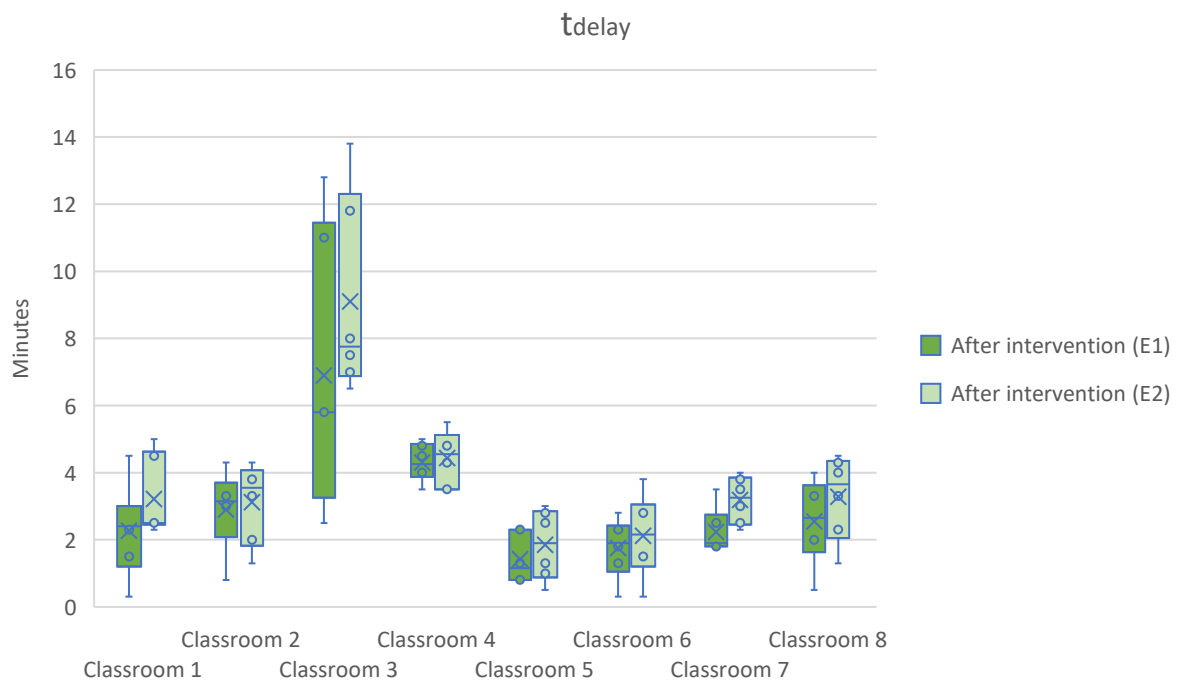


Figure 5. Boxplot of t_{delay} in primary schools at 8 classrooms for the different locations of emission (E1 and E2).

The local air change rate is directly linked to the 100-fold recovery time. A short 100-fold recovery time corresponds to a high local ventilation rate. This variable is represented for primary schools in Figure 6. The median local ventilation rate ($\text{ACH}_{\text{local}}$) falls between approximately 3.5 and 12.5 ACH.

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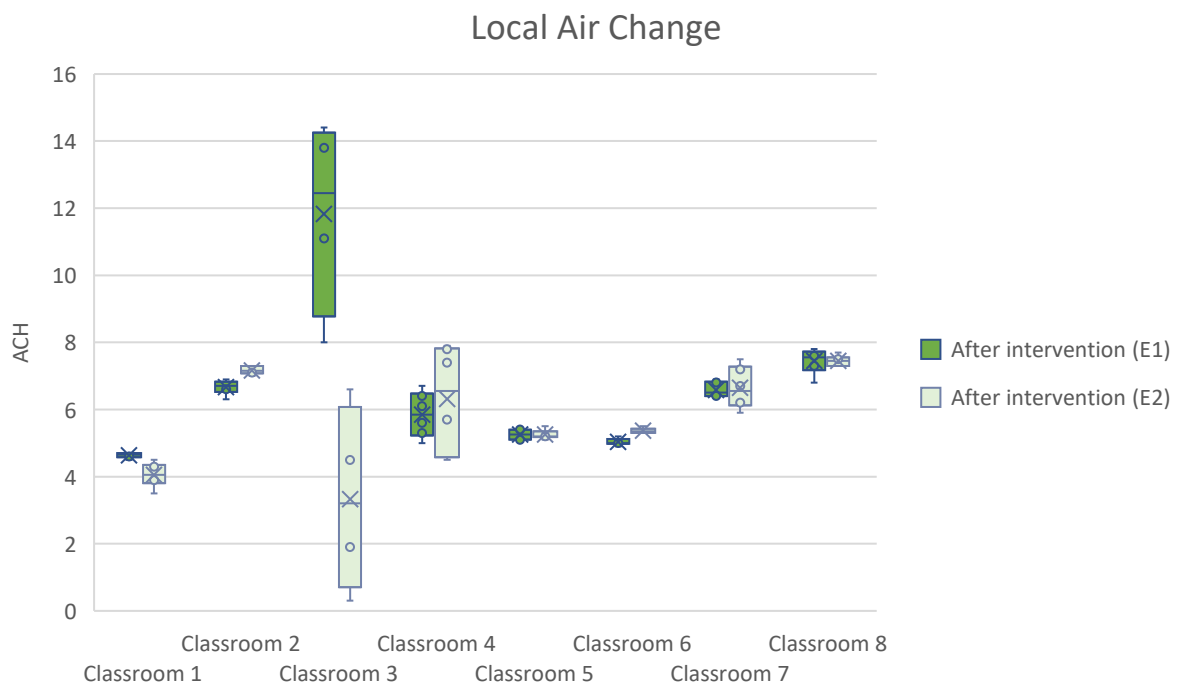


Figure 6. Boxplot of the local air change rate per hour in primary schools at 8 classrooms for the different locations of emission (E1 and E2).

4. Comparison before and after the intervention

Summary results of measurements

In this section, the summarized main results of the measurements are presented.

The 100-fold increase time measures how quickly the particle concentration rises at a specific location in a room. A shorter increase time indicates a rapid increase in particle concentration, whereas a longer increase time suggests that fewer particles are reaching that position. This can occur for several reasons: the distance between the emitter and the particle counter may be large, the particle counter may be located at a position with a "low-airflow dead zone," or the ventilation system may remove particles from the air before they reach the particle counter.

As shown in the figure, before the intervention, the 100-fold increase time ranged from 1 to 187 minutes, while after the intervention, it ranged from 1 to 937 minutes. When comparing before and after the intervention, the average increase time was longer in five of the eight classrooms after the intervention. In these locations, there was also a wide variation between the shortest and longest values, indicating that while particles reached some positions (closer to the emitter) quickly, they did not reach other areas of the room as easily. Given these variations, drawing definitive conclusions based solely on this variable were challenging. Figure 12 in the appendix shows the maximum particle concentrations per classroom and measurement location for each emitter location. It shows that classrooms 3 and 8 have an inhomogeneous maximum particle concentration throughout the classroom which results in longer increase times and recovery times as well.

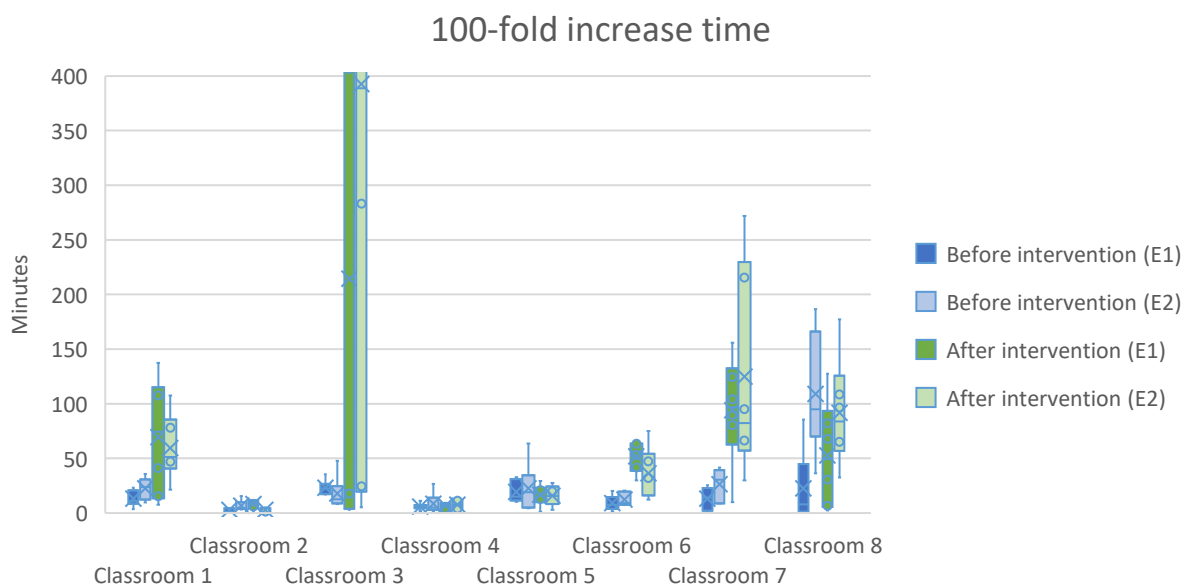


Figure 7. Boxplot of the 100-fold increase time in primary schools at 8 classrooms for the different locations of emission (E1 and E2) both before and after the intervention was implemented.

The 100-fold recovery time measures the effectiveness of a ventilation system in flushing a space and removing particles and other airborne contaminants. A longer recovery time indicates that the system requires more time to clear contaminants from the air. The 100-fold recovery time has a direct relationship with the local air exchange rate.

Deliverable Work package 2

As shown in the Figure 8, before the intervention, the 100-fold recovery time ranged from 49 to 1403 minutes, with an average of 181 minutes. In Figure 4, the values are truncated to 400 minutes for readability. Values above 400 minutes are considered extreme. After the intervention, this range decreased to 19 to 1082 minutes, with an average of 59 minutes. In general, the recovery time was shorter after the intervention, except in Classroom 3, where the implemented intervention did not function optimally. Excluding classroom 3 (which malfunctioned during measurements) the range was reduced from 19 to 78 with an average of 48 minutes. Additionally, the variation between different particle counters within the same classroom was smaller after the intervention, indicating a more homogeneous distribution of air throughout the room.

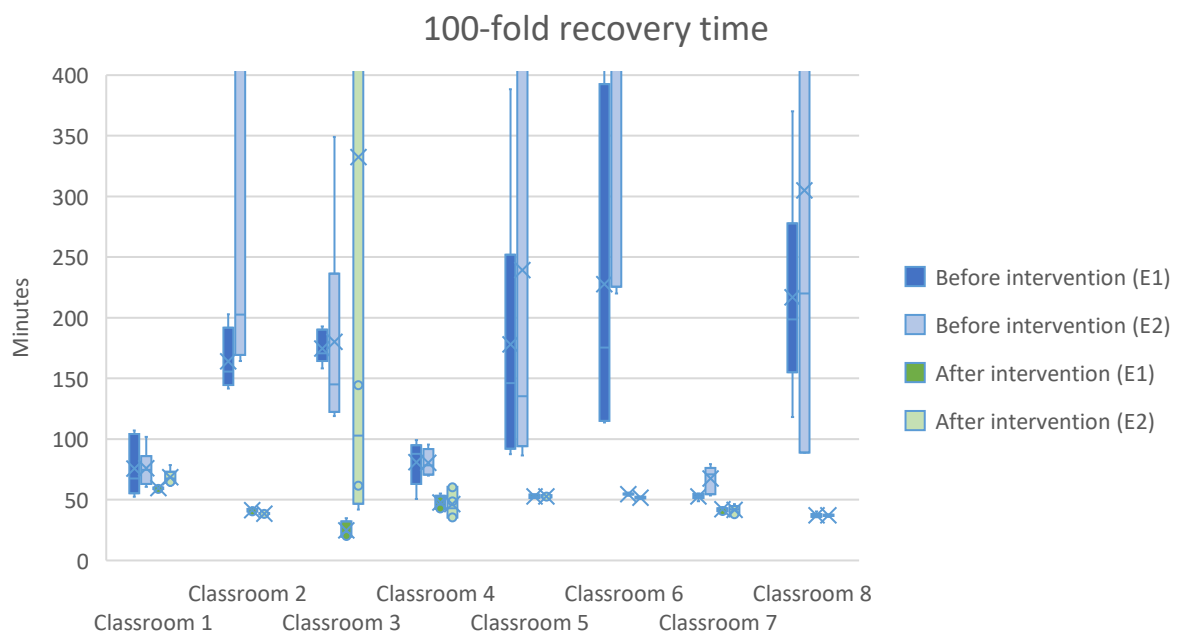


Figure 8. Boxplot of the 100-fold recovery time in primary schools at 8 classrooms for the different locations of emission (E1 and E2) both before and after the intervention was implemented.

Deliverable Work package 2

As shown in Figure 9, before the intervention, the ventilation rate ranged from 0.2 to 5.7 ACH, with an average of 2.6 ACH. After the intervention, the ventilation rate increased, ranging from 0.3 to 14.4 ACH, with an average of 6.1 ACH. Excluding classroom 3 after intervention (which malfunctioned during measurements) the range was reduced from 2.6 to 6.0. While extreme values were observed in the 100-fold recovery time, they are less pronounced in the local ventilation rate.

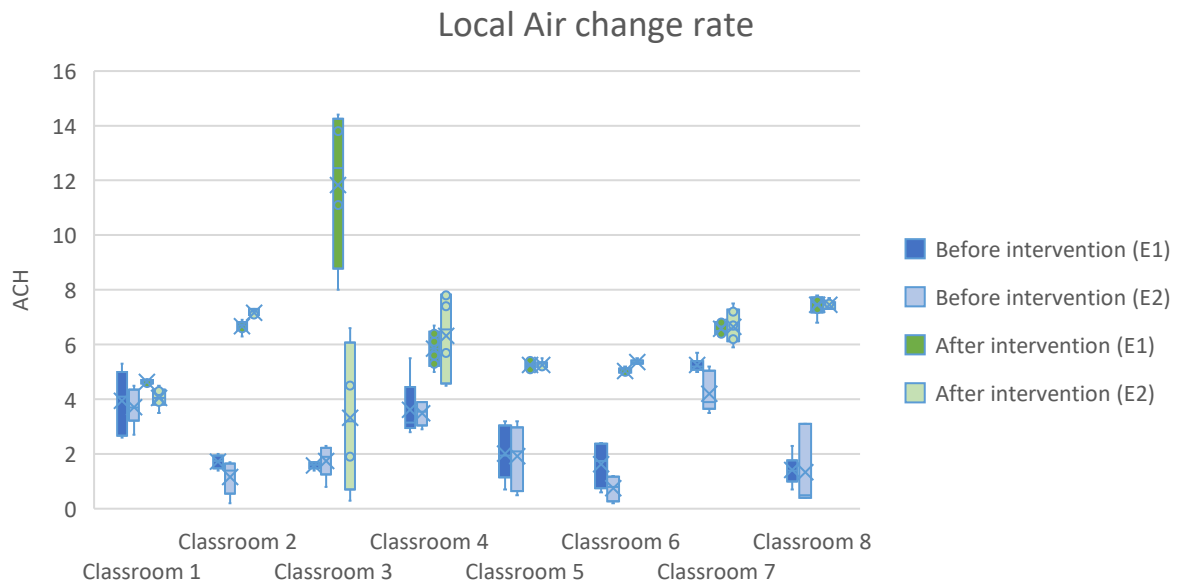


Figure 9. Boxplot of the local air change rate per hour in primary schools at 8 classrooms for the different locations of emission (E1 and E2) both before and after the intervention was implemented.

The time it takes for emissions to become detectable at the measurement locations after the start of emission (t_{delay}) is influenced by airflow patterns and the distance between the emission and measurement points. A long t_{delay} indicates either that the distance between the emission and measurement point is large, and it takes more time for the particles to reach the measurement point, and/or the velocity of the air is low or even opposite to the direction from emission to the measurement point.

As shown in Figure 10, before the intervention, t_{delay} ranged from 0.3 to 14.0 minutes, with an average of 3.7 minutes. After the intervention, t_{delay} varied between 0.3 and 13.8 minutes, with an average of 3.4 minutes. Excluding classroom 3 (since the intervention malfunctioned during the measurements) the average was reduced from 3.7 to 2.8 minutes. Prior to the intervention, longer t_{delay} values were more frequent, and the variation between different particle counters within the same classroom was generally larger. After the intervention, the differences between measurement points within a classroom were smaller. Additionally, t_{delay} appears to be largely independent of the emission source (E1 or E2).

Deliverable Work package 2

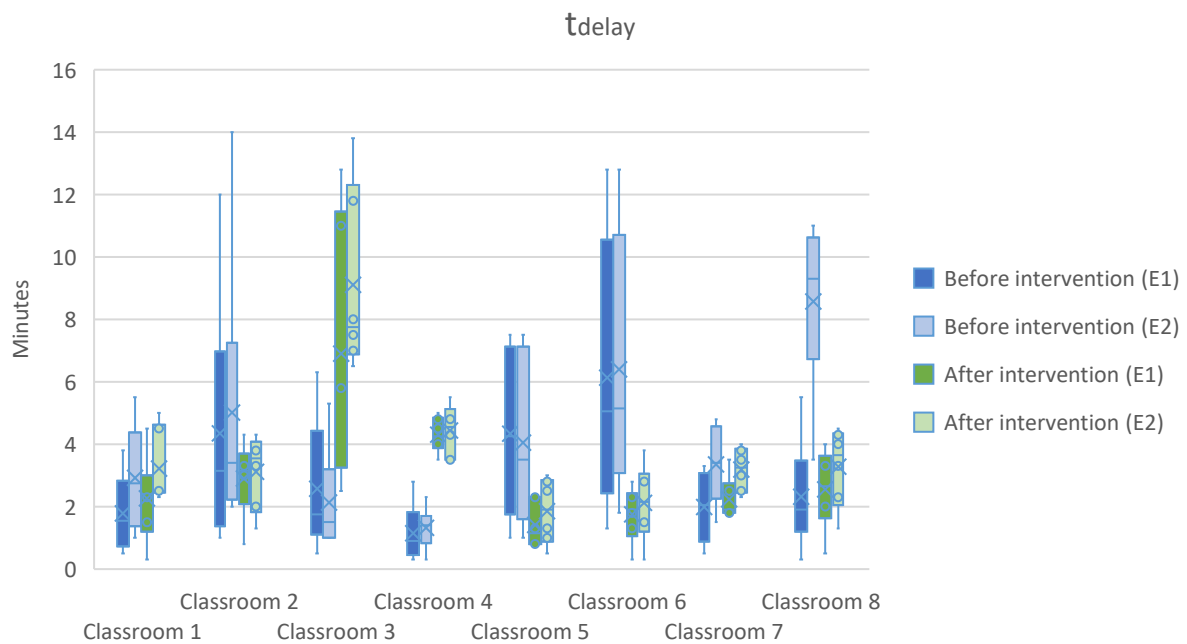


Figure 10. Boxplot of t_{delay} in primary schools at 8 classrooms for the different locations of emission (E1 and E2) both before and after the intervention was implemented.

In two classrooms, measurements were conducted using an air cleaner as second intervention. In classroom 2, the air cleaner was tested at two different settings (setting 1: 600 m³/h (Annex B, intervention A) and setting 2: 2100 m³/h (Annex B intervention B)), in classroom 3, the air cleaner was set to 400 m³/h (Annex C, intervention A). Figure 11 presents the 100-fold recovery time, showing that this time is shorter after the introduction of an air cleaner compared to before the intervention. However, when ventilation supply rates are comparable, replacing the ventilation system appears to be more effective than using an air cleaner for removing particles from the room.

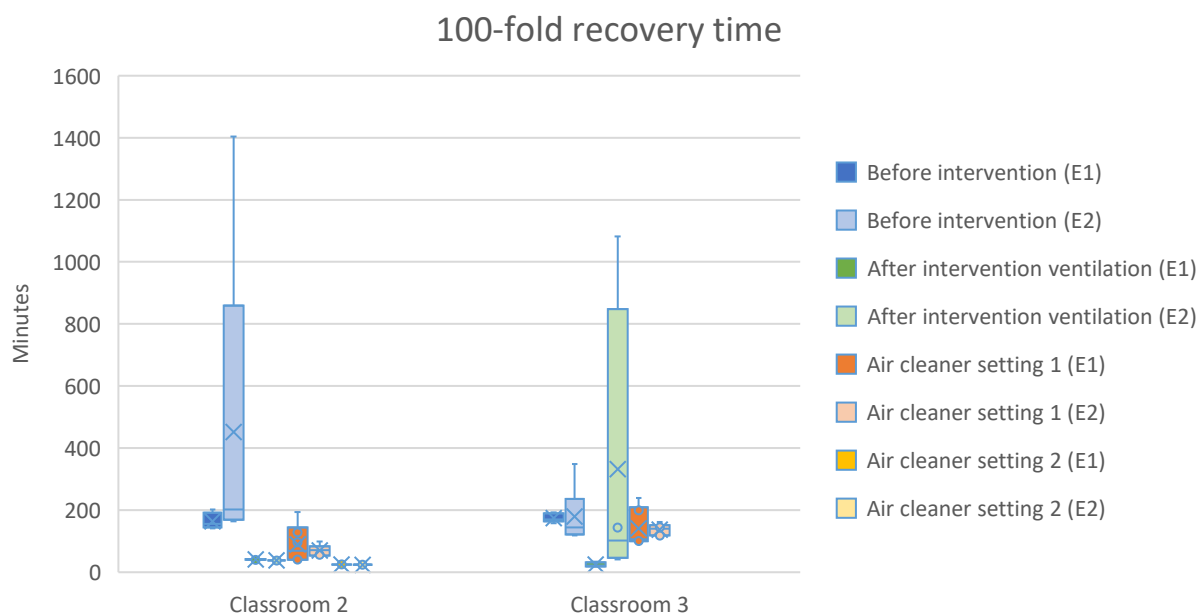


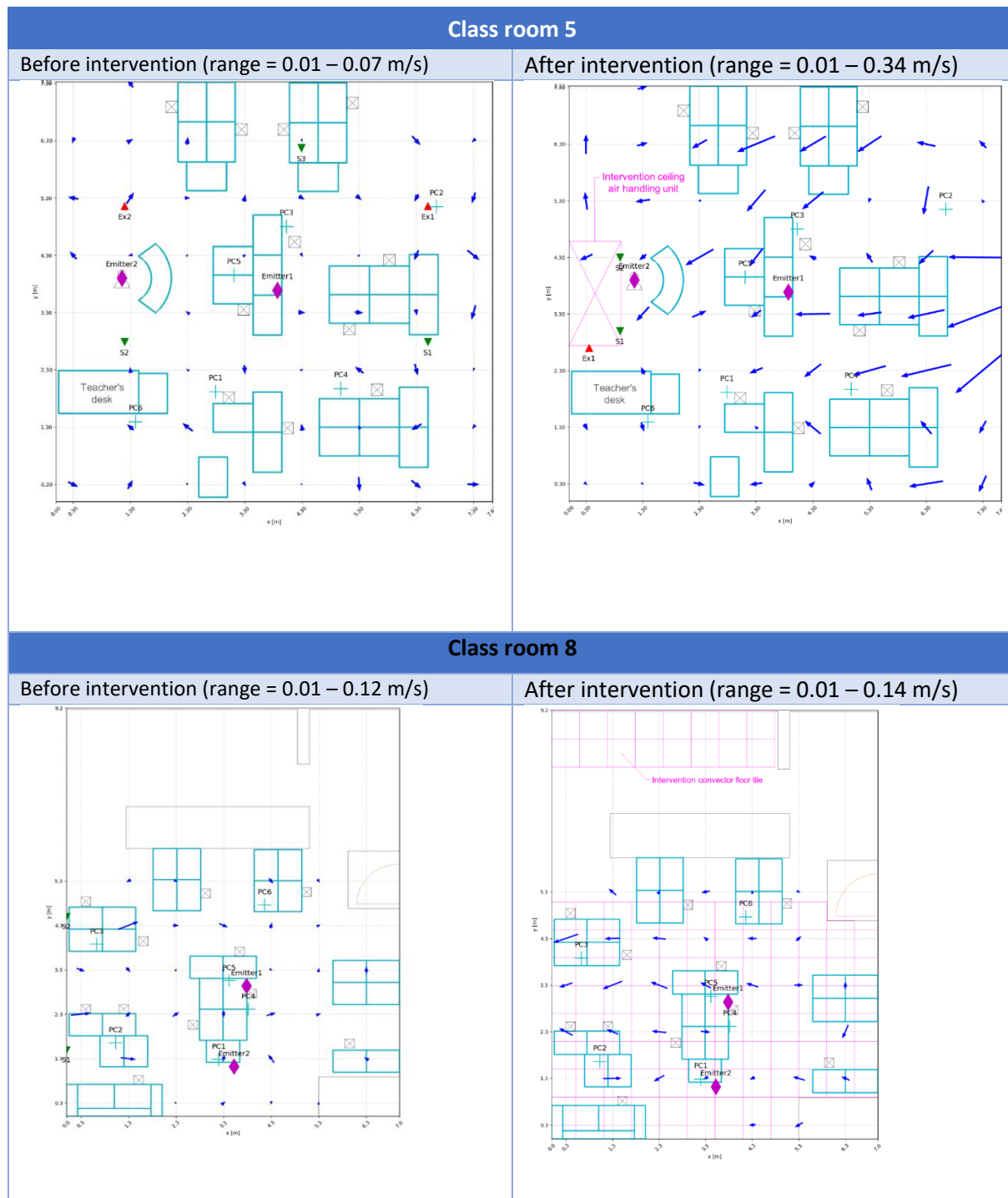
Figure 11. 100-fold recovery time before and after intervention and with air cleaners present for two different settings (in case of classroom 2).

In addition to particle measurements, airflow measurements were conducted in eight classrooms. The measurement positions were set at the same heights as the particle counters during the particle measurements, allowing for a direct comparison between the two methods. A detailed description of the airflow measurements can be found in Annex A – H. Table 1 presents the airflow velocity and direction at a height of 1.0 meter for selected locations. Air velocities lower than 0.01 m/s are not displayed in the figures.

Before the intervention, the low air velocities made it difficult to identify a dominant airflow, regardless of whether the ventilation system was natural or had a mechanical component with a low capacity. After the intervention, most locations exhibited a more pronounced airflow within the room, often accompanied by higher air velocities. However, the height of the air velocity largely depends on the specific mechanical ventilation system installed, particularly the capacity and positioning of the air supply and exhaust. The air velocities are highest for classroom 5 with a maximum of 0.34 m/s, these high air velocities could result in a draft at the back of the classroom.

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Table 1. Comparison flow measurements before and after intervention in classrooms 5 and 8.



5. Conclusions

Measurements were conducted before and after intervention regarding the ventilation system in eight primary school classrooms. Prior to the intervention, six of these classrooms relied on natural ventilation systems, while one had mechanical supply and exhaust ventilation with low capacity, and another had mechanical exhaust with natural supply ventilation. After the intervention, all classrooms were equipped with mechanical supply and exhaust ventilation systems, type D.

Ventilation system upgrades led to faster and more uniform particle removal. Compared to the situation before intervention, the situation after intervention showed a notable reduction in recovery time, indicating improved flushing of airborne contaminants. It also showed a reduced variability between measurement points within classrooms, suggesting more homogeneous air distribution post-intervention. This confirms that the interventions not only improved average performance but also enhanced consistency across different areas in the room.

It is challenging to draw concise conclusions from the 100-fold increase time. Overall, the 100-fold increase time was longer in five out of eight classrooms post-intervention, this could indicate that particles were less likely to reach distant or low-airflow zones quickly. Furthermore, it could indicate that improved ventilation may have prevented widespread particle dispersion, keeping contaminants closer to the source and enhancing localized removal. This shift indicates a more controlled and targeted airflow environment, contributing to better infection control strategies.

Deliverable Work package 2

6. Appendices

Table 1 - Characterization of the classrooms

Class room												
		1	2			3		4	5	6	7	8
Floor area		56.3 m ²	50.7 m ²			48.7 m ²		57 m ²	55.5 m ²	56.3 m ²	56.3 m ²	64.4 m ²
Height		3-4 m	2.5-3.5 m			3.2 m		3.2 m	3.3-4.2 m	3 m	3 m	4.1 m
Orientation facade		South-West	West			West		South	North-East	East	South	North-East
Built in		1990	1989			1931		1972	1921	1980	1981	1882
Number of students including staff		26	26			31		26	32	21	26	26
Ventilation system	Before intervention	natural	natural			natural		natural	mechanical supply and exhaust	natural supply and mechanical exhaust	natural	natural
	After intervention	mechanical	mechanical			mechanical		mechanical	mechanical	mechanical	mechanical	mechanical
Fenestrations	Before intervention	3 tilt and turn windows	2 window grills			3 window grills		4 tilt windows	2 supply ceiling grills and 2 exhaust ceiling grill	3 window grills and 1 exhaust ceiling grill	3 tilt windows and 2 roof vents	2 tilt and turn windows
	After intervention	2 supply grills and 1 exhaust grill	4 supply grills and 2 exhaust ceiling grill	Air cleaner	Air cleaner	Raised floor with air socks and ceiling panels	Air cleaner	2 supply grills and 1 ceiling grill	2 supply grills and 1 exhaust grill	2 supply grills and 1 exhaust grill	4 supply ceiling grills and 4 exhaust ceiling grills	Raised floor with air socks and ceiling panels
Amount of supply air	Before intervention	-	-			-		-	256 m ³ /h	195 m ³ /h	-	-
	After intervention	Design capacity: 796 m ³ /h	Design capacity: 796 m ³ /h	600 m ³ /h	2100 m ³ /h	715 m ³ /h	400 m ³ /h	Design capacity: 796 m ³ /h	Design capacity: 979 m ³ /h	Design capacity: 796 m ³ /h	721 m ³ /h	1034 m ³ /h
Measured situation	Before intervention	Windows all open (tilted), door closed	Window grills all open, windows and door closed.			Window grills all open, windows and door closed.		Windows all open (tilted), door closed	Windows and door closed	2 of the 3 window grills open, windows and door closed	2 of the 3 windows open, door closed	Windows all open and the doors were closed
	After intervention	Windows and door closed	Windows, window grills and door closed	Windows and door closed,	Windows and door closed, window	Windows, window grills and	Window grills open, windows	Windows and door closed	Windows and door closed	Windows, window grills and door closed	Windows and door closed	Windows and door closed

Deliverable Work package 2

Class room																
1			2		3		4		5		6		7		8	
				window grills open	grills open	door closed	and door closed.									

Table 2. Characterization of the indoor and outdoor conditions.

Class room																		
		1		2		3			4		5		6		7		8	
		Before	After	Before	After	Before	After (1)	After (2)	Before	After	Before	After	Before	After	Before	After	Before	After
Surface area temperature	Wall (North)	26.4	18.4	23.9	21.8	26.0	28.1	17.4	24.3	18.9	23.6	18.2	26.3	22.0	21.8	16.8	17.0	19.8
	Wall (East)	26.0	16.6	23.0	22.2	26.3	27.3	16.4	24.7	18.6	23.8	19.3	27.3	20.9	22.3	17.0	17.7	19.5
	Wall (South)	25.0	16.5	24.5	22.6	26.8	27.2	15.4	24.0	18.9	24.2	19.2	26.5	21.8	22.1	16.3	18.2	19.5
	Wall (West)	26.3	17.6	23.2	21.8	26.4	27.9	15.8	24.6	23.2	24.1	19.2	26.2	21.8	21.8	16.4	18.1	20.0
	Ceiling	27.0	18.4	24.3	22.4	26.3	28.1	16.8	24.9	17.2	24.1	19.8	27.6	22.1	23.5	18.4	18.9	20.7
Air temperature	Floor	25.3	17.1	22.5	22.0	24.1	27.0	15.0	23.3	20.3	24.3	19.5	25.8	22.0	23.4	18.1	18.4	21.1
	Min	18.5	16.6	18.7	22.2	24.1	24.8	16.4	23.5	16.7	20.2	19.8	23.3	21.6	17.2	17.3	16.3	16.2
	Mean	26.4	18.8	22.6	24.4	25.7	27.8	17.3	25.9	18.8	25.2	20.9	26.6	23.8	21.9	20.6	18.5	20.4
Relative humidity	Max	27.9	19.8	25.9	26.5	26.6	29.6	18.0	27.6	20.2	26.4	21.5	29.4	27.8	24.6	25.9	19.8	21.9
	Min	40.1	63.2	58.9	48.7	52.0	50.4	55.3	39.0	48.2	35.5	50.4	48.6	52.2	51.8	60.5	63.4	55.3
	Mean	42.8	67.0	65.6	56.6	54.9	53.7	58.1	42.3	54.8	42.2	57.3	55.8	63.5	56.8	71.0	69.6	61.3
Outdoor air temperature	Max	55.3	71.1	73.3	60.6	59.5	57.5	62.5	47.4	63.6	55.4	66.3	68.6	71.3	66.4	77.5	79.8	76.2
	Min	10.2	5.3	11.7	11.5	16.6	16.3	4.9	11.8	7.4	12.9	7.3	15.4	10.4	11.7	12.9	9.7	9.7
	Mean	20.6	11.3	16.2	17.8	18.7	21.4	8.8	19.7	8.6	20.6	14.3	20.3	16.9	15.5	15.6	11.5	11.5
Outdoor relative humidity	Max	27.2	15.4	21.0	23.8	22.0	26.3	10.8	26.3	9.6	27.1	19.8	24.9	21.5	19.9	17.9	21.5	21.5
	Min	28	66	53	49	48	53	82	30	85	20	45	39	66	61	79	87	87
	Mean	54	85	79	74	72	66	88	54	93	48	72	65	79	77	88	93	93
Wind velocity	Max	94	99	99	97	90	81	94	98	95	82	98	92	92	93	96	98	98
	Min	0.5	3.0	1.5	1.0	4.0	2.3	2.0	0.8	3.0	1.0	2.0	1.5	3.0	2	3.0	3.0	3.0
	Mean	1.8	7.4	2.8	1.8	6.5	4.4	4.4	2.3	6.3	3.0	3.0	3.0	4.2	7.4	4.3	5.8	5.8
Wind direction	Max	4.0	12.0	5.0	3.0	8.0	7.0	7.0	5.0	7.0	5.0	6.0	6.0	6.0	12	5.0	8.0	8.0
		North East	South West	West	South South West	West South West	West South West	West	North East	South	North East	North West	West	West	West South West	South South East	South South West	South South West

Deliverable Work package 2

		Air cleaner			
Measuring					
	location	E1	E2	E1	E2
classroom 1	1	3,46E+07	3,39E+07		
	2	1,40E+07	2,46E+07		
	3	2,72E+07	4,10E+07		
	4	1,27E+07	2,59E+07		
	5	1,35E+07	3,06E+07		
	6	1,67E+07	4,86E+07		
classroom 2	1	4,17E+07	3,99E+07	2,99E+07	3,56E+07
	2	4,39E+07	5,18E+07	3,01E+07	3,15E+07
	3	2,36E+08	5,91E+07	4,82E+07	5,50E+07
	4	3,45E+07	3,45E+07	2,68E+08	7,79E+07
	5	3,33E+07	4,17E+07	1,02E+08	5,79E+07
	6	3,09E+07	3,11E+07	1,17E+08	7,34E+07
classroom 3	1	1,13E+08	4,22E+06	6,19E+07	5,35E+07
	2	4,27E+07	7,05E+06	6,64E+07	6,49E+07
	3	1,09E+07	5,99E+07	4,60E+07	6,90E+07
	4	4,48E+07	5,17E+06	8,79E+07	5,84E+07
	5	1,92E+07	5,86E+06	5,44E+07	1,09E+08
	6	7,15E+06	8,07E+07	4,11E+07	5,34E+07
classroom 4	1	3,67E+07	3,76E+07		
	2	2,92E+07	2,52E+07		
	3	6,22E+07	2,87E+07		
	4	3,54E+07	4,09E+07		
	5	3,38E+07	4,59E+07		
	6	3,23E+07	6,01E+07		
classroom 5	1	2,44E+07	4,19E+07		
	2	2,91E+07	2,37E+07		
	3	2,92E+07	2,25E+07		
	4	2,46E+07	3,11E+07		
	5	1,14E+08	1,93E+07		
	6	2,61E+07	6,14E+07		
classroom 6	1	3,75E+07	4,36E+07		
	2	4,25E+07	4,81E+07		
	3	5,07E+07	6,76E+07		
	4	3,58E+07	4,04E+07		
	5	2,72E+07	2,82E+07		
	6	4,57E+07	6,82E+07		
classroom 7	1	2,44E+07	1,99E+07		
	2	2,16E+07	1,89E+07		
	3	2,43E+07	3,60E+07		
	4	9,08E+07	3,79E+07		
	5	2,71E+07	4,19E+07		
	6	2,08E+07	3,53E+07		
classroom 8	1	2,37E+07	9,30E+06		
	2	9,90E+06	6,73E+06		
	3	9,89E+06	1,31E+07		
	4	7,77E+07	1,13E+07		
	5	1,01E+07	1,19E+07		
	6	1,38E+07	1,77E+07		

Figure 12 Maximum particle concentrations after intervention per measurement location (1-6) per classroom (1-8) per emitter location (E1, E2). The deviation from the average concentration per classroom is indicated with a red bar; locations with longer bars can be seen as critical locations.

ANNEXES A-H

ANNEX A, RESULTS CLASSROOM 1

Experiments in-situ

WP2, experiments after interventions

DATUM 08-02-2024

AUTEURS Ir. A. de Lange

ORGANISATIE TNO

1. Results baseline measurement location classroom 1

The results discussed in this report include both the situation before and after the interventions. The intervention was initiated by the primary school to optimize or adapt the ventilation system.

The interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system regarding capacity, function or system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes that are reported (before and after the intervention).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of ventilation window grills and openable windows and doors. In this location the windows were opened and the door was closed during the measurements.

For this location the intervention consists of the replacement of the ventilation system: new, different or updated system regarding capacity, function or system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). The new system consists of a balanced CO₂ controlled ventilation system with heat recovery. The heat recovery unit that has been installed has a heat recovery efficiency of 90%. The unit is designed to meet the requirements for Class B of 'PvE Frisse Scholen 2021' and has a (design) capacity of 795 m³/h based on 25 students and one teacher.

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1.1 Characteristics of room and system

Description of the room

The school is located in a suburban environment and was originally built in 1990. The classroom that was considered during this analysis, has a surface area of 56.3 m² and was located on the ground floor. The façade was orientated towards the South-West and the height of the room was between 3.0 and 4.0 m. At the time of the measurements, this room was designed for appr. 25 students and one teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has four tilt and turn windows and a door which can be opened (see Figure 1-2). The same applies for the exhaust of air. It should be noted that during the measurement period two of the four windows were opened and the door was closed. An overview of the ventilation system can be seen in Table 1.1.

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	2 openable windows	N/A
	Total	N/A
Ventilation (exhaust)		
	2 openable windows	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 W. There were, furthermore, 11 static heat sources that each emit 80 W representing the children in the classroom. In general, humans are the main emitter and receiver of particles, which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements followed the same method except the difference in the ventilation system.

The particle counters (PC), PC1, PC2, PC3, PC4 and PC5 were located at 1.0 m height since this represents the breathing zone of sitting children. PC6 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at a height of 1.6 m near the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.37 to 3.0 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 58 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

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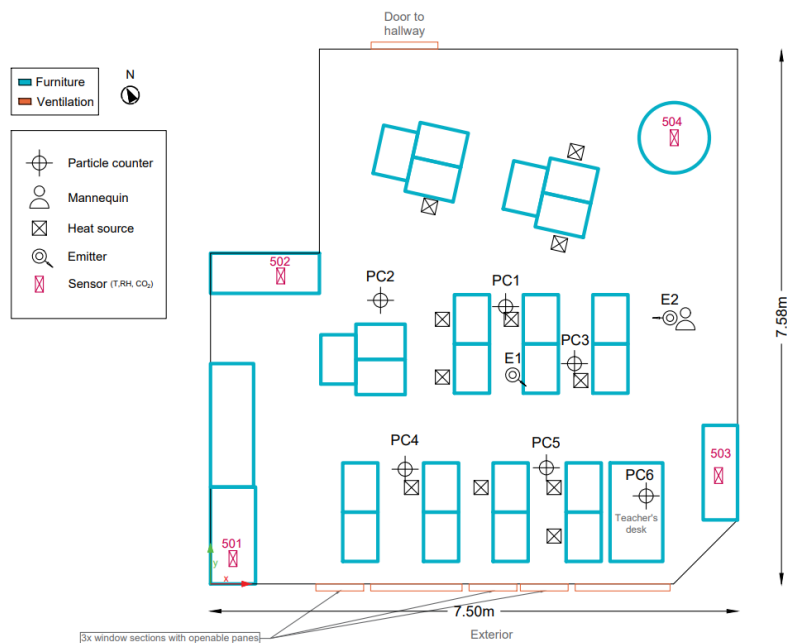


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

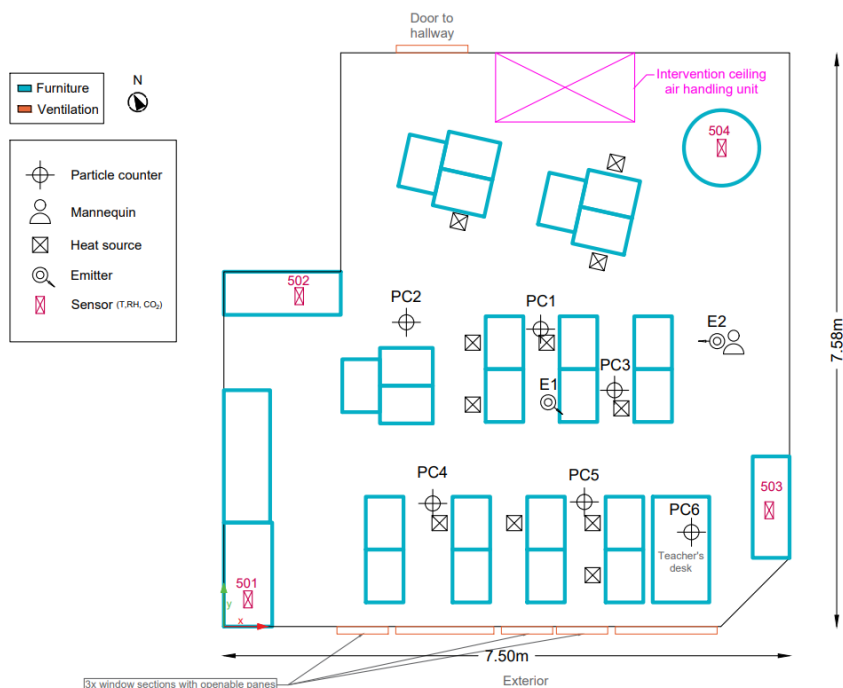


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

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2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 18.5 and 27.9 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: East, Wall 2: South, Wall 3: West, Wall 4: North. Meteorological data is from weerstatistieken.nl of a nearby weather station.

17-06-2023				
Surface area temperature (°C)		11:30	15:00	
	Wall 1	25.5	26.4	
	Wall 2	24.6	25.5	
	Wall 3	25.4	27.2	
	Wall 4	25.7	27.0	
	Ceiling**	26.0	27.9	
	Floor	25.0	25.5	
	Glass surface of the windows	25.5	28.0	
		Min*	Mean*	Max*
Air temperature (°C)		18.5	26.4	27.9
Relative humidity (%)		40.1	42.8	55.3
Outdoor air temperature (°C)		10.2	20.6	27.2
Outdoor relative humidity (%)		28	54	94
Wind	Velocity (m/s)	0.5	1.8	4.0
	Direction	North-East (52°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-19:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

** Ceiling is 17.8 °C at the highest point of the room and 26.0 °C in the middle of the room (in the morning) and 29.9 °C at the highest point of the room and 27.9 °C in the middle of the room (in the afternoon).

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 of the main report are calculated for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 3.6 – 23.2 min for emitter location E1 and has a range of 9.7 – 35.7 min for emitter location E2. The 100-fold increase time is the longest at emitter location E2 for PC4, PC5 and PC6 (29.1, 28.4 and 35.7 min). These particle counters are all located near the window at an angle from the emitter. This indicates that the increase of the particle concentration goes slower near the window. The 100-fold increase time is the shortest for PC3 emitter

Deliverable Work package 2

location E1 (3.6 min). This particle counter is located in close proximity to the emitter E1 which means that the particles can reach this particle counter relatively faster.

The 100-fold recovery time has a range of 52.4 – 107.0 min for emitter location E1 and has a range of 60.8 – 101.7 min for emitter location E2. The 100-fold recovery time is the longest at location PC4 for both emitter location E1 and E2 (103.3 and 101.7 min) and at PC2 at emitter location E1 (107.0). Both locations also have a more gradual increase in the particle concentration during the emission period (long 100-fold increase time). The shortest 100-fold recovery time is at PC5 and PC6 for emitter location E1 (56.5 and 52.4 min).

The air change rate per hour (ACH) is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called ‘Programma van Eisen frisse scholen’, these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a ‘Sufficient’ air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a ‘Good’ air quality, this requires a ventilation rate of 30.6 m³/h per person. When 25 children and one teacher are taken into account, this results in a ventilation rate of 562 m³/h (2.9 ACH) for a Class C and 796 (4.0 ACH) m³/h for Class B. When these recommendations are compared with the ACH values in Table 2.2, it can be seen that Class B is met at PC5 and PC6 for both emitter locations and at PC1 and PC3 for emitter location E1. Class C is met at all locations except at PC4 for both emitter locations and at PC2 for emitter location E1.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.5 – 3.8 min for emitter location E1 and has a range of 1.0 – 5.5 min for emitter location E2. t_{delay} is the longest for PC4 emitter location E2 (5.5 min). This location also had a long 100-fold recovery time and 100-fold increase time. For PC4 emitter location E1, however, t_{delay} is 2.3 min while the 100-fold recovery time is similar to PC4 E2. This indicates that at this location the decrease in the particle concentration starts sooner after the emission stopped but the actual decrease is similar to PC4 E2. t_{delay} is shortest for PC1, PC3 and PC6 emitter location E1 (0.8, 0.5 and 0.8 min). Specifically for PC3, the emitter is located very close to this location which results in a high particle concentration at the end of the emission period.

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Table 2.2 - Overview of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at six different measurement locations and for two different emitter locations.

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	10.1	69.0	4.0	0.8
	E2	13.1	72.4	3.8	1.0
PC2	E1	20.2	107.0	2.6	3.8
	E2	18.9	76.8	3.6	1.5
PC3	E1	3.6	66.0	4.2	0.5
	E2	9.7	80.7	3.4	3.0
PC4	E1	23.2	103.3	2.7	2.3
	E2	29.1	101.7	2.7	5.5
PC5	E1	11.0	56.5	4.9	2.5
	E2	28.4	60.8	4.5	4.0
PC6	E1	10.5	52.4	5.3	0.8
	E2	35.7	63.8	4.3	2.5

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.07 m/s).

