CLAIRE | CLEAN AIR FOR EVERYONE

Deliverable Work package 2

RESULTS

Experiments in-situ

WP 2, experiments phase 1

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Contents

1. Summary

This report pertains to the first phase of the work being carried out within Work Package 2 of the Clean Air for Everyone (CLAIRE) program. 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.

This report describes the theoretical framework based on which the measurements for the interventions were conducted. Additionally, it presents the results of the measurements for interventions in 8 classrooms within the primary schools and 2 communal living rooms within long-term care facilities. When selecting the spaces, it was requested that interventions would take place, which is why the performance of the selected spaces is likely suboptimal. Based on the measurements before the intervention, it can be concluded that generally low air velocities are present, and as a result, no dominant airflow pattern can be identified based on this information.

In the second part of the research, the performance of the systems after the intervention will be presented.

2. 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 baseline assessment of ventilation efficiency at critical positions and recovery time in test environments, Figure 1. This is the planned deliverable in month 12 of the project. This concerns the measurements up to October 2023 at 10 (8 primary schools and 2 long term care) locations.

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) Ventilation systems 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 first step is to determine the critical positions by measurements using concentrations at grid points in the room based on NEN-EN-ISO 14644-3. The locations where people are mostly present will be used as “critical positions”. These critical positions will also be determined by calculations in WP4. Results of these measurements and calculations may be compared to tune the calculation model. If the model is validated, it will be possible to determine these critical positions by calculations only. 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 the ventilation efficiency and recovery time at the critical positions.

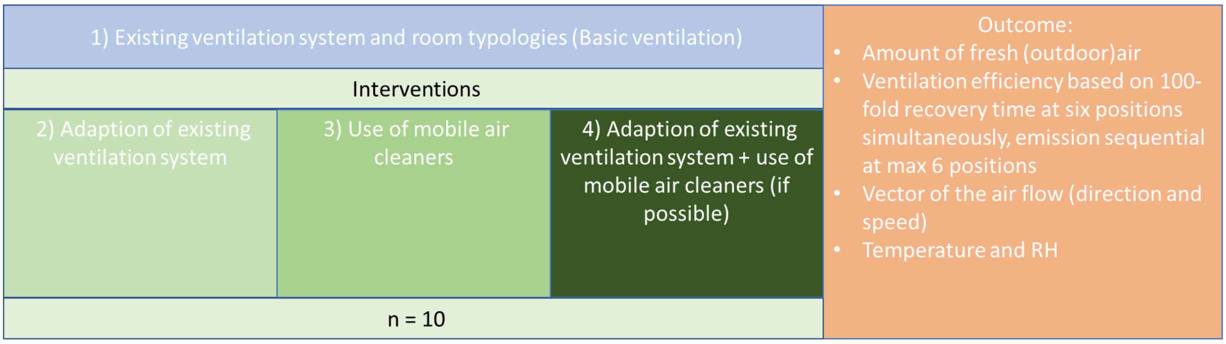

Figure 1. Summary of the approach for working program 2.

The CLAIRE project is powered by Health~Holland, Top Sector Life Sciences & Health, through its Public-Private Partnership (PPP) Allowance programme. 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.

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2.1 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. We therefore propose to focus the CLAIRE project on primary schools, with approximately 80% of pilots being schools.
The MIST project has 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. As of yet, the precise relation between MIST and CLAIRE has not yet been determined.

Project CLAIRE is funded through the Top Sector Life Sciences & Health (Health~Holland) under project number LSHM22032.

3. Theoretical framework

The knowledge development in this WP takes place through experiments that can provide insights into the role of building ventilation in preventing airborne infections. For the design of these experiments, research has been conducted on various measurement methods suitable for this research. The project includes conducting these experiments in in-situ situations, representative of the building portfolio in primary schools and long-term care facilities in the Netherlands. An in-situ environment involves measuring at an existing location in primary schools or long-term care facilities without people present in the room.

This leads to two research questions:

1. What are robust indicators and measurement methods to test the ability of a ventilation system to reduce aerosol spread of viruses and pathogens?
2. Which parameters need to be determined to assess the indicators, and how can they be measured?

This chapter answers these two research questions. Based on the findings, a research protocol has been established for the in-situ experiments that have been conducted in WP 2.

3.1 Literature review: method

Ventilation systems are used for various purposes and can be evaluated based on many parameters. The parameters investigated for research question 2 are:

- Temperature of supplied air
- Internal loads (heat sources, cold sources, and cold air falls)
- Movement of people through the room
- Breathing (continuous or pulsed)
- Objects (doors & furniture)

To answer the research questions, a scoping review was conducted. A scoping review involves keeping the search process as broad as possible. This form of literature research is suitable for studies where the subject is complex, less clear, or less specifically investigated. The online database Scopus (https://www.scopus.com/) was used to search for scientific publications using search strings. The search terms are in English as they align best with the available literature. In addition to the scoping review, important handbooks on ventilation were included in the literature search. These handbooks include:

- REHVA Guidebook – Ventilation effectiveness (Mundt et al., 2004)
- AIVC (Air Infiltration and Ventilation Centre) – A guide to Contaminant Removal Effectiveness (Brouns, 1991)

Some publications were also found through snowballing. By following chains of citations (snowballing), researchers can locate related works that might not have been easily discoverable through traditional search methods. This technique is particularly valuable when studying topics with limited availability in established databases.

The scoping review consists of three parts, each with a defined search string. The first search string is a general review of the research area, and the remaining two delve deeper into each of the two research questions.
For the following search strings, boolean operators OR & AND were used. All terms within each bullet point are connected with an OR operator, and all bullet points are connected with an AND operator.

Search Strings General:
- Internal space, indoor environment, indoor climate
- Ventilation, occupancy, lighting, temperature, humidity
- Experimental research, experiment
- Case study, mock-up, mockup, in-situ study
- Viral exposure, infection risk, pathogen spread, airborne transmission, inhalation exposure
- Aerosol, virus particles, pathogens

Hits: 244
Inclusion: 61

Search Strings Research Question 1:
- Indoor, internal space
- Ventilation efficacy, ventilation evaluation, ventilation effectiveness, ventilation performance, contaminant removal efficacy, contaminant removal evaluation, contaminant removal effectiveness, contaminant removal performance, air change efficacy, air change evaluation, air change effectiveness, air change performance, air change rate removal efficacy, air change rate removal evaluation, air change rate removal effectiveness, air change rate removal performance, decontamination efficacy, decontamination evaluation, decontamination effectiveness, decontamination performance
- Aerosol, virus particles, pathogens, contaminants, airborne particulate, airborne particles
- Experimental research, experiment

Hits: 21
Inclusion: 11

Deliverable Work package 2

Search Strings Research Question 2:

- Experimental research, experiment
- Indoor, internal space
- Ventilation, airing, HVAC, air conditioning
- Internal gains, heating loads, cooling loads, thermal loads, movement, walking, travel, transport, perturbation, breath, breathing, inhale, exhale, inhalation, exhalation, cough, coughing, sneeze, sneezing, cold air, downdraft, falling air
- Contaminant removal, air change rate, decontamination, pandemic prevention, infection prevention, disease control

Hits: 30
Inclusion: 9

Whether the "hits" (papers found per search string) are included or excluded depends on their relevance to the research questions. These decisions are based on similar reasons summarized in the inclusion and exclusion criteria.

Inclusion Criteria:
The most important topics to select papers for inclusion are:

- Paper describes a measurement method, instrument, or indicator for particle measurements or airflow measurements;
- The study investigates the indoor climate of long-term care locations and how it is affected, particularly by internal loads and people (breathing, movement, and heat sources);
- The study describes existing long-term care locations;
- The paper investigates the behavior of particles or aerosols in an indoor environment;
- The paper describes a method for creating room interior mock-ups.

Exclusion Criteria:
Literature found fulfilling the following criteria were excluded:

- Paper focuses on simulation and computation, Markov chains LES (Large Eddy Simulation) which is a section within CFD (Computational Fluid Dynamics);
- Study on PM (particulate matter).

3.2 Results literature research

Based on the considered literature, a number of indicators have been selected to visualize the performance of ventilation systems. These are presented below.

Ventilation Effectiveness (VE)

A common term for quantifying the effectiveness of a ventilation system is ventilation effectiveness. This term can be divided into specific indicators that measure the ability of a ventilation system: (Mundt et al., 2004).

Air Change Efficiency (ACE)

ACE measures the ability to refresh the air in a space.

Contaminant Removal Effectiveness (CRE)

CRE measures the ability to remove contaminant particles from a space.

Similar indicators to ACE and CRE can be calculated for local points within a space, respectively:
Local Air Change Efficiency (LACE)
Local Air Quality Index (LAQI)

The above VE indicators will be further discussed and described in this section.

3.2.1 Related Indicators

In addition to the VE indicators, there are other indicators with similar definitions. The difference often lies in the specific locations where they are measured. Examples include:

<u>Contaminant exposure index (CEI)</u>
The CEI is calculated using the same method as the LAQI, but specifically compares the ratio of particles inhaled by the exposed person to particles exhaled by an infected person. (Aganovic & Cao, 2019) (W. Liu et al., 2021).
Since the LAQI is more widely applicable than the CEI, it will be further developed in section 4.2. However, the calculations described there also apply to the CEI if the measurement directly relates to exhaled air between individuals.

<u>Intake fraction (IF)</u>
The intake fraction is defined as the ratio of particles inhaled by an exposed person to particles exhaled by an infected person. It is similar to the LAQI and CEI, but the difference is that the IF is calculated based on the total amount of particles within a certain period of time, rather than the concentration at a specific time. (W. Liu et al., 2021) This will not be further discussed since similar information can already be represented more simply with the LAQI. Additionally, the LAQI allows for clearer and easier representation of changes over time.

<u>Cumulative exposure level (CEL)</u>
The CEL is the amount of particles measured at a specific point over a certain period of time. It is calculated by integrating the particle concentration over the exposure duration. (Ren et al., 2022) This index contains little information and will not be further discussed in this review.

<u>100-fold recovery time</u>
The 100-fold recovery time is defined as the time required for a particle concentration to decrease by a factor of 100 (measured from the end of the period in which particles are emitted). It can be calculated by exponential extrapolation of the rate of decrease of the respective particle concentration. (Traversari et al., 2022) This concept is related to the nominal time constant used in the calculation of (L)ACE.

<u>Ventilation Rates</u>
Air changes per hour (ACH) and ventilation rates are often used as proxy indicators to approximate the infection mitigation potential of air handling systems. However, ACH is simplistic and limited, especially in environments where the air is poorly mixed. (Pantelic & Tham, 2013).

3.2.2 Air Distribution Flows and Patterns

Measured air flows can contribute to an explanation of measured indicators such as ACE. Individually, they can provide a qualitative picture of ventilation performance in a space, but given the complexity of such flows, only a static picture is possible, and standardized quantification is difficult to establish.

Considering the direct relationship between ventilation, air flows, and the airborne spread of aerosols, and considering their strong ability to support and explain other ventilation indicators, the possibilities for measuring and visualizing air flows in a space will be further explored in section 4.3.2.

The following section will provide a more detailed discussion of the VE indicators (ACE, CRE, LACE, and LAQI), as they are relevant to research question 2, are commonly used as standards, and form the basis of much research on the ability of ventilation systems based on these indicators.

Ventilation Effectiveness

As indicated in the previous section, VE can be divided into four indicators. Two of these indicators are global (ACE, CRE), and two are local (LACE, LAQI). Furthermore, two indicators relate to the ability of a ventilation system to refresh the air in a space (ACE, LACE), while the other two measure the ability of a ventilation system to remove contaminant particles from a space (CRE, LAQI). This is summarized in the table below:

Table 1. Relationships between ventilation effectiveness indicators.

Subject	**Global**	**Local**
Measuring air ventilation capacity	Air Change Efficiency (ACE)	Local Air Change Efficiency (LACE)
Measuring the ability of particle removal.	Contaminant Removal Effectiveness (CRE)	Local Air Quality Index (LAQI)

Air Change Efficiency

The ACE is a measure of how effectively a space is ventilated. It is important to note that the ability of a ventilation system to refresh a space is not the same as the ventilation rate within that space. For instance, a space can have poor ventilation with a high airflow if the clean air only reaches a small portion of the space (airflow short-circuiting). Therefore, the ACE can also be described as the effectiveness of a ventilation system in providing clean air to every location in a space or how well it mixes the air in a space during ventilation. To approach this indicator, the abstract concept of "age of air" is used. This concept describes the theoretical average time that the air remains in a space or how "old" the air is when it leaves the space (at the exhaust). For the ACE, this is often referred to as the nominal time constant τ_n, or also the air changes per hour (ACH). It can be calculated using:

$\tau_n = \mathrm{ACH} = \frac{\mathrm{V}}{\mathrm{q}_v}$ (Equation 1)

Where:
V is the volume of the space,
q_v is the airflow rate (volume per unit time).