In Figure 2-1, it can be seen that there is an air flow from the walls of the room towards the center of the room. There is no dominant air flow from the windows into the room at a height of 1.0 m. The air velocity is most prominent in the center of the room (highest velocity) and is the lowest near the windows. There is an air flow from E1 towards PC1 and there seems to be a smaller air flow towards PC3. For location E2, there is an air flow with low velocities away from the emitter but this is not a dominant flow.

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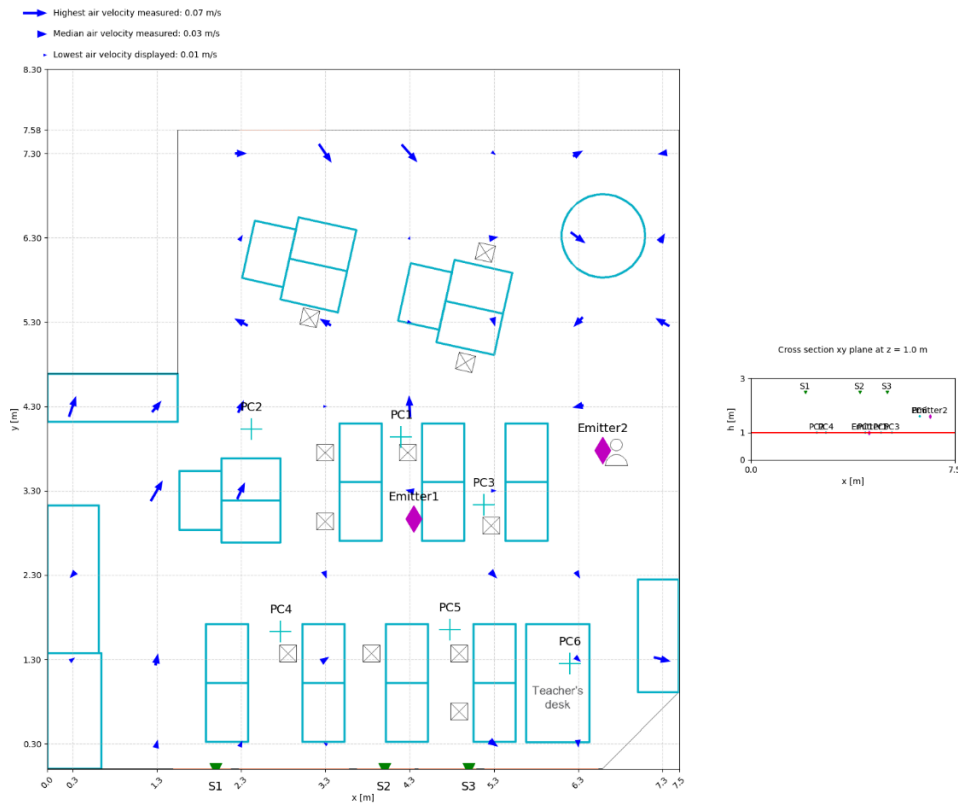


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analysed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.07 m/s). In this figure the air flow from the windows is more dominant (higher velocities). Furthermore, the air velocities at the other side of the room are smaller compared to the air velocities at a height of 1.0 m. Specifically for PC6, there is an air flow from E1 towards PC6 and an air flow with lower velocities from the windows that might also pass PC6.

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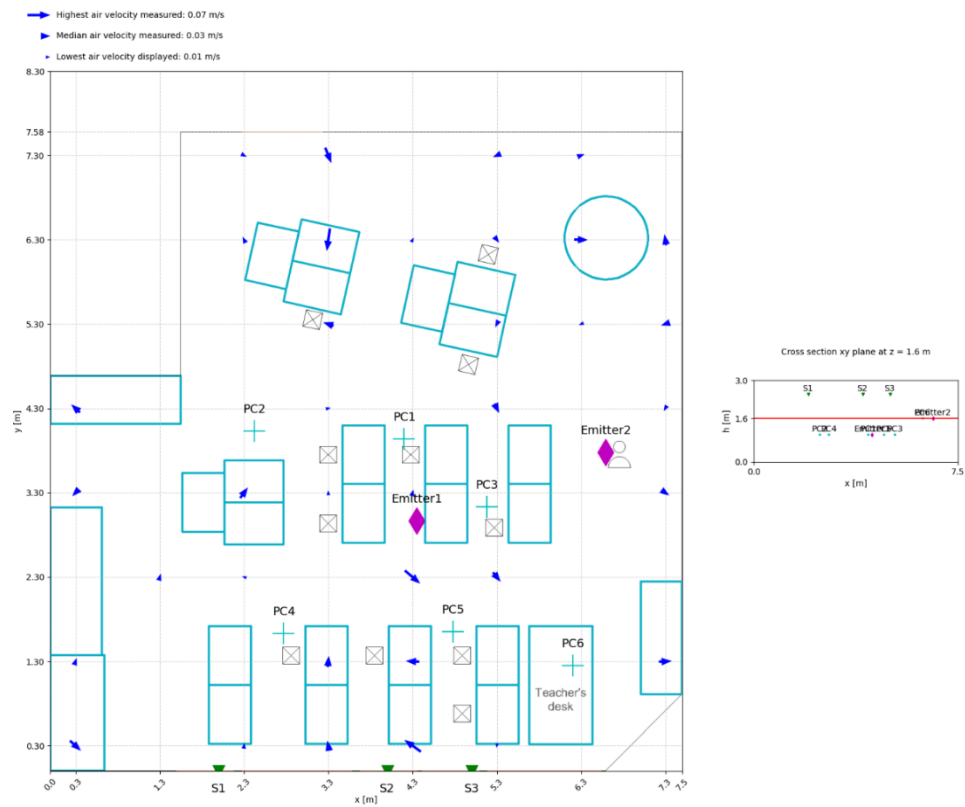


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

Deliverable Work package 2

3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system is CO₂-controlled. For air supply, the classroom has two supply grilles and one exhaust grille. Due to the design (shape) and the height of the ventilation system, it was not possible to measure the air flow rate at the supply and the exhaust of air in the room. Furthermore, four openable windows are present in the room. It should be noted that these windows and the door were closed during the measurements. Table 3.1 presents an overview of the ventilation system.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Ceiling grille	N/A
	Ceiling grille	N/A
	Total	N/A
Ventilation (exhaust)		
	Ceiling grille	N/A
	Total	N/A



Figure 3-1 – Ventilation system after intervention

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements are presented in Table 3.2. The room temperature was between 16.6 and 19.8 °C throughout the day.

Deliverable Work package 2

Table 3.2 - Conditions during the measurement period. Wall 1: East, Wall 2: South, Wall 3: West, Wall 4: North. Meteorological data is from weerstatistieken.nl of a nearby weather station.

13-11-2023				
Surface area temperature (°C)		10:30	14:00	
	Wall 1	16.1	17.1	
	Wall 2	16.1	16.8	
	Wall 3	17.2	17.9	
	Wall 4	18.2	18.6	
	Ceiling*	18.2	18.6	
	Floor	16.7	17.5	
	Glass surface of the windows	17.9	18.7	
		Min**	Mean**	Max**
Air temperature (°C)		16.6	18.8	19.8
Relative humidity (%)		63.2	67.0	71.1
Outdoor air temperature (°C)		5.3	11.3	15.4
Outdoor relative humidity (%)		66	85	99
Wind	Velocity (m/s)	3.0	7.4	12.0
	Direction	South-West (221°)		

* Ceiling is 18.6 °C at the highest point of the room and 18.2 °C in the middle of the room (in the morning) and 19.0 °C at the highest point of the room and 18.6 °C in the middle of the room (in the afternoon).

** The mean value is calculated by taking the average values of all four sensors between 10:00-16:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) in the situations both before and after the intervention. The 100-fold increase time has a range of 7.8 – 137 min for emitter location E1 and has a range of 21.4 – 107 min for emitter location E2. The 100-fold increase time is relatively long at almost all locations, this could be related to the relatively low particle concentrations that reach each measurement location. The 100-fold increase time is longest for PC4 at emitter location E1 (137 min). The 100-fold increase time is shortest for PC3 at emitter location E1 (7.8 min) which could be explained by the small distance between emitter location E1 and PC3.

The 100-fold recovery time has a range of 58.3 - 61.9 min for emitter location E1 and has a range of 61.5 – 78.5 min for emitter location E2. The range for the 100-fold recovery time is small, which indicates that the decrease rate of the particle concentration is similar at different locations in the

Deliverable Work package 2

room (homogeneous). The 100-fold recovery time is always longer at emitter location E2 compared to emitter location E1 which could be explained by the direction of the air flow in the room.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'Sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'Good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When 25 children and 1 teacher are taken into account, this results in a ventilation rate of 562 m³/h (2.9 ACH) for Class C and 796 m³/h (4.0 ACH) for Class B. When these values are compared with the ACH values in Table 3.3 (ACH 3.5 – 4.7), it can be seen that all values meet the requirements for Class B, except PC2 and PC4 at emitter location E2; they meet Class C.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.3 – 4.5 min for emitter location E1 and has a range of 2.3 – 5.0 min for emitter location E2. t_{delay} is the longest at PC2 for both emitter locations (4.5 min) and at PC1 emitter location E1 (5.0 min). At PC2, the 100-fold increase time was also long, which could indicate that the overall particle concentration is low at this location. t_{delay} is the shortest for PC3 emitter location E1 (0.3 min). At this location, the 100-fold increase time was also the shortest. This indicates that the increase at this location is quick after the emission started.

Table 3.3 - Overview of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before and after the intervention, and for both emitter locations.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	10.1	15.5	69.0	59.7	4.0	4.6	0.8	1.5
	E2	13.1	50.8	72.4	66.7	3.8	4.1	1.0	5.0
PC2	E1	20.2	107.7	107.0	59.0	2.6	4.7	3.8	4.5
	E2	18.9	107.5	76.8	78.5	3.6	3.5	1.5	4.5
PC3	E1	3.6	7.8	66.0	58.3	4.2	4.7	0.5	0.3
	E2	9.7	47.1	80.7	61.5	3.4	4.5	3.0	2.5
PC4	E1	23.2	137.5	103.3	61.9	2.7	4.5	2.3	2.5
	E2	29.1	78.1	101.7	71.3	2.7	3.9	5.5	2.5
PC5	E1	11.0	107.6	56.5	59.5	4.9	4.6	2.5	2.3
	E2	28.4	52.0	60.8	68.5	4.5	4.0	4.0	2.3
PC6	E1	10.5	41.3	52.4	59.1	5.3	4.7	0.8	2.5
	E2	35.7	21.4	63.8	64.8	4.3	4.3	2.5	2.3

Deliverable Work package 2

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and the velocity at this height can be seen in Figure 3-2 (range 0.01 – 0.24 m/s).

In Figure 3-2 it is visualized that the air velocities are highest near the windows of the classroom and are directed towards the ventilation system. The air flows are lowest near the ventilation system at this height. Specifically for the particle counters, there is an air flow from both emitter locations towards PC1 and PC3. Furthermore, there is a dominant air flow near PC4 and PC5 which is directed away from the particle counters towards the emitter locations.

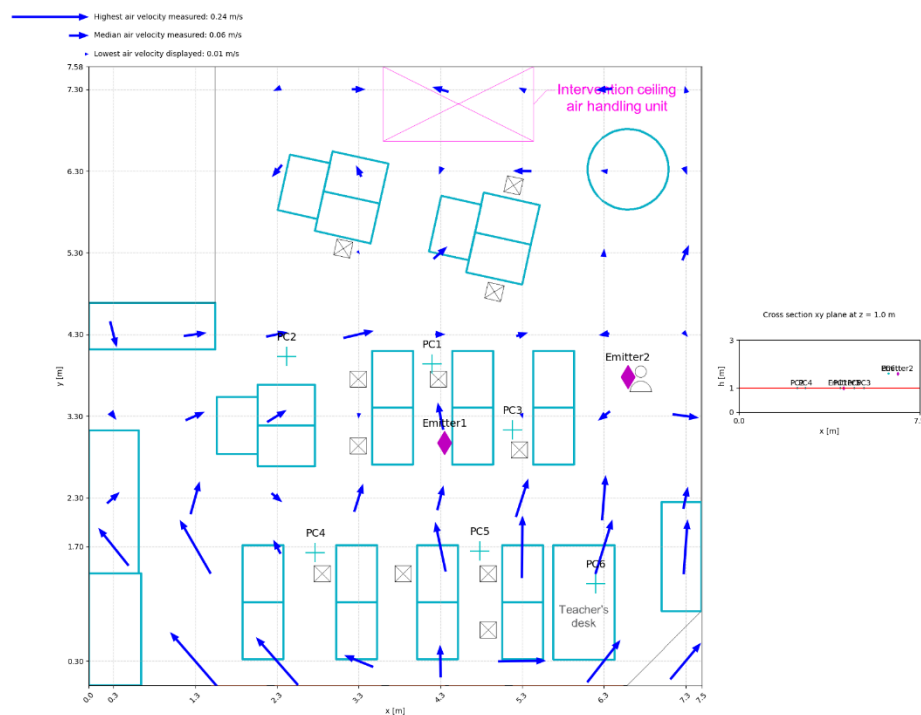


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 3-3 (range 0.01 – 0.13 m/s). In this figure, it can be seen that the air velocities are lower at this height and the direction of the air flow is less dominant. When both figures are compared, it becomes clear that the direction of the air flow can be significantly different at different heights in the room. At the height of 1.6 m, there is an air flow towards the windows but there is also an air flow in the direction of the ventilation system. The air velocities are still lowest in close proximity to the ventilation system. Specifically for PC6, it seems that

Deliverable Work package 2

there is an air flow from PC6 directed away from the particle counter in the direction of Emitter location E2.

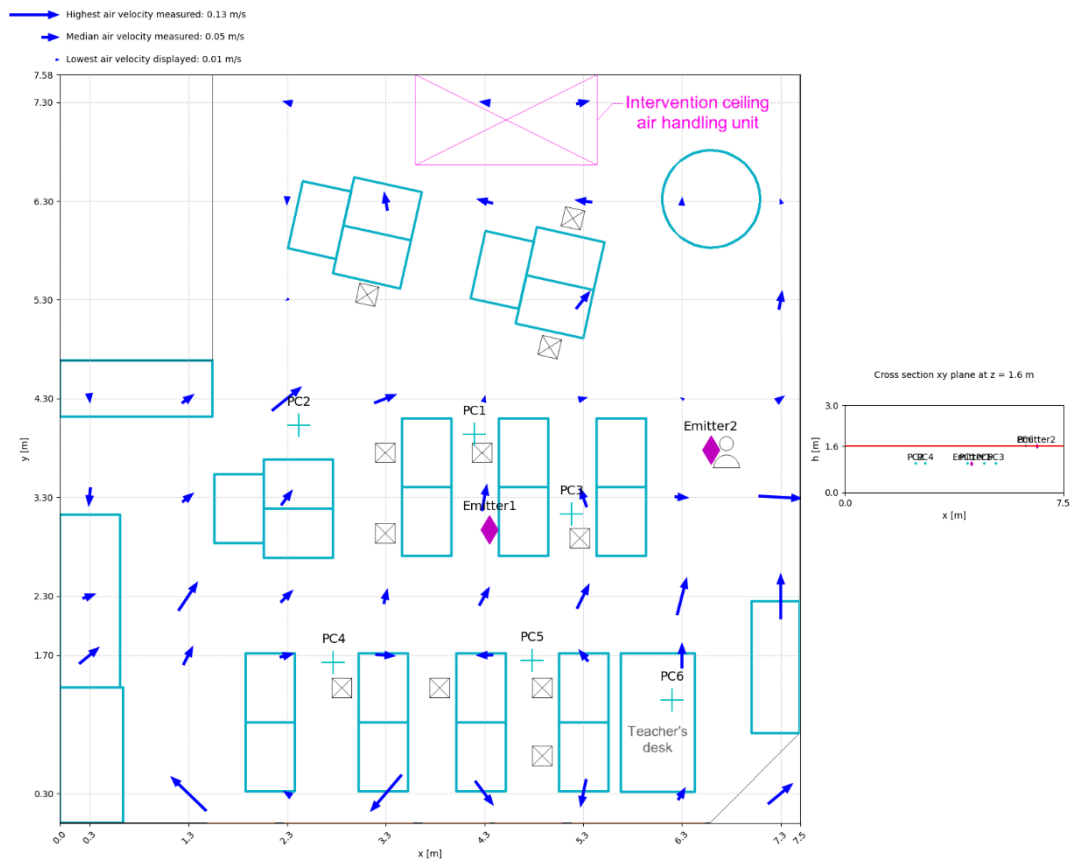


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

Deliverable Work package 2

4. Conclusions

This section describes the performances of the ventilation systems before and after the intervention and compares them through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before the intervention, the 100-fold increase time has a range of 3.6 – 23.2 min for emitter location E1 and has a range of 9.7 – 35.7 min for emitter location E2. After intervention, the 100-fold increase time has a range of 7.8 – 137.5 min for emitter location E1 and has a range of 21.4 – 107.5 min for emitter location E2. After the intervention, the range of the 100-fold increase time is larger and the 100-fold increase time is (in general) longer (Figure 4-1). This could be explained by the direction of the air flow in the room (Figure 3-2). After the intervention, the direction of the air flow from emitter locations E1 and E2 is in the direction of the exhaust of the ventilation system and not in the direction of most of the particle counters. This results in a low particle concentration at the particle counters and therefore a long 100-fold increase time.

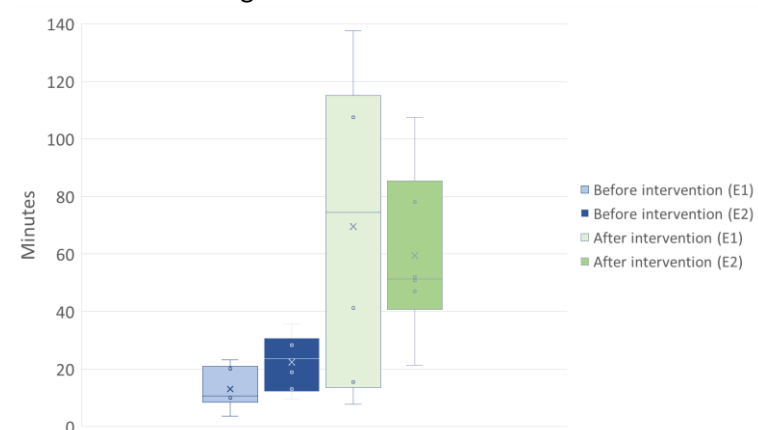


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before the intervention, the 100-fold recovery time has a range of 52.4 – 107.0 min for emitter location E1 and has a range of 60.8 – 101.7 min for emitter location E2. After the intervention, the 100-fold recovery time has a range of 58.3 – 61.9 min for emitter location E1 and has a range of 61.5 – 78.5 min for emitter location E2. The 100-fold recovery time is (in general) shorter, especially the long recovery times have been reduced. The 100-fold recovery time also has a smaller range after the intervention took place. This indicates that there is more homogeneous mixing in the classroom (Figure 4-2).

Deliverable Work package 2

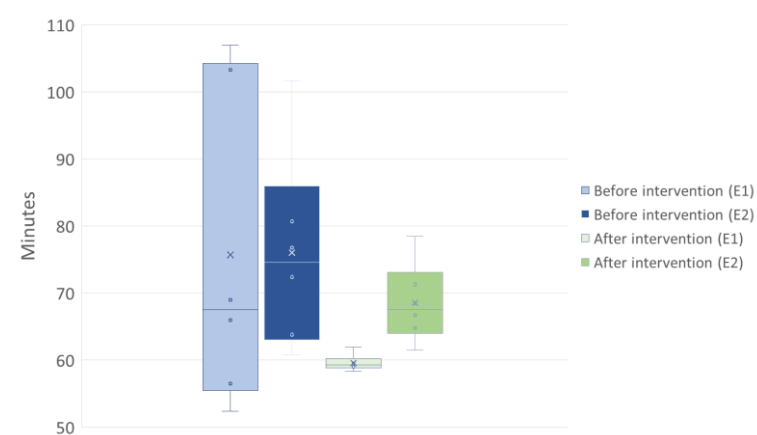


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before the intervention, t_{delay} has a range of 0.5 – 3.8 min for emitter location E1 and has a range of 1.0 – 5.5 min for emitter location E2. After the intervention, t_{delay} has a range of 0.3– 4.5 min for emitter location E1 and has a range of 2.3 – 5.0 min for emitter location E2. The values for t_{delay} have a similar range before and after the intervention. Specifically, PC1 and PC2 at emitter location E2 have a longer t_{delay} after the intervention while PC4 and PC5 (E2) have a shorter t_{delay} after the intervention. This could be related to the air flow which is highest near PC4 and PC5 which means the particle concentration rises quickly after the emission starts.

Air change per hour

Before the intervention, the air change rate is 2.6 – 4.9 ACH for emitter location E1 and 2.7 – 4.5 ACH for emitter location E2. After intervention, the air change rate is 4.5 – 4.7 ACH for emitter location E1 and 3.5 – 4.5 ACH for emitter location E2. The range between the different measurement points is smaller after the intervention took place, this indicates that the possible exposure to particles is similar at different locations in the room. Before the intervention, Frisse Scholen Class B was met at PC5 and PC6 for both emitter locations and at PC1 and PC3 for emitter location E1. After the intervention, Class B is met at all locations except PC2 and PC4 at emitter location E2.

4.2 Air flow measurements

Before the intervention took place, the highest air velocities were found from the walls towards the center of the classroom, but there was no dominant air flow present from the (open) windows into the room.

The particle concentration measurements and the air flow measurements show that the air velocities are lowest near the window which could explain the relatively long 100-fold increase time for the particle counters near the windows (PC4, PC5 and PC6). Furthermore, the air flow is (in general) less dominant from emitter location E2 which could explain the (in most cases) longer 100-fold increase time and t_{delay} at the particle counters.

After the intervention, there is a dominant air flow from the windows in the direction of the ventilation system. Furthermore the air velocities are lowest near the ventilation system both at a height of 1.0 m

Deliverable Work package 2

and a height of 1.6 m. Overall, the velocities are lower at a height of 1.6 m compared to the height of 1.0 m.

The particle concentration measurements and the air flow measurements show that the air velocities are higher after intervention which explains the shorter 100-fold recovery time. Furthermore, the air flow is directed away from PC4 and PC5 which could explain the relatively long 100-fold increase time at these locations. Furthermore, there is also an air flow directed away from PC2 in the direction of PC1 which could explain the long 100-fold increase time at location PC2.

In conclusion, when both ventilation systems are compared it becomes clear that the air velocities are higher after the intervention. Furthermore, the direction of the air flow is more dominant. Due to this, the particle spread throughout the room has a lower dependence on the proximity of the particle counter to the emission source location. The air flow throughout the room becomes the most dominant factor.

Concluded, due to the intervention the location of the children and teacher in the room becomes a less prominent determinant for possible exposure and the overall risk of exposure is lower.

ANNEX B, RESULTS CLASSROOM 2

Experiments in-situ

WP2, experiments after intervention A

DATUM	08-01-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location classroom 2

The results discussed in this report include both the situation before and after interventions. The intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of ventilation window grills and openable windows and doors. In this location the windows and the doors were closed but the window grills were opened.

In the case of this location, three different interventions were tested. The first two interventions involved the use of a mobile air cleaner. This mobile air cleaner was tested at two different flow settings. At power setting 6, it has a capacity of 2100 m³/h (intervention B) and at power setting 1, it has a capacity of 600 m³/h (intervention B). The second intervention consisted of the replacement of the ventilation system (intervention C): new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). This system consisted of a ventilation system that is connected to the heat pump which is able to heat and cool the room with the ventilation system.

In this report, the mobile air cleaner was placed at the position behind the teacher, near the board, at a flow of 600 m³/h will be discussed as the intervention.

Deliverable Work package 2

1.1 *Characteristics of room and system*

Description of the room

The school is located in a suburban environment and was originally built in 1989. The classroom that was considered during this analysis, has a surface area of 50.7 m² and was located on the ground floor. The façade was orientated towards the West and the height of the room was 2.5-3.5 m. During the measurements, this room was designed for circa 25 students and 1 teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has two window grills which can be opened (see Figure 1-2). The same applies for the exhaust of air. There are, furthermore, two openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

Deliverable Work package 2

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	2 window ventilation grills	N/A
	Total	N/A
Ventilation (exhaust)		
	2 window ventilation grills	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

Deliverable Work package 2

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 W. There were, furthermore, 11 static heat sources that each emit 80 W representing the children in the classroom. In general, humans are the main emitter and receiver of particles, which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements followed the same method except the difference in the ventilation system.

The particle counters (PC), PC1, PC2, PC3, PC4 and PC5 were located at 1.0 m height since this represents the breathing zone of sitting children. PC6 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at a height of 1.6 m near the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.13 to 2.45 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 49 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

Deliverable Work package 2

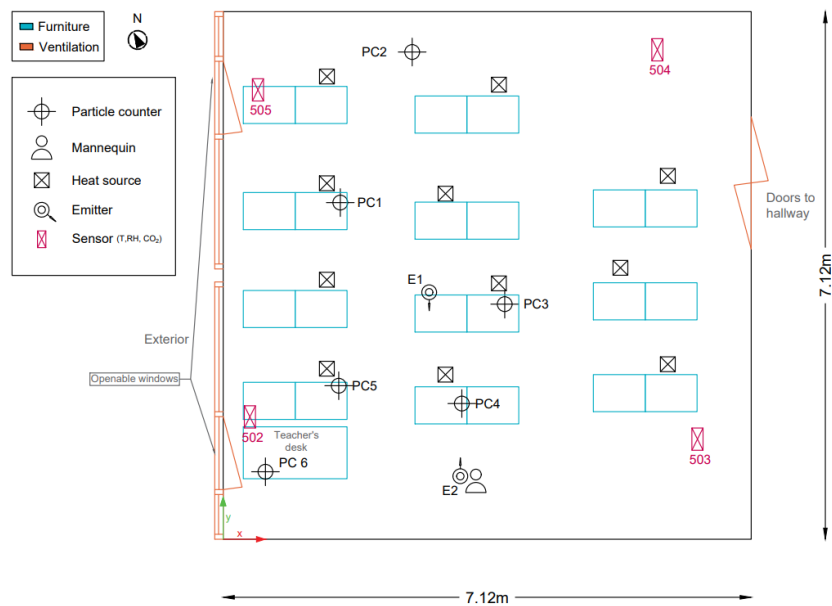


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

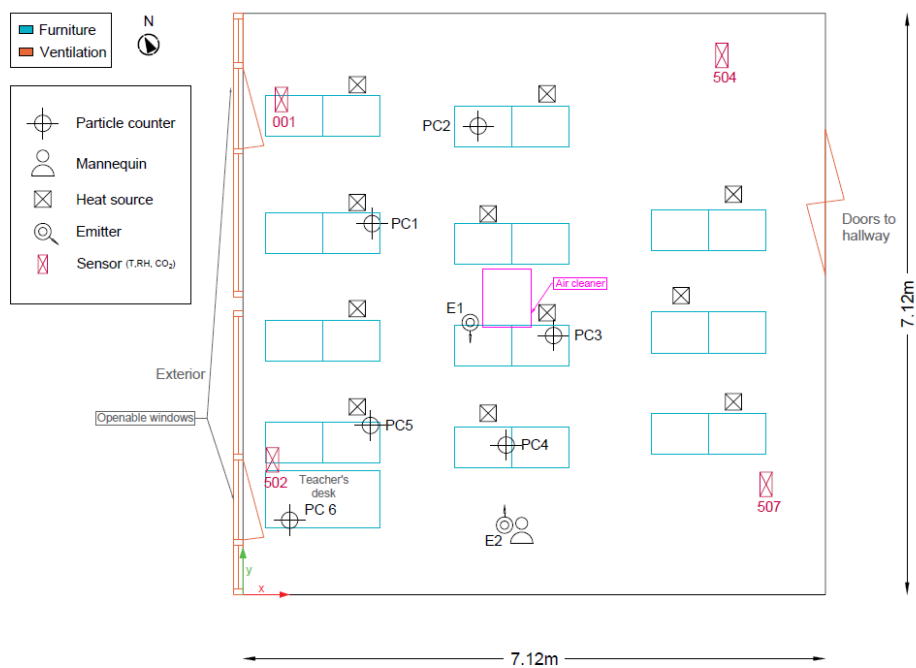


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

Deliverable Work package 2

2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 18.7 and 25.9 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

09-08-2023				
Surface area temperature (°C)		12:00	16:30	
	Wall 1	21.7	26.0	
	Wall 2	21.0	25.0	
	Wall 3	22.1	26.9	
	Wall 4	21.1	25.3	
	Ceiling	22.1	26.5	
	Floor	21.3	23.6	
	Glass surface of the windows	21.9	26.8	
		Min*	Mean*	Max*
Air temperature (°C)		18.7	22.6	25.9
Relative humidity (%)		58.9	65.6	73.3
Outdoor air temperature (°C)		11.7	16.2	21.0
Outdoor relative humidity (%)		53	79	99
Wind	Velocity (m/s)	1.5	2.8	5.0
	Direction	West (263°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-19:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 of the main report for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 0.4 – 13.0 min for emitter location E1 and has a range of 3.3 – 15.7 min for emitter location E2. The 100-fold increase time is the longest at PC2 for both emitter locations (13.0 – 15.7 min). This particle counter is located at a relative far distance from both emitter location which means it takes long before the particle concentration starts to increase. The 100-fold increase time is the shortest for PC4 and PC5 emitter location E1 (0.4 min). These particle counters are both located relatively close to the emitter which means the particle concentration can

Deliverable Work package 2

increase faster. Emitter E2, however, is also located close to PC4 and PC5 but from this location it does not result in a high 100-fold increase time (4.4 – 4.1 min).

The 100-fold recovery time has a range of 141.7 – N/A for emitter location E1 and has a range of 164.4 – N/A for emitter location E2. The 100-fold recovery time is the longest at PC2 for both locations and at PC1 for emitter location E1. The particle counters had a negative 100-fold recovery time which means the particle concentration increased during the 15 min recovery period. The shortest 100-fold recovery period is at PC4 and PC5 emitter location E1 (141.7 and 153.5 min) which also had the shortest 100-fold increase time.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m³/h (3.7 ACH) for a Class C and 796 m³/h (5.2 ACH) for a Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 1.0 – 12.0 min for emitter location E1 and has a range of 2.0 – 14.0 min for emitter location E2. t_{delay} is the longest for PC2 at both emitter locations (12.0 – 14.0 min). This location also had a long 100-fold recovery time which indicates that it takes long until the particle concentration starts to decrease after the emission period and afterwards the decrease goes relatively slow. The t_{delay} is the shortest for PC4 and PC5 emitter location E1 (1.0 – 1.5 min). This means that at these locations the decrease of the particle concentration starts quickly after the emission stopped. Both locations are located quite close to the emitter location and have a high particle concentration at the end of the emission period.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	1.1	N/A*	N/A*	2.8
	E2	4.3	315.3	0.9	4.3
PC2	E1	13.0	N/A*	N/A*	12.0
	E2	15.7	N/A*	N/A*	14.0
PC3	E1	1.1	202.9	1.4	5.3
	E2	8.1	1403.4	0.2	5.0
PC4	E1	0.4	141.7	2.0	1.0

Deliverable Work package 2

	E2	4.4	174.4	1.6	2.5
PC5	E1	0.4	153.5	1.8	1.5
	E2	4.1	164.4	1.7	2.3
PC6	E1	1.7	158.0	1.7	3.5
	E2	3.3	202.7	1.4	2.0

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC3, PC4 and PC5 the measurements have been analyzed at a height of 0.86 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.07 m/s).

In Figure 2-1, air flows from the walls of the room towards the center of the room are present. There is no dominant air flow from the windows towards the room at this specific height. There is an air flow from the emitter E1 towards PC5 and PC4. Furthermore, there is an air flow from emitter E2 which is also directed towards PC5.

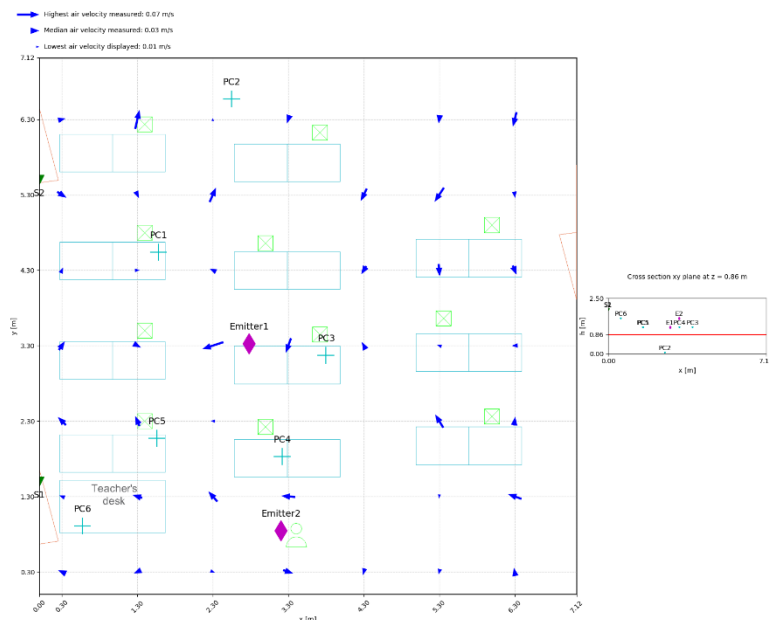


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 0.86 m.

For PC6, the air flow is analysed at a height of 1.46 m, see Figure 2-2 (range 0.01 – 0.07). In this figure the air velocities are highest at the back of the classroom. Specifically for PC6, there is an air flow directed away from the particle counter for this plane.

Deliverable Work package 2

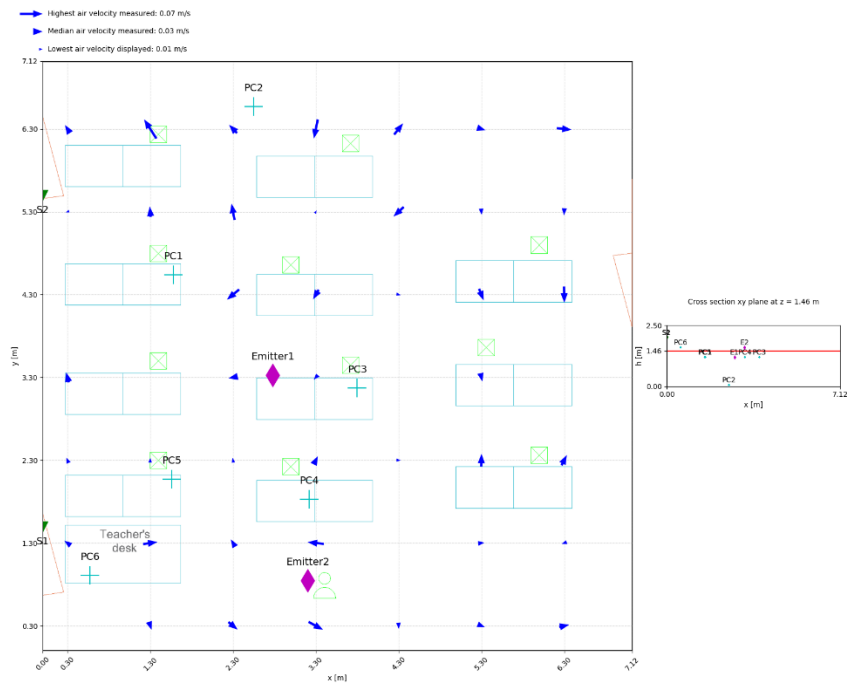


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

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3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system consists of a mobile air cleaner (PM10 50% filter and HEPA14 filter). The air cleaner was set to setting 1 which results in a designed flow rate of 600 m³/h. Due to the design of the ventilation system, it was not possible to measure the supply of air in the room. There are furthermore, two openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. The windows grilles were, however, open during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Mobile air cleaner	N/A
	Total	N/A
Ventilation (exhaust)		
	Mobile air cleaner	N/A
	Total	N/A



Figure 3-1 – Ventilation system after intervention

Deliverable Work package 2

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. During these measurements the surface temperature of the walls, ceiling and floor was not measured. The room temperature was between 19.0 and 20.4 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Metrological data is from weerstatistieken.nl of a nearby weather station.

05-02-2024				
		Min*	Mean*	Max*
Air temperature (°C)		19.0	19.7	20.4
Relative humidity (%)		53.0	54.8	58.3
Outdoor air temperature (°C)		8.6	9.4	10.2
Outdoor relative humidity (%)		80	85	89
Wind	Velocity (m/s)	4	10	13
	Direction	South-West (236°)		

* The mean value is calculated by taking the average values of all sensor 001, 502, 504 and 507 between 15:00-21:30. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before and after the intervention. The 100-fold increase time has a range of 6.7 – 273.8 min for emitter location E1 and has a range of 18.3 – 72.3 min for emitter location E2. The 100-fold increase time has a large range between different particle counters, this indicates that the increase of the particle concentration in the room is not homogeneous. The 100-fold increase time is longest at PC1 and PC2 for emitter location E1 (273.8 – 126.9 min). These particle counters are both located at a relative far distance from the emitter location and the direction of the emitter is towards the opposite side of the room.

The 100-fold recovery time has a range of 38.9 – 194.2 min for emitter location E1 and has a range of 48.2 – 99.6 min for emitter location E2. The difference between the shortest and longest 100-fold recovery time is still relative large which indicates that the decrease of the particle concentration is different at different locations in the room. The 100-fold recovery time is the shortest for PC6 at emitter location E1 (38.9 min). This could potentially be explained by the air flow in the room.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air

Deliverable Work package 2

quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teachers, this results in a ventilation rate of 562 m³/h (3.7 ACH) for a Class C and 796 m³/h (5.2 ACH) for a Class B. When these values are compared with the ACH values in Table 3.3, it can be seen that Class C is not met for PC1 (E1 & E2), PC2 (E1 & E2) and PC3 (E1). Class B is not met for all particle counters except PC4 (E1), PC5 (E1) and PC6 (E1 & E2). It should, however, be noted that the set ventilation rate was lower than the requirements according to 'PvE frisse scholen'. The PvE is used for fresh air (ventilation), while an air cleaner does not supply fresh air.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 1.8 – 8.3 min for emitter location E1 and has a range of 3.0 – 9.0 min for emitter location E2. t_{delay} is the longest for PC1 and PC2 which were also the locations with the longest 100-fold increase time. Furthermore, t_{delay} is the shortest for PC4 (E1) this locations also had a relative short 100-fold increase time and 100-fold recovery time. This could be related to the small distance between the particle counter and the emitter. Furthermore, the direction of the emitter is directly towards PC4.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	1.1	273	N/A*	194	N/A*	1.4	2.8	8.3
	E2	4.3	72.3	315.3	99.6	0.9	2.8	4.3	9.0
PC2	E1	13.0	126	N/A*	128	N/A*	2.1	12.0	8.3
	E2	15.7	49.1	N/A*	78.0	N/A*	3.5	14.0	5.3
PC3	E1	1.1	87.7	202	97.3	1.4	2.8	5.3	6.8
	E2	8.1	55.6	1403	74.8	0.2	3.7	5.0	5.5
PC4	E1	0.4	6.7	141	41.5	2.0	6.7	1.0	1.8
	E2	4.4	23.9	174	56.3	1.6	4.9	2.5	4.3
PC5	E1	0.4	51.4	153	42.5	1.8	6.5	1.5	4.5
	E2	4.1	47.3	164	68.4	1.7	4.0	2.3	5.5
PC6	E1	1.7	23.3	158	38.9	1.7	7.1	3.5	4.3
	E2	3.3	18.3	202	48.2	1.4	5.7	2.0	3.0

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

Deliverable Work package 2

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 3-2 (range 0.1 – 0.01 m/s).

In Figure 3-2 it is visualized that there is no dominant air flow in the room when the air cleaner is set at 600 m³/h. The highest air velocities are in the back of the classroom but there is no clear direction of the air flow in the room. Specifically for the particle counters, the air velocities are low near PC1 and PC2. Furthermore, there seems to be an air flow from emitter location E2 in the direction of PC4.

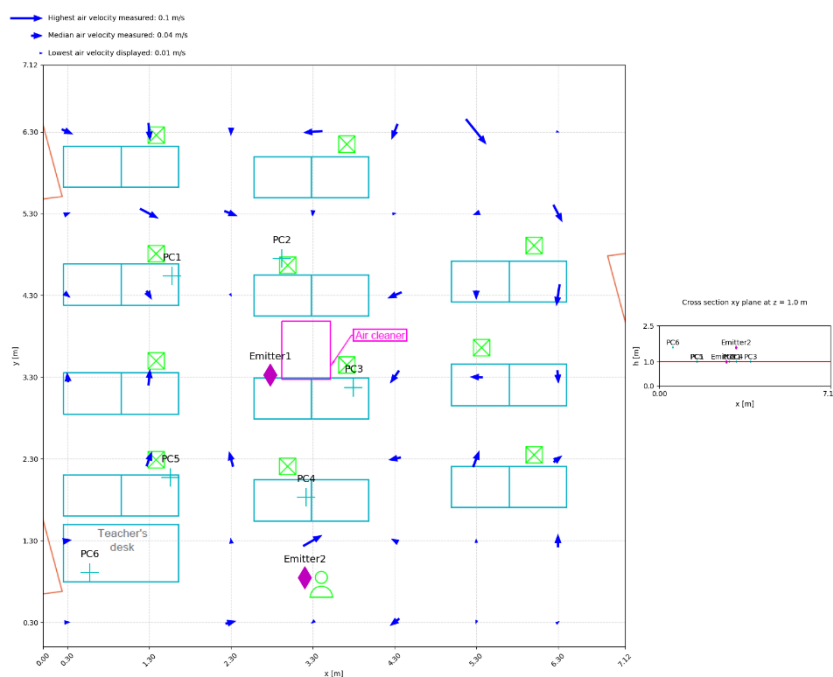


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 3-3 (range 0.01-0.06). In this figure, it can be seen that the air velocities are lower at this height and there is still no dominant air flow present in the room. From this figure, it becomes clear that the air velocities can change significantly at different heights in the room. When looking specifically towards particle counter PC6, the air velocities are low in the area of the particle counter.

Deliverable Work package 2

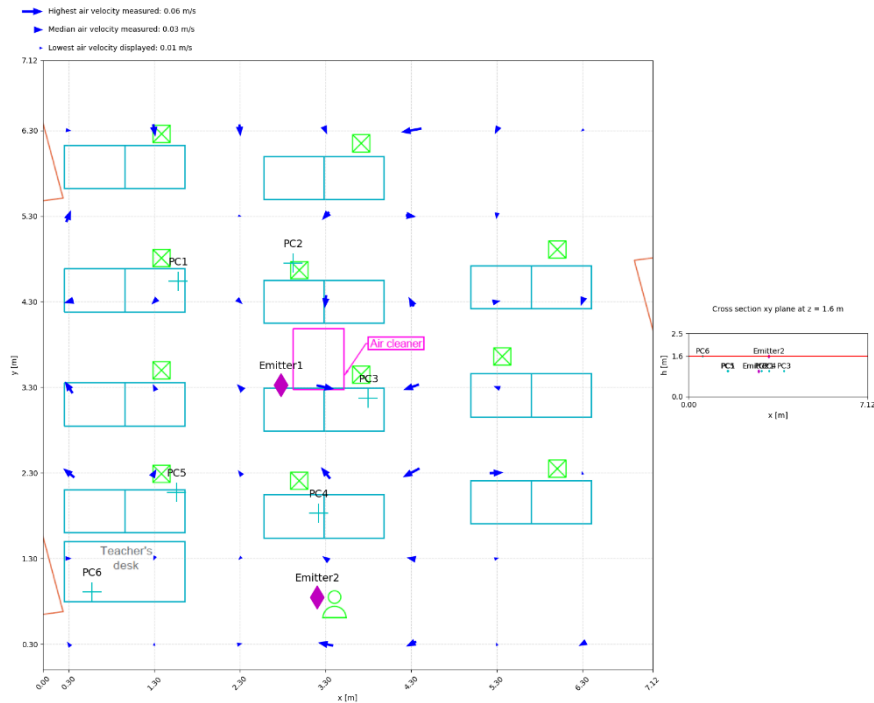


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

4. Conclusions

In this section, the performance of the ventilation system before and after intervention are described and compared through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before intervention, the 100-fold increase time has a range of 0.4 – 13.0 min for emitter location E1 and has a range of 3.3 – 15.7 min for emitter location E2. After intervention, the 100-fold increase time has a range of 6.7 – 273.8 min for emitter location E1 and has a range of 18.3 – 72.3 min for emitter location E2. After intervention, the range of the 100-fold increase time is larger and the 100-fold increase time is longer. This indicates that it takes longer for the particle concentration to increase at different locations in the room. This can also be seen by the overall increase in particle concentration which (in general) is lower after the intervention took place compared to before the intervention (Figure 4-1).

Deliverable Work package 2

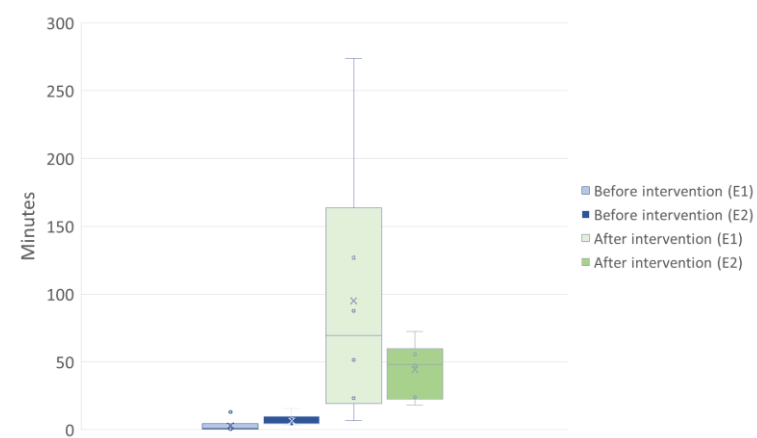


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before the intervention, the 100-fold recovery time has a range of 141.7 – N/A min for emitter location E1 and has a range of 164.4 – N/A min for emitter location E2. After intervention, the 100-fold recovery time has a range of 38.9 – 194.2 min for emitter location E1 and has a range of 48.2 – 99.6 min for emitter location E2. The 100-fold recovery time is shorter and has a smaller range after the intervention took place. This indicates that there is more homogeneous mixing in the classroom compared to before the intervention. The 100-fold recovery time is, however, with a maximum of 194.2 min still relatively long (Figure 4-2).