Based on this, the ACE is defined as:

$ACE = \frac{\tau_n}{\tau_r} \times 100\%$ (Equation 2)

$\overline{\tau_r} = 2 \times \langle\overline{\tau}\rangle$ (Equation 3)

Where:
$\overline{\tau}_r$ represents the "actual" time that the air has been in the space.
$\langle\overline{\tau}\rangle$ represents the room mean age of air.

It heavily depends on the airflows and ventilation strategies within a space. For example, in a "perfectly" displacement-ventilated space, such as a piston or subway tunnel where the air moves uniformly in a column through the space without stagnation, the actual time $\overline{\tau}_r$ is equal to the nominal time constant τ_n, resulting in ACE=100%. (Mundt et al., 2004)

The ACE aims to summarize the mixing of air in a space in a single value but may not be suitable for representing potentially significant local variations in air ventilation within a space, such as those caused by airflow short-circuiting. This is where the LACE (Local Air Change Efficiency) comes into play.

Local Air Change Efficiency

For LACE, the same principles apply as for ACE, except that a local actual time constant $\overline{\tau}_p$ is used. In a perfectly mixed space, all LACE values within a space are equal to the ACE value. ACE can also be approximated by taking the average of all LACE values.

In practice, τ_n, $\overline{\tau}_r$, and $\overline{\tau}_p$ need to be measured. Particle measurements or tracer gas are often used for this purpose. Aerosols are emitted into the space until a steady state concentration is reached, and the particle concentration in the room at different points is constant. Then, the decrease in concentration is measured, and τ_n, $\overline{\tau}_r$, and $\overline{\tau}_p$ can be calculated. The complete method is described in (Mundt et al., 2004).

Contaminant Removal Effectiveness

CRE, the ability to remove contaminant particles from the air, is closely related to ACE. After all, contaminants are removed by replacing contaminated air with clean air. The difference between CRE and ACE lies in the presence of a (pollution) source and its location within a space. In a space with theoretically perfect mixing and thus a uniform concentration (100% mixed space), CRE is directly proportional to ACE; the measurement method is also the same for both indicators. (Mundt et al., 2004) (Jurelionis et al., 2016a). In the case of an uneven distribution of concentration (where the air is not perfect mixed), CRE can only be calculated for that specific setup (emitter location). If the emitter is in a different location, the particles are distributed differently through the space (for not perfect mixing), resulting in a different CRE. Therefore, a different CRE is calculated for each emitter setup.

CRE is defined as:

$CRE = \frac{c_e}{\overline{c}}$ (Equation 4)

Where:
c_e is the concentration of pollution in the exhaust air,
$\overline{c}$ is the average concentration of pollution in the space (steady-state).

CRE can also be defined as:

$CRE = \frac{\tau_n}{{\tau_t}^c}$ (Equation 5)

Where:
τ_n is the nominal time constant or ACH (see Equation 1),
τ_t^c is the removal time of the contaminant particles, i.e., the age of pollution at the exhaust.

Equation 3 assumes that the supplied air does not contain any contaminants. In practice, this is rarely the case. To correct for this, the concentration of contaminant particles from the inlet, c_i, needs to be subtracted from c_e and $\overline{c}$:

$CRE = \frac{c_e - c_i}{\overline{c} - c_i}$ (Equation 6)

As mentioned before, the difference between CRE and ACE is related to the distribution of contaminant particles in the air. In the case of perfectly mixed pollution, ACE can be calculated, but in the case of uneven pollution, CRE is calculated.
In the context of research question 1 (testing the ability of a ventilation system to reduce airborne transmission of viruses and pathogens), the location of the emission source is crucial, and the emphasis will be more on CRE than ACE.

<u>Local Air Quality Index (LAQI)</u>
For Contaminant Removal Effectiveness, there is a similar local index called the LAQI. It is defined as:

$LAQI = \frac{c_e - c_i}{c_p - c_i}$ (Equation 7)

Where:
c_e is the steady-state particle concentration at the exhaust,
c_p is the concentration at point p in steady-state,
c_i is the concentration at the supply.

In not perfect mixed spaces, CRE can be approximated by taking the average of all LAQI values. (Mundt et al., 2004)

Within the context of CLAIRE, the LAQI is most important. The reasons for this are that:

It involves the removal of aerosolized pathogens that can be emitted at different locations within a space. In this case, CRE and LAQI are the most relevant indicators.
In addition to quantifying the overall performance of the ventilation system (CRE), it is also important to understand the underlying reasons for its performance and identify possible measures to reduce exposure. The LAQI provides spatial information to support such considerations.
The other indicators are important when less spatial detail is needed (CRE) or when a more general assessment of performance is desired, independent of emitter location (ACE and LACE).

3.3 Measurement Methods

Particle measurements using particle counters are a commonly used method to assess air quality in ventilation systems and buildings. Particles are emitted from an emitter placed at a specific location in the space. By placing particle counters at specific locations in the space, the concentration and size distribution of particles in the air can be measured. This allows for direct measurement of all particle concentrations needed for the equations to determine the VE indicators.

Various types of substances can be used for such measurements. Generally, these fall into two categories:

- Particles/aerosols
- Gases

3.3.1 Particles/Aerosols

Compared to gases emitting aerosols has the advantage of better reflecting the actual dispersion of virus particles. It is important that the tracer properties match the properties and behavior of the particles being simulated. These include density, evaporation rate, and diameter. In addition to diffusion behavior, factors such as deposition (sedimentation) and resuspension of aerosols can influence particle dispersion in a space. For example, deposited (sedimented) aerosols can accumulate in hidden spaces and serve as a reservoir of pollutants that can be re-suspended and spread through the room by higher air velocities. Different mechanisms contribute to deposition and resuspension depending on the size of the particles. While not discussed further here, it is important to consider these effects to better understand certain phenomena when measuring particle concentrations. More information on deposition and resuspension can be found in (Shen et al., 2021), (Tang et al., 2020), (Wan et al., 2009), and (Horve et al., 2020).
The emission method is also important to mimic human respiration or ventilation conditions. For example, sneezing, coughing, breathing, or leaky pipes or open windows can result in significantly different airflow characteristics and particle concentrations.
The disadvantage of investigations using aerosol emissions is that it can be more expensive and complex than using gas emissions, as it requires special emitters and consideration of particles that may deposit as residues. Therefore, cleaning the air or disposing of waste after the experiment is more important.

Particle emitters can emit discrete particles or atomized liquids (W. Liu et al., 2021). Common examples include:

Atomized paraffin oils: This type of tracer consists of small oil droplets atomized in the space. The advantage of these tracers is that they are harmless to people under normal conditions (ATI, 2016), leave little residue, are relatively easy to use, and generate particles of similar size to those released during normal speech and respiration (between 0.2 and 5 µm). It is important to note that aerosols generated by atomizing oils are more stable than those produced by humans due to their inert properties, resulting in little to no evaporation. In order to mimic this behavior, water with glycerine (and salt) is mixed in multiple studies (Pantelic & Tham, 2013) (Wan et al., 2009) (Chen et al., 2013). However, since the behavior of aerosols smaller than 5 µm is independent of their size, non-mixed oil-based aerosols may be representative of these smaller particle sizes (Traversari et al., 2022).

Fluorescent aerosol tracers: Fluorescent aerosol tracers are particles that contain a fluorescent dye, making them detectable and traceable. One advantage of using fluorescent aerosol tracers is that they can be detected at low concentrations. However, a disadvantage is that they are generally more expensive than other types of tracers. Additionally, surfaces in the space need to be thoroughly cleaned after use to remove the deposited particles, making them unsuitable for use in occupied locations. For these reasons, this tracer is not suitable for answering research question 2.

Bioaerosol generation: Bioaerosol generation involves using organisms such as bacteria, fungi or bacteriophage as particles. For example, bacteria can be cultured in a liquid solution and then introduced into the air using an aerosol generator. Petri dishes can then be placed around the room to measure the amount of bacterial or fungal colonies (Liu et al., 2021). The use of bioaerosols as tracers provides an opportunity to study and measure the behavior of real biological agents such as viruses and bacteria. However, bioaerosol generation may be less suitable for on-site measurements due to potential hygiene and health risks associated with the release of bacteria or viruses, especially in spaces that need to be quickly reoccupied.

3.3.2 Variables that focus on dynamic behavior of systems

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 (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.

100-fold recovery time

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

$$\boldsymbol{c_t = c_0 \cdot e^{-\frac{Q\,x\,t}{V}}} \quad \text{(Equation 8)}$$

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)

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. This variable is not independent. 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:

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

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:

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

Where:

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

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 (t_{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.

3.3.3 Tracer Gases

In tracer gas experiments, a specific gas is introduced into a space to mimic respiration or air supply, and its concentration is measured using detectors. Important considerations for using gas as a tracer are that the gas is inert and does not react with other substances in the air, and it is easily measurable. For example, CO_2 is often used as a tracer gas (Gilkeson et al., 2013), but other tracer gases regularly used include:

- C_3H_8 (Propane)
- SF_6 (Sulfur hexafluoride)
- NaCl (Sodium chloride)
- N_2O (Nitrous oxide) (Cermak & Melikov, 2007)

The disadvantage of tracer gases is that they spread through space differently than (virus-carrying) aerosols, they do not exhibit deposition or resuspension. For this reason, the method of emitting aerosols was chosen. Among all the aforementioned tracer particles/aerosols, atomized paraffin oils are the most applicable for measuring VE within the context of research question 1.

3.3.4 Airflow Measurements

In Program Line II of P^{3}Venti, Computational Fluid Dynamics (CFD) experiments will be conducted to investigate VE indicators from a broader perspective. To validate the CFD models used for this purpose, airflow patterns in a space need to be experimentally mapped as much as possible for comparison with CFD simulations. Airflow meters or anemometers can be used for this purpose.

<u>One dimensional airflow meters, the simplest and most common examples of these are (Loomans, 1998):</u>

<u>*Mechanical airflow meters*</u>

Mechanical airflow meters, such as windmills and vane anemometers, measure the air (wind) speed by converting the movement of the air into a rotating motion of the rotor, which is then converted into a wind speed. This method is relatively simple, inexpensive, and reliable, but it is not suitable for low air flow speeds and determining the direction of airflow.

<u>*Thermal anemometers*</u>

A thermal anemometer measures the air (wind) speed by detecting a change in temperature of a heated wire or film exposed to the airflow. The higher the speed, the more heat is dissipated, causing a decrease in the temperature of the wire or film. The temperature decrease is measured and converted into an air velocity. (J. Li et al., 2015) (Tominaga & Blocken, 2016)

Although the above-mentioned airspeed meters can be effective for measuring airflow, they only provide information about the absolute speed but not the direction of airflow. For determining three-dimensional air velocities with speed measurement of three velocity components to allow calculation of the velocity vector, other measurement methods need to be employed:

<u>Three dimensional airflow meters</u>

<u>*Ultrasound anemometers*</u>

The three-dimensional vector of an airflow can be determined at a point using three ultrasound anemometers. This technique utilizes the relationships between the speed of sound, relative humidity, and temperature. By measuring the speed of sound in two opposite directions between two sets of microphones and speakers and locally capturing the air temperature and relative humidity, the speed of the airflow in the axis between the microphones and speakers can be determined. By performing this measurement in three axes, intersecting in the middle of the sphere, the three-dimensional air velocity vector can be determined.

An additional advantage is that the point being measured does not come into contact with any equipment, unlike a thermal anemometer, ensuring no pressure loss, sensitivity loss, or contamination. However, the thin structure positioning the transmitters and receivers can disturb the airflow to some extent. A high temperature range is also a significant advantage (Van Schaik et al., 2010).

By taking measurements at multiple points in space, a visual representation of the airflow in that space can be generated through interpolation. The resolution depends on the number of measurement points but is typically orders of magnitude smaller than that of the PIV method discussed below.

Particle Image Velocimetry (PIV)

Tracer particles are emitted and illuminated by a stroboscopic laser that shines in 2D "slices" through the space. The illuminated particles are photographed in synchronization with the frequency of the laser to determine their positions. A tracking algorithm is applied to calculate the trajectory of individual particles between each photo. This allows for the visualization of airflow in 2D. By extending this technique to three axes, the 3D airflow within a space can be calculated (splicing) (J. Li et al., 2015) (Pantelic & Tham, 2013) (Motamedi et al., 2022). (Fu et al., 2015) provides a comprehensive overview of potential equipment.

An advantage of PIV is that the measurement involves taking photographs, allowing for a qualitative visual representation before the data needs to be analyzed. PIV is suitable for measuring the overall distribution of airflow in small indoor spaces. For larger spaces, it becomes more challenging due to the extensive number of measurements required. Overall, application of PIV has been limited due to high price and safety concerns.