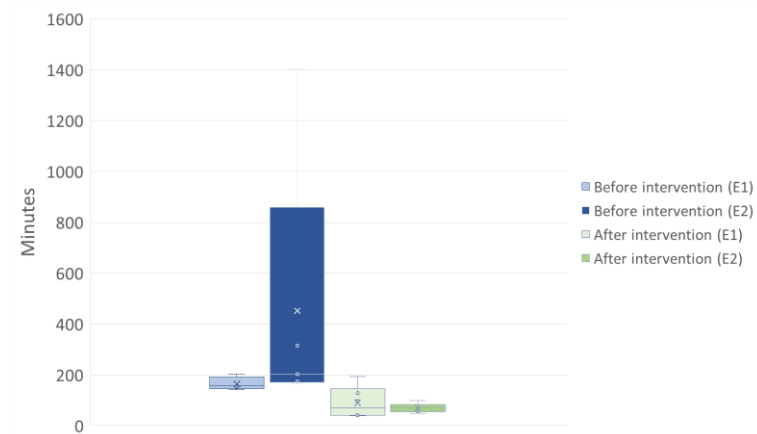


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 1.0– 12.0 min for emitter location E1 and has a range of 2.0 – 14.0 min for emitter location E2. After intervention, t_{delay} has a range of 1.8 – 8.3 min for emitter location E1 and has a range of 3.0 – 9.0 min for emitter location E2. t_{delay} has similar values when comparing before and after the intervention. t_{delay} is, however, longer at PC1 after the intervention and is shorter at PC2.

Air change per hour

Before intervention, the ACH has a range of N/A – 2.0 ACH for emitter location E1 and has a range of N/A – 1.7 ACH for emitter location E2. After intervention, the ACH has a range of 1.4 – 7.1 for emitter

Deliverable Work package 2

location E1 and has a range of 2.8 – 5.7 for emitter location E2. The ACH is larger after the intervention took place which indicates that there is a higher local air velocity at the location of the particle counters. For the measurements before the intervention, no air change rate meet the requirements for Class B (5.2) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'. After intervention, only PC4 and PC5 (E1) and PC6 (E1 and E2) meet the requirements for Class B (5.2).

4.2 *Air flow measurements*

Before the intervention took place, the highest air velocities are present at the center of the room but this is no dominant air flow present in the room. Furthermore, there is no clear air flow visible from the window grills into the room.

The particle concentration measurements and the air flow measurements show that the air velocities are lowest near PC1 and PC3, this can explain the long 100-fold recovery time at these locations. Furthermore, the 100-fold recovery time is also long at PC2. At this location, the air velocities are also low and this particle counter was located near the ground where the air velocities are even lower.

After intervention, there is still no dominant air flow present in the room but the air velocities are larger compared to the set-up before the intervention took place. Furthermore, the air velocities are higher for a height of 1.0 m compared to the height of 1.6 m.

The particle concentration and the air flow measurements show that the air velocities are lowest near PC1 and PC2 which can explain the long 100-fold increase time at these locations. Furthermore, there is an air flow directed from both emitter locations towards PC4 which can explain the relative short 100-fold increase time for this particle counter.

In conclusion, when both ventilation systems are compared it becomes clear that the air velocities are slightly higher after the intervention took place. There is, however, still no clear dominant direction of the air flow throughout the room. Due to this, the particle spread throughout the room is also after the intervention dependent on the proximity of the particle counter to the emission source location. The decrease of the particle concentration after the emission stopped is, however, better after the intervention took place.

ANNEX B, RESULTS CLASSROOM 2

Experiments in-situ

WP2, experiments after intervention B

DATUM	08-01-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location classroom 2

The results discussed in this report include both the situation without any interventions and the situation after the intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of ventilation window grills and openable windows and doors. In this location the windows and the doors were closed but the window grills were opened.

In the case of this location, three different interventions will be tested. The first two interventions were the use of a mobile air cleaner. This mobile air cleaner was tested at 2 different power settings. At power setting 6, it has a capacity of 2100 m³/h and at power setting 2, it has a capacity of 600 m³/h. The second intervention consist of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). This system consist of a ventilation system that is connected to the heat pump which is able to heat and cool the room with the ventilation system.

In this report, the mobile air cleaner at power of 2100 m³/h will be discussed as the intervention.

Deliverable Work package 2

1.1 *Characteristics of room and system*

Description of the room

The school is located in a suburban environment and was originally built in 1989. The classroom that was considered during this analysis, has a surface area of 50.7 m² and was located on the ground floor. The façade was orientated towards the West and the height of the room was 2.5-3.5 m. During the measurements, this room was designed for circa 25 students and 1 teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has two window grills which can be opened (see Figure 1-2). The same applies for the exhaust of air. There are, furthermore, two openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

Deliverable Work package 2

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	2 window ventilation grills	N/A
	Total	N/A
Ventilation (exhaust)		
	2 window ventilation grills	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

Deliverable Work package 2

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 11 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC1, PC3, PC4 and PC5 were located at +/- 1.0 m height since this represents the breathing zone of sitting children. PC6 is located at a height of +/- 1.6 m since this represents the breathing zone of a standing teacher. PC2 was located at a height of 0.02 m since this was close to the exhaust of the intervention. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.13 to 2.45 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 49 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

Deliverable Work package 2

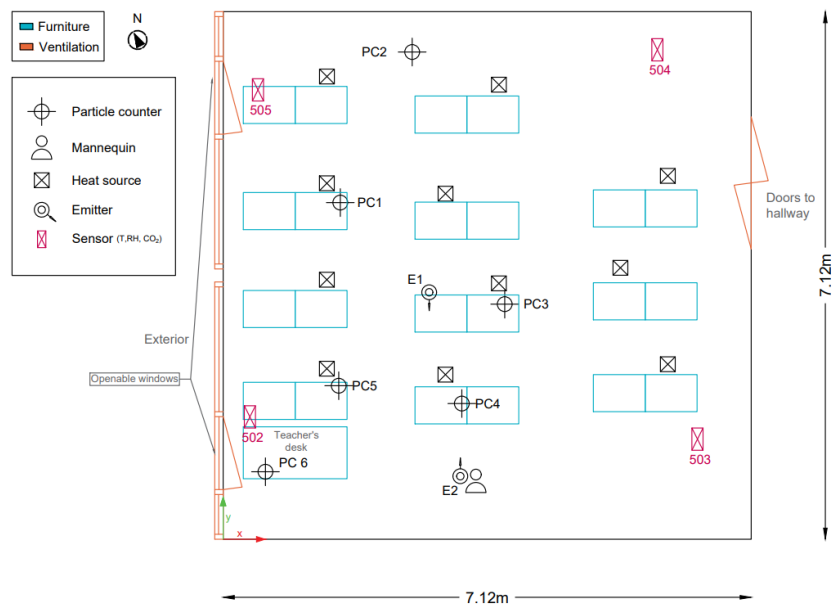


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

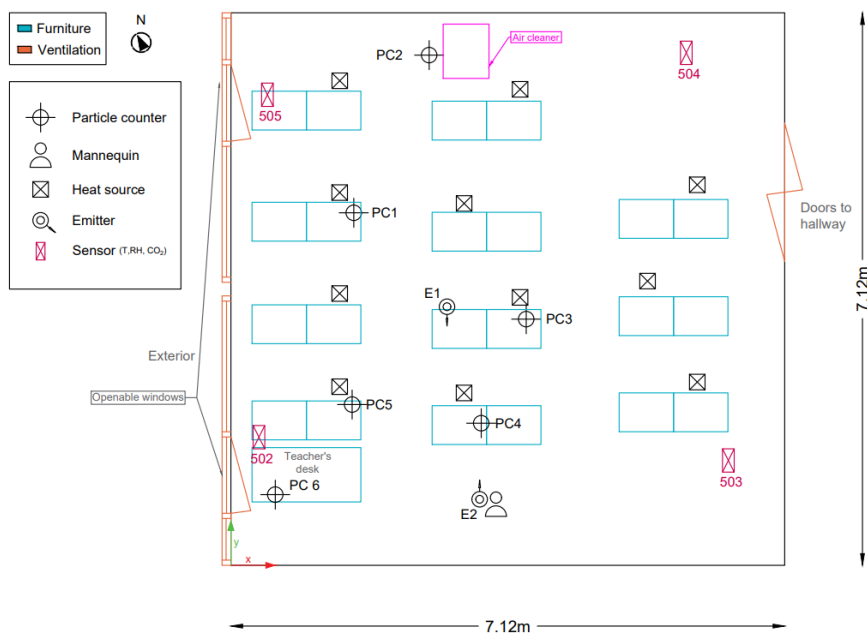


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

Deliverable Work package 2

2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 18.7 and 25.9 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

09-08-2023				
Surface area temperature (°C)		12:00	16:30	
	Wall 1	21.7	26.0	
	Wall 2	21.0	25.0	
	Wall 3	22.1	26.9	
	Wall 4	21.1	25.3	
	Ceiling	22.1	26.5	
	Floor	21.3	23.6	
	Glass surface of the windows	21.9	26.8	
		Min*	Mean*	Max*
Air temperature (°C)		18.7	22.6	25.9
Relative humidity (%)		58.9	65.6	73.3
Outdoor air temperature (°C)		11.7	16.2	21.0
Outdoor relative humidity (%)		53	79	99
Wind	Velocity (m/s)	1.5	2.8	5.0
	Direction	West (263°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-19:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 0.4 – 13.0 min for emitter location E1 and has a range of 3.3 – 15.7 min for emitter location E2. The 100-fold increase time is the longest at PC2 for both emitter locations (13.0 – 15.7 min). This particle counter is located at a relative far distance from both emitter location which means it takes long before the particle concentration starts to increase. The 100-fold increase time is the shortest for PC4 and PC5 emitter location E1 (0.4 min). These particle counters are both located relatively close to the emitter which means the particle concentration can increase faster. Emitter E2,

Deliverable Work package 2

however, is also located close to PC4 and PC5 but from this location it does not result in a high 100-fold increase time (4.4 – 4.1 min).

The 100-fold recovery time has a range of 141.7 – N/A for emitter location E1 and has a range of 164.4 – N/A for emitter location E2. The 100-fold recovery time is the longest at PC2 for both locations and at PC1 for emitter location E1. The particle counters had a negative 100-fold recovery time which means the particle concentration increased during the 15 min recovery period. The shortest 100-fold recovery period is at PC4 and PC5 emitter location E1 (141.7 and 153.5 min) which also had the shortest 100-fold increase time.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m³/h (3.7 ACH) for a Class C and 796 m³/h (5.2 ACH) for a Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 1.0 – 12.0 min for emitter location E1 and has a range of 2.0 – 14.0 min for emitter location E2. t_{delay} is the longest for PC2 at both emitter locations (12.0 – 14.0 min). This location also had a long 100-fold recovery time which indicates that it takes long until the particle concentration starts to decrease after the emission period and afterwards the decrease goes relatively slow. The t_{delay} is the shortest for PC4 and PC5 emitter location E1 (1.0 – 1.5 min). This means that at these locations the decrease of the particle concentration starts quickly after the emission stopped. Both locations are located quite close to the emitter location and have a high particle concentration at the end of the emission period.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	1.1	N/A*	N/A*	2.8
	E2	4.3	315.3	0.9	4.3
PC2	E1	13.0	N/A*	N/A*	12.0
	E2	15.7	N/A*	N/A*	14.0
PC3	E1	1.1	202.9	1.4	5.3
	E2	8.1	1403.4	0.2	5.0
PC4	E1	0.4	141.7	2.0	1.0

Deliverable Work package 2

	E2	4.4	174.4	1.6	2.5
PC5	E1	0.4	153.5	1.8	1.5
	E2	4.1	164.4	1.7	2.3
PC6	E1	1.7	158.0	1.7	3.5
	E2	3.3	202.7	1.4	2.0

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC3, PC4 and PC5 the measurements have been analyzed at a height of 0.86 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.07 m/s).

In Figure 2-1, air flows from the walls of the room towards the center of the room are present. There is no dominant air flow from the windows towards the room at this specific height. There is an air flow from the emitter E1 towards PC5 and PC4. Furthermore, there is an air flow from emitter E2 which is also directed towards PC5.

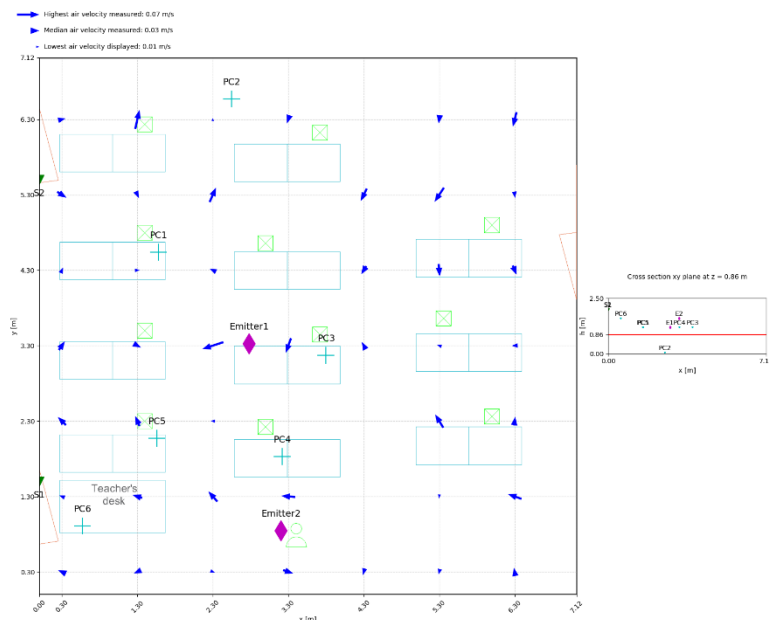


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 0.86 m.

For PC6, the air flow is analysed at a height of 1.46 m, see Figure 2-2 (range 0.01 – 0.07). In this figure the air velocities are highest at the back of the classroom. Specifically for PC6, there is an air flow directed away from the particle counter for this plane.

Deliverable Work package 2

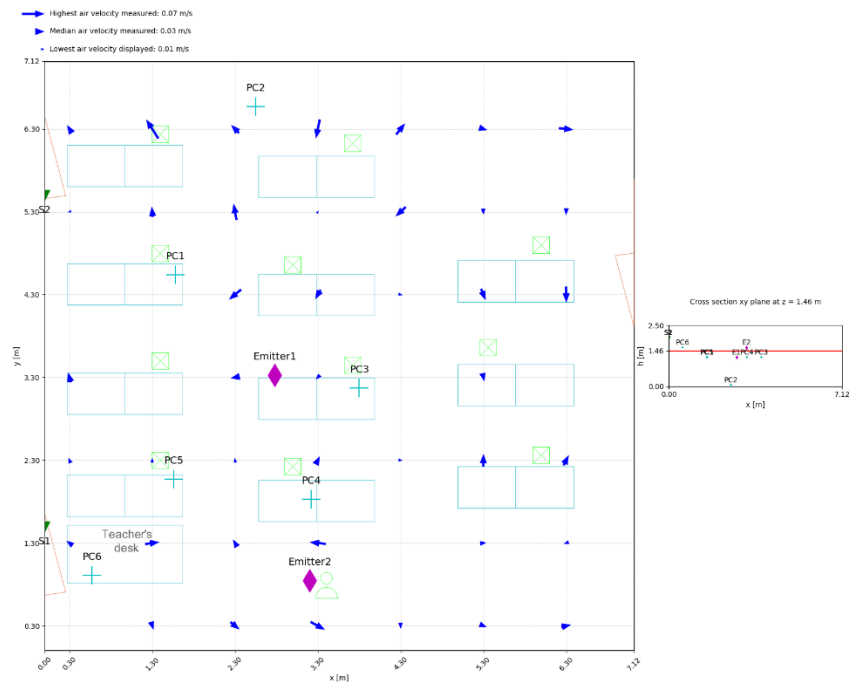


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

Deliverable Work package 2

3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system consists of a mobile air cleaner. The air cleaner was set to set-up 6 which results in a designed flow rate of 2100 m³/h. Due to the design of the ventilation system, it was not possible to measure the supply of air in the room. There are furthermore, two openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Mobile air cleaner	N/A
	Total	N/A
Ventilation (exhaust)		
	Mobile air cleaner	N/A
	Total	N/A



Figure 3-1 – Ventilation system after intervention

Deliverable Work package 2

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 22.2 and 26.5 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

10-08-2023				
Surface area temperature (°C)		09:30	12:00	
	Wall 1	20.6	22.9	
	Wall 2	21.3	23.1	
	Wall 3	21.6	23.6	
	Wall 4	21.0	22.6	
	Ceiling	21.2	23.5	
	Floor	21.5	22.5	
	Glass surface of the windows	19.9	22.6	
		Min*	Mean*	Max*
Air temperature (°C)		22.2	24.4	26.5
Relative humidity (%)		48.7	56.6	60.6
Outdoor air temperature (°C)		11.5	17.8	23.8
Outdoor relative humidity (%)		49	74	97
Wind	Velocity (m/s)	1.0	1.8	3.0
	Direction	South-South-West (194°)		

* The mean value is calculated by taking the average values of all sensor 502, 503, 504 and 505 between 10:00-14:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before and after the intervention. The 100-fold increase time has a range of 1.3 – 3.9 min for emitter location E1 and has a range of 2.9 – 13.3 min for emitter location E2. The 100-fold increase time is always shorter for the particle counters when the emitter is located at location E1 compared to E2. This could be explained by the air flow in the room.

The 100-fold recovery time has a range of 25.3 – 25.7 min for emitter location E1 and has a range of 24.2 – 24.8 min for emitter location E2. The difference between the shortest and longest 100-fold recovery times is small which indicates that the decrease of the particle concentration is similar at

Deliverable Work package 2

different locations in the room (homogeneous). This short 100-fold recovery time is related to the high ventilation rate in the room with a set value of 2100 m³/h.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teachers, this results in a ventilation rate of 562 m³/h (3.7 ACH) for a Class C and 796 m³/h (5.2 ACH) for a Class B. When these values are compared with the ACH values in Table 3.3, it can be seen that all values meet the requirements for either one of the classes. It should, however, be noted that the set ventilation rate was higher than the requirements according to 'PvE frisse scholen'.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.5 – 0.8 min for emitter location E1 and has a range of 0.3 – 1.0 min for emitter location E2. t_{delay} is short at all locations in the room, this indicates that after the emission has stopped the decrease of the particle concentration starts quickly. This can be explained by the high ventilation rate in the room which results in high air velocities in the room. Both 100-fold recovery time and the t_{delay} times after intervention where constant throughout the different particle counter locations.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	1.1	3.2	N/A*	25.3	N/A*	10.9	2.8	0.8
	E2	4.3	10.3	315.3	24.3	0.9	11.4	4.3	0.5
PC2	E1	13.0	3.9	N/A*	25.3	N/A*	10.9	12.0	0.8
	E2	15.7	13.3	N/A*	24.2	N/A*	11.4	14.0	1.0
PC3	E1	1.1	1.4	202.9	25.5	1.4	10.8	5.3	0.8
	E2	8.1	10.4	1403.4	24.3	0.2	11.4	5.0	0.3
PC4	E1	0.4	1.3	141.7	25.7	2.0	10.8	1.0	0.8
	E2	4.4	2.9	174.4	24.6	1.6	11.2	2.5	0.3
PC5	E1	0.4	1.7	153.5	25.5	1.8	10.8	1.5	0.8
	E2	4.1	7.3	164.4	24.4	1.7	11.3	2.3	0.5
PC6	E1	1.7	1.8	158.0	25.6	1.7	10.8	3.5	0.5
	E2	3.3	6.8	202.7	24.8	1.4	11.1	2.0	0.5

Deliverable Work package 2

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC3, PC4 and PC5 the measurements have been analyzed at a height of 0.86 m. The direction and velocity of the air flow at this height can be seen in Figure 3-2 (range 0.02 – 0.22 m/s).

In Figure 3-2 it is visualized that the air velocities are highest at the left of the classroom. Furthermore, there is a clear dominant air flow in the direction of the air cleaner (directed towards the exhaust). Specifically for the particle counters, there is an air flow from emitter E2 towards PC4 and PC3. Furthermore, there is an air flow directed away from PC1 and PC5 in the direction of emitter E1 and the exhaust of the room.

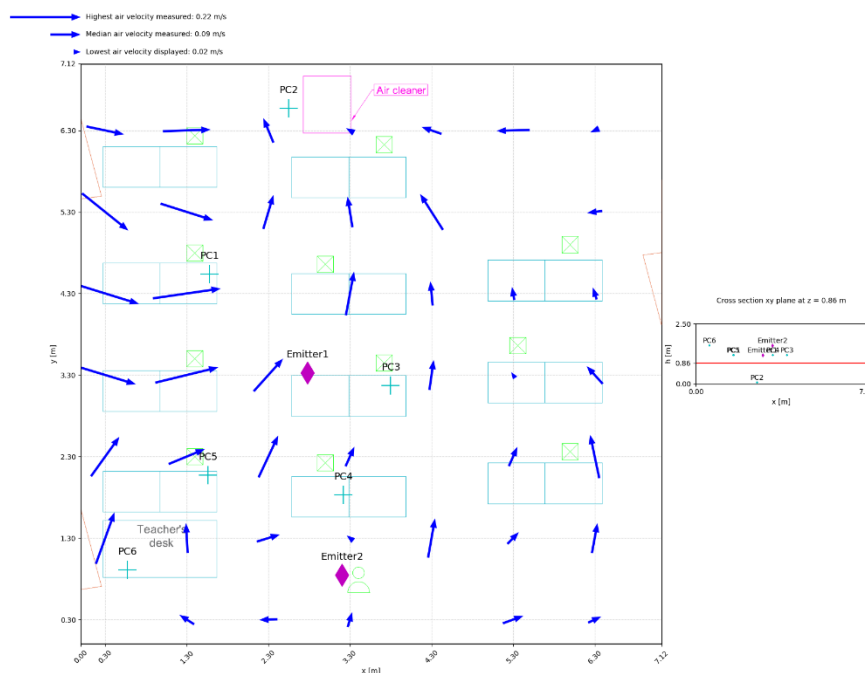


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 0.86 m.

For PC6, the air flow is analyzed at a height of 1.46 m, see Figure 3-3 (range 0.02 – 0.17). In this figure, it can be seen that the air velocities are lower at this height and the direction of the air flow is from the front of the classroom towards the mobile air cleaner. From this figure, it becomes clear that the direction of the air flow can change significantly at different heights in the room. When looking specifically towards particle counter PC6, it seems that there is an air flow directed away from the particle counter in the direction of the exhaust.

Deliverable Work package 2

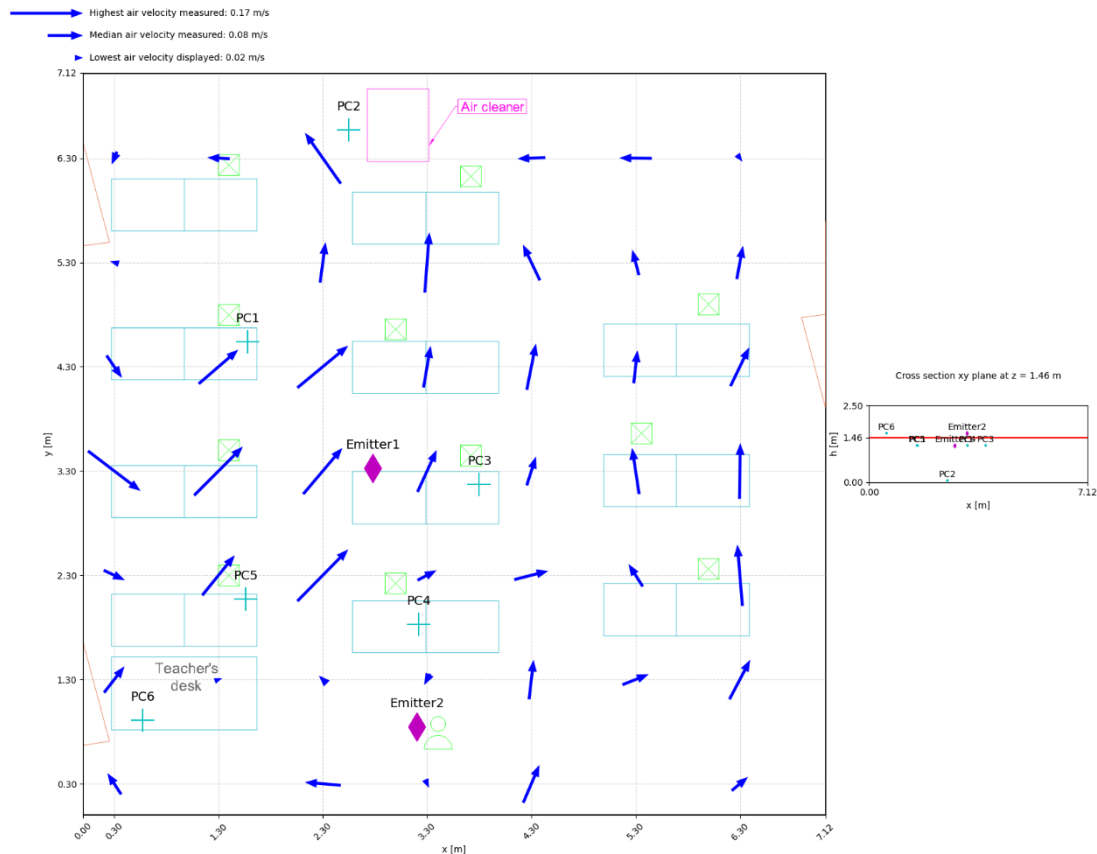


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.46 m.

4. Conclusions

In this section, the performance of the ventilation system before and after intervention are described and compared through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before intervention, the 100-fold increase time has a range of 0.4 – 13.0 min for emitter location E1 and has a range of 3.3 – 15.7 min for emitter location E2. After intervention, the 100-fold increase time has a range of 1.3 – 3.9 min for emitter location E1 and has a range of 2.9 – 13.3 min for emitter location E2. After intervention, specifically for E1, the range of the 100-fold increase time is smaller and the 100-fold increase time is shorter. This indicates there is faster mixing in the room which means the particle concentration increases faster at different locations in the room (Figure 4-1).

Deliverable Work package 2

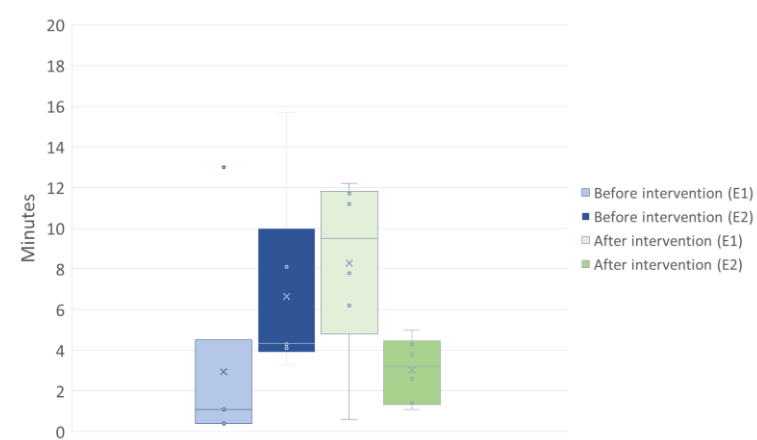


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before intervention, the 100-fold recovery time has a range of 141.7 – N/A (over 900 min) min for emitter location E1 and has a range of 164.4 – N/A for emitter location E2. After intervention, the 100-fold recovery time has a range of 25.3 – 25.7 min for emitter location E1 and has a range 24.2 – 24.8 min for emitter location E2 (Figure 4-2). The 100-fold recovery time is shorter and has a small range after the intervention took place. This indicates that there is more homogeneous mixing in the classroom. It should, however, be noted that the ventilation rate was set at a higher set point than required according to 'PvE frisse scholen'.

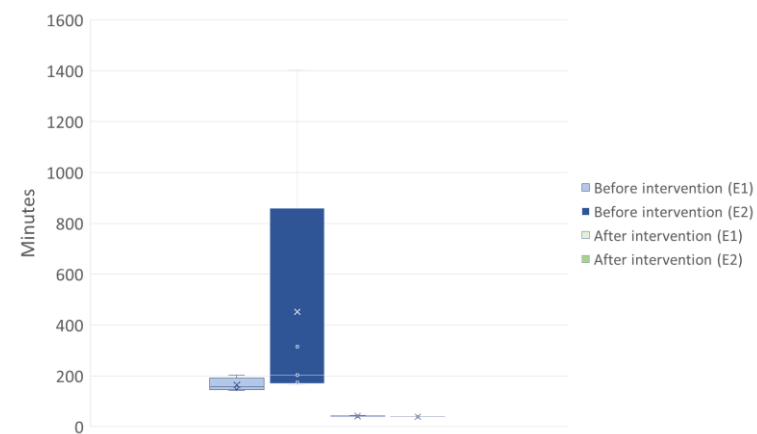


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 1.0– 12.0 min for emitter location E1 and has a range of 2.0 – 14.0 min for emitter location E2. After intervention, t_{delay} has a range of 0.5 – 0.8 min for emitter location E1 and has a range of 0.3 – 1.0 min for emitter location E2. t_{delay} is shorter after the intervention took place. This indicates that after the emission stopped, the particle concentration starts to decrease faster due to a higher air flow in the room.

Air change per hour

Before intervention, the ACH has a range of N/A – 2.0 ACH for emitter location E1 and has a range of N/A – 1.7 ACH for emitter location E2. After intervention, the ACH has a range of 10.8 – 10.9 for emitter

Deliverable Work package 2

location E1 and has a range of 11.2 – 11.4 for emitter location E2. The range between the different measurement points is smaller after the intervention took place, this indicates that the possible exposure to particles is similar at different locations in the room. For the measurements before the intervention, no air change rate meet the requirements for both Class C (3.7) and Class B (5.2) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'. After intervention, all requirements are met for both Class C (3.7) and Class B (5.2).

4.2 *Air flow measurements*

Before the intervention took place, the highest air velocities are present at the center of the room but this is no dominant air flow present in the room. Furthermore, there is no clear air flow visible from the window grills towards the room.

The particle concentration measurements and the air flow measurements show that the air velocities are lowest near PC1 and PC3, this can explain the long 100-fold recovery time at these locations. Furthermore, the 100-fold recovery time is also long at PC2. At this location, the air velocities are also low and this particle counter was located near the ground where the air velocities are even lower.

After intervention, there is a clear dominant towards the mobile air cleaner in the classroom (direction of the exhaust). The air velocities are slightly higher at a height of 0.86 m compared to the height of 1.46 m.

The particle concentration measurements and the air flow measurements show that the air velocities are higher after the intervention which explains the shorter 100-fold recovery time. Furthermore, the air velocities are lower near emitter location E2 compared to emitter location E1 which could explain the longer 100-fold increase time for the particle counters when the emitter is located at location E2.

In conclusion, when both ventilation systems are compared it becomes clear that the air velocities are higher after the intervention. Furthermore, there is a clear dominant direction of the air flow throughout the room. Due to this, the particle spread throughout the room has a lower dependence on the proximity of the particle counter to the emission source location. It should, however, be noted that the setting of the intervention that was described in this report is not a realistic setting due to the high ventilation rate and therefore the high noise disturbance.

ANNEX B, RESULTS CLASSROOM 2

Experiments in-situ

WP2, experiments after intervention C

DATUM 08-01-2024

AUTEURS Ir. A. de Lange

ORGANISATIE TNO

1. Results baseline measurement location classroom 2

The results discussed in this report include both the situation before and after the interventions. The intervention was initiated by the primary school to optimize or adapt the ventilation system.

The interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system regarding capacity, function or system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes that are reported (before and after the intervention).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of ventilation window grills and openable windows and doors. In this location the windows were opened and the door was closed during the measurements.

For this location, three different interventions will be tested. The first two interventions were the use of a mobile air cleaner. This mobile air cleaner was tested at 2 different power settings. At power setting 6, it has a capacity of 2100 m³/h and at power setting 2, it has a capacity of 900 m³/h. The second intervention consist of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). This system consist of a ventilation system that is connected to the heat pump which is able to heat and cool the room with the ventilation system.

In this report, the replacement of the ventilation system will be discussed as the intervention.

Deliverable Work package 2

1.1 *Characteristics of room and system*

Description of the room

The school is located in a suburban environment and was originally built in 1989. The classroom that was considered during this analysis, has a surface area of 50.7 m² and was located on the ground floor. The façade was orientated towards the West and the height of the room was 2.5-3.5 m. During the measurements, this room was designed for circa 25 students and 1 teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has two window grills which can be opened (see Figure 1-2). The same applies for the exhaust of air. There are, furthermore, two openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

Deliverable Work package 2

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	2 window ventilation grills	N/A
	Total	N/A
Ventilation (exhaust)		
	2 window ventilation grills	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

Deliverable Work package 2

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 11 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC1, PC3, PC4 and PC5 were located at +/- 1.0 m height since this represents the breathing zone of sitting children. PC6 is located at a height of +/- 1.6 m since this represents the breathing zone of a standing teacher. PC2 was before the intervention located at a height of 0.02 m since this was close to the exhaust of the intervention. After the intervention, PC2 was located at a height of 1.0 m. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.13 to 2.45 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 49 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

Deliverable Work package 2

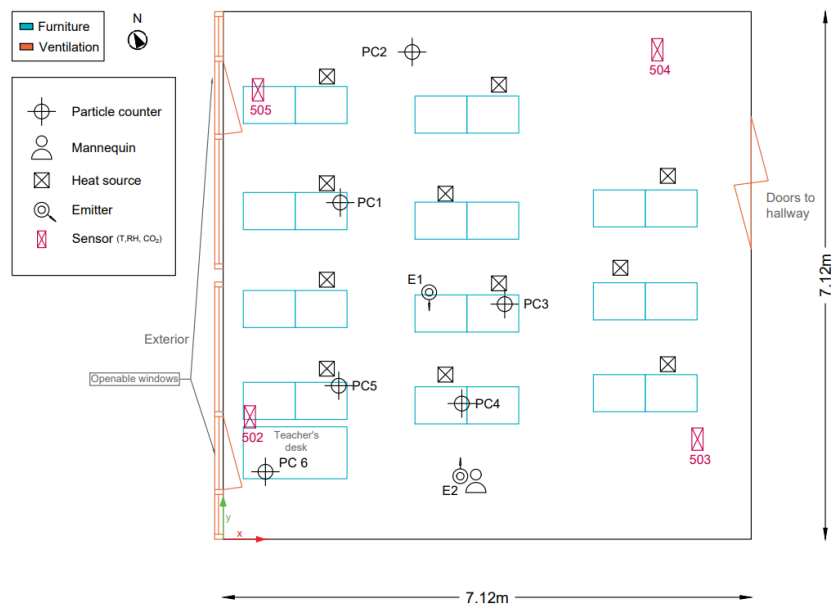


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

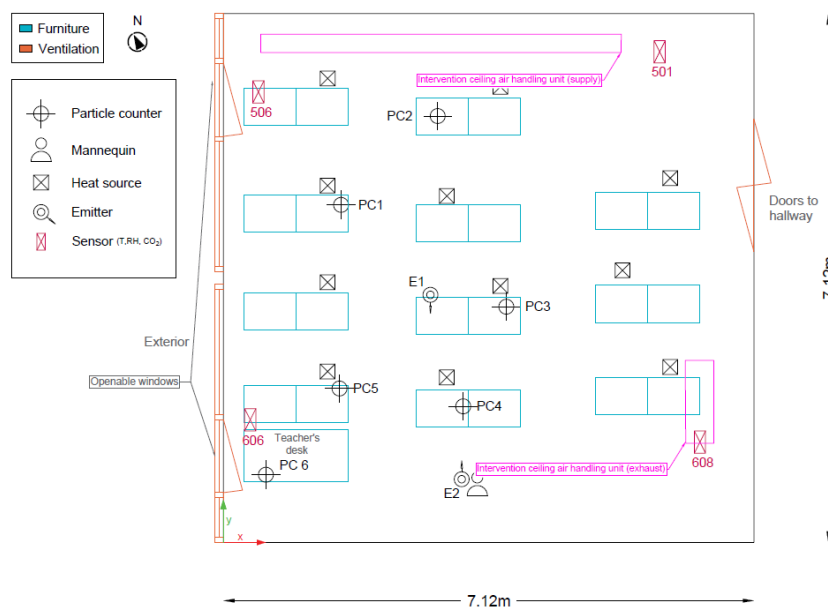


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

Deliverable Work package 2

2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 18.7 and 25.9 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

09-08-2023				
Surface area temperature (°C)		12:00	16:30	
	Wall 1	21.7	26.0	
	Wall 2	21.0	25.0	
	Wall 3	22.1	26.9	
	Wall 4	21.1	25.3	
	Ceiling	22.1	26.5	
	Floor	21.3	23.6	
	Glass surface of the windows	21.9	26.8	
		Min*	Mean*	Max*
Air temperature (°C)		18.7	22.6	25.9
Relative humidity (%)		58.9	65.6	73.3
Outdoor air temperature (°C)		11.7	16.2	21.0
Outdoor relative humidity (%)		53	79	99
Wind	Velocity (m/s)	1.5	2.8	5.0
	Direction	West (263°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-19:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 0.4 – 13.0 min for emitter location E1 and has a range of 3.3 – 15.7 min for emitter location E2. The 100-fold increase time is the longest at PC2 for both emitter locations (13.0 – 15.7 min). This particle counter is located at a relative far distance from both emitter location which means it takes long before the particle concentration starts to increase. The 100-fold increase time is the shortest for PC4 and PC5 emitter location E1 (0.4 min). These particle counters are both located relatively close to the emitter which means the particle concentration can increase faster. Emitter E2,

Deliverable Work package 2

however, is also located close to PC4 and PC5 but from this location it does not result in a high 100-fold increase time (4.4 – 4.1 min).

The 100-fold recovery time has a range of 142 – N/A for emitter location E1 and has a range of 164.4 – N/A for emitter location E2. The 100-fold recovery time is the longest at PC2 for both locations and at PC1 for emitter location E1. The particle counters had a negative 100-fold recovery time which means the particle concentration increased during the 15 min recovery period. The shortest 100-fold recovery period is at PC4 and PC5 emitter location E1 (142 and 153 min) which also had the shortest 100-fold increase time.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m³/h (3.7 ACH) for a Class C and 796 m³/h (5.2 ACH) for a Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 1.0 – 12.0 min for emitter location E1 and has a range of 2.0 – 14.0 min for emitter location E2. t_{delay} is the longest for PC2 at both emitter locations (12.0 – 14.0 min). This location also had a long 100-fold recovery time which indicates that it takes long until the particle concentration starts to decrease after the emission period and afterwards the decrease goes relatively slow. The t_{delay} is the shortest for PC4 and PC5 emitter location E1 (1.0 – 1.5 min). This means that at these locations the decrease of the particle concentration starts quickly after the emission stopped. Both locations are located quite close to the emitter location and have a high particle concentration at the end of the emission period.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	1.1	N/A*	N/A*	2.8
	E2	4.3	315	0.9	4.3
PC2	E1	13.0	N/A*	N/A*	12.0
	E2	15.7	N/A*	N/A*	14.0
PC3	E1	1.1	202	1.4	5.3
	E2	8.1	1403	0.2	5.0
PC4	E1	0.4	142	2.0	1.0

Deliverable Work package 2

	E2	4.4	174	1.6	2.5
PC5	E1	0.4	153	1.8	1.5
	E2	4.1	164	1.7	2.3
PC6	E1	1.7	158	1.7	3.5
	E2	3.3	203	1.4	2.0

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC3, PC4 and PC5 the measurements have been analyzed at a height of 0.86 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.07 m/s).

In Figure 2-1, air flows from the walls of the room towards the center of the room are present. There is no dominant air flow from the windows towards the room at this specific height. There is an air flow from the emitter E1 towards PC5 and PC4. Furthermore, there is an air flow from emitter E2 which is also directed towards PC5.

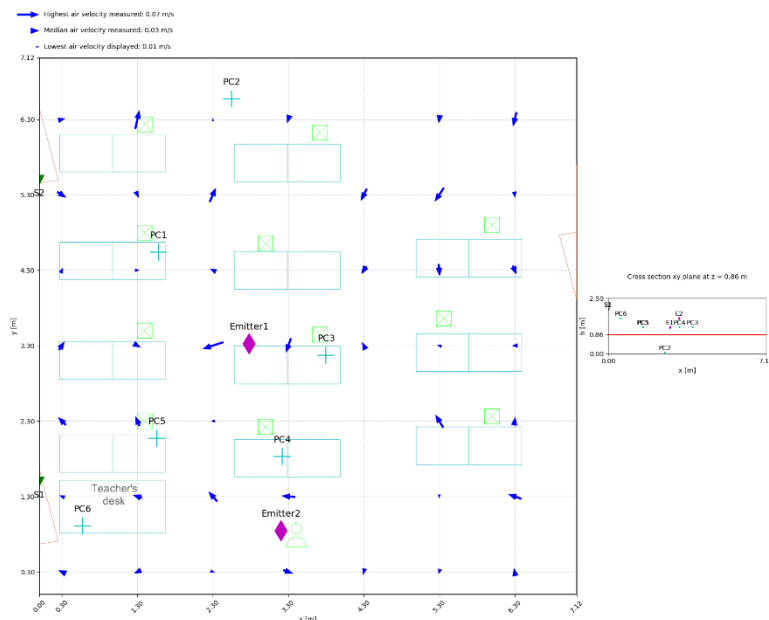


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 0.86 m.

For PC6, the air flow is analysed at a height of 1.46 m, see Figure 2-2 (range 0.01 – 0.07). In this figure the air velocities are highest at the back of the classroom. Specifically for PC6, there is an air flow directed away from the particle counter for this plane.

Deliverable Work package 2

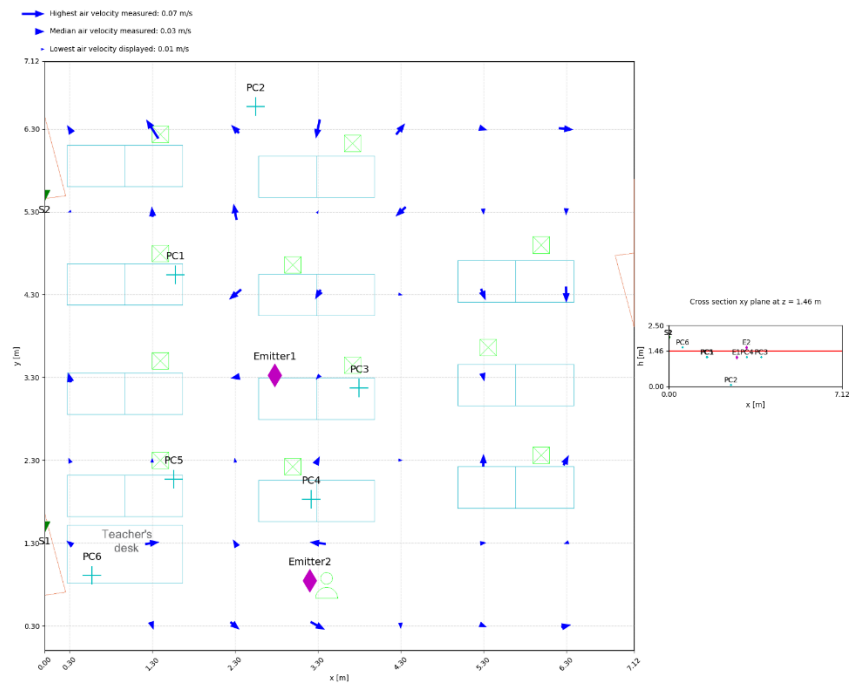


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system consists of a CO² controlled ventilation system which consists of 4 supply vents and 2 exhausts vents in the ceiling. The ventilation system was set-up according to 'PvE Frisse scholen' Class B with a design for 25 students and one teacher (796 m³/h). Due to the design of the ventilation system, it was not possible to measure the supply of air in the room. There are furthermore, two openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	4 supply vents	N/A
	Total	N/A
Ventilation (exhaust)		
	2 exhausts vents	N/A
	Total	N/A



Figure 3-1 – Ventilation system after intervention C

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. During these measurements the surface temperature of the walls, ceiling and floor was not measured. The room temperature was between 17.6 and 20.4 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Metrological data is from weerstatistieken.nl of a nearby weather station.

10-08-2023				
		Min*	Mean*	Max*
Air temperature (°C)		17.6	19.4	20.4
Relative humidity (%)		45.0	49.6	56.9
Outdoor air temperature (°C)		8.6	9.4	10.2
Outdoor relative humidity (%)		80	85	89
Wind	Velocity (m/s)	4	10	13
	Direction	South-West (236°)		

* The mean value is calculated by taking the average values of all sensor 501, 506, 606 and 608 between 15:00-21:30. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before and after the intervention. The 100-fold increase time has a range of 0.6 – 12.2 min for emitter location E1 and has a range of 1.1 – 5.0 min for emitter location E2. The 100-fold increase time is (except at PC3) shorter for emitter location E2 compared to emitter location E1. The 100-fold increase time is the shortest for PC3 (E1) this can be explained by the short distance between the particle counter and the emitter location.

The 100-fold recovery time has a range of 40.1 – 43.8 min for emitter location E1 and has a range of 38.0 – 39.3 min for emitter location E2. The difference between the shortest and the longest 100-fold recovery time is small which indicates that the decrease of the particle concentration is similar at different locations in the classroom.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results

Deliverable Work package 2

in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teachers, this results in a ventilation rate of 562 m³/h (3.7 ACH) for a Class C and 796 m³/h (5.2 ACH) for a Class B. When these values are compared with the ACH values in Table 3.3, it can be seen that all requirements are met for both Class C and Class B.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.8 – 4.3 min for emitter location E1 and has a range of 1.3 – 4.3 min for emitter location E2. t_{delay} is the shortest for PC3 emitter location E1 (0.8 min) and PC2 emitter location E2 (1.3 min). For PC3 this can be explained by the location of the particle counter close to the emitter, this results in a high concentration of particle at the location of the particle counter. For PC2, it could be explained by the close proximity of the particle counter near the air ventilation unit which means the particle concentration can start to decrease quickly.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention C.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	1.1	12.2	N/A*	43.8	N/A*	6.3	2.8	3.0
	E2	4.3	5.0	315.3	38.5	0.9	7.3	4.3	3.8
PC2	E1	13.0	6.2	N/A*	41.2	N/A*	6.7	12.0	2.5
	E2	15.7	2.6	N/A*	39.3	N/A*	7.0	14.0	1.3
PC3	E1	1.1	0.6	202.9	40.4	1.4	6.8	5.3	0.8
	E2	8.1	4.3	1403.4	38.8	0.2	7.1	5.0	2.0
PC4	E1	0.4	7.8	141.7	42.1	2.0	6.6	1.0	3.5
	E2	4.4	1.4	174.4	38.3	1.6	7.2	2.5	4.3
PC5	E1	0.4	11.2	153.5	40.1	1.8	6.9	1.5	3.3
	E2	4.1	1.1	164.4	38.0	1.7	7.3	2.3	3.3
PC6	E1	1.7	11.7	158.0	41.5	1.7	6.7	3.5	4.3
	E2	3.3	3.8	202.7	38.8	1.4	7.1	2.0	4.0

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 3-2 (range 0.03 – 0.21 m/s).

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For Figure 3-2 it is visualized that there is a dominant airflow from the back of the classroom towards the front of the classroom. The highest air velocities are in the back and in the center of the classroom. Specifically for the particle counters, there is an air flow from emitter location E2 towards PC3 and PC4. Furthermore, there is an air flow from emitter location E1 towards PC2.