Visualization using smoke

A smoke plume is carried by existing airflow, making the flow patterns visually observable (Saarinen et al., 2018). This technique is used for visual validation without providing quantitative results unless the smoke particles are measured. In that case, it would be considered a particle or PIV measurement. Since this method does not provide quantification of airflow, it cannot address research question 2. However, it offers a simple and intuitive visualization of airflow that can support the findings.

Both 3-dimensional ultrasound anemometry and PIV can be applicable for research question 1. However, compared to 3-dimensional ultrasound anemometers, PIV measurements are more complex to execute. To capture the emitted particles effectively, they need to have a certain minimum size, and the space needs to be darkened. Furthermore, dividing the space into 2 dimensional slices is more intricate than distributing measurement points throughout the space.

Considering that measurements within the context of research question 1 will be conducted in locations that need to be quickly put back into use, it is recommended to minimize complexity and map the airflow using 3-dimensional ultrasound measurements. If there is a need for high-resolution visualizations of airflow, smoke can be used for this purpose.

4. Measurement method

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);
- 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 (10-15), 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 air displacement volume of ventilation 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).

<u>Step 1: Selecting the rooms</u>
Selection of ventilation systems and pilot location and determination of the basic ventilation system data.

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

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 and expert opinion. In WP 4 these 'critical positions' will also be assisted by CFD calculations. The results of these measurements and calculations will be used to validate the CFD model. If the model can be validated, the critical positions of other rooms (not included in the selection for measurements) will be determined through CFD calculation only. 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.

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

The measurements are executed as follows:

1. Determine the amount of supply and extract air from the room per grill with a pressure less air flow 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. It was assumed that after 10 minutes a steady state concentration is measured at the measuring locations,
    3) stop emitting and measure the decay in concentration.
3. Measure the vector of the airflow (speed and direction 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 air flow 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.

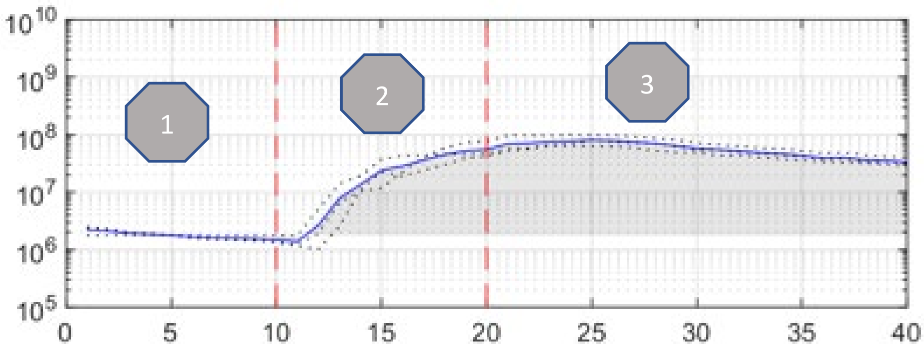


Figure 2. Particle concentration measurements.

These are the steps that have been carried out until now, for the situation without intervention.
The next steps will be performed and reported in the next phase of the project:

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 as 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.

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-fould 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

5. Results before interventions

Step 1: Selection of ventilation systems and pilot location and determination of the basic ventilation system data.

In this step, the pilot locations were selected. Initially it was stated that "The ventilation system typology should include a mechanical component (supply or exhaust). Purely natural ventilation will be excluded due to sensitivity to outdoor conditions (wind direction and speed).". However the schools that were planning to adapt the system and were able and willing to participate were mainly primary school with a natural ventilation system (supply and exhaust).
The selection took place based on the participating primary schools (comprising 80% of the pilots in this WP, meaning approximately 8-12 locations), and on the information about the intended adjustments to the ventilation system. The locations in the long-term healthcare sector were selected based on information regarding the intended adjustments to the ventilation system, and the willingness to implement air cleaners. The selected long-term healthcare facility locations may be the same ones used in P^{3}Venti.

At the publication of this report a total of 10 locations were visited and measured. The locations comprise of 8 elementary schools and 2 long term health care facilities. The detailed results are shown in annex A to I. All results presented concern the situation without any intervention to optimize the ventilation systems. Interventions are defined as modifications of the ventilation system 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 CO_2-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).

Most of the locations (6 out of 10) have a complete natural ventilation system. The main reason for this is that especially these primary schools want to change their ventilation systems to increase thermal comfort and at the same time control fresh air supply. During wintertime these locations need to open windows often, which can cause discomfort (cold, draft). Furthermore, it can significantly reduce the energy use during the winter period.

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.

5.1 Summary room and system characteristics

The characteristics of the rooms and the ventilation system for primary schools are presented in

Table 2. The rooms and systems from long-term care are summarized in

Table 3. From these tables, it is evident that the vast majority of the experiments were 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.

Table 2. Characterization of the class rooms.

	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	natural	natural	natural	natural	mechanical supply and exhaust	natural supply and mechanical exhaust	natural	natural
Ventilation facilities	3 tilt and turn windows	2 window grills	3 window grills	4 tilt windows	2 supply ceiling grills and 2 exhaust ceiling grills	3 window grills and 1 exhaust ceiling grill	3 tilt windows and 2 roof vents	2 tilt and turn windows
Amount of supply air	-	-	-	-	256 m^3/h	195 m^3/h	-	-
Measured situation	Windows all open (tilted),	Window grills all open, windows	Window grills all open, windows	Windows all open (tilted), door closed	Windows and door closed	2 of the 3 window grills open, windows	2 of the 3 windows open (tilted), roof vents	Windows all open and the doors were closed

	door closed	and door closed.	and door closed.			and door closed	open, door closed.	

Table 3. Characterization of the common rooms in the long term healthcare facilities.

Long term healthcare facilities		
	1	2
Floor area	61 m^2	67 m^2
Height	2.7 m	2.4 – 2.7 m
Orientation facade	South-West	South-West
Built in	2013	2013
Number of patients including the staff	10	10
Ventilation system	Natural supply and mechanical exhaust	Natural supply and mechanical exhaust
Ventilation facilities	2 window grills and 5 exhaust ceiling grills	4 window grills and 1 exhaust ceiling grille
Amount of supply air	80 m^3/h (exhaust grills)	15 m^3/h (exhaust grills)
Measured situation	All window grills open, windows and doors closed	2 of the 4 window grills open (normal situation), windows and doors closed.

5.2 Summary results of measurements

In this paragraph, the summarized results of the measurements are presented. The results for each location are shown in Appendix A through I.

The 100-fold increase time is a measure of how quickly the particle concentration increases at a specific location in space. The shorter this time, the faster the increase. This variable is represented for primary schools in Figure 3 and for long-term care in Figure 4. From these figures, it is evident that the median falls between 1 and 94 minutes, with outliers reaching up to 187 minutes. The 100-fold increase time is often longer for emission point E2 compared to emission point E1. This can be explained by the distance between the emitter and the particle counter which is (in general) larger for emission point E2. The 100-fold increase time is for all classrooms relative long so it can be concluded that the particle concentration disperses slowly in the measured spaces.

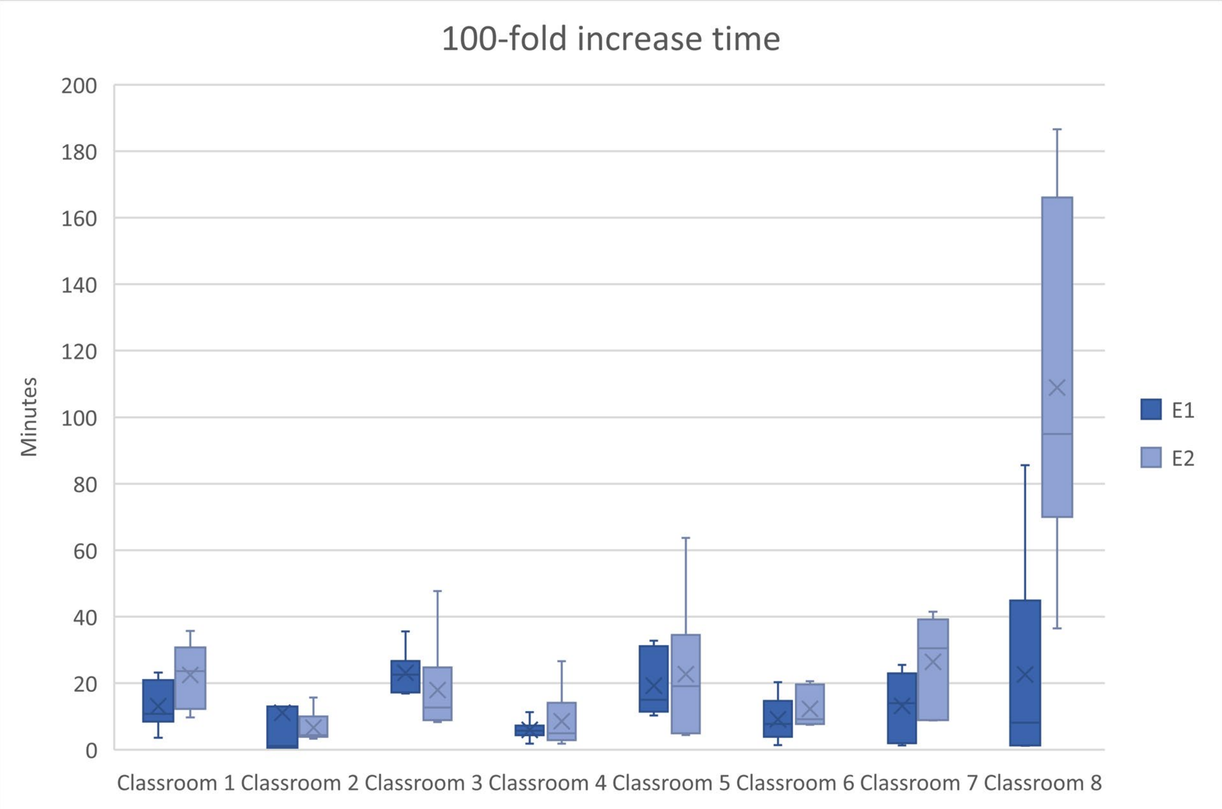


Figure 3. Boxplot of the 100-fold increase time in primary schools at the 8 measuring locations for the different locations of emission (E1 and E2).

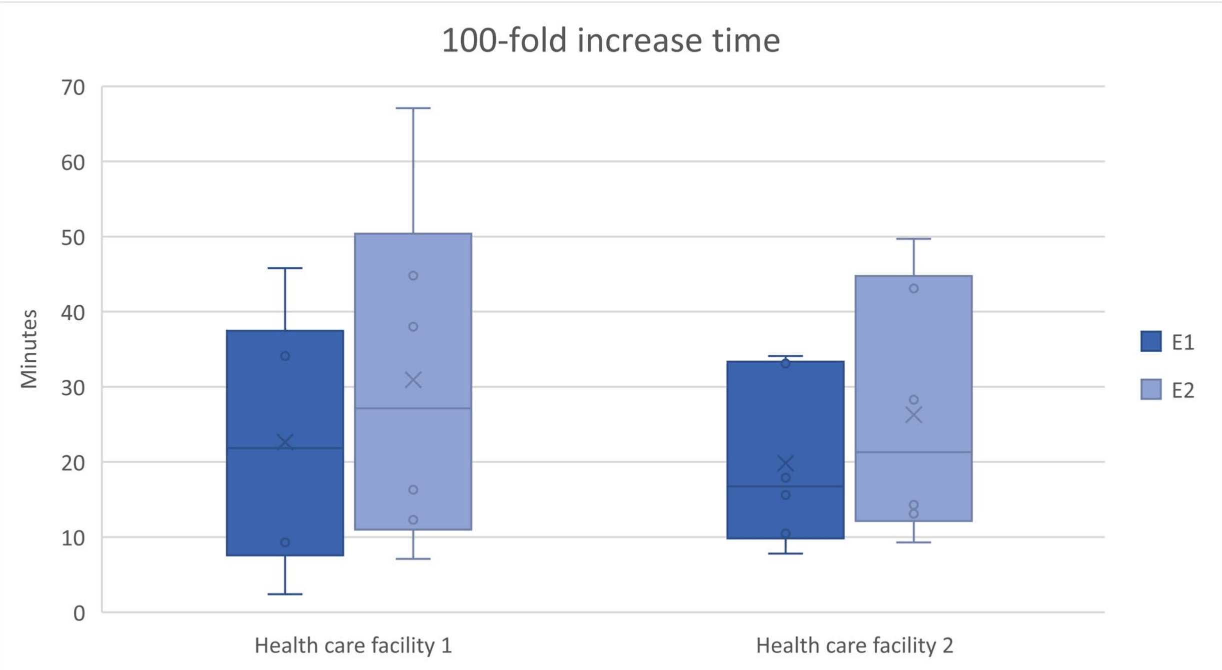


Figure 4. Boxplot of the 100-fold increase time in long term care facilities at the 2 measuring locations for the different locations of emission (E1 and E2).