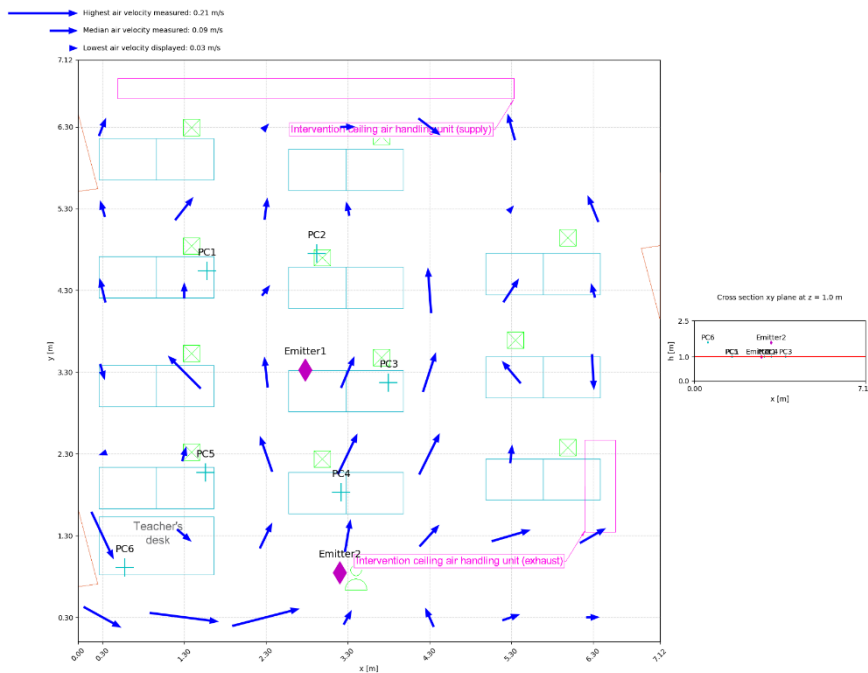


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analyzed at a height of 1.6 m, Figure 3-3 (range 0.01 – 0.28). In this figure, it can be seen that the air velocities are higher at this height and the dominant air flow has shifted towards the side of the windows of the classroom. From this figure, it becomes clear that the direction of the air flow can change significantly at different heights in the room. When looking specifically towards the particle counter PC6, there is an air flow from PC6 in the direction of the ventilation unit.

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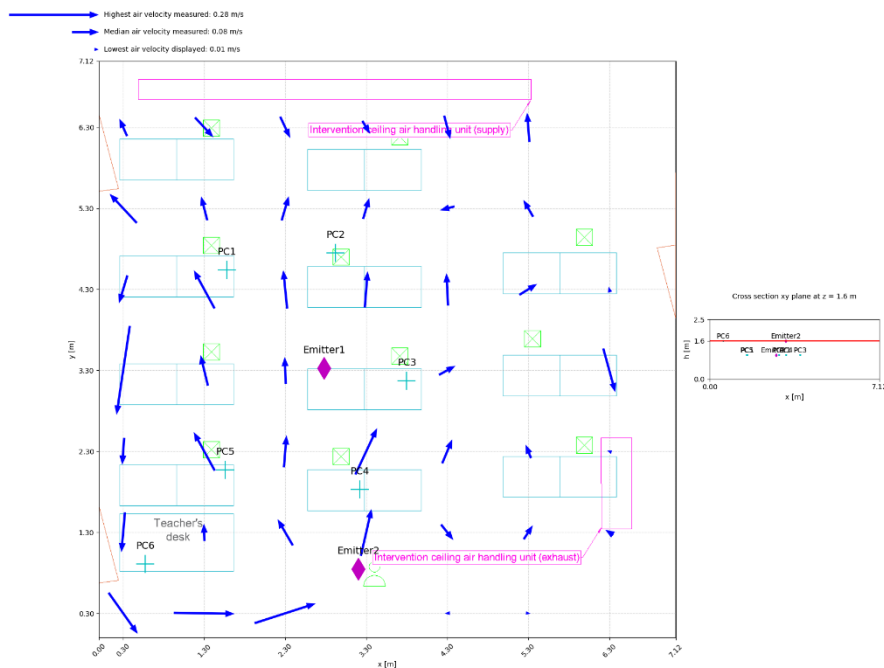


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

4. Conclusions

In this section, the performance of the ventilation system before and after intervention are described and compared through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before intervention, the 100-fold increase time has a range of 0.4-13.0 min for emitter location E1 and has a range 2.2 – 15.7 min for emitter location E2. After intervention, the 100-fold increase time has a range of 0.6 – 12.2 min for emitter location E1 and has a range of 1.1 – 5.0 min for emitter location E2. After the intervention, the average 100-fold increase time throughout the whole room is similar compared to before the intervention. At the specific locations of the particle counters, however, the 100-fold increase time is different. After the intervention, the 100-fold increase time is longest for the particle counters which are located near the windows when the emitter is located at E1 (Figure 4-1).

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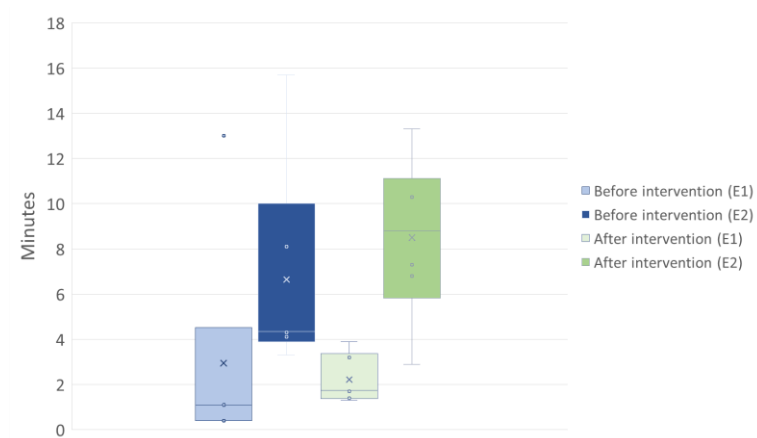


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before intervention, the 100-fold recovery time has a range of 141.7 – N/A min for emitter location E1 has a range of 164.4 – N/A min for emitter location E2. After intervention, the 100-fold recovery time has a range of 40.4 – 43.8 min for emitter location E1 and has a range of 38.0 – 39.3 for emitter location E2. The 100-fold recovery time is shorter and has a smaller range after the intervention took place. This indicates that there is more homogeneous mixing in the classroom compared to before the intervention (Figure 4-2).

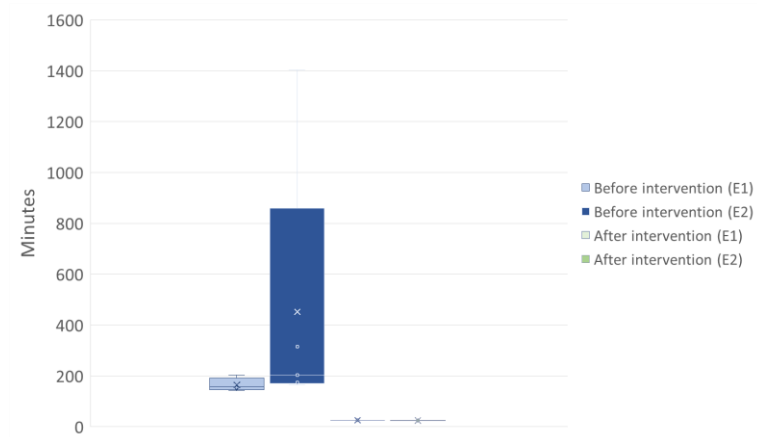


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 1.0– 12.0 min for emitter location E1 and has a range of 2.0 – 14.0 min for emitter location E2. After intervention, t_{delay} has a range of 0.8 – 4.3 min for emitter location E1 and has a range of 1.3 – 4.3 min for emitter location E2. t_{delay} has similar values when comparing before and after the intervention. t_{delay} is, however, longer at PC2 before the intervention. The reason for this could be that the location of the particle counter slightly changed between before and after intervention.

Air change per hour

Before intervention, the ACH has a range of N/A – 2.0 ACH for emitter location E1 and has a range of N/A – 1.7 ACH for emitter location E2. After intervention, the ACH has a range of 6.3 – 6.9 for emitter

Deliverable Work package 2

location E1 and has a range of 7.0 – 7.3 for emitter location E2. The ACH is larger after the intervention took place which indicates that there is a higher local air velocity at the location of the particle counters. For the measurements before the intervention, no air change rate meet the requirements for Class B (5.2) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'. After intervention, all air change rates meet the requirements for Class B (5.2).

4.2 *Air flow measurements*

Before the intervention took place, the highest air velocities are present at the center of the room but this is no dominant air flow present in the room. Furthermore, there is no clear air flow visible from the window grills towards the room.

The particle concentration measurements and the air flow measurements show that the air velocities are lowest near PC1 and PC3, this can explain the long 100-fold recovery time at these locations. Furthermore, the 100-fold recovery time is also long at PC2. At this location, the air velocities are also low and this particle counter was located near the ground where the air velocities are even lower.

After intervention, there is a dominant air flow from the back of the classroom towards the front of the classroom. Furthermore the air velocity are highest in the back of the classroom for both 1.0 m and 1.6 m. The air velocities are higher for a height of 1.6 m compared to a height of 1.0 m.

The particle concentration and the air flow measurements show that the air flow is directed towards the front of the classroom. From emitter location E1, the particles therefore flow directly towards the front which can explain the relative long 100-fold increase time for PC5 and PC6. Furthermore, the overall high air velocities throughout the whole room can explain the short 100-fold recovery time at all particle counters.

In conclusion, when both ventilation systems are compared it becomes clear that the air velocities are higher after the intervention took place. There is a dominant air flow present in the room. Due to this, the particle spread throughout the room has a lower dependence on the proximity of the particle counter to the emission source location. Concluded, due to the intervention the location of the children and teacher in the room becomes less prominent for a possible exposure and the overall risk to an exposure is lower.

ANNEX C, RESULTS CLASSROOM 3

Experiments in-situ

WP2, experiments after intervention B

DATUM	01-05-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location classroom 3

The results discussed in this report include both the situation without any interventions and the situation after the intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of ventilation window grills and openable windows and doors. In this location the windows and the doors were closed but the window grills were opened.

In the case of this location, two different interventions will take place. The first intervention was the use of a mobile air cleaner. At power setting 2, it has a capacity of 400 m³/h. The second intervention consist of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). This system consist of a raised floor with convectors for heating and cooling and airsocks for air distribution. There are panels in the ceiling for the exhaust of air.

In this report, the raised floor with convectors for heat and cooling will be discussed.

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1.1 *Characteristics of room and system*

Description of the room

The school is located in a suburban environment and was originally built in 1931. The classroom that was considered during this analysis, has a surface area of 48.7 m² and was located on the ground floor. The façade was orientated towards the West and the height of the room was 3.2 m. During the measurements, this room was designed for circa 30 students and 1 teacher. A visualization of the room can be seen in Figure 1-1.

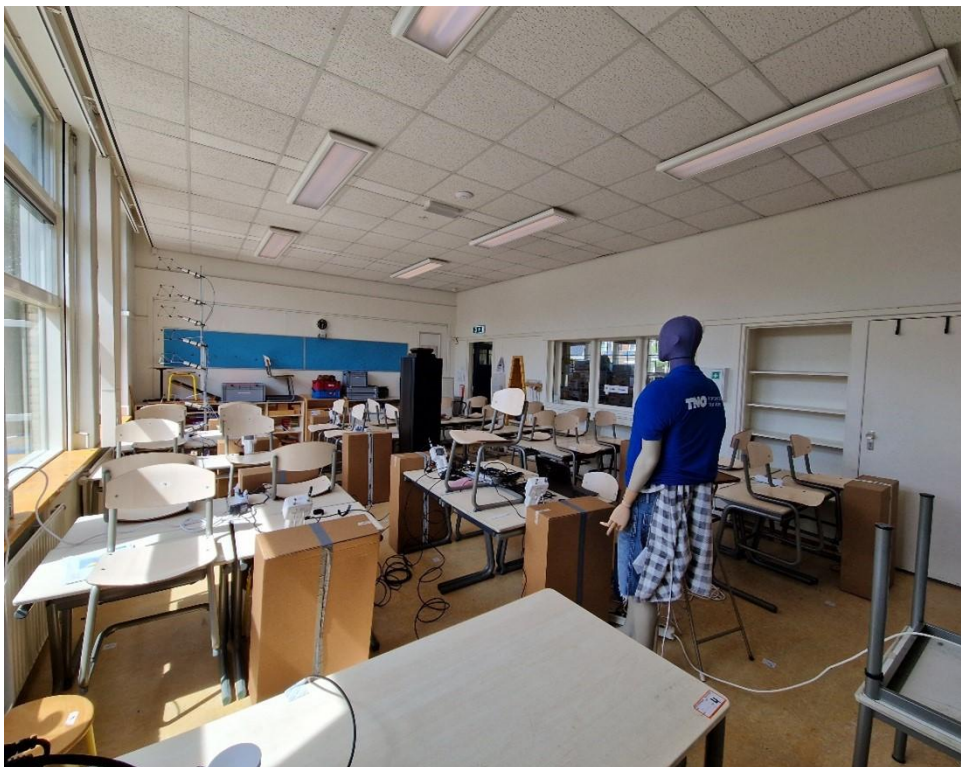


Figure 1.1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has three window grills which can be opened. The same applies for the exhaust of air (Figure 1-2). There are, furthermore, three openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

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Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	3 window ventilation grills	N/A
	Total	N/A
Ventilation (exhaust)		
	3 window ventilation grills	N/A
	Total	N/A



Figure 1.2 – Ventilation system before intervention

Deliverable Work package 2

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 11 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC2, PC3, PC4, PC5 and PC6 were located at 1.0 m height since this represents the breathing zone of sitting children. PC1 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.17 to 2.90 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 54 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

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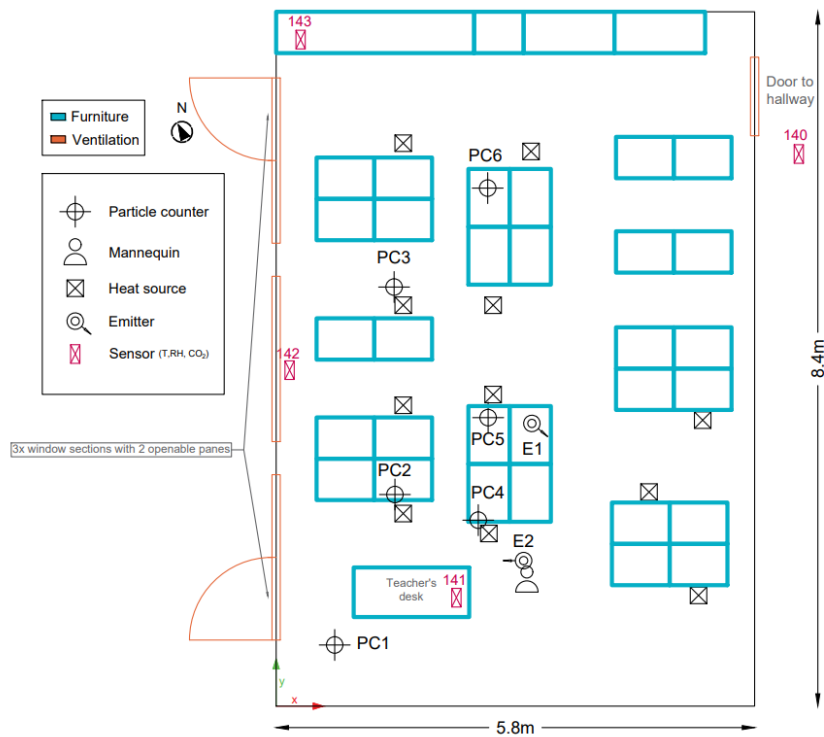


Figure 1.3 - Visualization of the classroom during the measurements (before intervention)

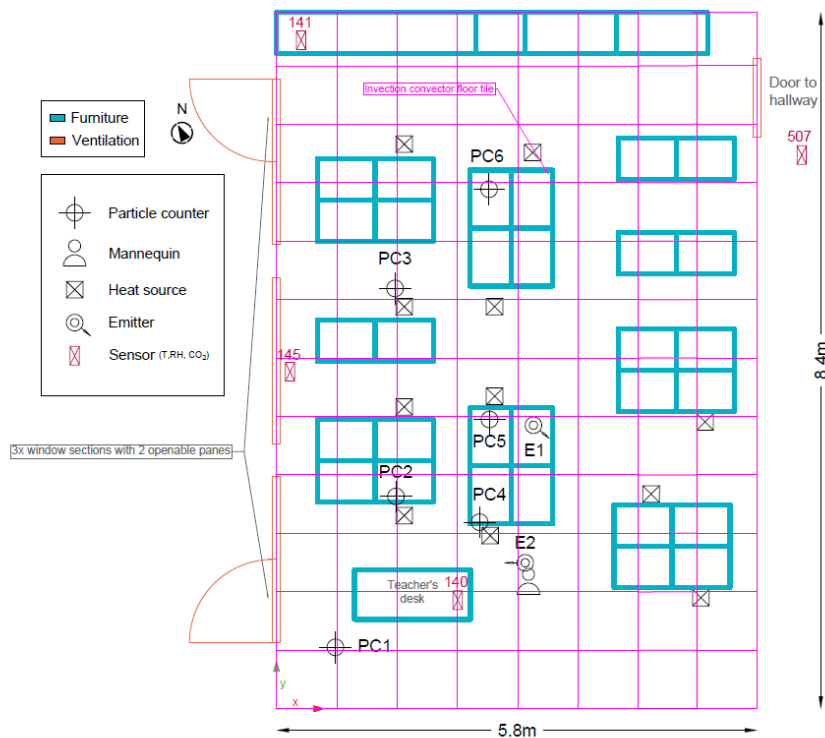


Figure 1.4 – Visualization of the classroom during the measurements (after intervention)

Deliverable Work package 2

2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 24.1 and 26.6 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: North, Wall 2: West, Wall 3: South, Wall 4: East. Metrological data is from weerstatistieken.nl of a nearby weather station.

12-07-2023				
Surface area temperature (°C)		10:30	14:00	
	Wall 1	25.3	26.7	
	Wall 2	25.8	26.8	
	Wall 3	26.4	27.2	
	Wall 4	25.5	27.2	
	Ceiling	25.4	27.1	
	Floor	22.6	25.5	
	Glass surface of the windows	25.4	27.2	
		Min*	Mean*	Max*
Air temperature (°C)		24.1	25.7	26.6
Relative humidity (%)		52.0	54.9	59.5
Outdoor air temperature (°C)		16.6	18.7	22.0
Outdoor relative humidity (%)		48	72	90
Wind	Velocity (m/s)	4.0	6.5	8.0
	Direction	West-South-West (245°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-16:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 16.9 – 35.6 min for emitter location E1 and has a range of 8.3 – 47.7 min for emitter location E2. The 100-fold increase time is the longest at PC6 for both emitter location E1 and E2 (35.6 and 47.7 min). This particle counter is located at a relatively far distance from both emitter locations which means it takes longer for the particles to reach the particle counter location the particle concentration. The 100-fold increase time is the shortest for both PC1 and PC4 at emitter location E2 (8.3 – 9.1 min). These particle counters are both located relatively close to the emitter which means that the particle concentration can increase faster.

Deliverable Work package 2

The 100-fold recovery time has a range of 158 – 192 min for emitter location E1 and has a range of 119 – 349 min for emitter location E2. The 100-fold recovery time is the longest near PC6 at emitter location E2, with a value of 349 min. The shortest 100-fold recovery time is at PC1, PC2 and PC4 for emitter location E2 (119, 135 and 123 min). At these location the 100-fold increase time was also the shortest meaning the particle concentration increases fast after emission and decrease relatively fast after the emission period ended.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'Good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 30 children and 1 teacher, this results in a ventilation rate of 670 m³/h (4.3 ACH) for a Class C and 949 m³/h (6.1 ACH) for Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.5 – 6.3 min for emitter location E1 and has a range of 1.0 – 5.3 min for emitter location E2. t_{delay} is the longest for PC6 for both emitter locations (5.3 and 6.3 min). This location was also the location with the longest 100-fold increase time which indicates that it takes long until the particle concentration starts to increase during the emission period and after the emission period it takes long until the particle concentration starts to decrease. t_{delay} is shortest for PC3 emitter location E1 (0.5 min). This means that at this location the decrease of the particle concentration starts quickly after the emission stopped.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	23.7	189	1.5	3.8
	E2	8.3	119	2.3	1.0
PC2	E1	17.3	172	1.6	1.3
	E2	9.7	135	2.0	1.0
PC3	E1	23.6	158	1.7	0.5
	E2	15.7	198	1.4	2.0
PC4	E1	16.9	169	1.6	1.5
	E2	9.1	123	2.2	1.0
PC5	E1	21.5	166	1.7	2.0
	E2	17.1	155	1.8	2.5
PC6	E1	35.6	192	1.4	6.3
	E2	47.7	349	0.8	5.3

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2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.09 m/s).

In Figure 2-1, an air flow from the windows towards the center of the room is present. Specifically near the particle counters, an air flow from the windows towards PC2, PC3 and PC4 and PC5 is present. This flow continues towards both emitter locations.

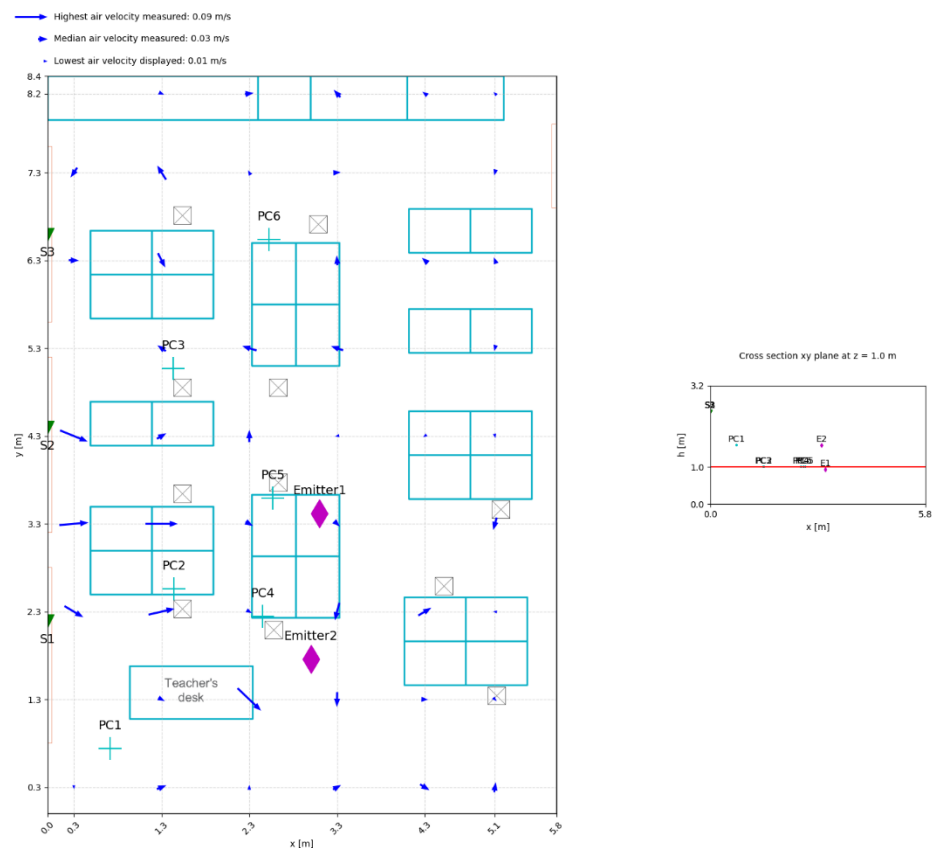


Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

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For PC1, the air flow is analysed at a height of 1.6 m, see Figure 2-2. In this figure, the air flow from the windows towards the classroom is less dominant (lower air velocities) than at a height of 1.0 m. An air flow from PC1 towards the windows is noticeable. There is no clear air flow near both emitter locations.

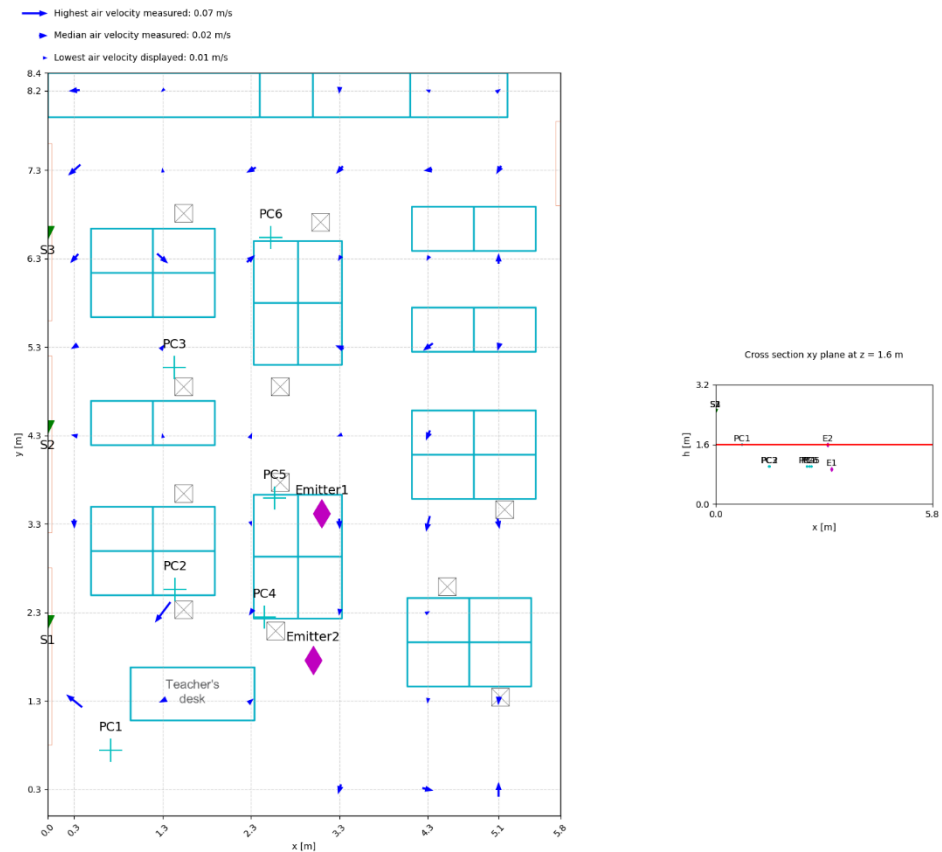


Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system consists of a raised floor with convectors for heating and cooling. Furthermore, it consists of airsocks for the distribution of air (see Figure 3.1). It is important to note that the ventilation did not work optimal during the measurement which means that the floor convectors did not distribute the air evenly throughout the room. The measured flow rate of 715 m³/h was measured by measuring the flow rate at each specific panel (8 x 12 in total). There are panels in the ceiling for the exhaust of air. There are, furthermore, three openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Floor air convector	715
	Total	715
Ventilation (exhaust)		
	Ceiling air ventilation	N/A
	Total	N/A



Figure 3.1 – Ventilation system after intervention

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Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 16.4 and 18.0 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

19-02-2023				
Surface area temperature (°C)		14:30	17:00	
	Wall 1	17.4	17.4	
	Wall 2	16.4	16.4	
	Wall 3	15.4	15.3	
	Wall 4	15.9	15.8	
	Ceiling	16.7	16.8	
	Floor	14.9	15.0	
		Min*	Mean*	Max*
Air temperature (°C)		16.4	17.3	18.0
Relative humidity (%)		55.3	58.1	62.5
Outdoor air temperature (°C)		4.9	8.8	10.8
Outdoor relative humidity (%)		82	88	94
Wind	Velocity (m/s)	2.0	4.4	7.0
	Direction	West (263°)		

* The mean value is calculated by taking the average values of all sensor 140, 141 and 145 between 12:00-17:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before and after the intervention. The 100-fold increase time has a range of 3.0 – 832.0 min for emitter location E1 and has a range of 5.2 – 936.4 min for emitter location E2. The 100-fold recovery time has a range of 19.2 – N/A for emitter location E1 and has a range of 41.9 – N/A for emitter location E2. It can be seen that the range for both the 100-fold increase time and the 100-fold recovery time is large between the different particle counters. This can be explained by the malfunctioning of the ventilation system during the measurement period. The air flow measurements that will be described in the next section can further visualize this malfunctioning of the system.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings

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there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 30 children and 1 teacher, this results in a ventilation rate of 670 m³/h (4.3 ACH) for a Class C and 949 m³/h (6.1 ACH) for Class B. When these values are compared with the ACH values in Table 3.3, it can be seen that 6 values meet the requirements for Class C and 5 values meet the requirements for Class B.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 2.5 – 12.8 min for emitter location E1 and has a range of 6.5 – 13.8 min for emitter location E2. In general, t_{delay} is the shortest when the 100-fold recovery time is also short.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	23.7	3.0	189.4	19.2	1.5	14.4	3.8	5.8
	E2	8.3	936.4	119.0	N/A*	2.3	N/A*	1.0	11.8
PC2	E1	17.3	17.9	172.3	20.1	1.6	13.8	1.3	2.5
	E2	9.7	283.2	135.0	1081.9	2.0	0.3	1.0	8.0
PC3	E1	23.6	832.0	158.3	N/A*	1.7	N/A*	0.5	11.0
	E2	15.7	24.4	198.6	61.5	1.4	4.5	2.0	7.5
PC4	E1	16.9	4.1	169.1	24.8	1.6	11.1	1.5	3.5
	E2	9.1	494.4	123.6	N/A*	2.2	N/A*	1.0	13.8
PC5	E1	21.5	23.8	166.5	34.7	1.7	8.0	2.0	5.8
	E2	17.1	610.9	155.0	144.3	1.8	1.9	2.5	7.0
PC6	E1	35.6	406.6	192.9	N/A*	1.4	N/A*	6.3	12.8
	E2	47.7	5.2	349.1	41.9	0.8	6.6	5.3	6.5

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.06 m/s).

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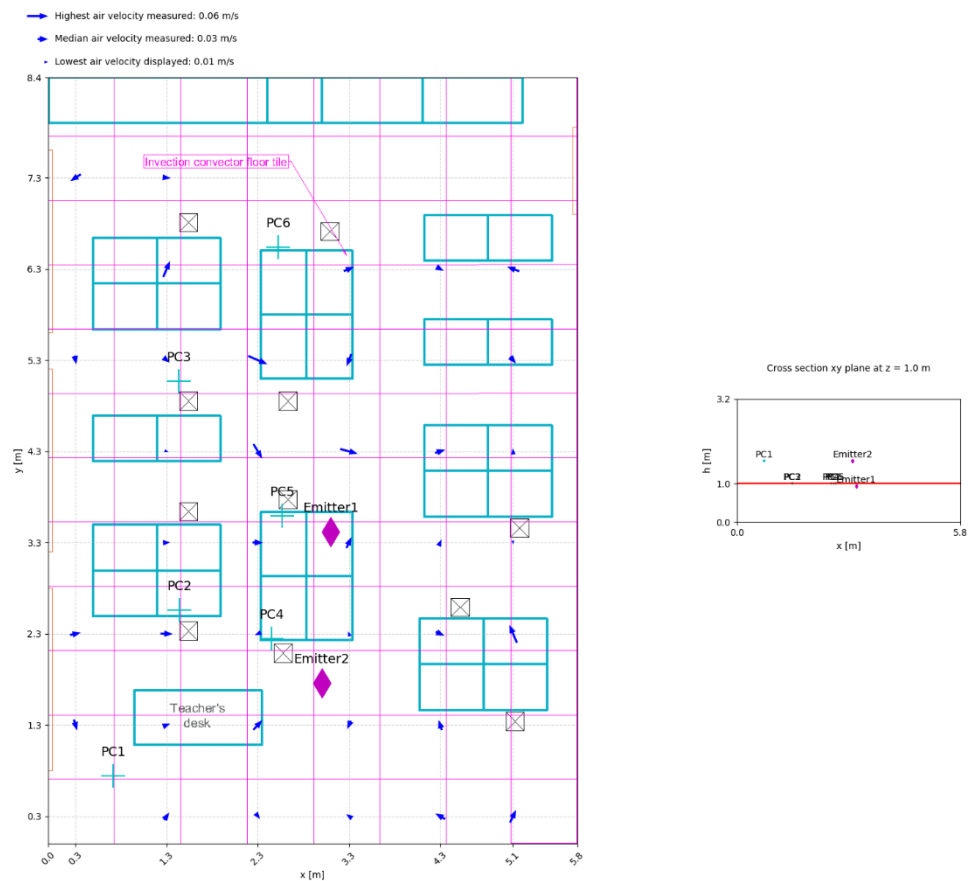


Figure 3.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC1, the air flow is analyzed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.07).

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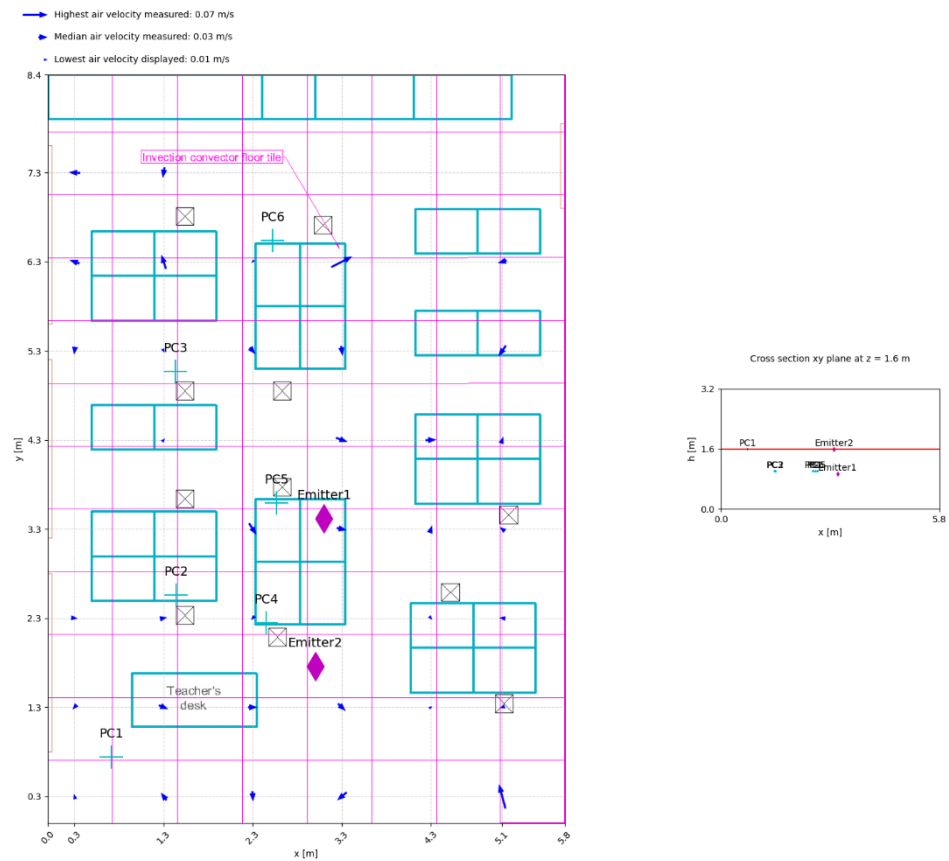


Figure 3.3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

From both figures, it can be concluded that the air velocities in the classroom are low during the measurement period. Furthermore, in Figure 3.4, it can be seen that there is only a clear air flow from the floor towards the ceiling at the front of the classroom. At the other locations there is no dominant air flow present.

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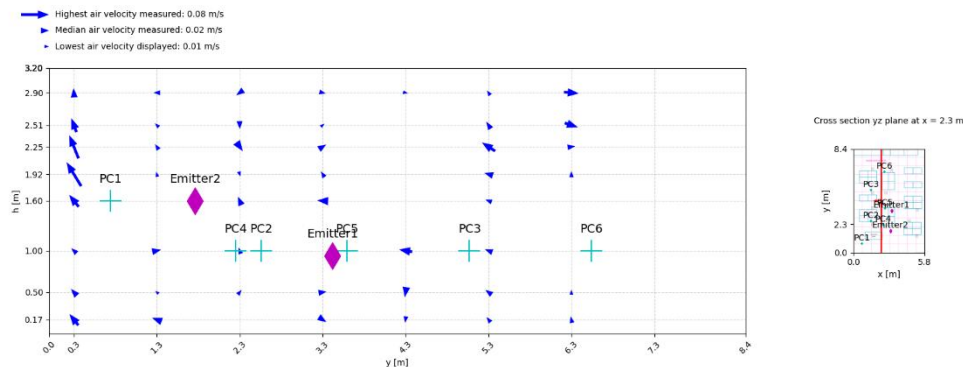


Figure 3.4 - Air flow (direction and velocity) in the YZ-plane for $X = 2.3$ m

4. Conclusions

For this measurement, it is difficult to compare the ventilation system before and after the intervention since the ventilation system did not work properly after the intervention was placed in the building. This resulted in a different air flow rate from the floor at different locations in the room. Therefore, the 100-fold recovery time and 100-fold increase time have a large variance between different locations in the room. Which indicates that the overall increase and decrease of particle concentration in the room is diverse throughout the room, so it is not homogeneous. But no conclusions can be made about the performance of this ventilation system based on these measurements.

ANNEX C, RESULTS CLASSROOM 3

Experiments in-situ

WP2, experiments after intervention A

DATUM	08-01-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location classroom 3

The results discussed in this report include both the situation without any interventions and the situation after the intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of ventilation window grills and openable windows and doors. In this location the windows and the doors were closed but the window grills were opened.

In the case of this location, two different interventions will take place. The first intervention was the use of a mobile air cleaner (intervention A). At power setting 2, it has a capacity of 400 m³/h. The second intervention consist of the replacement of the ventilation system (Intervention B): new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). This system consist of a raised floor with convectors for heating and cooling and airsocks for air distribution. There are panels in the ceiling for the exhaust of air.

In this report, the mobile air cleaner will be discussed as the intervention.

Deliverable Work package 2

1.1 Characteristics of room and system

Description of the room

The school is located in a suburban environment and was originally built in 1931. The classroom that was considered during this analysis, has a surface area of 48.7 m² and was located on the ground floor. The façade was orientated towards the West and the height of the room was 3.2 m. During the measurements, this room was designed for circa 30 students and 1 teacher. A visualization of the room can be seen in Figure 1-1.

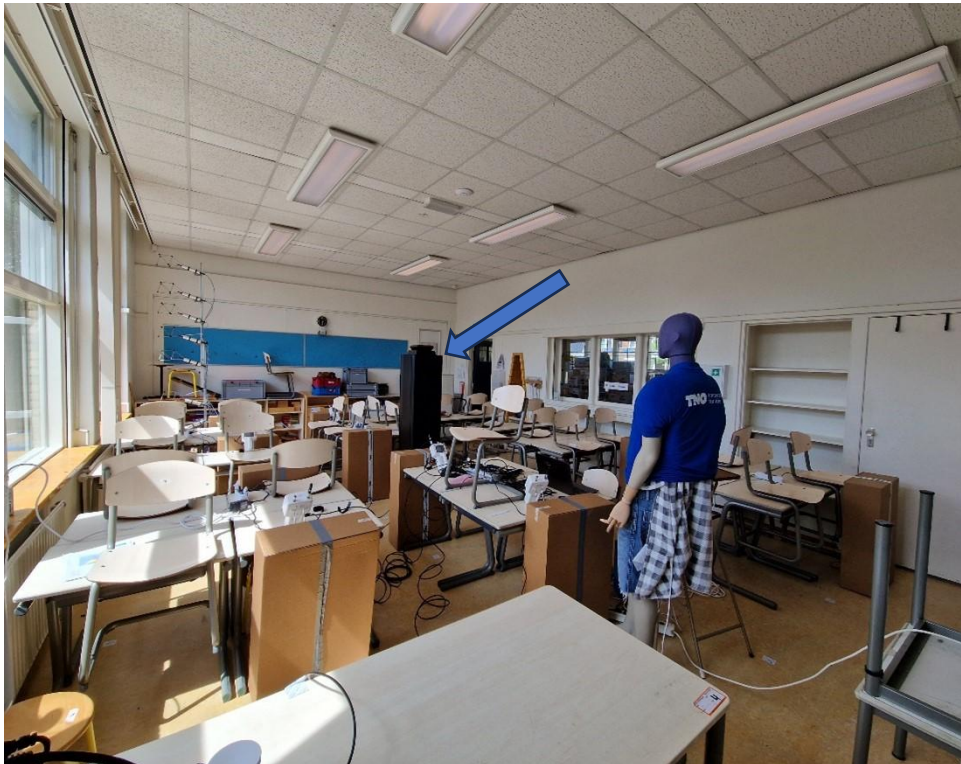


Figure 1-1 - Visualization of the classroom during the measurements, intervention A

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has three window grills which can be opened. The same applies for the exhaust of air (Figure 1-2). There are, furthermore, three openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

Deliverable Work package 2

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	3 window ventilation grills	N/A
	Total	N/A
Ventilation (exhaust)		
	3 window ventilation grills	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

Deliverable Work package 2

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 11 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC2, PC3, PC4, PC5 and PC6 were located at 1.0 m height since this represents the breathing zone of sitting children. PC1 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.17 to 2.90 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 54 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

Deliverable Work package 2

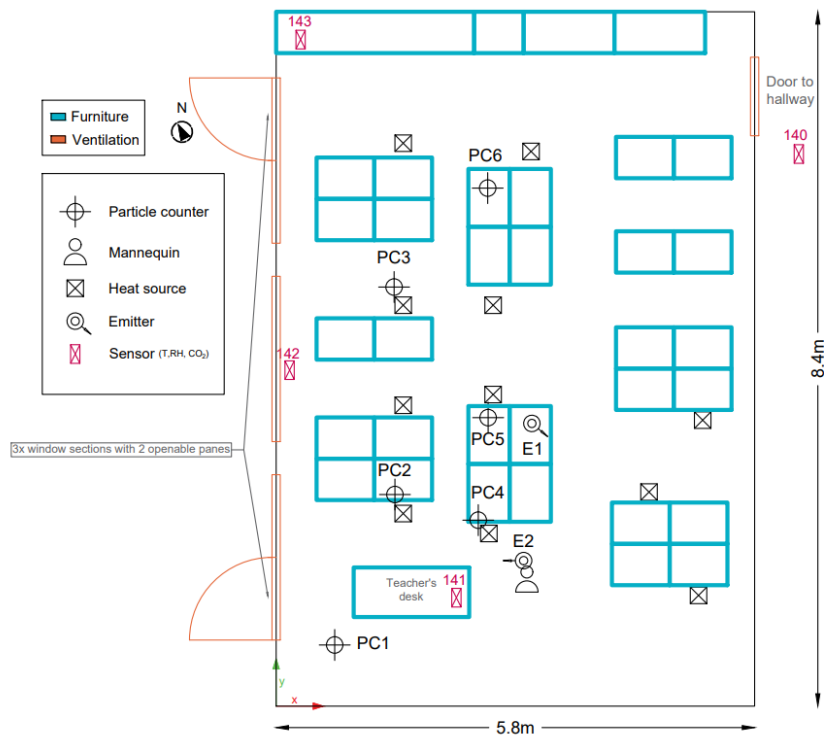


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

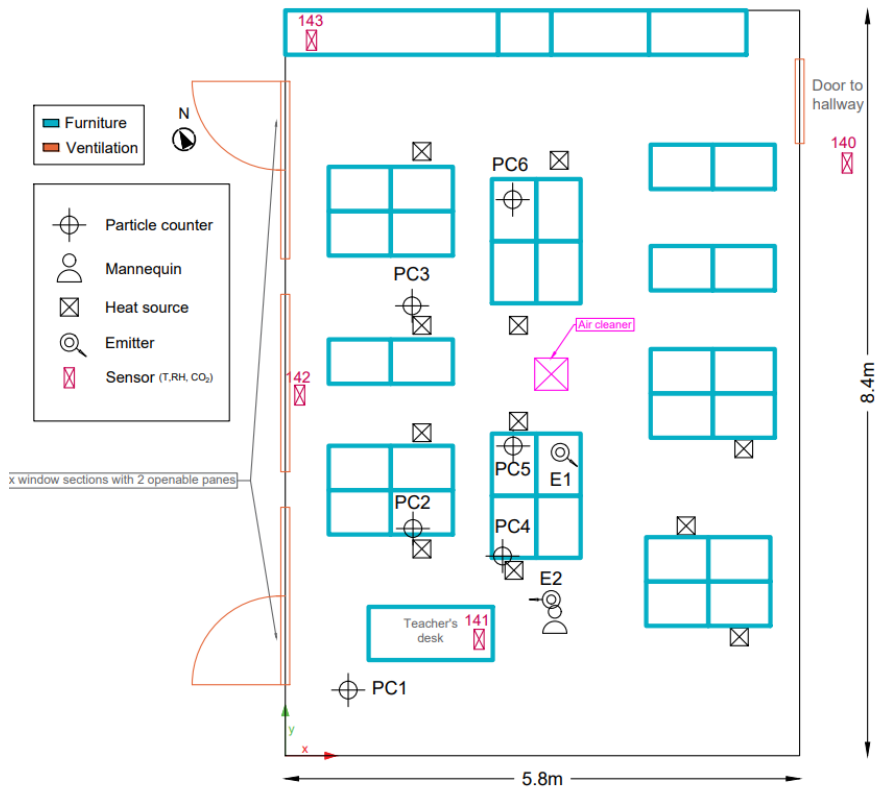


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

Deliverable Work package 2

2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 24.1 and 26.6 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: North, Wall 2: West, Wall 3: South, Wall 4: East. Metrological data is from weerstatistieken.nl of a nearby weather station.

12-07-2023				
Surface area temperature (°C)		10:30	14:00	
	Wall 1	25.3	26.7	
	Wall 2	25.8	26.8	
	Wall 3	26.4	27.2	
	Wall 4	25.5	27.2	
	Ceiling	25.4	27.1	
	Floor	22.6	25.5	
	Glass surface of the windows	25.4	27.2	
		Min*	Mean*	Max*
Air temperature (°C)		24.1	25.7	26.6
Relative humidity (%)		52.0	54.9	59.5
Outdoor air temperature (°C)		16.6	18.7	22.0
Outdoor relative humidity (%)		48	72	90
Wind	Velocity (m/s)	4.0	6.5	8.0
	Direction	West-South-West (245°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-16:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 16.9 – 35.6 min for emitter location E1 and has a range of 8.3 – 47.7 min for emitter location E2. The 100-fold increase time is the longest at PC6 for both emitter location E1 and E2 (35.6 and 47.7 min). This particle counter is located at a relative far distance from both emitter locations which means it takes longer for the particles to reach the particle counter location the particle concentration. The 100-fold increase time is the shortest for both PC1 and PC4 at emitter location E2 (8.3 – 9.1 min). These particle counters are both located relatively close to the emitter which means that the particle concentration can increase faster.

Deliverable Work package 2

The 100-fold recovery time has a range of 158 – 192 min for emitter location E1 and has a range of 119 – 349 min for emitter location E2. The 100-fold recovery time is the longest near PC6 at emitter location E2, with a value of 349 min. The shortest 100-fold recovery time is at PC1, PC2 and PC4 for emitter location E2 (119, 135 and 123 min). At these location the 100-fold increase time was also the shortest meaning the particle concentration increases fast after emission and decrease relative fast after the emission period ended.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'Good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 30 children and 1 teacher, this results in a ventilation rate of 670 m³/h (4.3 ACH) for a Class C and 949 m³/h (6.1 ACH) for Class B. When these values are compared with the ACH values in **Fout! Verwijzingsbron niet gevonden.**, it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.5 – 6.3 min for emitter location E1 and has a range of 1.0 – 5.3 min for emitter location E2. t_{delay} is the longest for PC6 for both emitter locations (5.3 and 6.3 min). This location was also the location with the longest 100-fold increase time which indicates that it takes long until the particle concentration starts to increase during the emission period and after the emission period it takes long until the particle concentration starts to decrease. t_{delay} is shortest for PC3 emitter location E1 (0.5 min). This means that at this location the decrease of the particle concentration starts quickly after the emission stopped.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	23.7	189	1.5	3.8
	E2	8.3	119	2.3	1.0
PC2	E1	17.3	172	1.6	1.3
	E2	9.7	135	2.0	1.0
PC3	E1	23.6	158	1.7	0.5
	E2	15.7	198	1.4	2.0
PC4	E1	16.9	169	1.6	1.5
	E2	9.1	123	2.2	1.0
PC5	E1	21.5	166	1.7	2.0
	E2	17.1	155	1.8	2.5
PC6	E1	35.6	192	1.4	6.3

Deliverable Work package 2

	E2	47.7	349	0.8	5.3
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2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 1-3 (range 0.01 – 0.09 m/s).

In Figure 1-3, an air flow from the windows towards the center of the room is present. Specifically near the particle counters, an air flow from the windows towards PC2, PC3 and PC4 and PC5 is present. This flow continues towards both emitter locations.

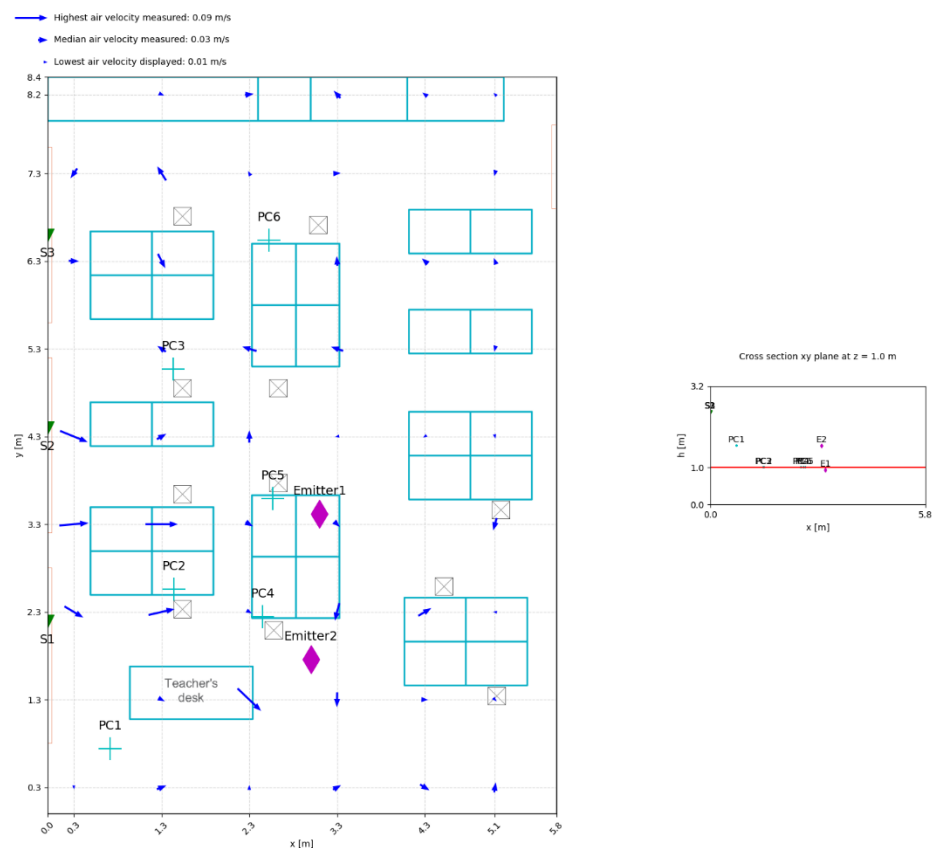


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

Deliverable Work package 2

For PC1, the air flow is analysed at a height of 1.6 m, see Figure 1-4. In this figure, the air flow from the windows towards the classroom is less dominant (lower air velocities) than at a height of 1.0 m. An air flow from PC1 towards the windows is noticeable. There is no clear air flow near both emitter locations.

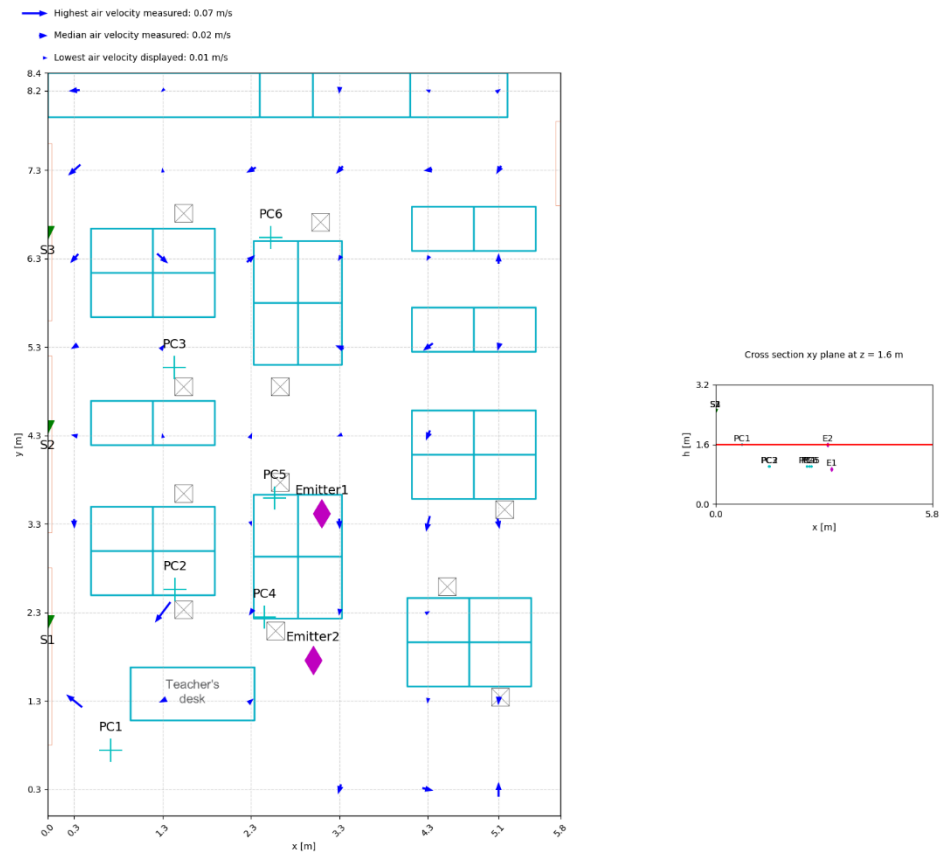


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system consists of a mobile air cleaner. The air cleaner was set to set-up 2 which results in a designed flow rate of 400 m³/h. Due to the design of the ventilation system, it was not possible to measure the supply of air in the room. There are furthermore, three openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Deliverable Work package 2

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Mobile air cleaner	N/A
	Total	N/A
Ventilation (exhaust)		
	Mobile air cleaner	N/A
	Total	N/A



Figure 3-1 – Ventilation system after intervention A

Deliverable Work package 2

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 24.8 and 29.6 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

11-07-2023				
Surface area temperature (°C)		10:30	14:00	
	Wall 1	27.3	28.8	
	Wall 2	27.0	27.5	
	Wall 3	27.2	27.1	
	Wall 4	27.7	28.0	
	Ceiling	27.3	28.8	
	Floor	26.4	27.5	
	Glass surface of the windows	29.6	35.3	
		Min*	Mean*	Max*
Air temperature (°C)		24.8	27.8	29.6
Relative humidity (%)		50.4	53.7	57.5
Outdoor air temperature (°C)		16.3	21.4	26.3
Outdoor relative humidity (%)		53	66	81
Wind	Velocity (m/s)	2.3	4.4	7.0
	Direction	West-South-West (240°)		

* The mean value is calculated by taking the average values of all sensor 141, 142 and 143 between 10:00-14:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before and after the intervention. The 100-fold increase time has a range of 10.3 – 40.1 min for emitter location E1 and has a range of 2.1 – 37.6 min for emitter location E2. The 100-fold increase time is longest for PC3 at emitter location E1 (40.1 min) and at PC6 for emitter location E2 (37.6 min). The 100-fold increase time is shortest for PC5 emitter location E2 (2.1 min). The short 100-fold increase time at PC5 (E2) could be related to the location of the exhaust which is located directly next to PC5.

Deliverable Work package 2

The 100-fold recovery time has a range of 98.4 – 239 min for emitter location E1 and has a range of 117 – 162 min for emitter location E2. The 100-fold recovery time has similar values for the measurement after the intervention compared to before the intervention. This could be related to the relative low ventilation rate of the mobile air cleaner (+/- 400 m³/h). The 100-fold recovery time is longest for PC6 (E1), this particle counter is located at a far distance from the emitter location.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021),. First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 30 children and 1 teachers, this results in a ventilation rate of 670 m³/h (4.3 ACH) for a Class C and 949 m³/h (6.1 ACH) for Class B. When these values are compared with the ACH values in Table 3.3 for the measurement after intervention (ACH 1.4 – 2.8), it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.8 – 6.0 min for emitter location E1 and has a range of 0.5 – 4.0 min for emitter location E2. t_{delay} is the longest at PC6 (E1) and at PC2 (E2) with values of respectively 6.0 and 4.0 min. t_{delay} is the shortest for PC5 emitter location E2 (0.5 min). At this location, the 100-fold increase time was also the shortest. This indicates that the increase in particle concentration at this location is quick and the decrease starts quickly after the emission period stopped.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	23.7	10.3	189	103	1.5	2.7	3.8	1.0
	E2	8.3	18.4	119	162	2.3	1.7	1.0	1.0
PC2	E1	17.3	15.0	172	109	1.6	2.5	1.3	1.5
	E2	9.7	29.6	135	135	2.0	2.0	1.0	4.0
PC3	E1	23.6	40.1	158	199	1.7	1.4	0.5	2.8
	E2	15.7	22.6	198	118	1.4	2.3	2.0	2.8
PC4	E1	16.9	15.5	169	98.4	1.6	2.8	1.5	0.8
	E2	9.1	15.8	123	145	2.2	1.9	1.0	2.0
PC5	E1	21.5	20.8	166	100	1.7	2.7	2.0	2.3
	E2	17.1	2.1	155	117	1.8	2.4	2.5	0.5
PC6	E1	35.6	37.5	192	239	1.4	1.2	6.3	6.0
	E2	47.7	37.6	349	148	0.8	1.9	5.3	2.8

Deliverable Work package 2

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.09 m/s).

In Figure 2-1, it is visualized that the air velocities are relatively low with maximum values of 0.09 m/s at this height. The air flow is directed from the sides of the classroom in the direction of the mobile air cleaner in the classroom. Specifically for the particle counters, there is an air flow from PC2, PC4, PC5 and PC6 in the direction of the exhaust which is close to emitter location E1. There is no clear flow from the emitter locations in the direction of a particle counter.

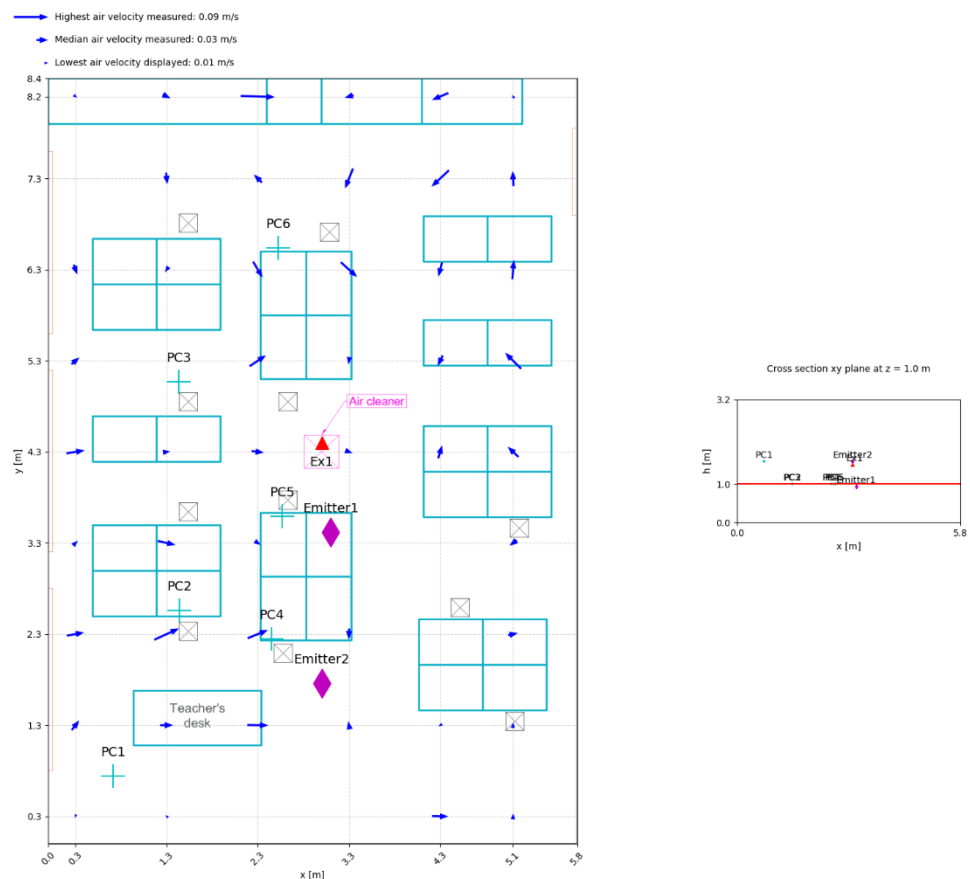


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

Deliverable Work package 2

For PC1, the air flow is analyzed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.15). In this figure, a clear air flow can be seen from the mobile air cleaner towards the room. Furthermore, there is no clear air flow in the direction of the air cleaner. When looking specifically towards particle counter PC1, the air velocities seem low near this location and there is no clear air flow near this particle counter.

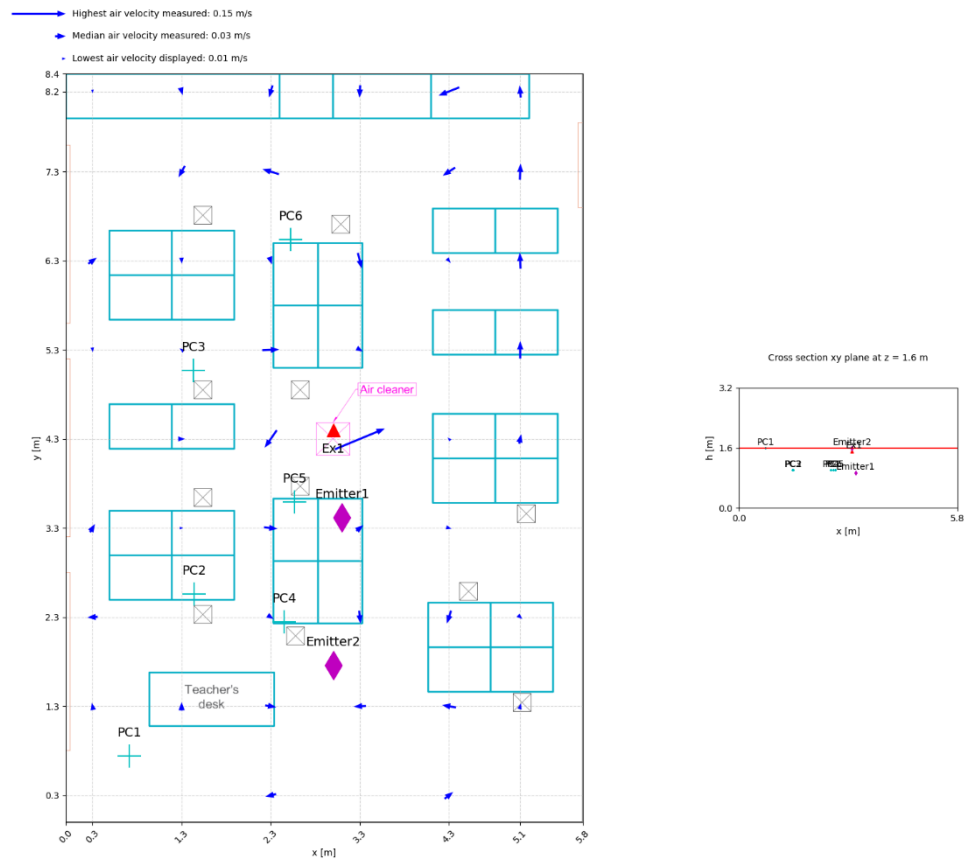


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

4. Conclusions

In this section, the performance of the ventilation system before and after intervention are described and compared through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before intervention, the 100-fold increase time has a range of 16.9 – 35.6 min for emitter location E1 and has a range of 8.3 – 47.7 min for emitter location E2. After intervention, the 100-fold increase time has a range of 10.3 – 40.1 min for emitter location E1 and has a range of 2.1 – 37.6 min for emitter location E2. There is no clear difference for the 100-fold increase time before and after the intervention. For both before and after the intervention, the values are longest for PC6 which can be explained by the far distance between the emitter locations and the location of this particle counter. Overall, the results indicate that the overall increase in particle concentration in the room is diverse throughout the room (before and after the intervention), so it is not homogenous (Figure 4-1).

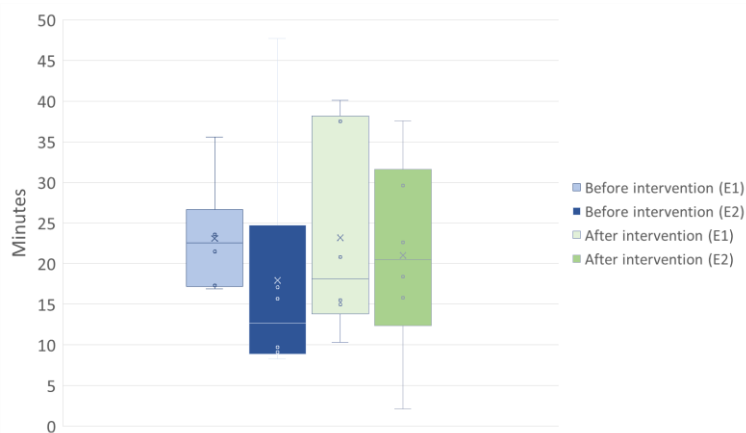


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before intervention, the 100-fold recovery time has a range of 158.3 – 192.9 min for emitter location E1 and has a range of 119.0 – 349.1 min for emitter location E2. After intervention, the 100-fold recovery time has a range of 98.4 – 239.8 min for emitter location E1 and has a range of 117.4 – 162.5 min for emitter location E2. There is no clear difference for the 100-fold recovery time before and after the intervention. There are values that are longer after the intervention took place but there are also values that are shorter. From this, it can be concluded that the classroom is not more homogeneously mixed after the intervention took place. It should be noted, however, that the wind speed and direction have an impact on the result before the intervention. The difference between before and after the intervention could have been larger if (for instance) the wind speed during the day was lower (Figure 4-2).

Deliverable Work package 2

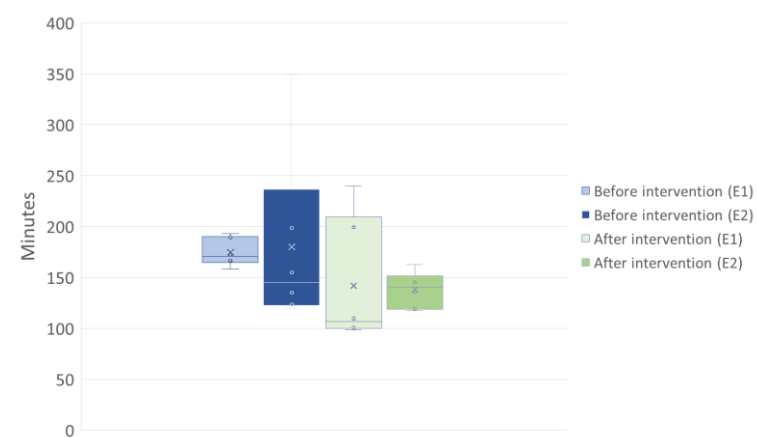


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 0.5 – 6.3 min for emitter location E1 and has a range of 1.0 – 5.3 min for emitter location E2. After intervention, t_{delay} has a range of 0.8 – 6.0 min for emitter location E1 and has a range of 0.5 – 4.0 min for emitter location E2. t_{delay} has similar values when comparing before and after the intervention. t_{delay} is (in general) longest when the 100-fold increase time also relative long is. This indicates that it takes long before the particle concentration starts to increase after the emission started and it takes long before the particle concentration starts to decrease after the emission period stopped.

Air change per hour

Before intervention, the ACH has a range of 1.4 – 1.7 ACH for emitter location E1 and has a range of 0.8 – 2.3 ACH for emitter location E2. After intervention, the ACH has a range of 1.2 – 2.8 ACH for emitter location E1 and has a range of 1.7 – 2.4 ACH for emitter location E2. The ACH is directly related to the 100-fold recovery time. There are, therefore, also no clear differences between the ACH values before and after the intervention took place. Both for the measurements before and after the intervention, no air change rate meet the requirements for Class B (6.1) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'.

4.2 Air flow measurements

Before intervention, there is an air flow from the windows towards the centre of the room. This air flow is dominant at a height of 1.0 m and is not present at a height of 1.6 m. The highest air velocities are also measured near the windows, the air velocities are low at other locations in the classroom.

The particle concentration measurements and the air flow measurements show that the air velocity is low near PC6 which could explain the relative high 100-fold increase time at this location. Furthermore, at a height of 1.0 m, there is an air flow from the windows directed towards PC2 and PC4 and PC5 which could explain the fact the 100-fold recovery time is shortest at these locations.

After intervention, the air velocities are relative low but there is an air flow in the direction of the mobile air cleaner. At a height of 1.6 meter there is an air flow from the air cleaner in the direction of the classroom but no directed towards the air cleaner.

Deliverable Work package 2

The particle concentration measurements and the air flow measurements show that there is no clear air flow directed from the emitters towards the particle counters which could explain the relative long 100-fold increase time for the particle counters. Furthermore, the air velocities are highest near PC2 and PC4 which could explain why the 100-fold recovery time is slightly shorter at these locations.

General conclusions

In conclusion, when both ventilation systems are compared it becomes clear that there is no clear difference after the intervention took place. There is no dominant direction of the air flow throughout the room. Due to this, the particle spread throughout the room is also after the intervention dependent on the proximity of the particle counter to the emission source location. It should be noted that the measurements before the intervention were dependent on weather conditions (wind) which means that there could have been a larger difference when the wind speed was (for instance) smaller.

ANNEX D, RESULTS CLASSROOM 4

Experiments in-situ

WP2, experiments after intervention

DATUM 08-04-2024

AUTEURS Ir. A. de Lange

ORGANISATIE TNO

1. Results baseline measurement location classroom 4

The results discussed in this report include both the situation before and after the interventions. The intervention was initiated by the primary school to optimize or adapt the ventilation system.

The interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system regarding capacity, function or system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes that are reported (before and after the intervention).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of ventilation window grills and openable windows and doors. In this location the windows were opened and the door was closed during the measurements.

In the case of this location the intervention consist of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). This system consist of a balanced CO₂ controlled ventilation system with heat recovery. The heat recovery unit that will be installed has a heat recovery efficiency of 90%. The unit is designed to meet de requirements for Class B of 'PvE Frisse Scholen 2021' and has a (design) capacity of 795,6 m³/h based on 25 students and one teacher.

Deliverable Work package 2

1.1 Characteristics of room and system

Description of the room

The school is located in a suburban environment and was originally built in 1972. The classroom that was considered during this analysis, has a surface area of 57.0 m² and was located on the ground floor. That façade was orientated towards the South and the height of the room was 3.2 m. During the measurements, this room was designed for circa 25 students and one teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has four tilt and turn windows and a door which can be opened (see Figure 1-2). The same applies for the exhaust of air. It should be noted that the windows were opened and the door was closed during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	4 openable windows	N/A
	Total	N/A
Ventilation (exhaust)		
	4 openable windows	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 11 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC1, PC2, PC3, PC4 and PC5 were located at 1.0 m height since this represents the breathing zone of sitting children. PC6 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.17 to 2.51 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 54 measurement points.

Deliverable Work package 2

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

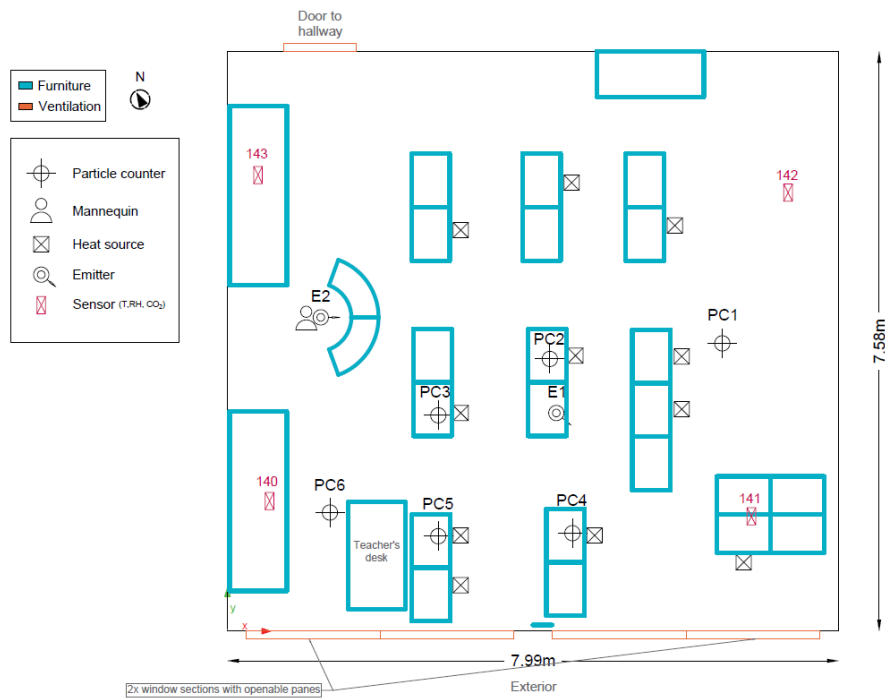


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

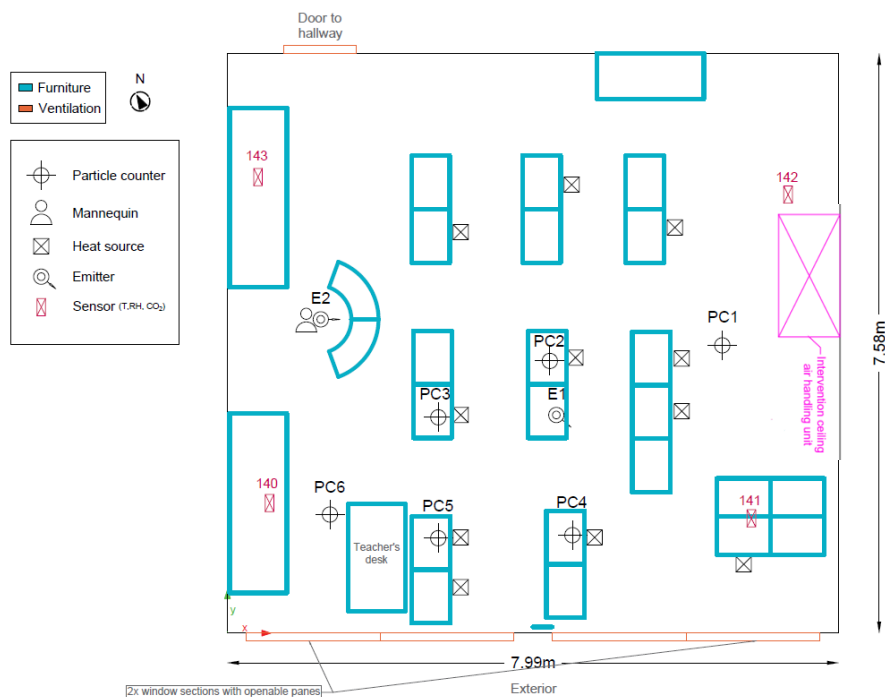


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 23.5 and 27.6 °C throughout the day. It should be noted that the surface area temperature was not measured during the afternoon since no particle or air flow measurements were performed during this time of the day.

Table 2.1 - Conditions during the measurement period. Wall 1: West, Wall 2: North, Wall 3: South, Wall 4: East. Metrological data is from weerstatistieken.nl of a nearby weather station.

16-06-2023				
Surface area temperature (°C)		11:00	16:00	
	Wall 1	24.6	N/A	
	Wall 2	24.3	N/A	
	Wall 3	24.7	N/A	
	Wall 4	24.0	N/A	
	Ceiling**	24.9	N/A	
	Floor	23.3	N/A	
	Glass surface of the windows	25.5	N/A	
		Min*	Mean*	Max*
Air temperature (°C)		23.5	25.9	27.6
Relative humidity (%)		39.0	42.3	47.4
Outdoor air temperature (°C)		11.8	19.7	26.3
Outdoor relative humidity (%)		30	54	98
Wind	Velocity (m/s)	0.8	2.3	5.0
	Direction	North-East (4°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-15:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 1.8 – 11.3 min for emitter location E1 and has a range of 1.8 – 26.6 min for emitter location E2. The 100-fold increase time is the longest on location PC1 for emitter location E2 (26.6 min). This particle counter is located relatively far away from the emitter. The 100-

Deliverable Work package 2

fold increase time is the shortest for both PC3 (E2) and PC6 (E1), both 1.8 min. These particle counters are both located relatively close to the emitter which means that the particle concentration can increase faster.

The 100-fold recovery time has a range of 50.7 – 99.3 min for emitter location E1 and has a range of 70.0 – 95.5 min for emitter location E2. The 100-fold recovery time is the longest at location PC5 for emitter location E1, with a value of 99.3 min. Furthermore, the 100-fold recovery time is relatively long for the particle counters that are located near the window. The shortest 100-fold recovery time is at PC2 for emitter location E1 (50.7 min) which is followed-up by PC6 (67.1 min).

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'Good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m³/h (3.1 ACH) for a Class C and 796 m³/h (4.4 ACH) for Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that only three values do not meet the requirements for Class C. Almost all locations do not meet the requirements for Class B, only PC2 emitter location E1 meets the recommendation.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.3 – 2.8 min for emitter location E1 and has a range of 0.3 – 1.5 min for emitter location E2. t_{delay} is the longest for PC2 for both emitter location E1 and E2 (2.8 – 2.3 min). The t_{delay} is shortest for PC3 emitter location E1 and E2 (0.3 min). This means that at these locations the decrease of the particle concentration starts quickly after the emission stopped. Both locations are located quite close to the emitter location and have a high particle concentration at the end of the emission period.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	5.2	88.2	3.1	0.5
	E2	26.6	70.9	3.9	1.0
PC2	E1	11.3	50.7	5.5	2.8
	E2	9.9	79.1	3.5	2.3
PC3	E1	5.8	93.4	3.0	0.3
	E2	1.8	77.5	3.6	0.3
PC4	E1	5.6	87.5	3.2	1.5
	E2	6.5	95.5	2.9	1.5

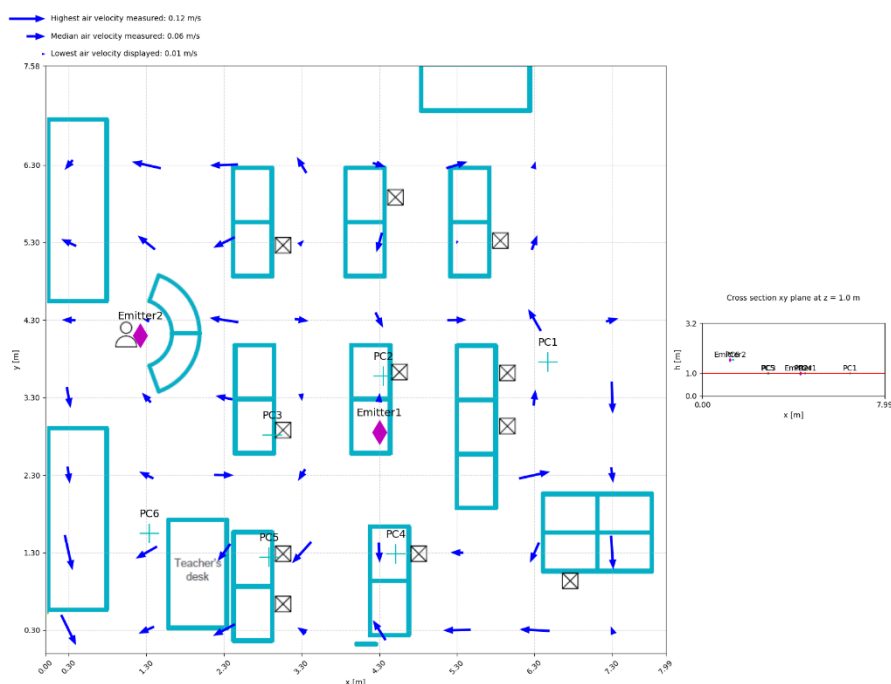
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PC5	E1	5.9	99.3	2.8	1.0
	E2	3.2	90.5	3.1	1.5
PC6	E1	1.8	67.1	4.1	0.8
	E2	3.4	70.0	3.9	1.3

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. It should be noted that the air flow measurements were not performed on the same day as the particle concentration measurements. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.12 m/s).

In Figure 2-1, it can be seen that the air velocities are highest at the sides of the room and is the lowest in the center of the room. There seems to be an air flow directed towards the front of the classroom but this is not a dominant air flow. Specifically for the particle counters, there is an airflow from PC1 inwards and there is an air flow from PC4 and PC5 directed towards the windows. There is no clear air flow from the emitter locations towards a particle counter.



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Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analysed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.20 m/s). In this figure the air velocities are higher compared to the analysed plane at 1.0 m. From the figure it can be seen that there is a dominant air flow near the windows in the direction of the front of the classroom. This could be explained by the windows which were open during the measurements. Specifically for PC6, there is an air flow from PC6 into the room. There is no clear air flow from the emitter locations towards PC6.

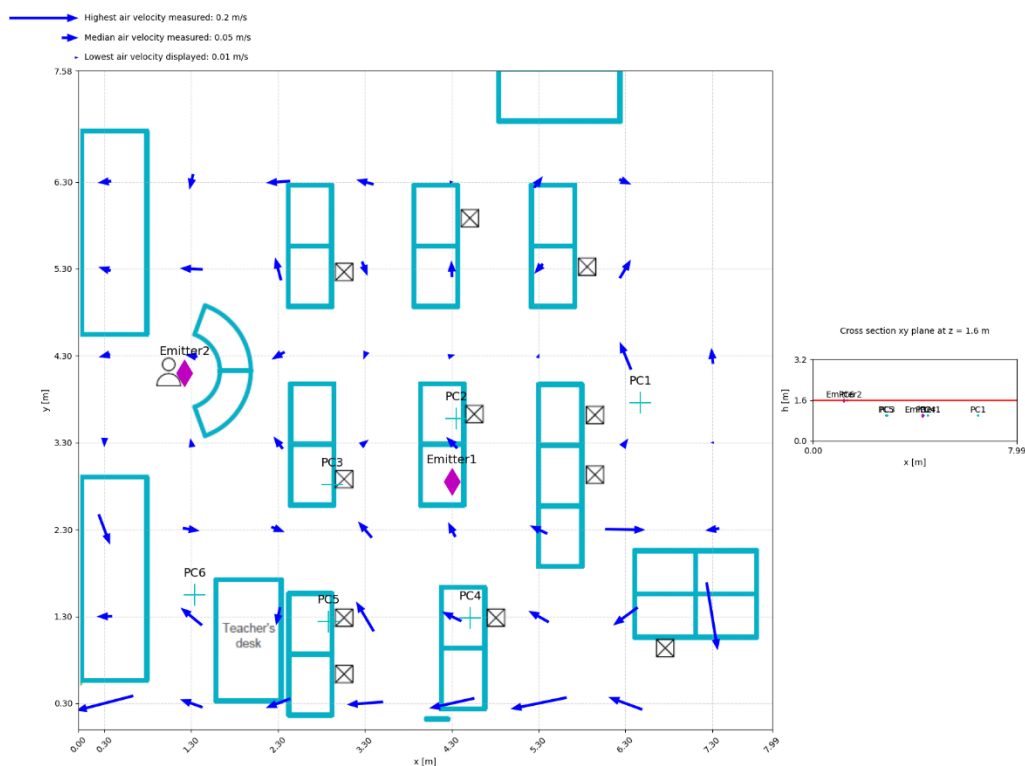


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

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3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system is CO₂-controlled. For air supply, the classroom has two supply grilles and for the exhaust of air the classroom has one exhaust grille. Due to the design and the height of the ventilation system, it was not possible to measure the supply and the exhaust of air in the room. There are, furthermore, four openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Ceiling grille	N/A
	Ceiling grille	N/A
	Total	N/A
Ventilation (exhaust)		
	Ceiling grille	N/A
	Total	N/A

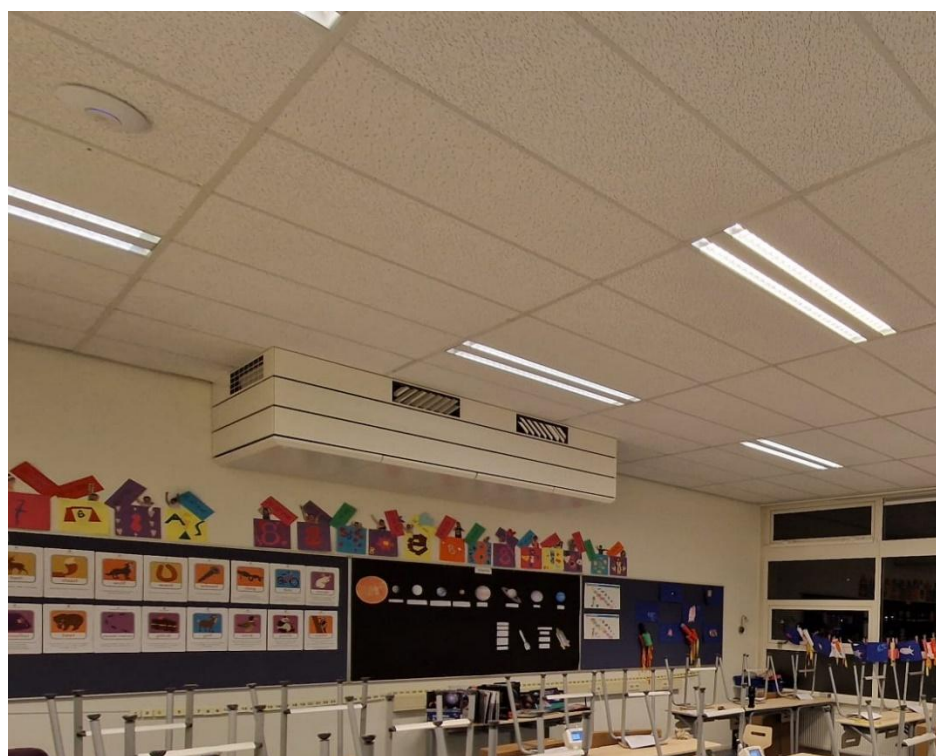


Figure 3-1 – Ventilation system after intervention

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Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 16.7 and 20.2 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Wall 1: West, Wall 2: North, Wall 3: South, Wall 4: East. Metrological data is from weerstatistieken.nl of a nearby weather station.

29-02-2024				
Surface area temperature (°C)		10:30	14:00	
	Wall 1	22.5	23.9	
	Wall 2	18.9	18.9	
	Wall 3	18.6	18.6	
	Wall 4	18.9	18.9	
	Ceiling*	17.2	17.2	
	Floor	20.3	20.3	
		Min*	Mean*	Max*
Air temperature (°C)		16.7	18.8	20.2
Relative humidity (%)		48.2	54.8	63.6
Outdoor air temperature (°C)		7.4	8.6	9.6
Outdoor relative humidity (%)		85	93	95
Wind	Velocity (m/s)	3.0	6.3	7.0
	Direction	South (178°)		

* The mean value is calculated by taking the average values of all four sensors between 15:30-20:30. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before the intervention and after the intervention took place. The 100-fold increase time has a range of 3.2 – 9.3 min for emitter location E1 and has a range of 3.7 – 12.5 min for emitter location E2. The 100-fold increase time is longest for PC1 and PC2 with the emitter at location E2 (11.4 – 12.5 min). This can be explained by the air flow in the room which will be described in the upcoming chapter. The 100-fold increase time is shortest for PC3 for both emitter locations. This can be explained by the close proximity to both particle counters.

The 100-fold recovery time has a range of 41.0 – 55.1 min for emitter location E1 and has a range of 34.9 – 61.1 min for emitter location E2. The range for the 100-fold recovery time is relatively small which indicates that the decrease of the particle concentration is similar at different locations in the

Deliverable Work package 2

room (homogeneous). The 100-fold recovery time is shortest for PC4, PC5 and PC6 at emitter location E2, these particle counters are all located near the window of the classroom.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and 1 teacher, this results in a ventilation rate of 562 m³/h (3.1 ACH) for a Class C and 796 m³/h (4.4 ACH) for Class B. When these values are compared with the ACH values in Table 3.3 (ACH 4.5 – 7.9), it can be seen that all values meet the requirements for both Class C and Class B.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 3.5 – 5.0 min for emitter location E1 and has a range of 3.5 – 5.5 min for emitter location E2. Overall, the values of t_{delay} have a small range between different particle counters. This indicates that after the emission stopped, the decrease of the particle concentration starts simultaneously at different locations in the room.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	5.2	8.3	88.2	49.5	3.1	5.6	0.5	4.0
	E2	26.6	11.4	70.9	48.6	3.9	5.7	1.0	5.0
PC2	E1	11.3	4.1	50.7	52.6	5.5	5.3	2.8	3.5
	E2	9.9	12.5	79.1	61.1	3.5	4.5	2.3	5.5
PC3	E1	5.8	3.2	93.4	55.1	3.0	5.0	0.3	4.0
	E2	1.8	3.7	77.5	60.4	3.6	4.6	0.3	3.5
PC4	E1	5.6	9.2	87.5	41.0	3.2	6.7	1.5	4.8
	E2	6.5	9.4	95.5	37.6	2.9	7.4	1.5	3.5
PC5	E1	5.9	7.4	99.3	42.9	2.8	6.4	1.0	5.0
	E2	3.2	5.5	90.5	35.6	3.1	7.8	1.5	4.8
PC6	E1	1.8	9.3	67.1	45.4	4.1	6.1	0.8	4.5
	E2	3.4	4.0	70.0	34.9	3.9	7.9	1.3	4.3

Deliverable Work package 2

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and the velocity at this height can be seen in Figure 3-2 (range 0.01 - 0.14 m/s).

In Figure 3-2 it is visualized that the air velocities are highest near the windows and in the front of the classroom. The air velocity is the lowest near the ventilation system at this specific height. Specifically for the particle counters, there is an air flow from PC4 and PC5 in the direction of the windows. Furthermore, the air velocities are low near PC1 and PC2.

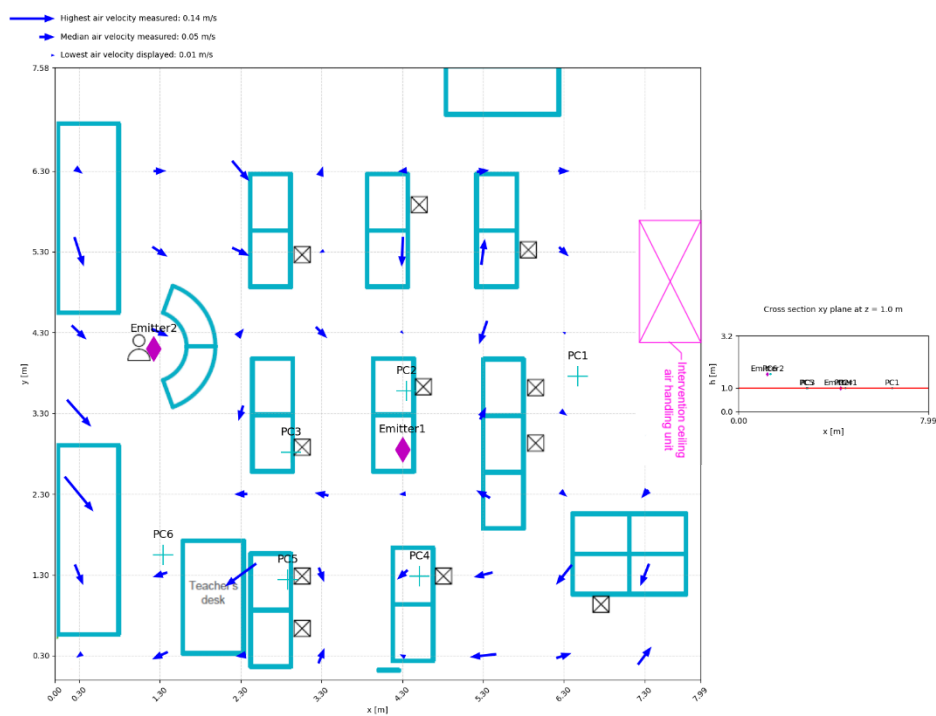


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 3-3 (range 0.01 – 0.11 m/s). In this figure, it can be seen that the air velocities are lower at this height. Specifically in the center of the room, the air velocities are low. Specifically for PC6, it seems that there is an air flow from PC6 in the direction of the windows.