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 the contaminants. The 100-fold recovery time has a direct relationship with the local air exchange rate. For primary schools, it is represented in Figure 5, and for long-term care facilities, it is shown in Figure 6. These figures indicate that for primary schools, in classrooms 2,6 and 8 at emission point 2 (E2), long recovery times have been observed. Longer recovery times have also been observed at emission point 1 (E1) in classrooms 5 and 6. The median falls between 53 and 606 minutes.

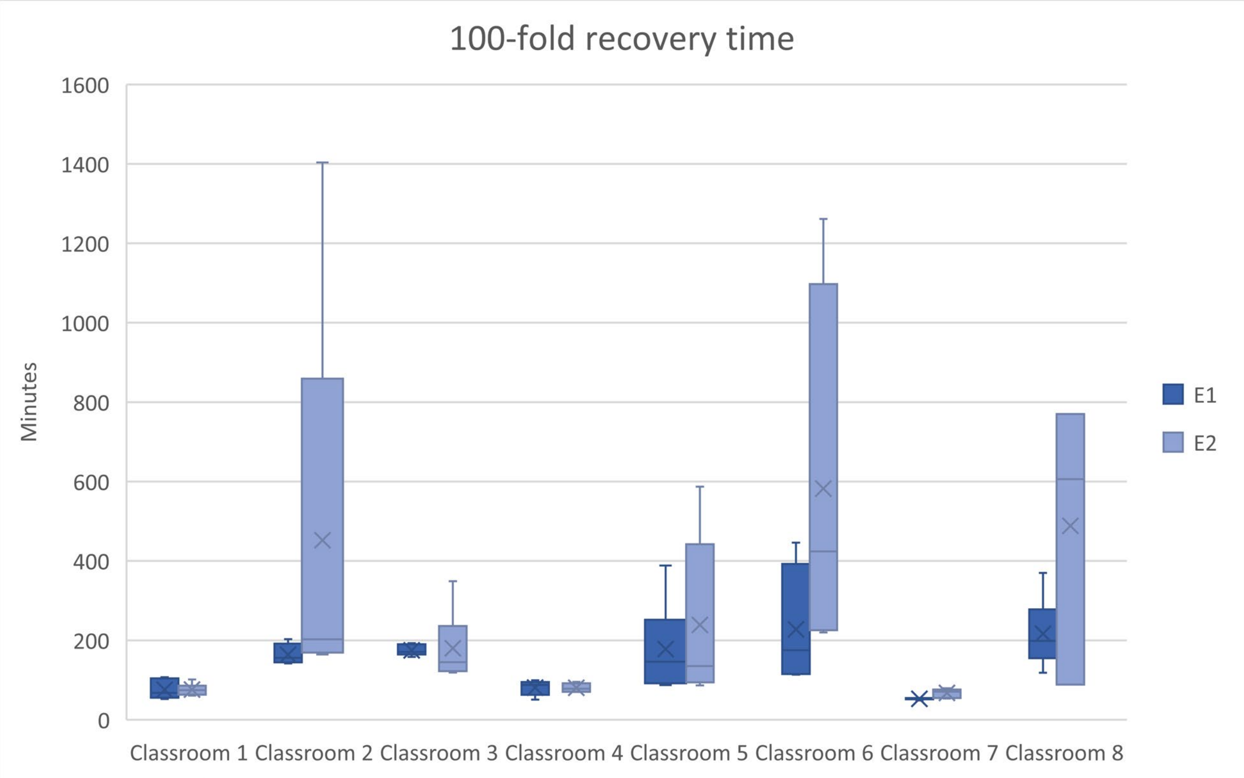


Figure 5. Boxplot of the 100-fold recovery time in primary schools at the 8 measuring locations for the different locations of emission (E1 and E2)..

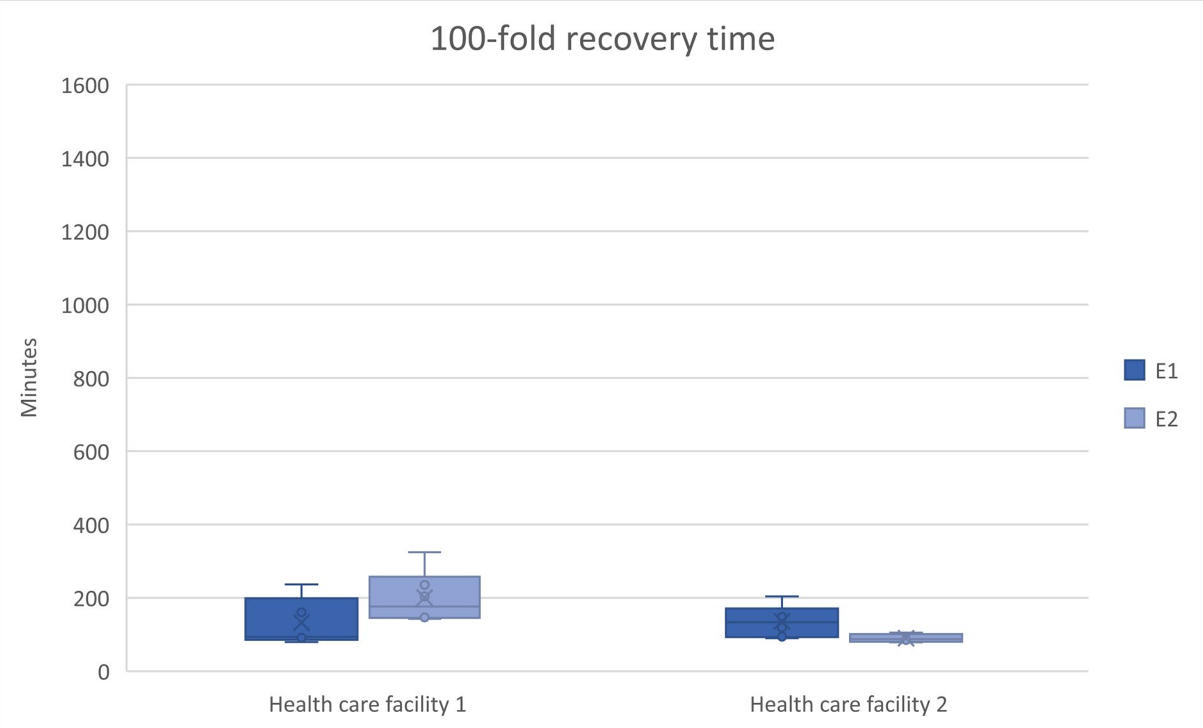


Figure 6. Boxplot of the 100-fold recovery time in long term care facilities at the 2 measuring locations for the different locations of emission (E1 and E2).