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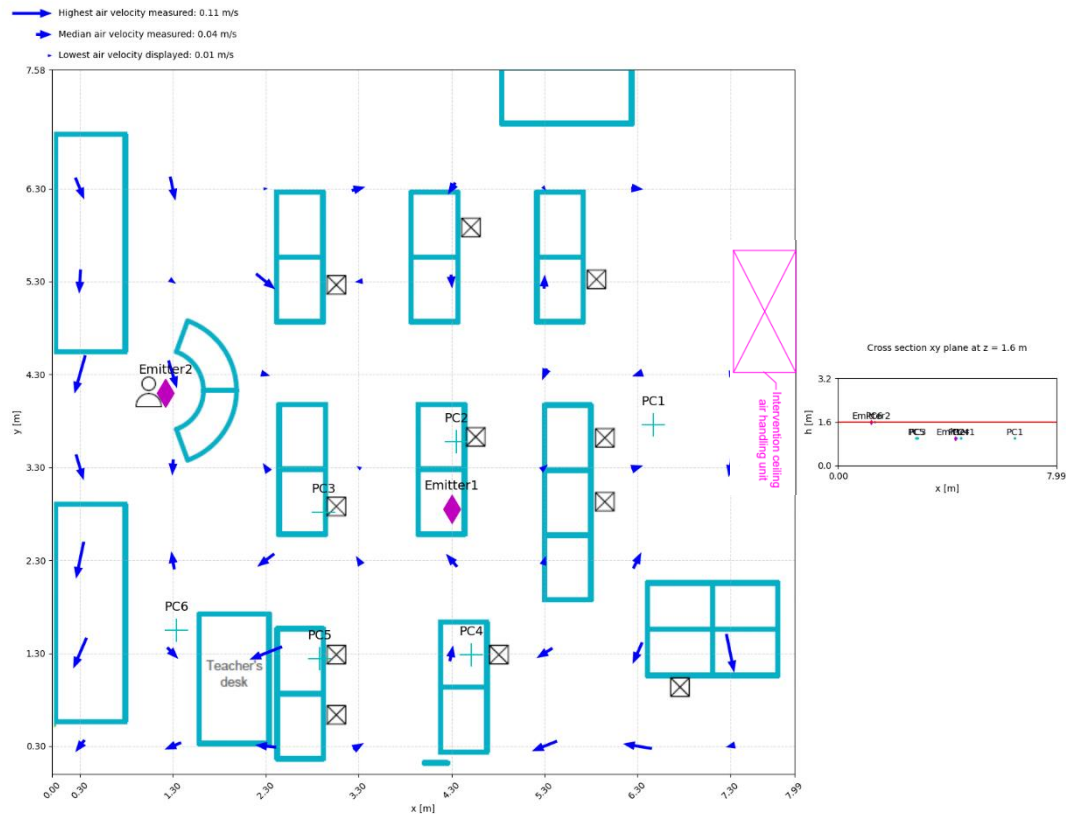


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m

4. Conclusions

In this section, the performance of the ventilation system before and after intervention are described and compared through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before the intervention, the 100-fold increase time has a range of 1.8 – 11.3 min for emitter location E1 and has a range of 1.8 – 26.6 min for emitter location E2. After intervention, the 100-fold increase time has a range of 3.2 – 9.3 min for emitter location E1 and has a range of 3.7 – 12.5 for emitter location E2. After the intervention, the 100-fold increase time is often longer than before the intervention. This indicates that it takes longer before the particle concentration starts to increase after the emission started. One explanation for this might be that the overall concentration that reaches the particle counter is also lower after the intervention was implemented (Figure 4-1).

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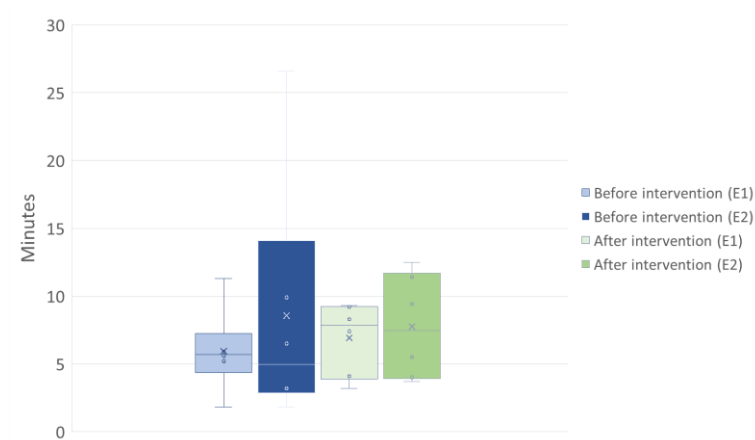


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before the intervention, the 100-fold recovery time has a range of 50.7 – 99.3 min for emitter location E1 and has a range of 70.0 – 95.5 min for emitter location E2. After the intervention, the 100-fold recovery time has a range of 41.0 – 55.1 min for emitter location E1 and has a range of 34.9 – 61.1 min for emitter location E2. The 100-fold recovery time is shorter after the intervention was installed. The 100-fold recovery time, furthermore, has a smaller range, this indicates that there is more homogeneous mixing in the classroom (Figure 4-2).

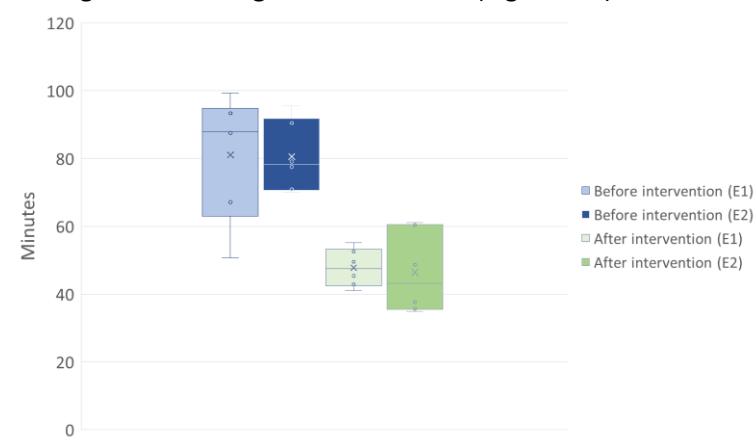


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before the intervention, t_{delay} has a range of 0.3 – 2.8 min for emitter location E1 and has a range of 0.3 – 2.3 min for emitter location E2. After the intervention, t_{delay} has a range of 3.5– 5.0 min for emitter location E1 and has a range of 3.5 – 5.5 min for emitter location E2. The values for t_{delay} have a similar range before and after the intervention. The t_{delay} is, however, slightly longer after the intervention took place indicating that it takes shorter before the particle concentration starts to increase after the emission stopped.

Air change per hour

Before the intervention, the ACH has a range of 2.8 – 5.5 ACH for emitter location E1 and has a range of 2.9 – 3.9 ACH for emitter location E2. After the intervention, the ACH has a range of 5.0 – 6.7 ACH

Deliverable Work package 2

for emitter location E1 and has a range of 4.5 – 7.9 ACH. The air change rate is higher after the intervention took place, this could be related to the fact that the local air velocity at specific particle counters is higher after the intervention. For the measurements before intervention, Class B is only met at PC2 for emitter location E1. After the intervention, Class B is met at all locations except PC2 and PC4 at emitter location E2.

4.2 *Air flow measurements*

Before the intervention took place, the highest air velocities were found at the sides of the room and the lowest air velocities in the centre of the classroom. Overall, there was no dominant air flow present in the room.

The particle concentration measurements and the air flow measurements show that the air velocities are lowest in the centre of the room which could explain the relatively long 100-fold increase time for PC1 and PC2. Furthermore, the air velocities near PC6 are high which could explain the relatively short 100-fold increase time at this location.

After the intervention, there is still not a highly dominant air flow but the air velocities are highest at the front of the classroom and near the windows. The air velocity are lowest near the centre of the room and near the ventilation system.

The particle concentration measurements and the air flow measurements show that the maximum air velocities are similar before and after the intervention. After the intervention the air velocities are lowest near PC1 and PC2 which could explain the relatively long 100-fold increase time at these locations. It is, however, not possible to explain the difference in 100-fold recovery time between before and after the intervention by the air flow in the room since there are no significant differences.

In conclusion, when both ventilation systems are compared it becomes clear that the air velocities are similar before and after the intervention. The 100-fold recovery time is, however, shorter after the new ventilation system was installed which indicates that the particle concentration throughout the room has a lower dependence on the proximity of the particle counter to the emission source location.

Specifically for the particle counters, there is an air flow from PC4 and PC5 in the direction of the windows. Furthermore, the air velocities are low near PC1 and PC2.

Concluded, due to the intervention the location of the children and teacher in the room becomes a less prominent determinant for exposure and the overall risk of exposure is lower.

ANNEX E, RESULTS CLASSROOM 5

Experiments in-situ

WP2, experiments after intervention

DATUM	03-01-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location classroom 5

The results discussed in this report include both the situation without any interventions and the situation after the intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system D and consist of two mechanical supply grills and 2 mechanical exhaust grills.

In the case of this location, the intervention that took place consists of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). The installation consist of a balance CO₂ controlled ventilation system. The unit will be CO₂ controlled and is designed to meet the requirements for Class B of 'PvE Frisse Scholen 2021' and has a (design) capacity of 979 m³/h based on 30 students and two teachers

Deliverable Work package 2

1.1 *Characteristics of room and system*

Description of the room

The school is located in a suburban environment and was originally built in 1921. The classroom that was considered during this analysis, has a surface area of 55.5 m² and was located on the ground floor. The façade was orientated towards the North-East and the height of the room was 3.3 m and 4.2 m. During the measurements, this room was designed for circa 30 students and two teachers. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was mechanical ventilation (mechanical supply and exhaust, system D). For air supply, the classroom has two supply ceiling grills. The same applies for the exhaust of air Figure 1-2. There are, furthermore, three openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. Furthermore, the ventilation system was set to stand 2 which is the design set-up. An overview of the ventilation system can be seen in Table 1.1.

Deliverable Work package 2

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Ceiling grille	115
	Ceiling grille	141
	Total	256
Ventilation (exhaust)		
	Ceiling grille	152
	Ceiling grille	133
	Total	285



Figure 1-2 – Ventilation system before intervention

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 11 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC1, PC2, PC3, PC4 and PC5 were located at 1.0 m height since this represents the breathing zone of sitting children. PC6 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two

Deliverable Work package 2

different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.37 to 3.08 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 55 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

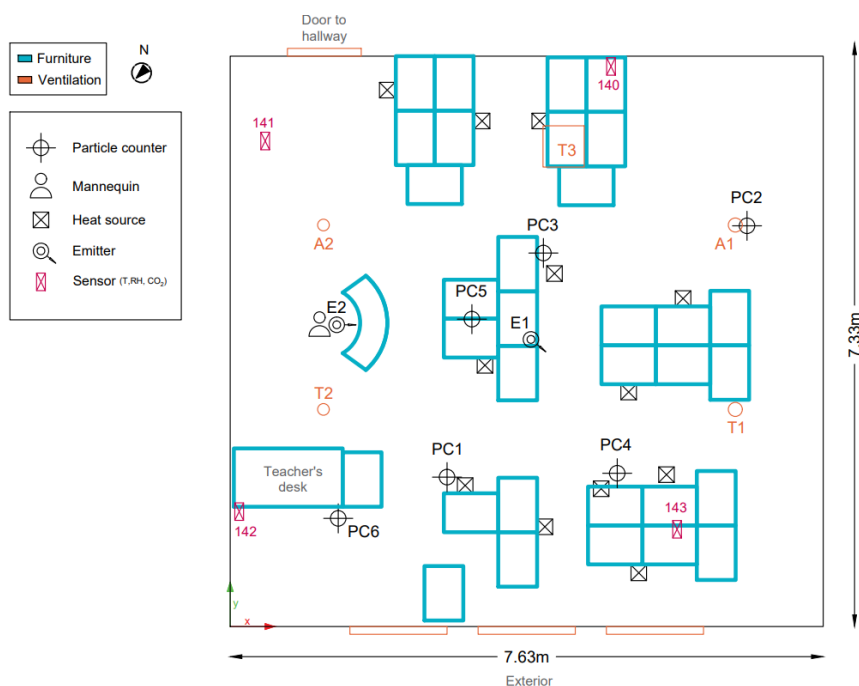


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

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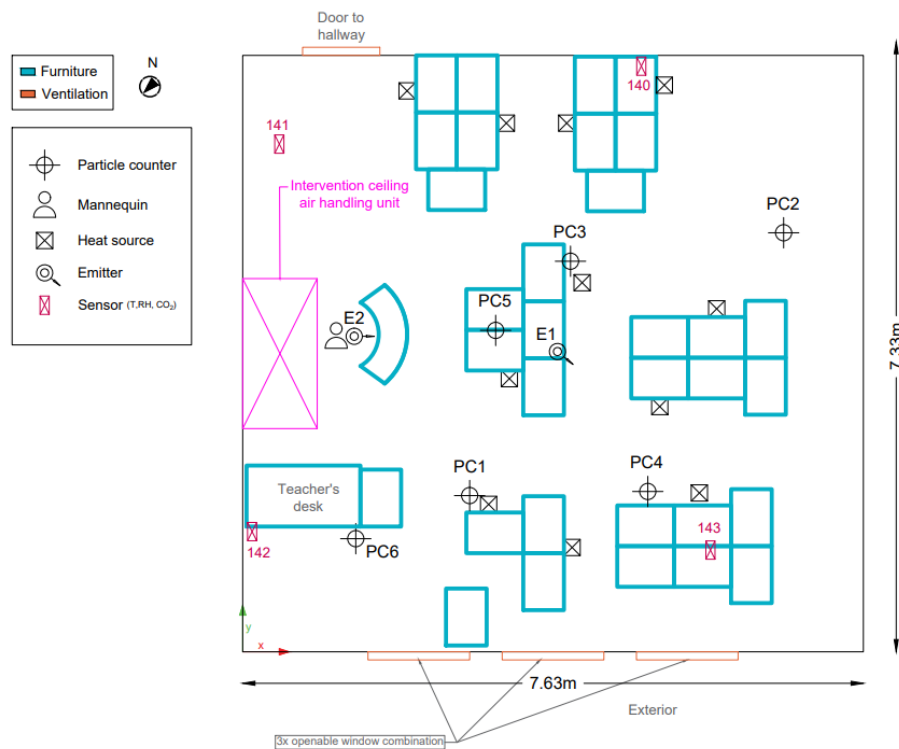


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

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2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 18.5 and 27.9 °C throughout the day.

Table 2.1. The room temperature was between 20.2 and 26.4 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

15-06-2023				
Surface area temperature (°C)		10:30	16:30	
	Wall 1	22.1	25.0	
	Wall 2	23.1	24.5	
	Wall 3	23.5	24.8	
	Wall 4	23.3	24.8	
	Ceiling	23.6	24.6	
	Floor	22.9	25.6	
	Glass surface of the windows	24.5	25.3	
		Min*	Mean*	Max*
Air temperature (°C)		20.2	25.2	26.4
Relative humidity (%)		35.5	42.2	55.4
Outdoor air temperature (°C)		12.9	20.6	27.1
Outdoor relative humidity (%)		20	48	82
Wind	Velocity (m/s)	1.0	3.0	5.0
	Direction	North-East (34°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-19:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 10.3 – 32.8 min for emitter location E1 and has a range of 4.4 – 63.7 min for emitter location E2. The 100-fold increase time is the longest at location PC2 for both emitter location E1 and E2 (32.8 - 63.7 min). This particle counter is located near the exhaust of the room which results in a gradual increase in the particle concentration during the emission period. The 100-fold increase time is the shortest for both PC1 and PC5 at emitter location E2 (5.1 – 4.4 min). These

Deliverable Work package 2

particle counters are both located relatively close to the emitter which means that the particle concentration can increase faster.

The 100-fold recovery time has a range of 87.6 – 388.4 min for emitter location E1 and has a range of 86.6 – 587.2 min for emitter location E2. The 100-fold recovery time is the longest at location PC4 at emitter location E2, with a value of 587.2 min. Other long values can be seen at PC2 which is the particle counter that is placed near the exhaust. This indicates that the particle concentration gradually decreases at this location. The shortest 100-fold recovery time is at PC1 for both emitter location E1 and E2 (87.6 – 86.6 min) which is followed-up by PC5 (93.4 – 96.8 min).

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 30 children and 2 teachers, this results in a ventilation rate of 691 m³/h (3.5 ACH) for a Class C and 979 m³/h (4.9 ACH) for Class B. When these values are compared with the ACH values in Table 2.2 it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 1.0 – 7.5 min for emitter location E1 and has a range of 1.0 – 7.5 min for emitter location E2. t_{delay} is the longest for PC2 and PC4 with values of 7.5 min and 7.0 min. These locations were also the locations with the longest 100-fold recovery time which indicates that it takes long until the particle concentration starts to decrease after the emission period and afterwards this decrease goes relatively slow. The t_{delay} is shortest for PC5 emitter location E1 and E2 (1.0 – 1.8 min) and for PC1 emitter location E2 (1.0 min). This means that at these locations the decrease of the particle concentration starts quickly after the emission stopped. Both locations are located quite close to the emitter location and have a high particle concentration at the end of the emission period.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	10.3	87.6	3.2	4.0
	E2	5.1	86.6	3.2	1.0
PC2	E1	32.8	388.4	0.7	7.5
	E2	63.7	393.6	0.7	7.5
PC3	E1	14.4	173.6	1.6	4.5
	E2	24.8	161.7	1.7	5.0
PC4	E1	30.6	206.4	1.3	7.0
	E2	18.7	587.2	0.5	7.0

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PC5	E1	11.8	93.4	3.0	1.0
	E2	4.4	96.8	2.9	1.8
PC6	E1	15.6	118.7	2.3	2.0
	E2	19.5	108.9	2.5	2.0

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.07 m/s).

In Figure 2-1 air velocities are lowest in the center of the classroom and highest at the sides of the classroom. Furthermore, at this height, there is no dominant air flow from the supply towards the exhaust of the room which would be expected. The air velocity is highest near PC4 and is lowest for PC5 and PC3. There is no clear air flow from the emitter locations towards the particle counters.

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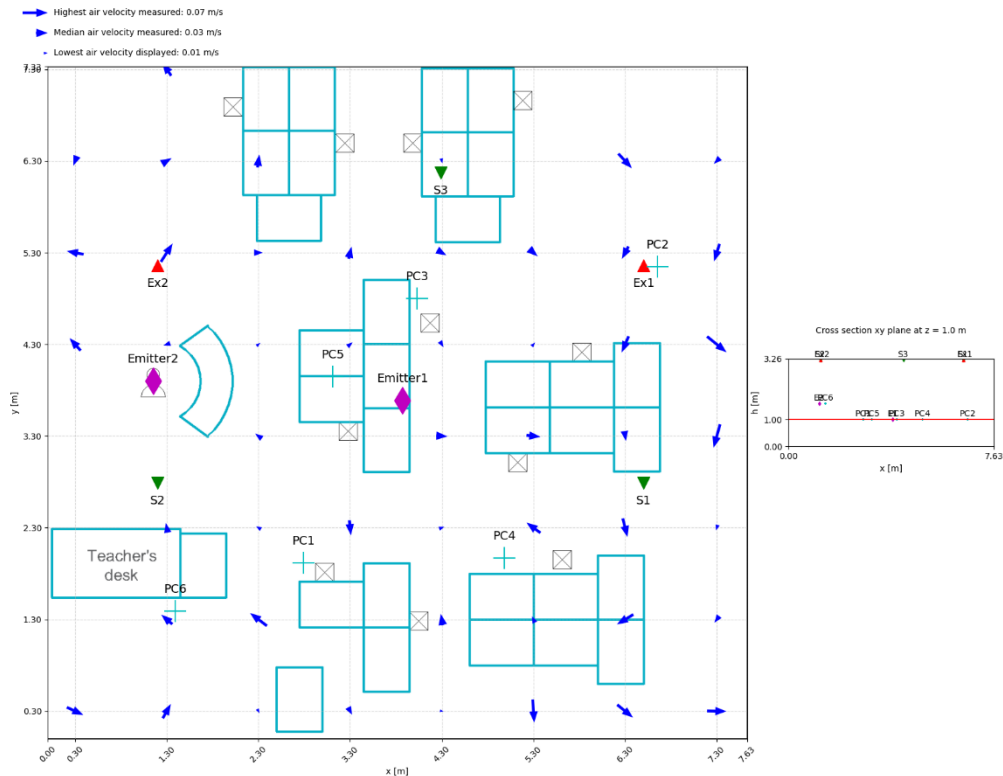


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.09 m/s). In this figure, it can be seen that the air flow is still highest near the wall and lowest at the center of the room in the XY-plane. There is still no clear air flow from the supply and towards the exhaust of the room. When looking specifically towards particle counter PC6, it seems that there is an air flow from emitter location E2 directed away from PC6. There is no clear air flow near PC6 present in the classroom resulting in very low velocities at that location.

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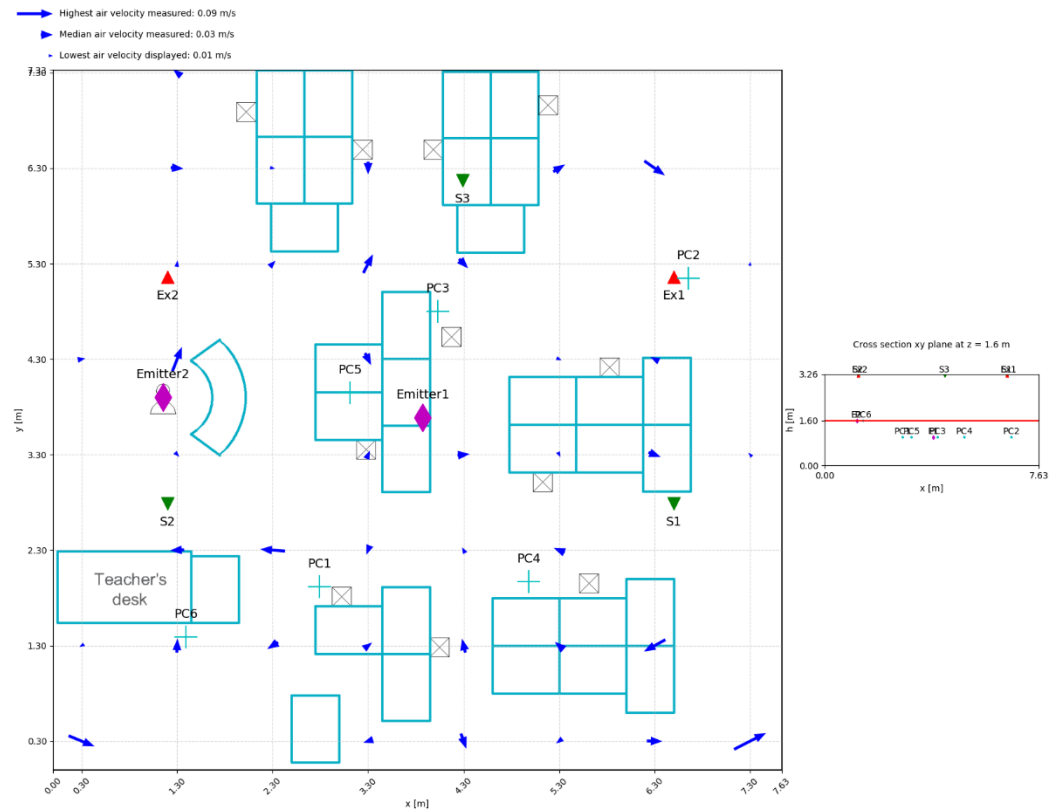


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

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3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system is CO₂-controlled. For air supply, the classroom has two supply grills and for the exhaust of air the classroom has two exhaust grills (Figure 1-4). Due to the design of the ventilation system, it was not possible to measure the exhaust of air in the room. There are, furthermore, three openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Ceiling grille	349
	Ceiling grille	351
	Total	700
Ventilation (exhaust)		
	Ceiling grille	N/A
	Total	N/A



Figure 3-1 – Ventilation system after intervention

Deliverable Work package 2

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 19.8 and 21.5 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Wall 1: North, Wall 2: East, Wall 3: South, Wall 4: West. Metrological data is from weerstatistieken.nl of a nearby weather station.

25-07-2023				
Surface area temperature (°C)		09:30	14:00	
	Wall 1	17.1	19.3	
	Wall 2	18.3	20.3	
	Wall 3	18.3	20.1	
	Wall 4	18.2	20.1	
	Ceiling	18.7	20.8	
	Floor	18.0	21.0	
	Glass surface of the windows	15.6	19.6	
		Min*	Mean*	Max*
Air temperature (°C)		19.8	20.9	21.5
Relative humidity (%)		50.4	57.3	66.3
Outdoor air temperature (°C)		7.3	14.3	19.8
Outdoor relative humidity (%)		45	72	98
Wind	Velocity (m/s)	2.0	3.0	6.0
	Direction	North-West (309°)		

* The mean value is calculated by taking the average values of all sensor 502, 503 and 504 between 10:00-14:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before the intervention and after the intervention took place. The 100-fold increase time has a range of 1.2 – 29.4 min for emitter location E1 and has a range of 2.9 – 27.7 min for emitter location E2. The 100-fold increase time is longest for PC6 at emitter location E1 (29.9 min) and at PC3 for emitter location E2 (27.7 min). The 100-fold increase time is shortest for PC5 emitter location E1 (1.2 min) and for PC6 emitter location E2 (2.9 min).

Deliverable Work package 2

The 100-fold recovery time has a range of 51.4 – 54.4 min for emitter location E1 and has a range of 49.9 – 54.4 min for emitter location E2. The difference between the shortest and longest 100-fold recovery times is small which indicates that the decrease of the particle concentration is similar at different locations in the room (homogeneous).

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 30 children and 2 teachers, this results in a ventilation rate of 691 m³/h (3.5 ACH) for a Class C and 979 m³/h (4.9 ACH) for Class B. When these values are compared with the ACH values in Table 3.3 (ACH 5.1 - 5.4), it can be seen that all values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.8 – 2.3 min for emitter location E1 and has a range of 0.5 – 2.8 min for emitter location E2. t_{delay} is the longest at PC2 and PC3 emitter location E2 (2.5- 2.8 min). These locations are both at a location relatively far from the emitter location. t_{delay} is the shortest for PC6 emitter location E2 (0.5 min). At this location, the 100-fold increase time was also the shortest. This indicates that the increase at this location is quick and the decrease starts quickly after the emission period stopped.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations before and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	10.3	21.1	87.6	54.3	3.2	5.1	4.0	2.3
	E2	5.1	11.3	86.6	53.6	3.2	5.2	1.0	1.3
PC2	E1	32.8	16.5	388.4	51.4	0.7	5.4	7.5	1.0
	E2	63.7	19.9	393.6	52.8	0.7	5.2	7.5	2.5
PC3	E1	14.4	12.9	173.6	51.6	1.6	5.4	4.5	0.8
	E2	24.8	27.7	161.7	52.5	1.7	5.3	5.0	2.8
PC4	E1	30.6	20.2	206.4	54.4	1.3	5.1	7.0	1.3
	E2	18.7	10.2	587.2	49.9	0.5	5.5	7.0	1.0
PC5	E1	11.8	1.2	93.4	51.7	3.0	5.3	1.0	0.8
	E2	4.4	23.2	96.8	53.0	2.9	5.2	1.8	3.0
PC6	E1	15.6	29.4	118.7	53.3	2.3	5.2	2.0	2.3
	E2	19.5	2.9	108.9	54.4	2.5	5.1	2.0	0.5

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3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the locations of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 3-2 (range 0.01 – 0.34 m/s).

In Figure 3-2 it is visualized that the air velocities are highest at the back of the classroom and are in the direction of the front of the classroom (directed towards the exhaust). Specifically for the particle counters, there is an air flow from PC1, PC3, PC4 and PC5 in the direction of the exhaust which is also close to emitter location E2. Furthermore, from emitter location E1 there is also a clear flow towards the front of the classroom.

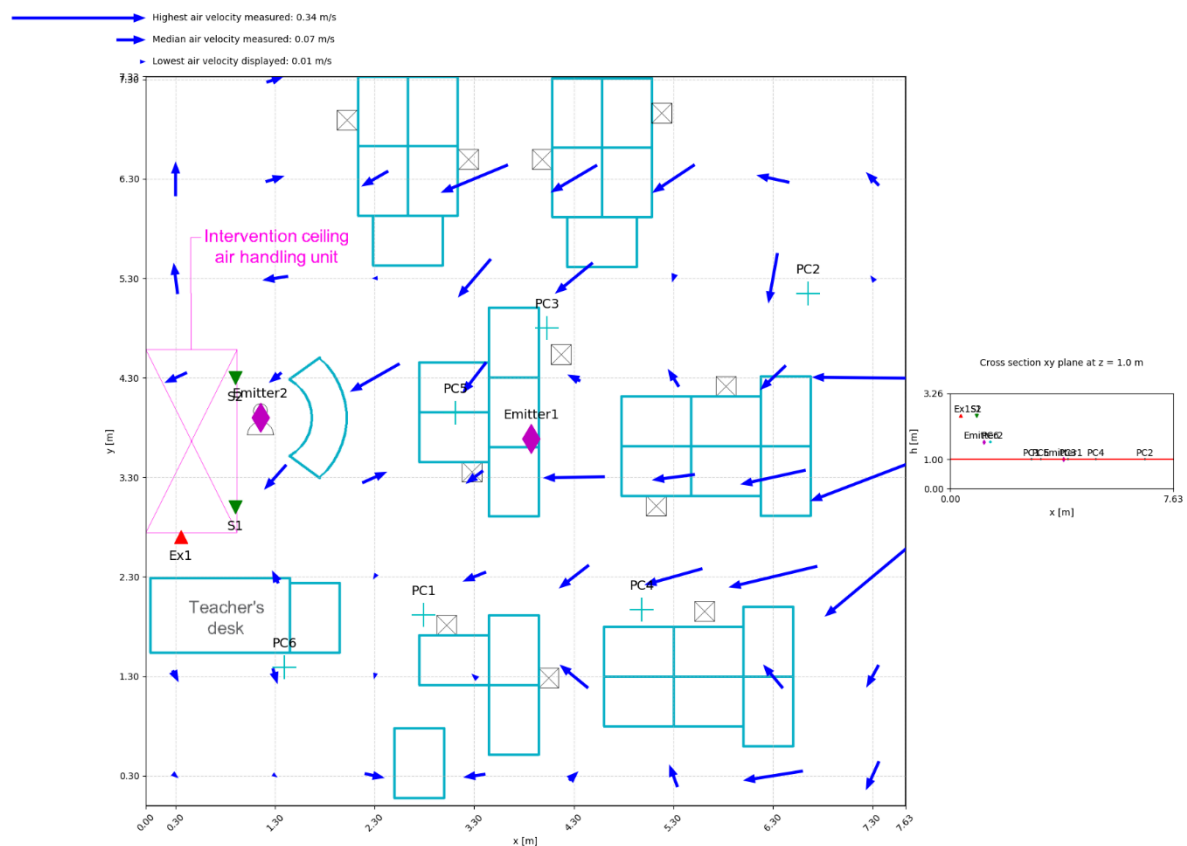


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

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For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 3-3 (range 0.02 – 0.15 m/s). In this figure, it can be seen that the air velocities are lower at this height. From this figure, it becomes clear that the direction of the air flow can change significantly at different heights in the room. At this height, there is an air flow towards the back of the room and in the center of the room there is a flow towards the front of the room. When looking specifically towards particle counter PC6, it seems that there is an air flow from emitter E2 towards PC6 which could explain the short 100-fold increase time at this location.

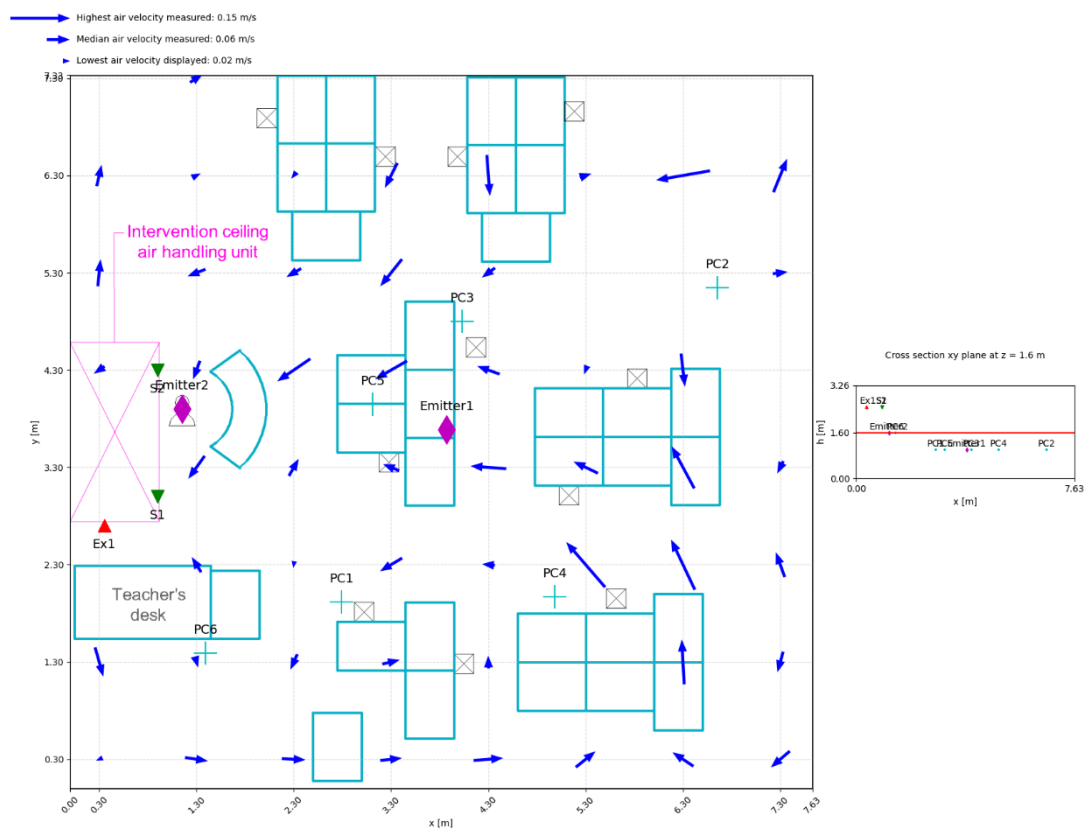


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

4. Conclusions

In this section, the performance of the ventilation system before and after intervention are described and compared through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before intervention, the 100-fold increase time has a range of 10.3 – 32.8 min for emitter location E1 and has a range of 4.4 – 63.7 min for emitter location E2. After intervention, the 100-fold increase time has a range of 1.2 – 29.4 min for emitter location E1 and has a range of 2.9 – 27.7 min for emitter location E2. After intervention, the range of the 100-fold increase time is smaller and the 100-fold increase time is (in general) shorter. This indicates there is faster and more homogenous mixing in the room which means the particle concentration increases faster at different locations in the room (Figure 4-1).

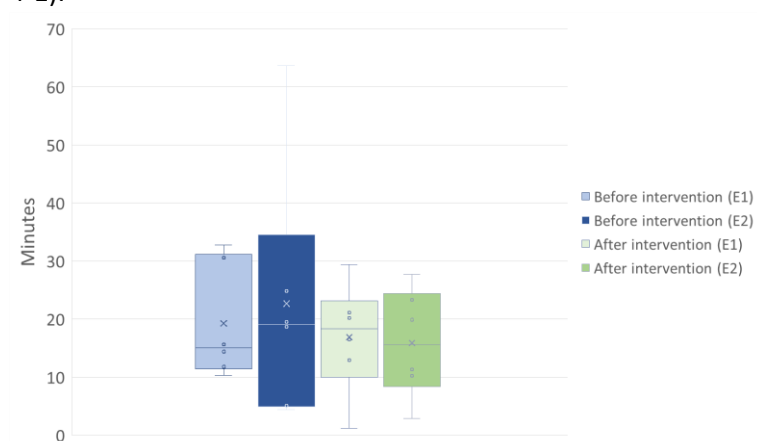


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before intervention, the 100-fold recovery time has a range of 87.6 – 388.4 min for emitter location E1 and has a range of 86.6 – 587.2 min for emitter location E2. After intervention, the 100-fold recovery time has a range of 51.4 – 54.4 min for emitter location E1 and has a range of 49.9 – 54.4 min for emitter location E2. The 100-fold recovery time is shorter and has a smaller range after the intervention took place. This indicates that there is more homogeneous mixing in the classroom (Figure 4-2).

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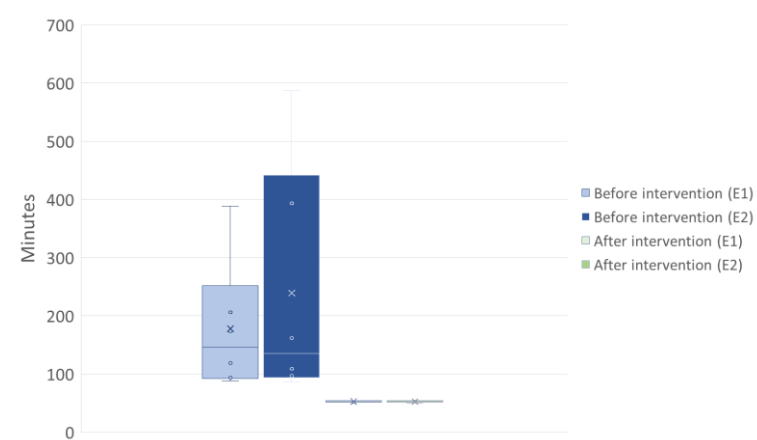


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 1.0 – 7.5 min for emitter location E1 and has a range of 1.0 – 7.5 min for emitter location E2. After intervention, t_{delay} has a range of 0.8 – 2.3 min for emitter location E1 and has a range of 0.5 – 2.8 min for emitter location E2. t_{delay} is, in general, shorter after the intervention took place. This indicates that after the emission stopped, the particle concentration starts to decrease faster due to a higher air flow in the room.

Air change per hour

Before intervention, the ACH has a range of 0.7 – 3.2 ACH for emitter location E1 and has a range of 0.5 – 3.2 ACH for emitter location E2. After intervention, the ACH has a range of 5.1 – 5.4 for emitter location E1 and has a range of 5.1 – 5.5 for emitter location E2. The range between the different measurement points is smaller after the intervention took place, this indicates that the possible exposure to particles is similar at different locations in the room. For the measurements before the intervention, no air change rate meet the requirements for both Class C (3.5) and Class B (4.9) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'. After intervention, all requirements are met for both Class C (3.5) and Class B (4.9).

4.2 Air flow measurements

Before the intervention took place, the highest air velocities were at the sides of the classroom and the lowest were located in the centre of the classroom. Furthermore, there is no clear air flow visible from the supply to the exhaust in the room for the analysed planes.

The particle concentration measurement and the air flow measurement show that the air velocities are lowest near PC5 and PC3. The short 100-fold increase time and 100-fold recovery time can be explained by the location of the particle counter since it is located in close proximity of both emitter locations. PC3, however, is also located in close proximity of the emitter locations but has a longer 100-fold recovery time and 100-fold increase time. This could be related to the low air velocities near the particle counter. The air flow is more significant (higher velocities) near PC1 and PC6 and these locations also have a short 100-fold recovery time.

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After intervention, there is a clear dominant air flow from the back of the classroom towards the front of the classroom (towards the exhaust). The air velocities are higher at a height of 1.0 m compared to the height of 1.6 m. Furthermore, at a height of 1.6 m, an air flow can be seen at the side of the room towards the back of the classroom.

The particle concentration measurement and the air flow measurement show that in general the air velocities are higher after intervention which explains the shorter 100-fold recovery time. Furthermore, the air flow is directed away (in the direction of E2) from PC3 and PC5 which could explain the relative long 100-fold increase time at emitter location E2. Furthermore, there is an air flow in the direction of PC6 from E2 (at a height of 1.6 m), this could explain the short 100-fold increase time.

In conclusion, when both ventilation systems are compared it becomes clear that the air velocities are higher after the intervention took place. Furthermore, the direction of the air flow is more dominant. Due to this, the particle spread throughout the room has a lower dependence on the proximity of the particle counter to the emission source location. The air flow throughout the room becomes the most dominant factor.

Concluded, due to the intervention the location of the children and teacher in the room becomes less prominent for a possible exposure and the overall risk to an exposure is lower.

ANNEX F, RESULTS CLASSROOM 6

Experiments in-situ

WP2, experiments after intervention

DATUM	08-02-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location classroom 6

The results discussed in this report include both the situation without any interventions and the situation after the intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system C and consists of three ventilation window grills and an exhaust ceiling grill.

In the case of this location, the intervention consists of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). This system consists of a balanced CO₂ controlled ventilation system and is designed to meet the requirements for Class B of 'PvE Frisse scholen 2021' and has a (design) capacity of 796 m³/h based on 25 students and one teacher.

Deliverable Work package 2

1.1 Characteristics of room and system

Description of the room

The school is located in a suburban environment and was originally built in 1980. The classroom that was considered during this analysis, has a surface area of 56.3 m² and was located on the ground floor. The façade was orientated towards the East and the height of the room was 3.0 m. During the measurements, this room was designed for appr. 30 students and 1 teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural supply and mechanical exhaust (system C). For air supply, the classroom has three window grills which can be opened. For the exhaust of air, the room has one mechanical ceiling grille (see Figure 1-2). There are, furthermore, three openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. Furthermore, two of the three window grills were open during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

Deliverable Work package 2

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	3 window ventilation grills	N/A
	Total	N/A
Ventilation (exhaust)		
	Ceiling grille	195
	Total	195



Figure 1-2 – Ventilation system before intervention

Deliverable Work package 2

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 12 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC1, PC2, PC3, PC4 and PC5 were located at 1.0 m height since this represents the breathing zone of sitting children. PC6 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at seven different heights from 0.35 to 2.6 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 54 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

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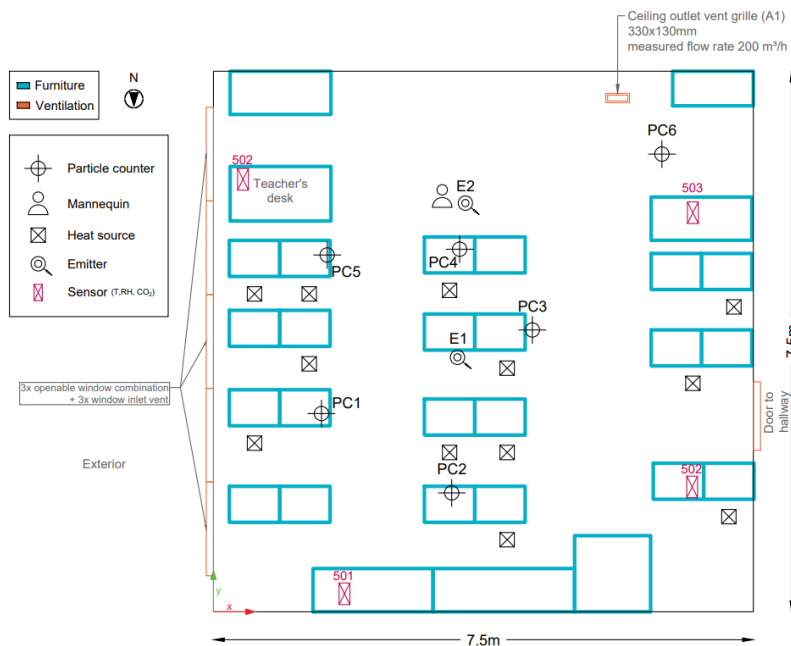


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

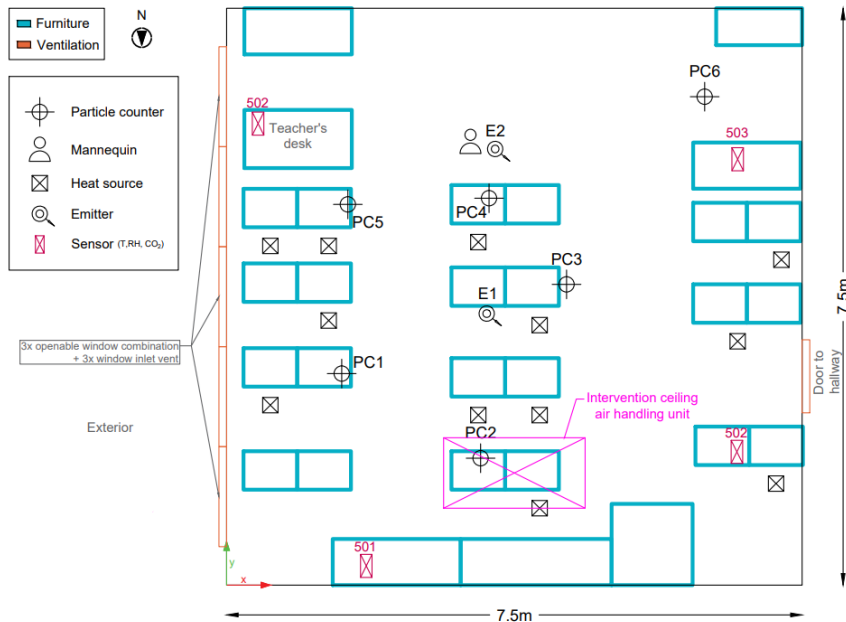


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

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5. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 5.1. The room temperature was between 23.3 and 29.4 °C throughout the day.

Table 5.1 - Conditions during the measurement period. Wall 1: East, Wall 2: South, Wall 3: West, Wall 4: North. Metrological data is from weerstatistieken.nl of a nearby weather station.

10-07-2023				
Surface area temperature (°C)		10:00	17:30	
	Wall 1	23.2	31.3	
	Wall 2	24.8	28.1	
	Wall 3	24.5	27.9	
	Wall 4	24.4	28.2	
	Ceiling	24.3	30.9	
	Floor	24.1	27.5	
	Glass surface of the windows	23.6	34.2	
		Min*	Mean*	Max*
Air temperature (°C)		23.3	26.6	29.4
Relative humidity (%)		48.6	55.8	68.6
Outdoor air temperature (°C)		15.4	20.3	24.9
Outdoor relative humidity (%)		39	65	92
Wind	Velocity (m/s)	1.5	3.0	6.0
	Direction	West (266°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-19:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 of the main report are calculated for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 1.4 – 20.3 min for emitter location E1 and has a range of 7.5 – 20.6 min for emitter location E2. The 100-fold increase time is the longest at location PC2 for both emitter location E1 and E2 (20.3 and 20.6 min). This particle counter is located at a relatively long distance from both emitter locations which indicates that the particles reach these locations slower. The 100-fold increase time is the shortest for PC5 at emitter location E1 (1.4 min).

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The 100-fold recovery time has a range of 113 – N/A min for emitter location E1 and has a range of 219.9 – N/A min for emitter location E2. The 100-fold recovery time is the longest at location PC2 for emitter location E2 (1261 min). There are, however, also 4 negative values which means that the particle concentration increased during the recovery period at these locations. Overall, the longest values are measured at PC1, PC2 and PC3 for both emitter locations. The shortest 100-fold recovery time is at PC4 and PC5 for emitter location E1 (119 – 113 min).

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'Good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and 1 teacher, this results in a ventilation rate of 562 m³/h (3.5 ACH) for a Class C and 796 m³/h (4.9 ACH) for Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that no values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. , t_{delay} has a range of 1.3 – 12.8 min for emitter location E1 and has a range of 1.8 – 12.8 min for emitter location E2. t_{delay} is the longest for PC1 for emitter location E2 and PC2 for emitter location E1 (12.8 min). These locations also had a long 100-fold recovery time which indicates that it takes long until the particle concentration starts to decrease after the emission period and afterwards this decrease goes relatively slow. t_{delay} is shortest for PC5 emitter location E1 and PC6 emitter location E2 (1.3 – 1.8 min). This means that at these locations the decrease of the particle concentration starts quickly after the emission stopped.

Table 5.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	4.7	N/A*	N/A*	9.8
	E2	7.8	N/A*	N/A*	12.8
PC2	E1	20.3	N/A*	N/A*	12.8
	E2	20.6	1261	0.2	5.3
PC3	E1	12.8	446.0	0.6	5.8
	E2	19.3	N/A*	N/A	10.0
PC4	E1	8.3	119	2.3	4.3
	E2	10.1	242	1.1	3.5
PC5	E1	1.4	113	2.4	1.3
	E2	8.3	219	1.2	5.0
PC6	E1	7.2	231	1.2	2.8
	E2	7.5	604	0.5	1.8

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* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.08 m/s).

In Figure 2-1 the air flow is most dominant in the center of the classroom. Furthermore, there seems to be an air flow with low velocities from the windows towards the center of the classroom. There is no clear air flow in the direction of the exhaust. There is a more dominant air flow from both emitter locations towards PC5. The air flow is directed away from PC3.

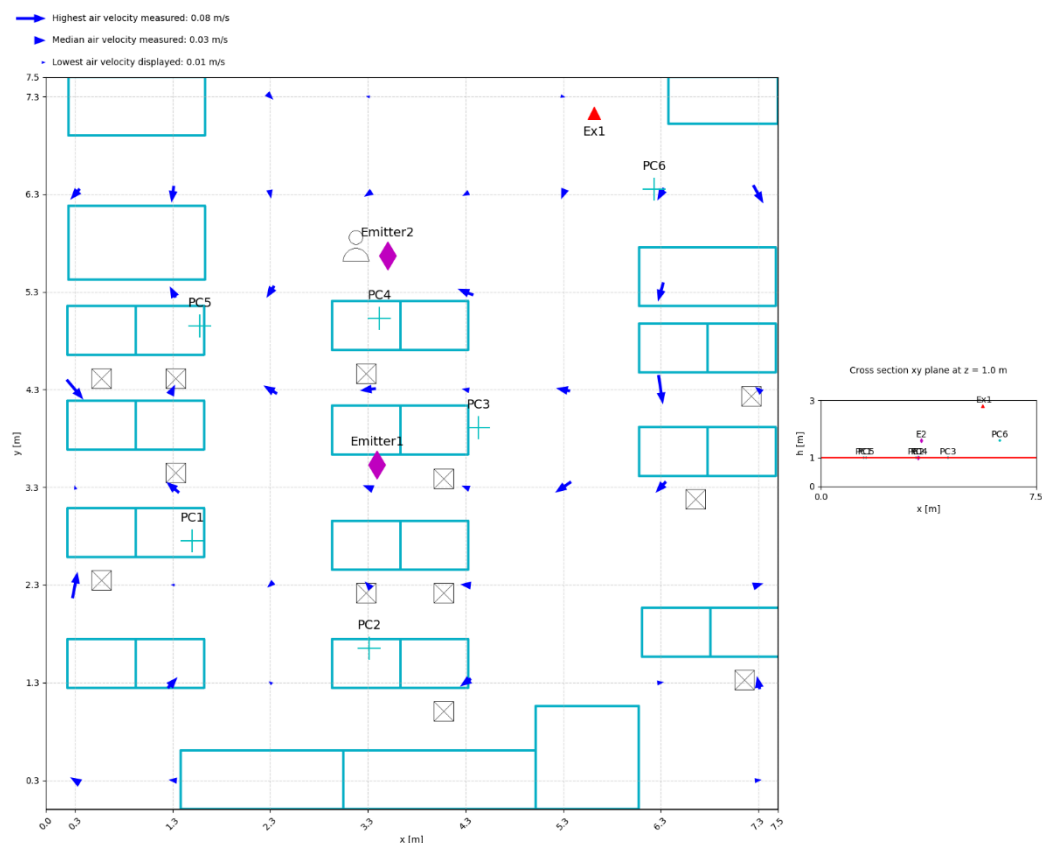


Figure 5-1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

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For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 2-2 (range 0.01 - 0.06 m/s). For this height, the air flow is most prominent at the opposite side of the windows. The air flow from the windows has lower velocities compared to the air flow at a height of 1.0 m. There is, furthermore, no dominant air flow towards the exhaust. Specifically for PC6, there is an air flow directed away from PC6 into the room.

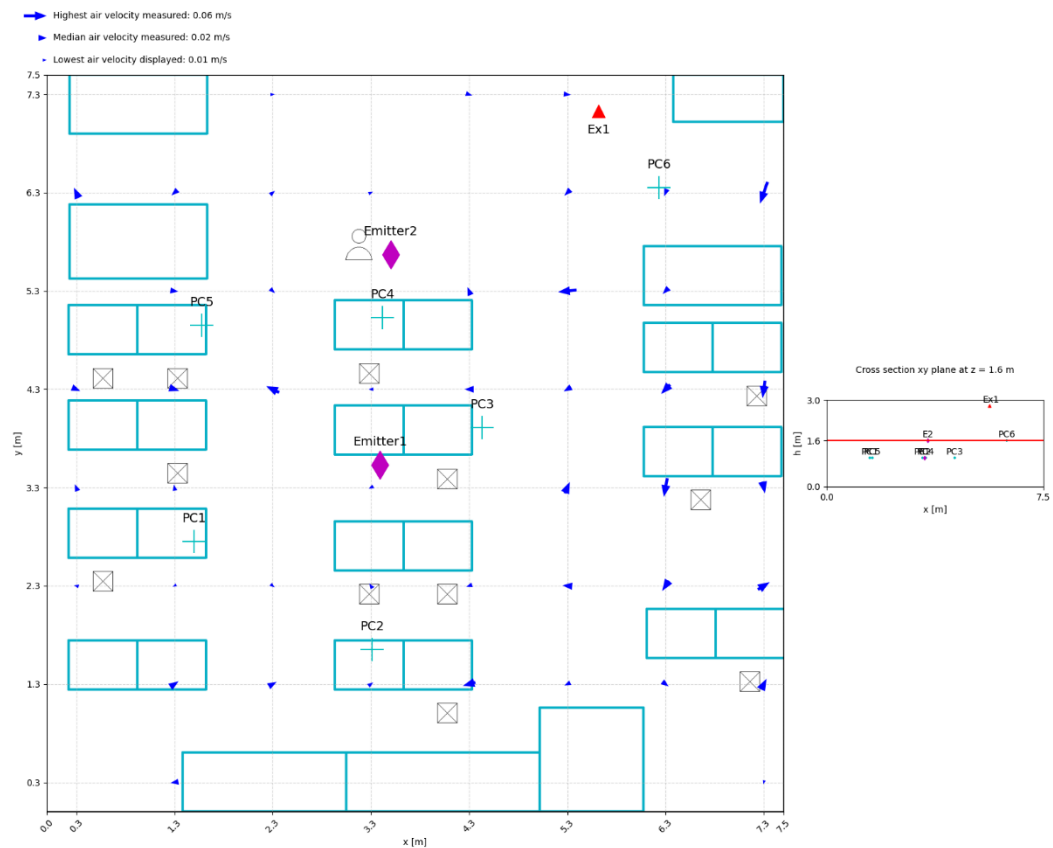


Figure 5-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

6. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system is CO₂-controlled. For air supply, the classroom has two supply grills and for the exhaust of air the classroom has one exhaust grill (Figure 6-1). Due to the design of the ventilation system, it was not possible to measure the supply and exhaust of air in the room. There are, furthermore, three tilt-and-turn windows present in the room these were all closed during the measurement period. An overview of the ventilation system can be seen in Table 6.1.

Table 6.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Ceiling grille	N/A
	Ceiling grille	
	Total	N/A
Ventilation (exhaust)		
	Ceiling grille	N/A
	Total	N/A



Figure 6-1 – Ventilation system after intervention

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Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 24.8 and 29.6 °C throughout the day.

Table 6.2 - Conditions during the measurement period. Wall 1: East, Wall 2: South, Wall 3: West, Wall 4: North. Metrological data is from weerstatistieken.nl of a nearby weather station.

24-07-2023				
Surface area temperature (°C)		09:30	14:30	
	Wall 1	20.1	21.7	
	Wall 2	20.7	22.9	
	Wall 3	20.9	22.7	
	Wall 4	20.7	23.3	
	Ceiling	20.6	23.6	
	Floor	20.9	23.0	
	Glass surface of the windows	19.7	26.8	
		Min*	Mean*	Max*
Air temperature (°C)		21.6	23.8	27.8
Relative humidity (%)		52.2	63.5	71.3
Outdoor air temperature (°C)		10.4	16.9	21.5
Outdoor relative humidity (%)		66	79	92
Wind	Velocity (m/s)	3.0	4.2	6.0
	Direction	West (271°)		

* The mean value is calculated by taking the average values of all sensor 502, 503, and 504 between 10:00-15:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before the intervention and after the intervention took place. The 100-fold increase time has a range of 30.0 – 64.0 for emitter location E1 and has a range of 12.4 – 74.9 for emitter location E2. The 100-fold increase time is relatively long at (almost) all measurement points which indicates that the particle concentration increases slowly at all locations in the classroom.

The 100-fold recovery time has a range of 53.4 – 55.9 min for emitter location E1 and has a range of 50.6 – 52.5 min for emitter location E2. The difference between the shortest and the longest 100-fold recovery time is very small which indicates that the decrease of the particle concentration is similar at different locations in the room (homogeneous).

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The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and 1 teacher, this results in a ventilation rate of 562 m³/h (3.5 ACH) for a Class C and 796 m³/h (4.9 ACH) for Class B. When these values are compared with the ACH values in Table 3.3 (ACH 4.9 – 5.5), it can be seen that all values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.8 – 2.8 min for emitter location E1 and has a range of 0.3 – 2.8 min for emitter location E2. t_{delay} is the longest at PC1 and PC2 for both emitter locations and at PC5 (E2). Overall, however, the t_{delay} is relatively short at all measurement locations. This indicates that the particle concentration starts to decrease quickly after the emission stopped.

Table 6.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	4.7	64.0	N/A*	55.9	N/A*	4.9	9.8	2.8
	E2	7.8	47.5	N/A*	50.6	N/A*	5.5	12.8	2.8
PC2	E1	20.3	41.7	N/A*	54.7	N/A*	5.0	12.8	2.3
	E2	20.6	32.2	1261	51.4	0.2	5.4	5.3	2.8
PC3	E1	12.8	30.0	446	54.7	0.6	5.1	5.8	2.0
	E2	19.3	17.4	N/A*	52.4	N/A*	5.3	10.0	1.5
PC4	E1	8.3	53.2	119	53.4	2.3	5.2	4.3	1.8
	E2	10.1	34.0	242	52.5	1.1	5.3	3.5	1.5
PC5	E1	1.4	63.4	113	54.9	2.4	5.0	1.3	0.8
	E2	8.3	74.9	219	51.5	1.2	5.4	5.0	3.8
PC6	E1	7.2	59.2	231	54.8	1.2	5.0	2.8	1.3
	E2	7.5	12.4	604	52.5	0.5	5.3	1.8	0.3

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

Deliverable Work package 2

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC1, PC2, PC3, PC4 and PC5 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 6-2 (range 0.01-0.22 m/s).

In Figure 6-2 it is visualized that the air velocities are highest at the right of the classroom and are in the direction of the air handling unit (directed towards the exhaust). Specifically for the particle counters, there is an air flow from PC4 and PC5 towards the emitter location E1. Furthermore, the air velocity seems lower near PC1 and PC2.

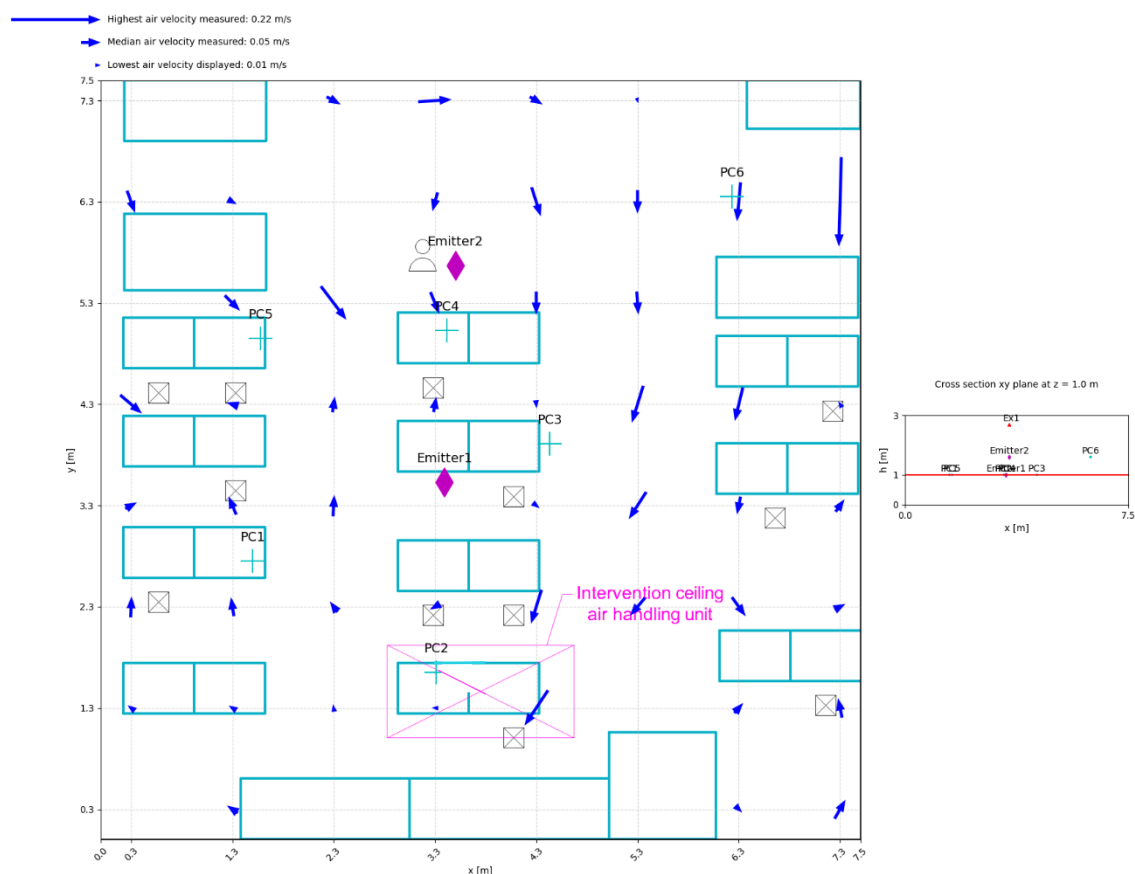


Figure 6-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 6-3 (range 0.01-0.09 m/s). In this figure, it can be seen that the air velocities are lower at this height and the direction of the airflow is less dominant. From this figure, it becomes clear that the direction of the air flow can change significantly

Deliverable Work package 2

at different heights. At this height, there is still an air flow towards the exhaust of the room but this air flow is less dominant. When looking specifically towards particle counter PC6, it seems that there is no clear air flow in the direction of PC6 and the air velocities are low near this point.

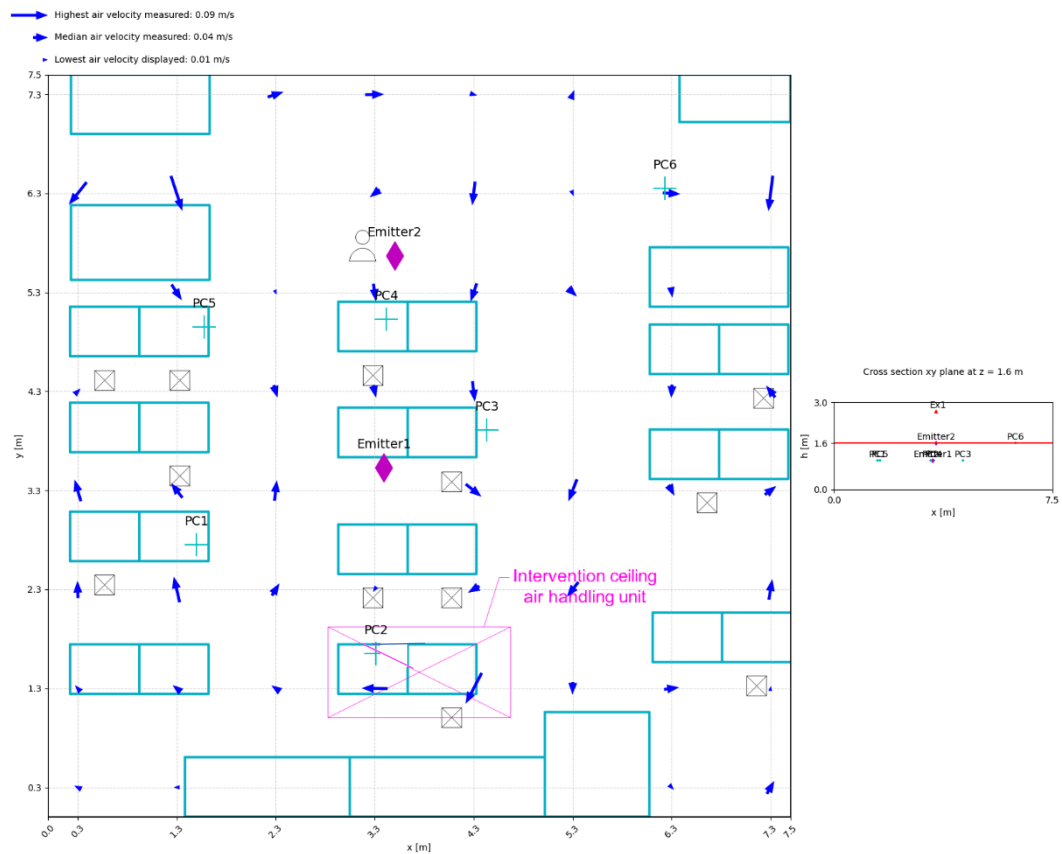


Figure 6-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

7. Conclusions

In this section, the performance of the ventilation system before and after the intervention and compares them through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before intervention, the 100-fold increase time has a range of 1.4 – 20.3 min for emitter location E1 and has a range of 7.4 – 20.6 min for emitter location E2. After intervention, the 100-fold increase time has a range of 30.0 – 64.0 min for emitter location E1 and has a range of 12.4 – 74.9 min for emitter location E2. After the intervention the 100-fold increase time is longer which can be explained by the higher air flow in the room. Overall, the particles do not reach the particle counters which can be seen by the lower particle concentration measured by the particle counters compared to before the intervention (Figure 7-1).

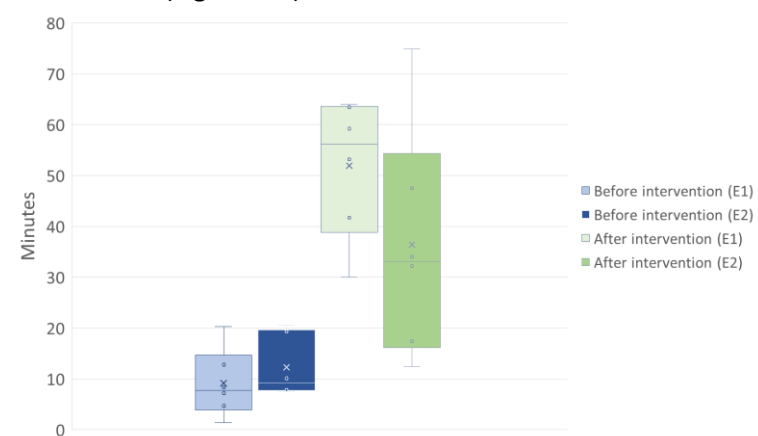


Figure 7-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before intervention, the 100-fold recovery time has a range of 113 – N/A min for emitter location E1 and has a range of 219 – N/A min for emitter location E2. After the intervention, the 100-fold recovery time has a range of 53.4 – 55.9 min for emitter location E1 and has a range 50.6 – 52.5 min for emitter location E2. The 100-fold recovery time is shorter and has a smaller range after the intervention took place. This indicates that the possible exposure to particles is similar at different locations in the room (Figure 7-2).

Deliverable Work package 2

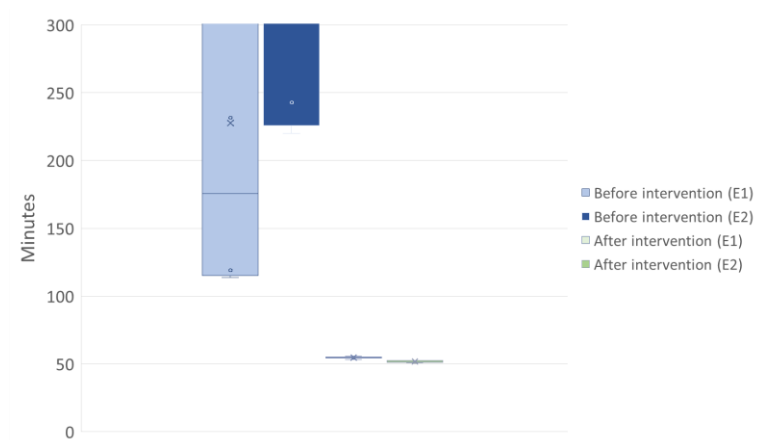


Figure 7-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 1.3 – 12.8 min for emitter location E1 and has a range of 1.8 – 12.8 min for emitter location E2. After intervention, t_{delay} has a range of 0.8 – 2.8 min for emitter location E1 and has a range of 0.3 – 2.8 min for emitter location E2. t_{delay} is, in general, shorter after the intervention took place. This indicates that after the emission stopped, the particle concentration starts to decrease faster due to a higher air flow in the room.

Air change per hour

Before intervention, the ACH has a range of N/A – 2.44, ACH for emitter location E1 and has a range of N/A – 1.2 ACH for emitter location E2. After intervention, the ACH has a range of 4.9 – 5.2 ACH for emitter location E1 and has a range of 5.3 – 5.5 ACH for emitter location E2. The range between the different measurements is small after the intervention took place. This indicates that there is more homogeneous mixing in the classroom. For the measurements before the intervention, no air change rate meet the requirements for both Class C (3.5) and Class B (4.9) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'. After intervention, all requirements are met for both Class C (3.5) and Class B (4.9).

4.2 Air flow measurements

Before the intervention took place, the air flow is most dominant in the center of the classroom and there is no clear air flow in the direction of the exhaust in the room both at a height of 1.0 m and at a height of 1.6 m.

The particle concentration measurement and air flow measurement show that the air velocities are lowest near PC1 and PC2 this could explain the long 100-fold recovery time at these locations. Furthermore, there is an air flow from E1 towards PC5 which explains the short 100-fold increase time at this location.

Deliverable Work package 2

After intervention, the air velocity is highest at the right of the classroom. There is a dominant air flow towards the exhaust in the room. The air velocities are higher at a height of 1.0 compared to the height of 1.6 m.

The particle concentration measurements and the air flow measurements show that in general the air velocities are higher after intervention which explains the shorter 100-fold recovery time. Furthermore, there is an air flow directed away from PC5 towards the emitter locations, this could explain the long 100-fold increase time at this location. Furthermore, the air flow seems lowest at PC1 and PC2 which can also explain the long 100-fold increase time at this location.

In conclusion, when both ventilation systems are compared it becomes clear that (overall) the air velocities are higher after the intervention took place. Furthermore, the direction of the air flow is more dominant. The particle spread throughout the room has a lower dependence on the proximity of the particle counter to the emission source location. The air flow throughout the room becomes the most dominant factor.

Concluded, due to the intervention the location of the children and teacher in the room becomes less prominent for a possible exposure and the overall risk to particle exposure is lower.

ANNEX G, RESULTS CLASSROOM 7

Experiments in-situ

WP2, experiments after intervention

DATUM	08-01-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location classroom 7

The results discussed in this report include both the situation before and the situation after the intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of openable windows and doors. In this location two of the three windows were opened and the doors were closed.

In the case of this location, the intervention consists of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system). The system consist of a split air conditioning unit with balanced ventilation with heat recovery. The classroom has four supply vents for fresh air and four exhaust roof vents.

Deliverable Work package 2

1.1 Characteristics of room and system

Description of the room

The school is located in a suburban environment and was originally built in 1981. The classroom that was considered during this analysis, has a surface area of 56.3 m² and was located on the ground floor. The façade was orientated towards the South and the height of the room was 3.0 m. During the measurements, this room was designed for circa 25 students and one teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has three tilt and turn windows and an emergency exit which can be opened. The same applies for the exhaust of air (Figure 1-2). There are, furthermore, two roof outlet vents present but this is natural ventilation which is connected directly towards the roof (see Figure 1-1). It should be noted that 2 of the 3 windows were opened and the other window and the emergency exit were closed during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

Deliverable Work package 2

Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	3 openable windows	N/A
	Total	N/A
Ventilation (exhaust)		
	3 openable windows	N/A
	2 roof outlet vents	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

Deliverable Work package 2

1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 13 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC2, PC3, PC4, PC5 and PC6 were located at 1.0 m height since this represents the breathing zone of sitting children. PC1 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.35 to 2.5 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 56 measurement points.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

Deliverable Work package 2

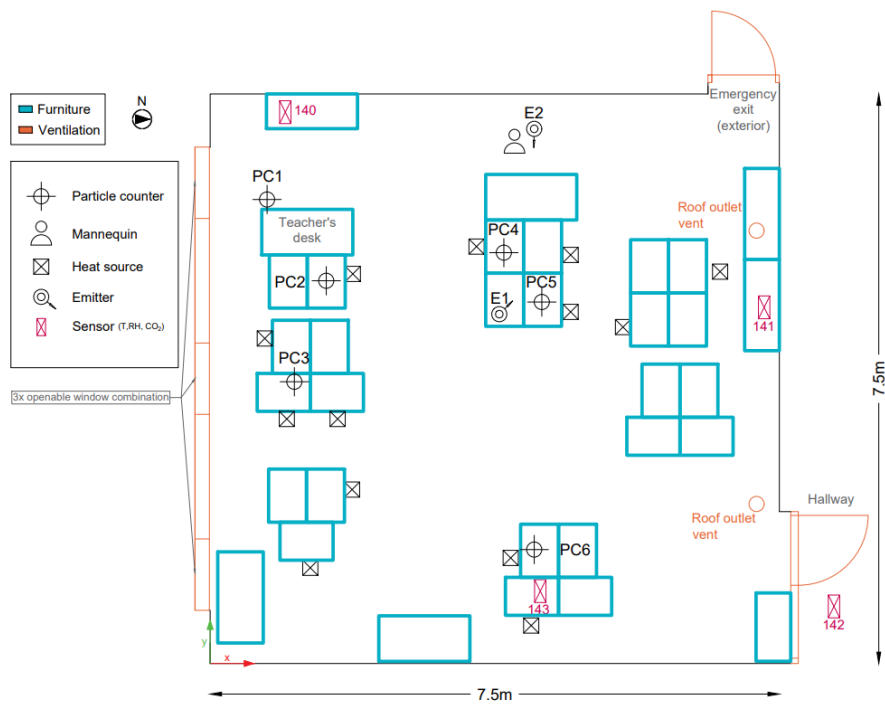


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

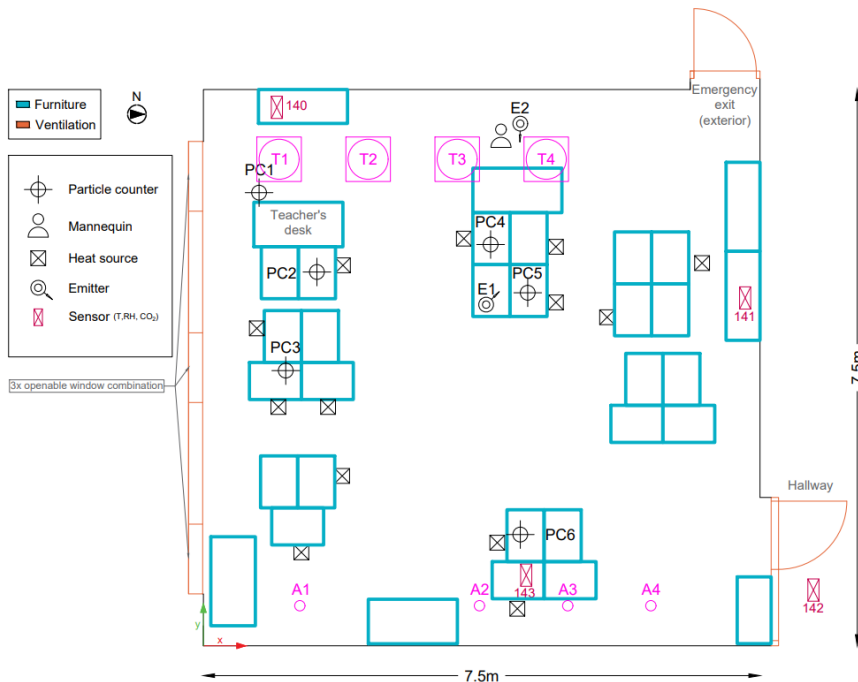


Figure 1-4 – Visualization of the classroom during the measurements (after intervention). T1-4 are the supply locations, A1-4 are the exhaust locations.

Deliverable Work package 2

2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 17.2 and 24.6 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: South, Wall 2: West, Wall 3: North, Wall 4: East. Metrological data is from weerstatistieken.nl of a nearby weather station.

05-07-2023				
Surface area temperature (°C)		12:00	16:00	
	Wall 1	21.2	22.9	
	Wall 2	21.5	22.1	
	Wall 3	21.5	22.1	
	Wall 4	21.7	22.8	
	Ceiling	22.0	24.9	
	Floor	22.9	23.8	
	Glass surface of the windows	19.9	24.0	
		Min*	Mean*	Max*
Air temperature (°C)		17.2	21.9	24.6
Relative humidity (%)		51.8	56.8	66.4
Outdoor air temperature (°C)		11.7	15.5	19.9
Outdoor relative humidity (%)		61	77	93
Wind	Velocity (m/s)	2	7.4	12
	Direction	West-South-West (242°)		

* The mean value is calculated by taking the average values of all four sensors between 09:00-18:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. **Fout! Verwijzingsbron niet gevonden.** gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 1.3 – 25.5 min for emitter location E1 and has a range of 8.8 – 41.5 min for emitter location E2. The 100-fold increase time is longest for PC1, PC2 and PC3 at emitter location E2 (37.4, 38.4 and 41.5 min). This means that it takes relatively long before the particle concentration has increased 100 fold. The shortest 100-fold increase time is at location E1 for PC4 (2.2 min) and PC5 (1.3 min). This can be explained by Figure 1-3, since the emitter E1 is located close to PC4 and PC5 which means that the particles reach these particle counters quickly which results in a short increase time.

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The 100-fold recovery time has a range of 48.7 – 55.2 min for emitter location E1 and has a range of 53.6 – 79.3 min for emitter location E2. The 100-fold recovery time is highly dependent on the emitter location and is (almost) always smaller at location E1 than at location E2. The longest recovery time is at emitter location E2 for PC3 (75.2 min) and PC6 (79.3 min), these two particle counters are located at a relatively long distance from the emitter. PC6 has the lowest 100-fold recovery time (48.7 min) for emitter location 1 while it is located relatively far away from the emitter location.

The Air change rate per hour is directly related to the 100-fold recovery time so should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m³/h (3.3 ACH) for a Class C and 796 m³/h (4.7 ACH) for Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that all ventilation rates are sufficient for class C (4.1 – 5.7) and 4 measurement locations do not meet the requirements of class B.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.5 – 3.0 min for emitter location E1 and has a range of 1.5 – 4.8 min for emitter location E2. The shortest t_{delay} is at emitter location E1 for PC5 (0.5 min) which means the particle concentration starts to decrease quickly after the emission period stopped. The longest value was measured at PC3 at emitter location E2 with a value of 4.8 min.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	22.1	55.2	5.0	3.0
	E2	41.5	73.0	3.8	1.5
PC2	E1	25.5	53.4	5.2	1.8
	E2	37.4	68.9	4.0	4.5
PC3	E1	14.1	52.5	5.3	2.3
	E2	38.4	75.2	3.7	4.8
PC4	E1	2.2	54.6	5.1	3.3
	E2	8.8	53.6	5.2	2.5
PC5	E1	1.3	52.5	5.2	0.5
	E2	8.9	54.9	5.0	3.3
PC6	E1	13.9	48.7	5.7	1.0

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	E2	23.6	79.3	3.5	3.5
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2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.13 m/s).

In Figure 2-1, there is an air flow present from the back of the room towards the center of the room. The air velocities are lowest at the front of the classroom, near emitter location E2. There is an air flow directed away from PC2, PC3 and PC6. The air flow from the emitter E1 crosses PC4. There are no clear air flows present directed from emitter location E2.

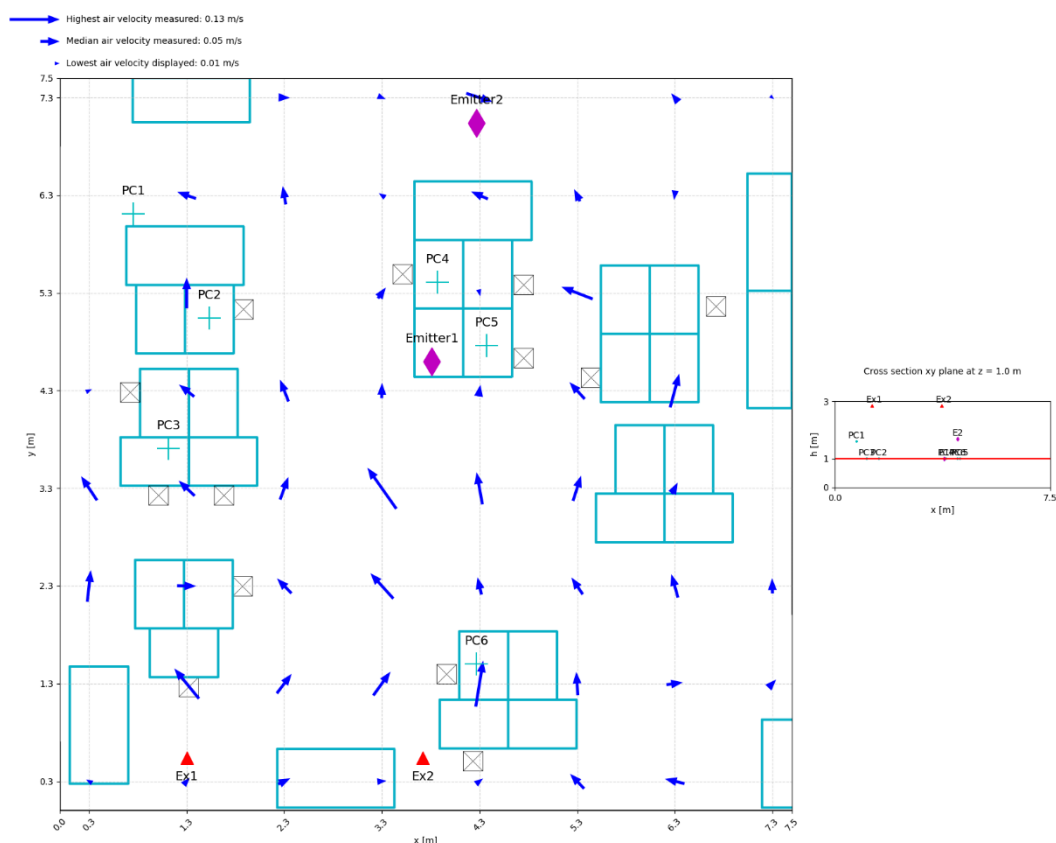


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

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For PC1, the air flow is analysed at a height of 1.6 m, see Figure 2-2. In this figure, the air flow from the windows into the classroom is less dominant (lower air velocities) than at a height of 1.0 m. An air flow from PC1 towards the windows is noticeable. There is no clear air flow near both emitter locations.

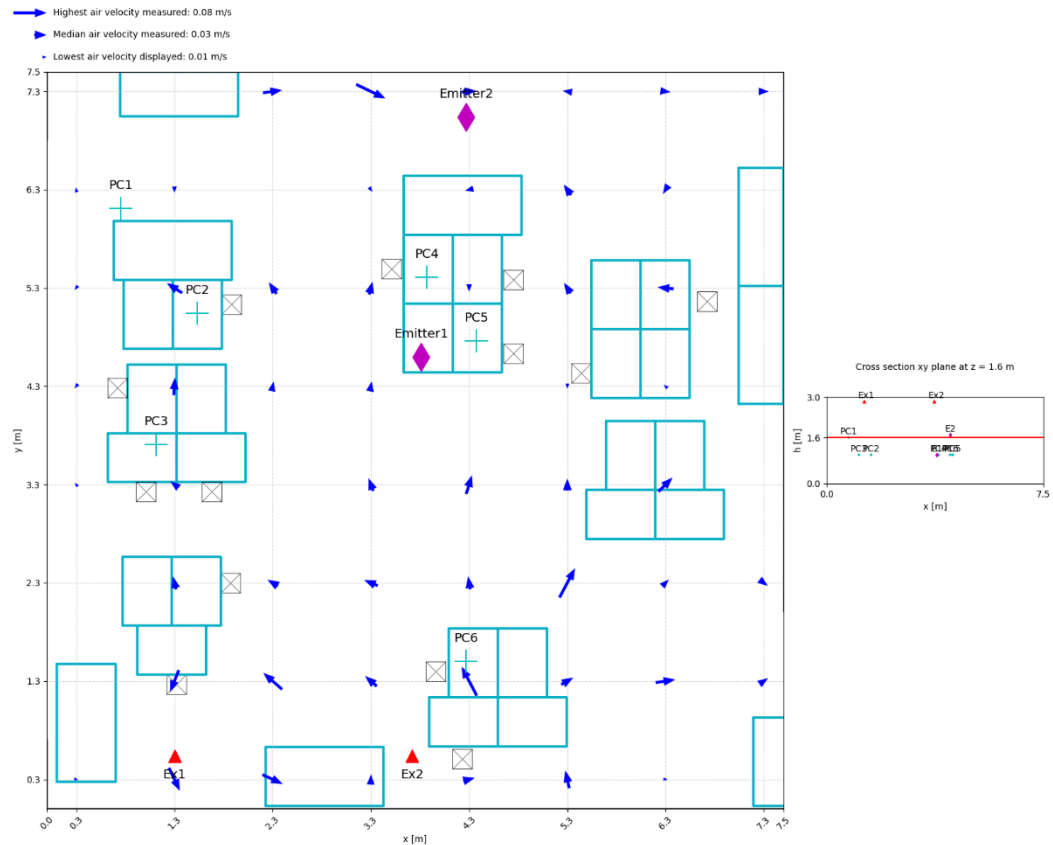


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

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3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system consists of a split air conditioning unit with balanced ventilation with heat recovery. There are four supply vents and four exhaust vents in the ceiling of the classroom (see Figure 3-1). There are, furthermore, three openable windows in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Ceiling vent	170
	Ceiling vent	168
	Ceiling vent	200
	Ceiling vent	183
	Total	721
Ventilation (exhaust)		
	Ceiling vent	110
	Ceiling vent	200
	Ceiling vent	210
	Ceiling vent	210
	Total	730



Figure 3-1 – Ventilation system after intervention

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Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 17.3 and 25.9 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Wall 1: South, Wall 2: West, Wall 3: North, Wall 4: East. Metrological data is from weerstatistieken.nl of a nearby weather station.

19-10-2023				
Surface area temperature (°C)		10:00	13:30	
	Wall 1	15.3	17.3	
	Wall 2	15.5	17.3	
	Wall 3	16.1	17.5	
	Wall 4	16.1	17.8	
	Ceiling	16.7	20	
	Floor	17.2	18.9	
	Glass surface of the windows	14.6	21.9	
		Min*	Mean*	Max*
Air temperature (°C)		17.3	20.6	25.9
Relative humidity (%)		60.5	71	77.5
Outdoor air temperature (°C)		12.9	15.6	17.9
Outdoor relative humidity (%)		79	88	96
Wind	Velocity (m/s)	3	4.3	5
	Direction	South-South-East (148°)		

* The mean value is calculated by taking the average values of all sensor 502, 503 and 506 between 10:00-14:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before and after the intervention. The results after the intervention are discussed here. The 100-fold increase time has a range of 10 – 156 min for emitter location E1 and has a range of 29.9 – 271 min for emitter location E2. The 100-fold increase time is longest for PC1 and PC2 at emitter location E2 (271-215 min). This indicates that the particle counters near the windows have a longer 100-fold increase time. This could be related to the air flow in the room. The 100-fold increase time is shortest for PC4 emitter location E1 (10 min), this particle counter is located close to the emitter location.

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The 100-fold recovery time has a range of 40.1 – 43.5 min for emitter location E1 and has a range of 37.1 – 46.5 min for emitter location E2. The 100-fold recovery time is shorter after the intervention took place (compared to before the intervention). Furthermore, the range is smaller which indicates that the homogeneous mixing in the classroom is better.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 30 children and 1 teachers, this results in a ventilation rate of 562 m³/h (3.3 ACH) for a Class C and 796 m³/h (4.7 ACH) for Class B. When these values are compared with the ACH values in Table 3.3 for the measurement after intervention (ACH 5.9 – 7.5), it can be seen that all values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 1.8 – 3.5 min for emitter location E1 and has a range of 2.3 – 4.0 min for emitter location E2. t_{delay} is the longest at PC1 and PC3 at emitter location E2 (4.0-3.8 min). t_{delay} is the shortest for PC1, PC4 and PC5 emitter location E1 (1.8 min). In general, the t_{delay} is relatively short at all locations and the range between the shortest and longest values is small.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	22.1	124	55.2	42.8	5.0	6.5	3.0	1.8
	E2	41.5	271	73.0	46.5	3.8	5.9	1.5	4.0
PC2	E1	25.5	104	53.4	40.8	5.2	6.8	1.8	2.0
	E2	37.4	215	68.9	44.4	4.0	6.2	4.5	3.5
PC3	E1	14.1	156	52.5	43.5	5.3	6.4	2.3	3.5
	E2	38.4	95.2	75.2	41.3	3.7	6.7	4.8	3.8
PC4	E1	2.2	10.0	54.6	40.1	5.1	6.9	3.3	1.8
	E2	8.8	29.9	53.6	43.0	5.2	6.4	2.5	3.0
PC5	E1	1.3	80.5	52.5	42.4	5.2	6.5	0.5	1.8
	E2	8.9	69.5	54.9	37.1	5.0	7.5	3.3	2.3
PC6	E1	13.9	89.7	48.7	43.0	5.7	6.4	1.0	2.5
	E2	23.6	66.4	79.3	38.1	3.5	7.2	3.5	2.5

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3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analysed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.13 m/s).

In Figure 2-1, it is visualized that the maximum air velocity in the room is 0.13 m/s. There is an air flow in the direction of the exhaust from the center of the room. The air velocities are lowest near the windows. Specifically for the particle counters, there is an air flow from PC6 towards the exhaust. Furthermore, from the supply vents there is an air flow towards PC2, PC4 and PC5. There is no clear flow from the emitter locations in the direction of a particle counter.

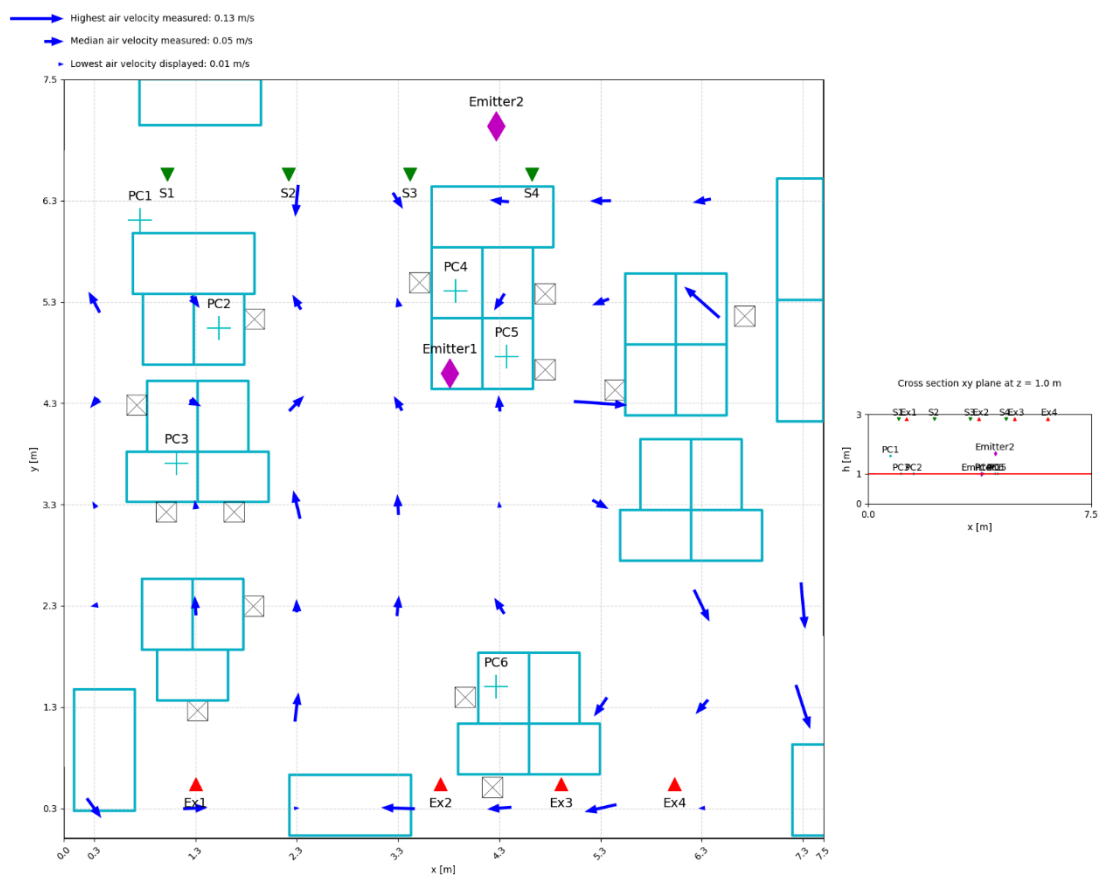


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

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For PC1, the air flow is analyzed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.18 m/s). The air velocities are higher at this height compared to the height of 1.0 m. This indicates that the air flow in the room can change at different heights. There is an air flow from the supply ceiling vents towards the exhaust. This flow is dominant at the right side of the classroom. When looking specifically towards particle counter PC1, the air velocities seem low near this location and there is no clear air flow near this particle counter.

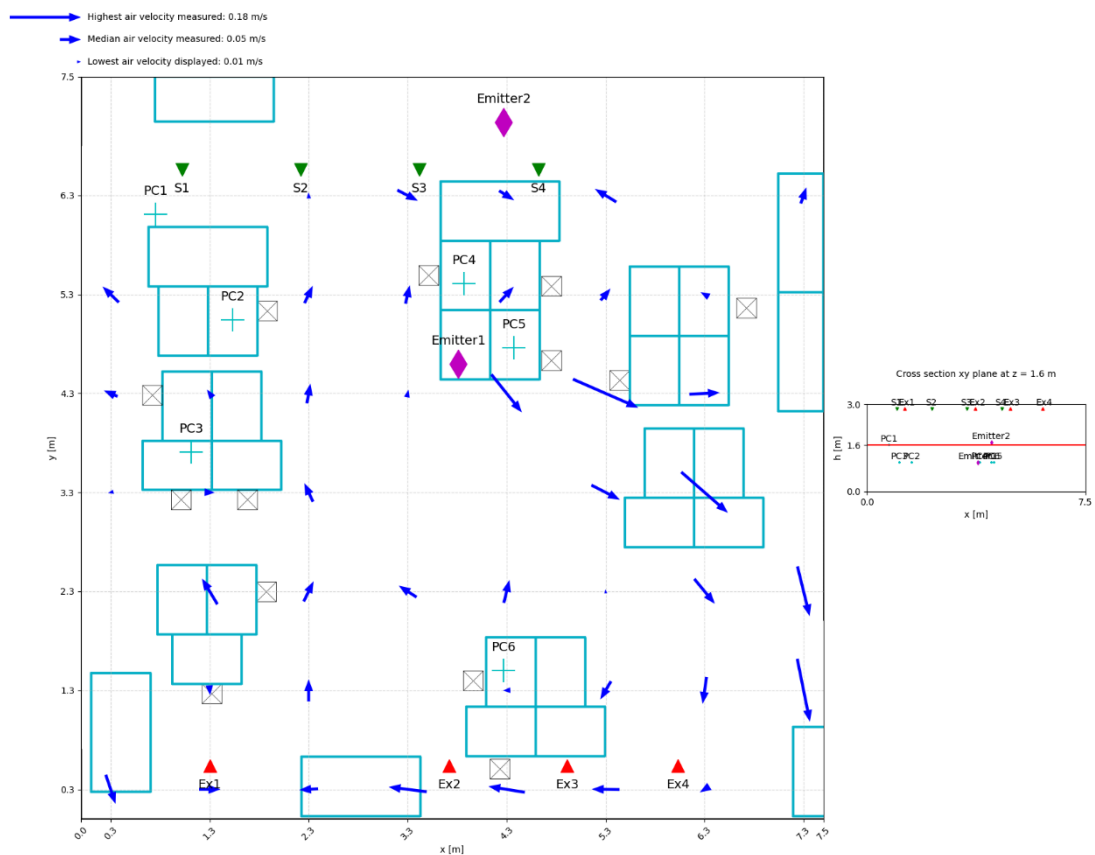


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

4. Conclusions

In this section, the performance of the ventilation system before and after the intervention are compared through the outcome parameters.

4.1 Particle concentration measurements

100-fold increase time

Before intervention, the 100-fold increase time has a range of 1.3 – 25.5 min for emitter location E1 and has a range of 8.8 – 41.5 min for emitter location E2. After intervention, the 100-fold increase time has a range of 10.0 – 156.0 min for emitter location E1 and has a range of 29.9 – 271.9 min for emitter location E2. After intervention, the range of the 100-fold increase time at different measurement points is larger. This can be explained by the overall low particle concentration that reaches the particle counters (Figure 4-1).

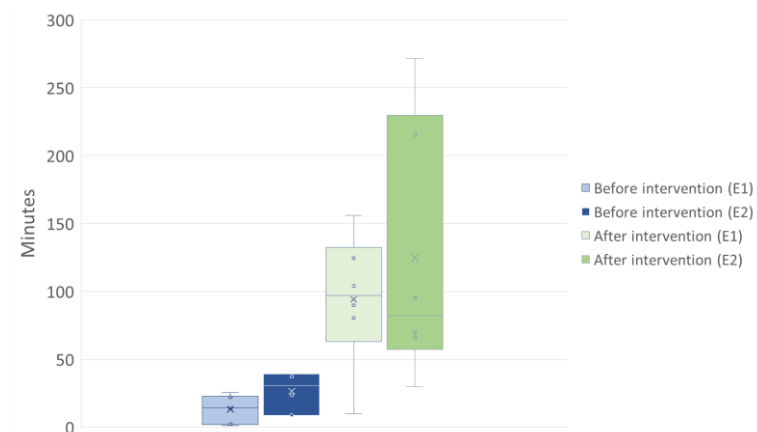


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before intervention, the 100-fold recovery time has a range of 48.7 – 55.2 min for emitter location E1 and has a range of 53.6 – 79.3 min for emitter location E2. After intervention, the 100-fold recovery time has a range of 40.1 – 43.5 min for emitter location E1 and has a range of 37.1 – 46.5 min for emitter location E2. Before intervention, the 100-fold recovery times were already relative short, this can be explained by the wind direction and velocity during the measurement day which had an average of 7.4 m/s directed towards the window façade. The 100-fold recovery time is shorter and has a smaller range after the intervention took place. This indicates that there is more homogeneous mixing in the class (Figure 4-2).

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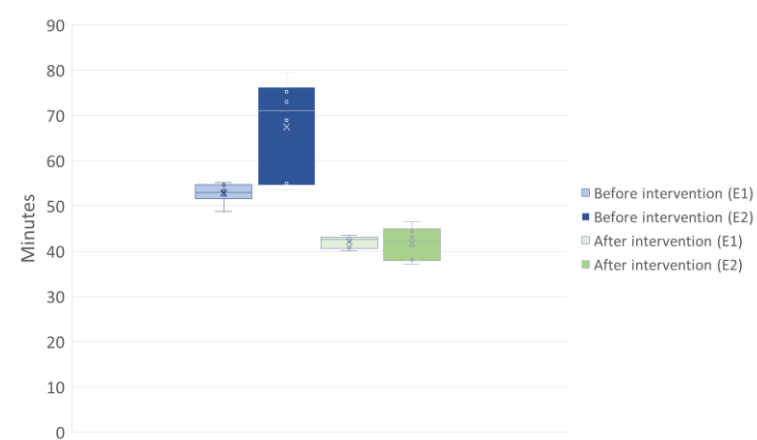


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 0.5 – 3.3 min for emitter location E1 and has a range of 1.5 – 4.8 min for emitter location E2. After intervention, t_{delay} has a range of 1.8 – 3.5 min for emitter location E1 and has a range of 2.3 – 4.0 min for emitter location E2. t_{delay} is, in general, similar before and after the intervention took place. The particle concentration at the start of the recovery period is, however, lower after the intervention took place which indicates that the air flow is higher.

Air change per hour

Before intervention, the ACH has a range of 5.0 – 5.7 ACH for emitter location E1 and has a range of 3.5 – 5.2 ACH for emitter location E2. After intervention, the ACH has a range of 6.4 – 6.9 ACH for emitter location E1 and has a range of 5.9 – 7.2 for emitter location E2. Despite the already relative high ACH before the intervention (related to the wind during that day). The ACH is higher after the intervention took place, this indicates that the risk of exposure for a longer period of time is lower after the intervention took place. For the measurements before the intervention, all measurements but four meet the requirements for Class B (4.7) according to the 'PvE Frisse Scholen', so these values are not considered 'sufficient'. After intervention, all requirements are met for Class B (4.7).

4.2 Air flow measurements

Before the intervention took place, the highest air velocities were from the back of the room towards the center of the classroom. The air velocities are lowest at the front of the classroom.

The particle concentration measurements and the air flow measurements show that the air velocities are lowest near PC1 and PC3 which can explain the relative long 100-fold increase time at these locations. Furthermore, the 100-fold recovery time is (in general) lower for the particle counters when the emitter is located at emitter location E1 compared to emitter location E2. This could be explained by the low air flow surrounding emitter location E2.

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After intervention, there is a dominant air flow from the supply vents towards the exhaust vents. This air flow is more dominant at a height of 1.6 m compared to 1.0 m. Furthermore, the air velocities are lowest near the windows of the room.

The particle concentration measurements and the air flow measurements show that in general the velocities are higher after intervention which explains the shorter 100-fold recovery time. Furthermore, the air velocities are lowest near the windows which explains the relative long 100-fold increase time for PC1, PC2 and PC3. The overall particle concentration after the emission period stopped is low at these locations due to the air flow in the room.

In conclusion, when both ventilation systems are compared it becomes clear that the air velocities are higher after the intervention took place. Furthermore, the air velocities and air flow in the room are no longer dependent on the outdoor conditions such as wind during. The overall particle spread throughout the room has a lower dependence on the proximity of the particle counters to the emission source location. The air flow throughout the room becomes the most dominant factor.

Concluded, due to the intervention the location of the children and teacher in the room becomes less prominent for a possible exposure and the overall risk to an exposure is lower.

ANNEX H, RESULTS CLASSROOM 8

Experiments in-situ

WP2, experiments after intervention

DATUM	09-01-2024
AUTEURS	Ir. A. de Lange
ORGANISATIE	TNO

1. Results baseline measurement location Classroom 8

The results discussed in this report include both the situation without any interventions and the situation after the intervention took place to optimize the ventilation system or situation.

Future interventions are defined as modifications to the current situation in terms of:

- Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system),
- Adjustment of controls: new control system based on actual CO₂-level/presence,
- Use of a mobile air cleaner,
- Adjustment of air flow: the air flows are adjusted according to design and the changes reported (before and after).

In systems with natural ventilation the fresh air supply is controlled by opening or closing windows and grills. During the measurements the windows and grills were set as during normal operating conditions during the winter season.

Before the intervention, the ventilation system or situation at the location was system A and consists of openable windows and doors. In this location the windows were opened and the doors were closed.

For this location, the intervention consists of the replacement of the ventilation system: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system)). The system consist of a raised floor with convectors for heating and cooling and airsocks for air distribution. There are panels in the ceiling for the exhaust of air. The ventilation system will be CO₂ controlled and is designed to meet de requirements for Class B of 'PvE Frisse Scholen 2021' and has a (design) capacity of 795 m³/h based on 25 students and two teachers

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1.1 *Characteristics of room and system*

Description of the room

The school is located in a suburban environment and was originally built in 1982. The classroom that was considered during this analysis, has a surface area of 64.4 m² and was located on the ground floor. The façade was orientated towards the North-East and the height of the room was 4.1 m. During the measurements, this room was designed for circa 25 students and one teacher. A visualization of the room can be seen in Figure 1-1.



Figure 1-1 - Visualization of the classroom during the measurements

Ventilation system in the room

Before intervention

Before the intervention took place, the ventilation system at this location was natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has two tilt and turn windows which can be opened. The same applies for the exhaust of air (Figure 1-2). It should be noted that the two tilt and turn windows were opened during the measurement period. An overview of the ventilation system can be seen in Table 1.1.

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Table 1.1 - Overview of the ventilation system present in the classroom before intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
A (Natural supply and exhaust)		
Ventilation (supply)		
	2 openable windows	N/A
	Total	N/A
Ventilation (exhaust)		
	2 openable windows	N/A
	Total	N/A



Figure 1-2 – Ventilation system before intervention

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1.2 Description of standard methodology

Two different measurements were performed in the classroom, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the children and the teacher in the room. The teacher was represented as a mannequin with a heating blanket that emits 120 watt. There were, furthermore, 11 static heat sources that each emit 80 watt representing the children in the classroom. In general, humans are the main emitter and receiver of particles which means that the measurement equipment was centered around these heat sources. The whole set-up during the measurements can be seen in Figure 1-3 for the measurements before intervention and in Figure 1-4 for the measurements after the intervention. Both measurements were the same except the difference in the ventilation system.

For the particle counters (PC), PC2, PC3, PC4, PC5 and PC6 were located at 1.0 m height since this represents the breathing zone of sitting children. PC1 is located at a height of 1.6 m since this represents the breathing zone of a standing teacher. The emission of the particles took place at two different positions (E1 and E2). Location E1 was located at a height of 1.0 m and represents a child that is speaking (emitting particles). Location E2 was located at 1.6 m nearby the mannequin heat source, this represents the teacher who is talking in the direction of the children. Different particle sizes are measured: 0.3 μm , 0.5 μm , 1.0 μm , 2.0 μm and 5.0 μm . In this analysis, only the particle size of 0.5 μm is considered since this is a good proxy for the remaining particle sizes.

During the air flow (vector: velocity and direction) measurements, the air flow was measured at eight different heights from 0.17 to 2.55 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 37 measurement points. The back of the room was not taken into account during these measurements since this area is not intended to be occupied by students.

There were also sensors for measuring temperature, humidity and CO₂ concentration in the room.

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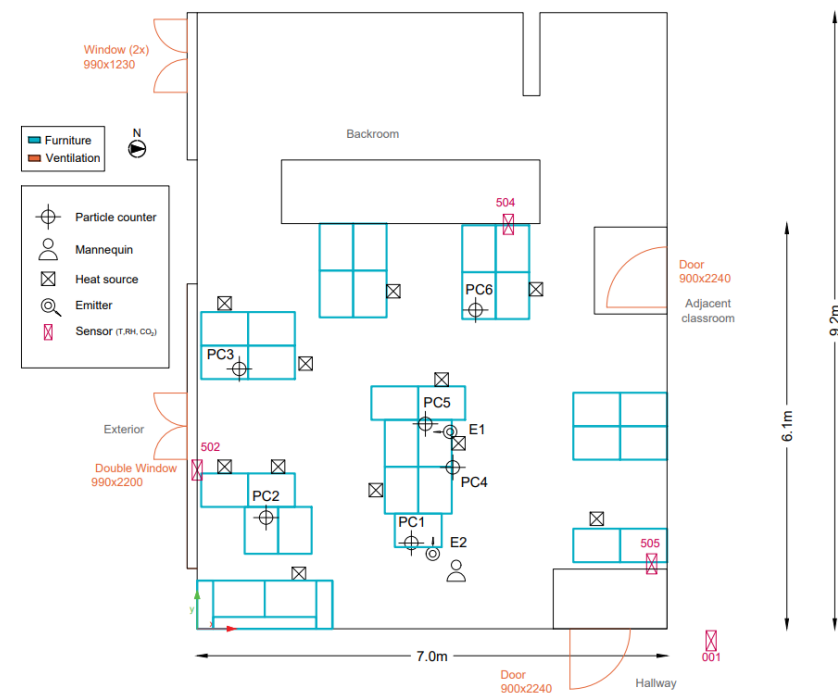


Figure 1-3 - Visualization of the classroom during the measurements (before intervention)

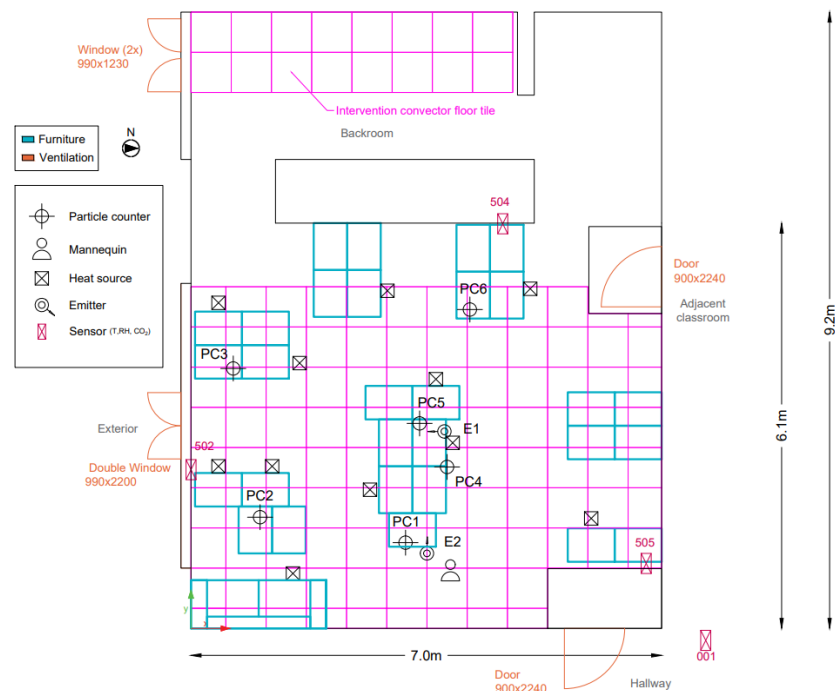


Figure 1-4 – Visualization of the classroom during the measurements (after intervention)

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2. Results (before intervention)

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 16.3 and 19.8 °C throughout the day.

Table 2.1 - Conditions during the measurement period. Wall 1: Northeast, Wall 2: Northwest, Wall 3: Southwest, Wall 4: Southeast. Metrological data is from weerstatistieken.nl of a nearby weather station.

24-10-2023				
Surface area temperature (°C)		11:30	16:30	
	Wall 1	16.3	17.7	
	Wall 2	18.0	18.2	
	Wall 3	18.2	18.1	
	Wall 4	17.1	18.2	
	Ceiling	18.9	18.9	
	Floor	17.9	18.9	
	Glass surface of the windows	14.7	14.9	
		Min*	Mean*	Max*
Air temperature (°C)		16.3	18.5	19.8
Relative humidity (%)		63.4	69.6	79.8
Outdoor air temperature (°C)		9.7	11.5	21.5
Outdoor relative humidity (%)		87	93	98
Wind	Velocity (m/s)	3.0	5.8	8.0
	Direction	South-South-West (195°)		

* The mean value is calculated by taking the average values of all four sensors between 10:30-17:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time has a range of 1.2 – 85.6 min for emitter location E1 and has a range of 36.5 – 186.6 min for emitter location E2. The 100-fold increase time is longest for PC1 and PC2 at emitter location E2 (159.2 and 186.6 min). This means that it takes long before the particle concentration has increased 100 fold. The shortest 100-fold increase time is at location PC1 and PC4 for E1 (1.2 and 1.3 min). This can be explained by Figure 1-2, since the emitter E1 is located close towards PC1 and PC4 which means that the particles reach these particle counters quickly which results in a short increase time.

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The 100-fold recovery time has a range of 118.3 – 370.1 min for emitter location E1 and has a range of 88.8 – N/A min for emitter location E2. The 100-fold recovery time is highly dependent on the emitter location and is (almost) always smaller at location E1 than at location E2. The longest recovery time is at emitter location E2 for PC1, PC2 and PC3, at these locations the 100-fold recovery time was negative which means the particle concentration increased during the recovery period (N/A). The lowest 100-fold recovery time is for E2 at PC6 (88.8), this is interesting since this particle counter is located quite far away from the emitter.

The air change rate per hour is directly related to the 100-fold recovery time so should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m³/h (2.0 ACH) for a Class C and 796 m³/h (2.8 ACH) for Class B. When these values are compared with the ACH values in Table 2.2, it can be seen that only PC3 (E1) and PC6 (E2) are sufficient for class C, the other ventilation rate are not sufficient for both the requirements of class C and class B.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.3 – 5.5 min for emitter location E1 and has a range of 3.5 – 11.0 min for emitter location E2. The shortest t_{delay} is at emitter location E1 for PC5 (0.3 min) which means the particle concentration starts to decrease quickly after the emission period stopped. The longest value was measured at PC1 at emitter location E2 with a value of 11.0 min.

Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	1.2	167	1.6	2
	E2	159	N/A	N/A	11
PC2	E1	14	227	1.2	1.5
	E2	186	N/A	N/A	9.8
PC3	E1	31.3	118	2.3	2.8
	E2	90.6	N/A	N/A	10.5
PC4	E1	1.3	169	1.6	1.8
	E2	99.3	605	0.5	7.8
PC5	E1	2.2	370	0.7	0.3
	E2	81.2	770	0.4	8.8
PC6	E1	85.6	247	1.1	5.5
	E2	36.5	88.8	3.1	3.5

Deliverable Work package 2

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

2.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.12 m/s).

In Figure 2-1, an air flow from the windows inwards to the center of the room can be seen. The air velocities are lower in the front and the back of the classroom. Specifically for the particle counters, there is an air flow from the windows which crosses PC2 and PC3. Furthermore, there is an air flow present (though with low velocities) from emitter location E2 towards PC5 and PC6.

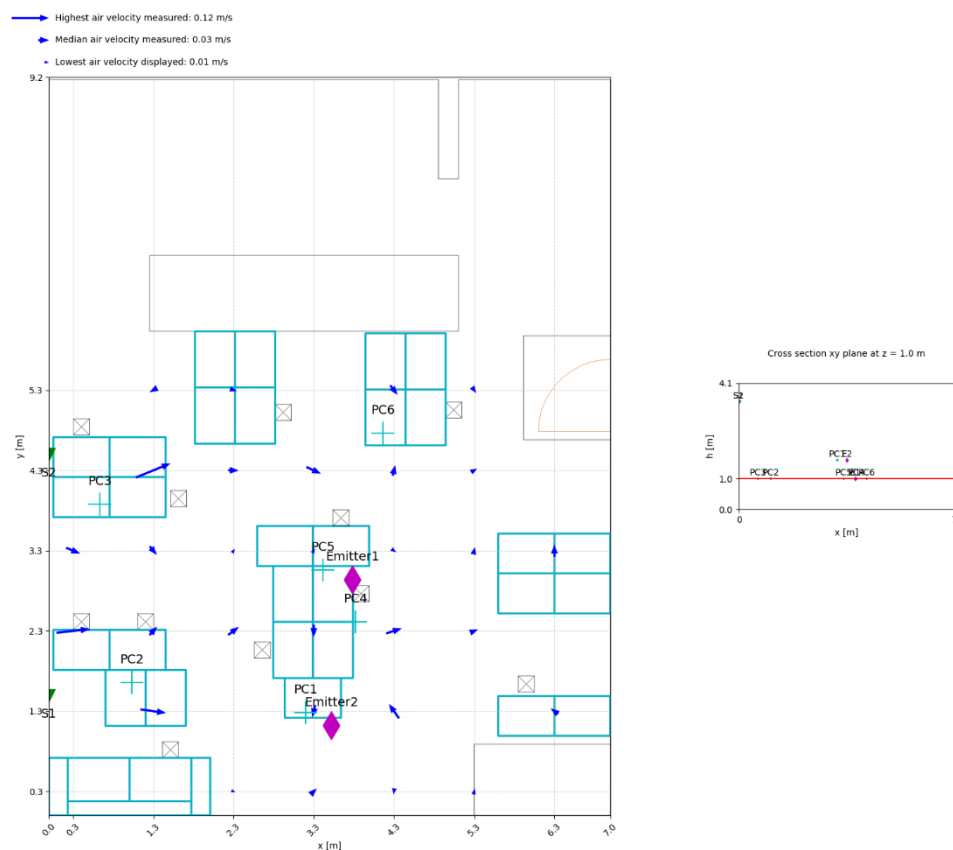


Figure 2-1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

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For PC1, the air flow is analyzed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.07 m/s). For this height, the air velocities are lower compared to the height of 1.0 m. Furthermore, the air flow from the windows inwards is less prominent. The air velocities seem to be lowest in the center of the room, near emitter location E1. Specifically for PC1, the air velocities are low near this particle counter and there are no clear air flows present.

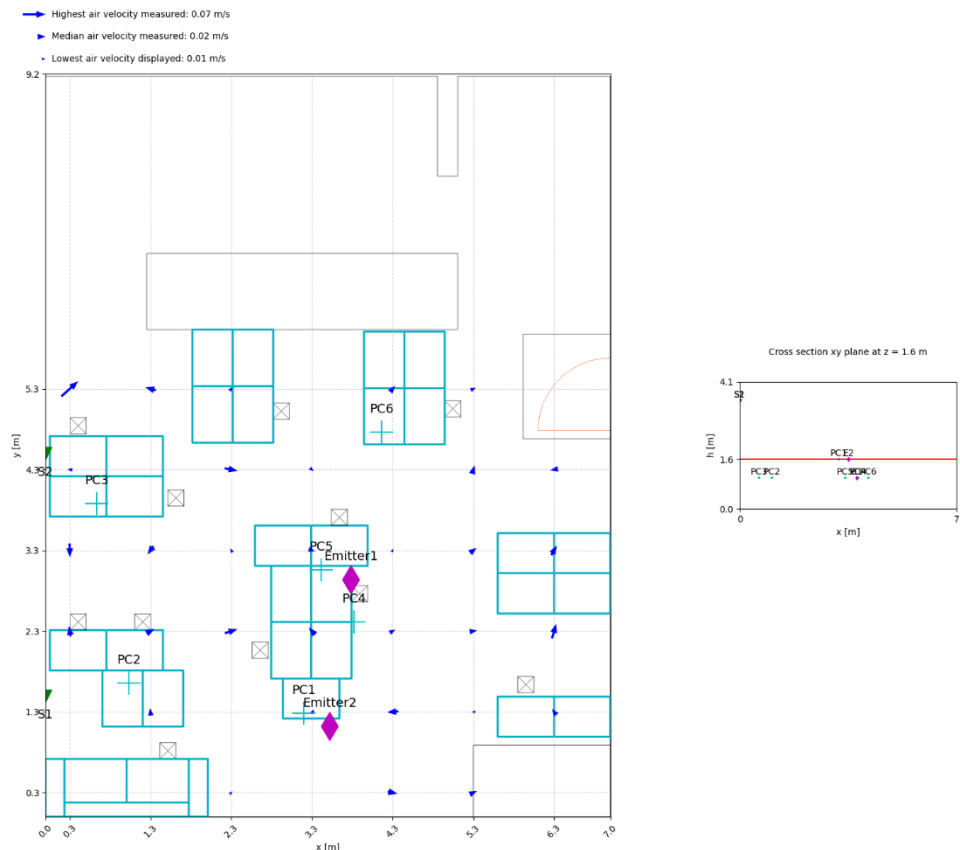


Figure 2-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

Deliverable Work package 2

3. Results (after intervention)

Ventilation system

After the intervention took place, the ventilation system at this location is mechanical ventilation (mechanical supply and exhaust, system D). The ventilation system consists of raised floor with convectors for heating and cooling. Furthermore, it consists of airsocks for the distribution of air (see Figure 3-1). There are panels in the ceiling for the exhaust of air. There are, furthermore, two openable windows present in the room. It should be noted that these windows and the door were closed during the measurement period. An overview of the ventilation system can be seen in Table 3.1. It should be noted that the measured flow rate is an approximation since it was not possible to measure the flow rate accurately due to not being able to use the FlowFinder for this type of inlet.

Table 3.1 – Overview of the ventilation system present in the classroom after intervention

Ventilation system		
	Type	Measured flow rate (m ³ /h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Air vent (for each tile)	9.4
	Total	1034
Ventilation (exhaust)		
	Ceiling vent	N/A
	Total	N/A

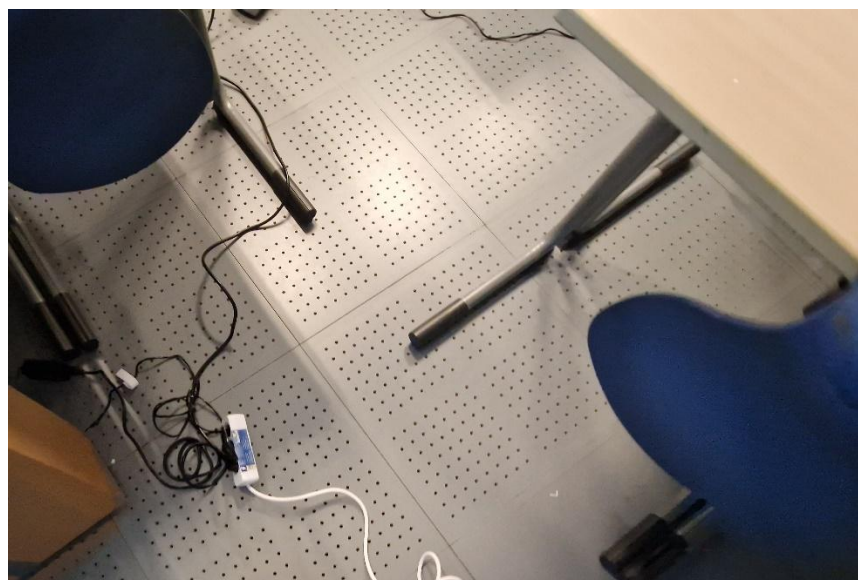


Figure 3-1 – Ventilation system after intervention

Deliverable Work package 2

Indoor & outdoor conditions

The indoor and outdoor conditions during the measurements can be seen in Table 3.2. The room temperature was between 16.2 and 21.9 °C throughout the day.

Table 3.2 - Conditions during the measurement period. Wall 1: Southwest, Wall 2: Northwest, Wall 3: Northeast, Wall 4: Southeast. Metrological data is from weerstatistieken.nl of a nearby weather station.

24-10-2023				
Surface area temperature (°C)		11:30	16:30	
	Wall 1	19.3	19.7	
	Wall 2	20.3	19.6	
	Wall 3	20	19.6	
	Wall 4	20	18.9	
	Ceiling	21.3	20	
	Floor	22.5	19.7	
	Glass surface of the windows	19.1	17.1	
		Min*	Mean*	Max*
Air temperature (°C)		16.2	20.4	21.9
Relative humidity (%)		55.3	61.3	76.2
Outdoor air temperature (°C)		9.7	11.5	12.5
Outdoor relative humidity (%)		87	93	98
Wind	Velocity (m/s)	4.5	5.8	8
	Direction	South-South-West (195°)		

* The mean value is calculated by taking the average values of all sensor 503, 506 and 509 between 10:00-17:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

3.1 Particle concentration measurements

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 3.3 gives an overview of the results for each measurement location (PC1 – PC6) for both before and after the intervention took place. The 100-fold increase time has a range of 2.4 – 127.4 min for emitter location E1 and has a range of 32.6 – 177.2 min for emitter location E2. The 100-fold increase time is longest for PC3 (E1) and PC2 (E2), these particle counters are both located near the windows at a relative far distance from the emitter locations. The 100-fold increase time is shortest for PC1 and PC4 (2.4 – 6.5 min) at emitter location E1, these particle counters are both located near the emitter location. PC5, however, is also located close to the emitter location E1 but has a relative longer 100-fold increase time (82.2 min).

Deliverable Work package 2

The 100-fold recovery time has a range of 35.6 – 40.4 min for emitter location E1 and has a range of 35.8 – 37.8 min for emitter location E2. The range of the 100-fold recovery time between different particle counters is small which indicates that the decrease of the particle concentration is similar at different locations in the room (homogenous). Furthermore, the 100-fold recovery time is short for all measurement points with the longest value of 40.4 this indicates that the decrease in particle concentration is relative fast.

The air change rate per hour is directly related to the 100-fold recovery time so this variable should show the same trend as the 100-fold recovery time. The ACH is calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For school buildings there are regulations called 'Programma van Eisen frisse scholen', these have subdivided the recommendations into two classes (RVO, 2021). First, there is a class C which results in a 'sufficient' air quality, this requires a ventilation rate of 21.6 m³/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m³/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m³/h (2.0 ACH) for a Class C and 796 m³/h (2.8 ACH) for Class B. When these values are compared with the ACH values in Table 3.3 (ACH 6.8 – 7.7), it can be seen that all values meet the requirements for either one of the classes.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} has a range of 0.5 – 4.0 min for emitter location E1 and has a range of 1.3 – 4.5 min for emitter location E2. t_{delay} is the longest at PC2, PC4 and PC6 at emitter location E2 (4.5, 4.3 – 4.0 min) and at PC5 emitter location E1 (4.0 min). The long values at PC2 and PC6 can be explained by the far distance between the particle counter and the emitter. This is not the case for PC4 and PC5, these values can (potentially) be explained by the air flow in the room. t_{delay} is the shortest for PC4 emitter location E1 (0.5 min). At this location, the 100-fold increase time was also the shortest. This indicates that the increase at this location is quick and the decrease starts quickly after the emission period stopped.

Table 3.3 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations for both before the intervention and after the intervention.

		100-fold increase time (min)		100-fold recovery time (min)		Local air change rate per hour (ACH)		t_{delay} (min)	
		Before	After	Before	After	Before	After	Before	After
PC1	E1	1.2	6.5	167.5	36.0	1.6	7.7	2	2.0
	E2	159	96.6	N/A	37.7	N/A	7.3	11	3.3
PC2	E1	14.0	68.0	227.4	35.6	1.2	7.8	1.5	2.0
	E2	186	177	N/A	37.5	N/A	7.4	9.8	4.5
PC3	E1	31.3	127	118.3	36.3	2.3	7.6	2.8	3.3
	E2	90.6	108	N/A	37.8	N/A	7.3	10.5	1.3
PC4	E1	1.3	2.4	169.8	37.0	1.6	7.5	1.8	0.5
	E2	99.3	70.8	605.9	36.9	0.5	7.5	7.8	4.3
PC5	E1	2.2	82.2	370.1	40.4	0.7	6.8	0.3	4.0
	E2	81.2	65.1	770	36.9	0.4	7.5	8.8	2.3

Deliverable Work package 2

PC6	E1	85.6	30.6	247	37.6	1.1	7.3	5.5	3.5
	E2	36.5	32.6	88.8	35.8	3.1	7.7	3.5	4.0

* N/A means that the particle concentration increased during the recovery period instead of decreased (negative calculated recovery time).

3.2 Vector of the air flow

To be able to compare the particle concentration measurements with the air flow measurements, the results of the air flow measurements have been analyzed at the location of the particle counters. The arrows indicate the direction of the measured air flow in that plane and the length of the arrow provides an indication of the air velocity at that location. Air velocities below 0.01 m/s are not considered in this analysis. For PC2, PC3, PC4, PC5 and PC6 the measurements have been analyzed at a height of 1.0 m. The direction and velocity of the air flow at this height can be seen in Figure 2-1 (range 0.01 – 0.14 m/s).

In Figure 2-1, it is visualized that the air velocities are highest near the windows and are also in the direction of the windows of the classroom. Specifically for the particle counters, there is an air flow from emitter location E1 in the direction of PC5 and PC3. Furthermore, there is an air flow directed away from PC6.

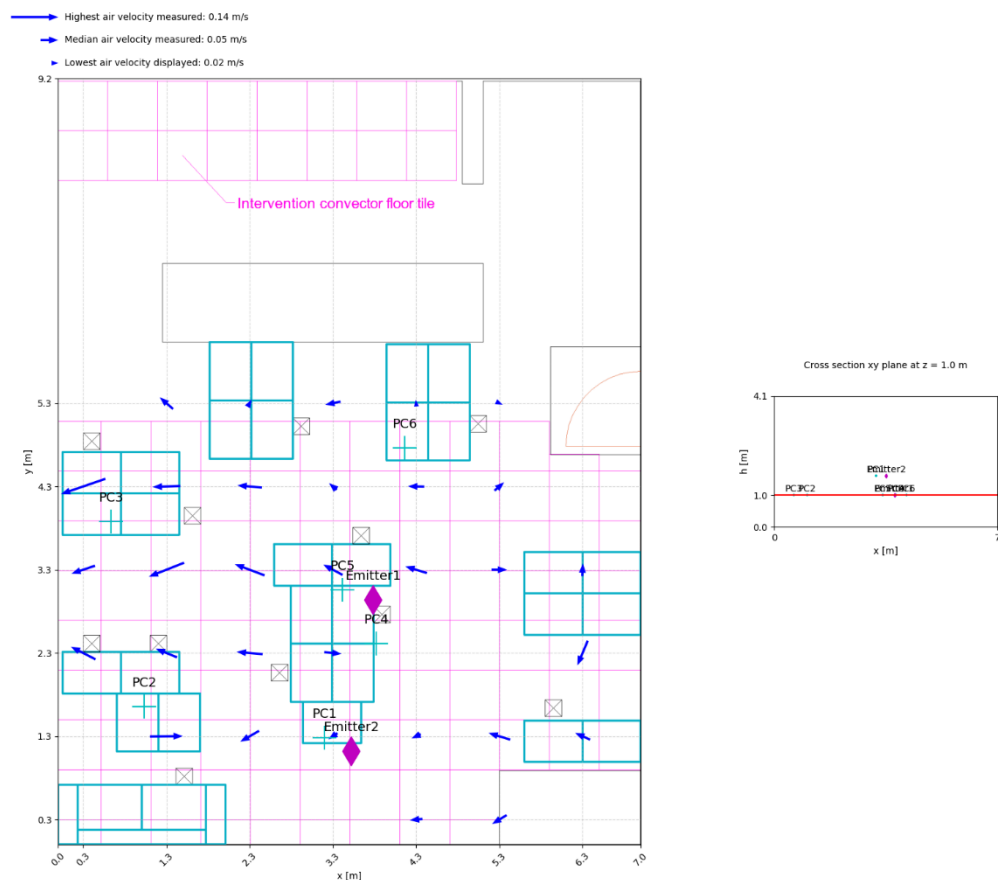


Figure 3-2 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

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For PC1, the air flow is analyzed at a height of 1.6 m, see Figure 2-2 (range 0.01 – 0.09 m/s). In this figure, it can be seen that the air velocities are lower at this height and the direction of the air flow is less dominant. It is clear that the air flow can change significantly at different heights in the room. The highest air flow are now present in the center of the classroom and are directed mainly towards the windows. When looking specifically towards particle counter PC1, there is no clear air flow present near this particle counter.

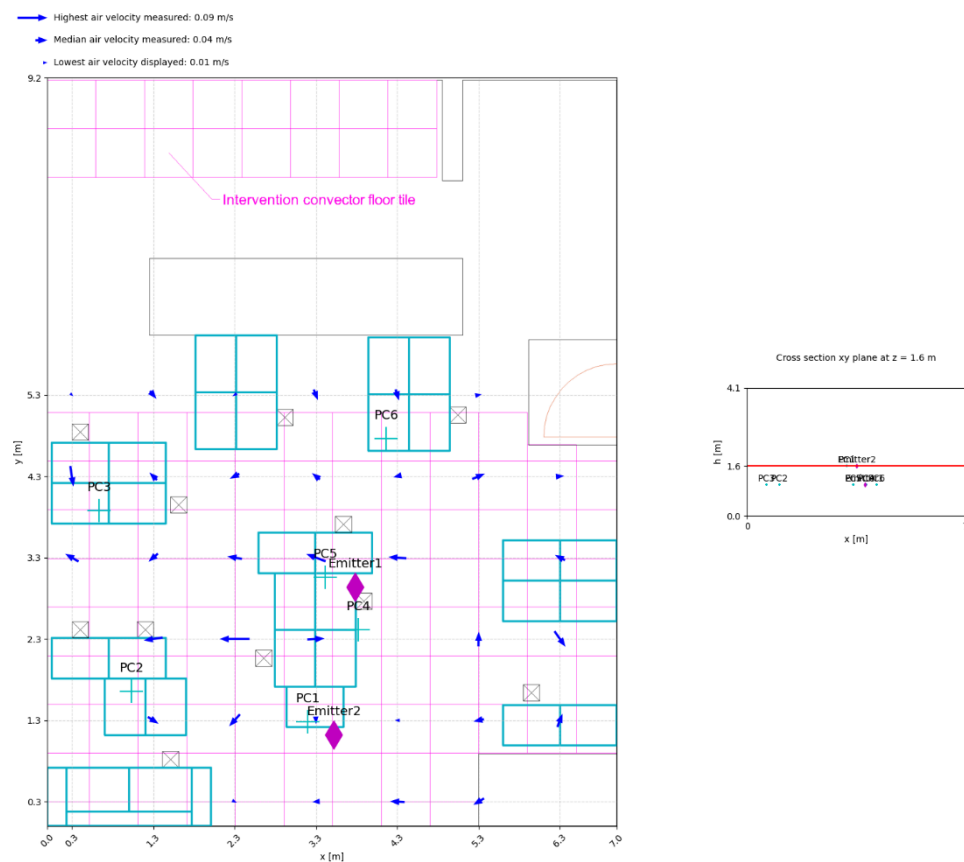


Figure 3-3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

In Figure 3-4, a visualization of the intersection at 1.3 m can be seen at 8 different heights (range 0.01-0.14 m/s). From this figure, the dominant air flow from the floor towards the ceiling becomes apparent.

Deliverable Work package 2

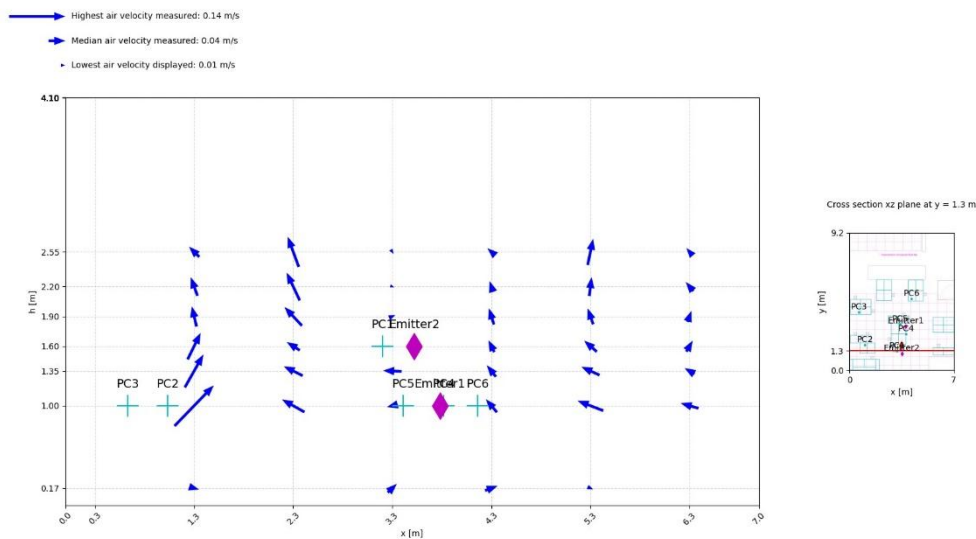


Figure 3-4 - Air flow (direction and velocity) in the XZ-plane at $y = 1.3$ m

4. Conclusions

In this section, the performance of the ventilation system before and after intervention are described and compared through the outcome parameters.

4.1 Particle concentration measurements

In this section, the performance of the ventilation system before and after the intervention are described and compared through the outcome parameters.

100-fold increase time

Before intervention, the 100-fold increase time has a range of 1.2 – 85.6 min for emitter location E1 and has a range of 36.5 – 186 min for emitter location E2. After intervention, the 100-fold increase time has a range of 2.4 – 127 min for emitter location E1 and has a range of 32.6 – 177 min for emitter location E2. Before intervention the 100-fold increase time is long at almost all measurement points when the emitter is positioned at location E2. After intervention the 100-fold increase time is longest at the measurement points near the windows. This indicates that the air flow in the room has changed (Figure 4-1).

Deliverable Work package 2

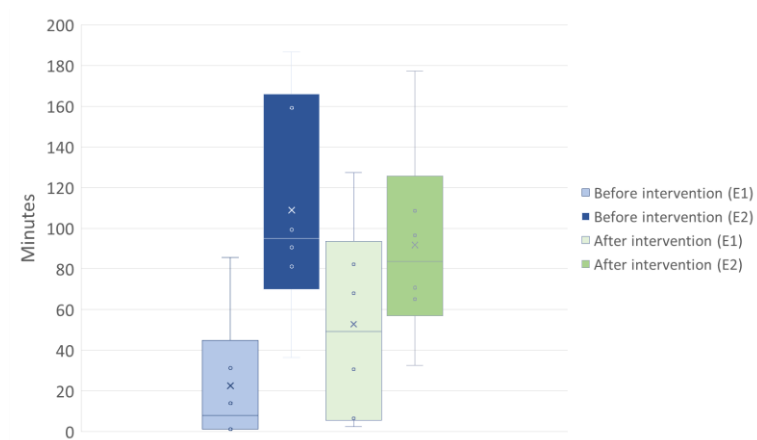


Figure 4-1. Boxplot of the 100-fold increase time for the different locations of emission (E1 and E2).

100-fold recovery time

Before intervention, the 100-fold recovery time has a range of 118 – 370.1 min for emitter location E1 and has a range of 88.8 – N/A for emitter location E2. After intervention, the 100-fold recovery time has a range of 35.6 – 40.4 min for emitter location E1 and has a range of 35.8 – 37.8 for emitter location E2. The 100-fold recovery time has a small range after the intervention and is shorter compared to the measurement before the intervention. This indicates that there is more homogeneous mixing in the classroom (Figure 4-2).

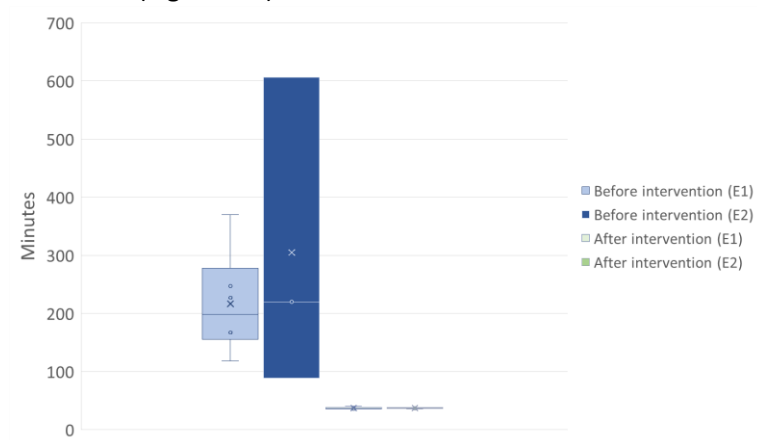


Figure 4-2. Boxplot of the 100-fold recovery time for the different locations of emission (E1 and E2).

t_{delay}

Before intervention, t_{delay} has a range of 0.3 – 5.5 min for emitter location E1 and has a range of 3.5 – 11.0 min for emitter location E2. After intervention, t_{delay} has a range of 0.5 – 4.0 min for emitter location E1 and has a range of 1.3 – 4.5 min for emitter location E2. The range between the different measurement points is smaller after the intervention took place. Furthermore, with four exceptions, t_{delay} is shorter after the intervention took place. This indicates that after the emission stopped, the particle concentration starts to decrease faster.

Air change per hour

Before intervention, the ACH has a range of 0.7 - 2.3 ACH for emitter location E1 and has a range of N/A – 3.1 ACH for emitter location E2. After intervention, the ACH has a range of 6.8 – 7.7 ACH for

Deliverable Work package 2

emitter location E1 and has a range of 7.3 – 7.7 ACH for emitter location E2. The range between the different measurement points is smaller after the intervention took place, this indicates that the possible exposure to particles is similar at different locations in the room. For the measurements before the intervention, no air change rate meet the requirements for Class B (2.8 ACH) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'. After the intervention, all requirements are met for Class B.

4.2 *Air flow measurements*

Before the intervention took place, the highest air velocities were from the windows towards the centre of the room. The air velocities are lower in the front and at the back of the classroom.

The particle concentration measurements and the air flow measurements show that there is an air flow from PC2 and PC3 towards emitter location E2. This could explain the relative high 100-fold increase time at this locations. Furthermore, the long 100-fold recovery times for the particle counters when the emission took place at emitter location E2 could be related to the low air velocities near emitter location E2.

After intervention, there is a clear air flow from the centre of the classroom towards the windows. The velocities are higher at a height of 1.0 m compared to the height of 1.6 m. Furthermore, a clear dominant air flow can be seen from the floor (supply) towards the ceiling of the room, the highest air velocities are measured near the floor of the room.

The particle concentration measurements and the air flow measurements show that in general the air velocities are higher after intervention which explains the short 100-fold recovery time. Furthermore, the particle concentration at different measurement points is lower after the intervention took place compared to prior the intervention. This could be explained by the upwards air flow which results in a low particle concentration at the measurement points.

In conclusion, when both ventilation systems are compared it becomes clear the air velocities are higher after the intervention took place. Furthermore the direction of the air flow is more dominant. Due to this, the particle spread throughout the room has a lower dependence on the proximity of the particle counter to the emission source location. The air flow throughout the room becomes the most dominant factor.

Concluded, due to the intervention the location of the children and teacher in the room becomes less prominent for a possible exposure and the overall risk to an exposure is lower.