The local ventilation rate is directly linked to the 100-fold recovery time, as indicated above. A short 100-fold recovery time corresponds to a high local ventilation rate. This variable is represented for primary schools in Figure 7 and for long-term care facilities in Figure 8. The extremes, as seen in the 100-fold recovery time for primary schools in classrooms 2 and 6, are less pronounced here with low local ventilation rates. The median falls between a local ventilation rate of 0.5 to 5.2.

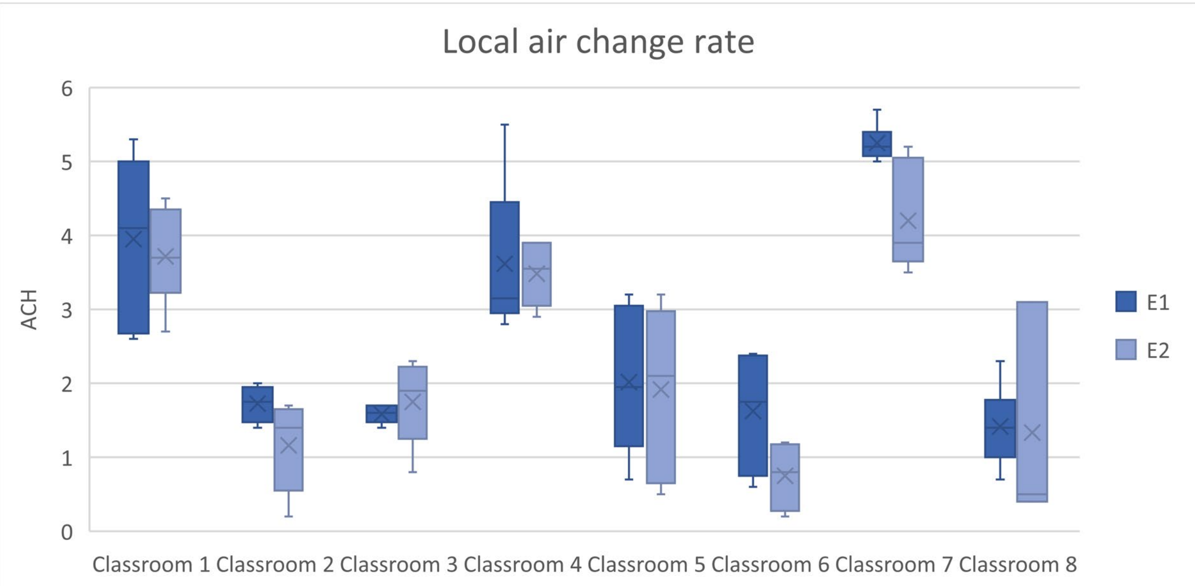


Figure 7. Boxplot of the local air change rate per hour in primary schools at the 8 measuring locations for the different locations of emission (E1 and E2).

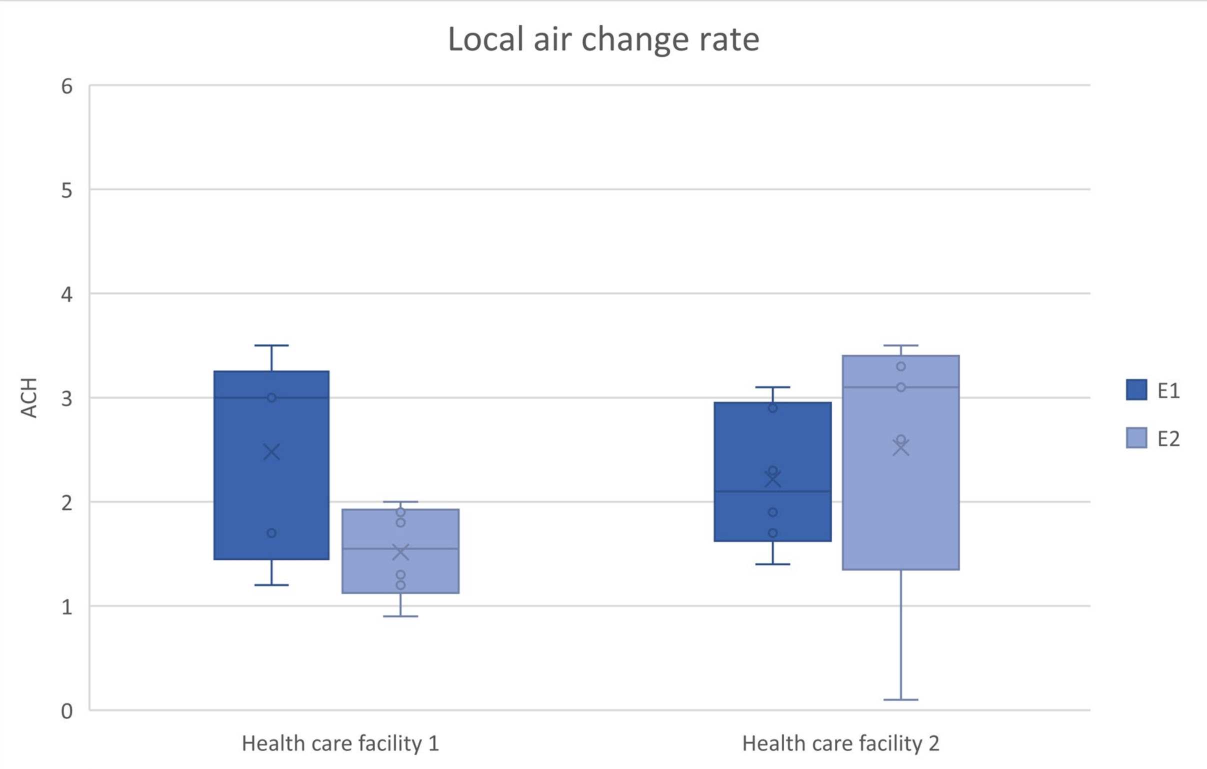


Figure 8. Boxplot of the local air change rate per hour in long term care facilities at the 2 measuring locations for the different locations of emission (E1 and E2).

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 airflow vector is low or even opposite to the direction from emission to the measurement point. This variable is represented for primary schools in Figure 9 and for long-term care facilities in Figure 10. The median of t_{Delay} falls between 0.9 and 9.3 minutes. However, there are also extreme values observed, up to 14 minutes. The lower limit is generally around 0.5 minute. This t_{Delay} appears to be less dependent on the emission point (E1 or E2).

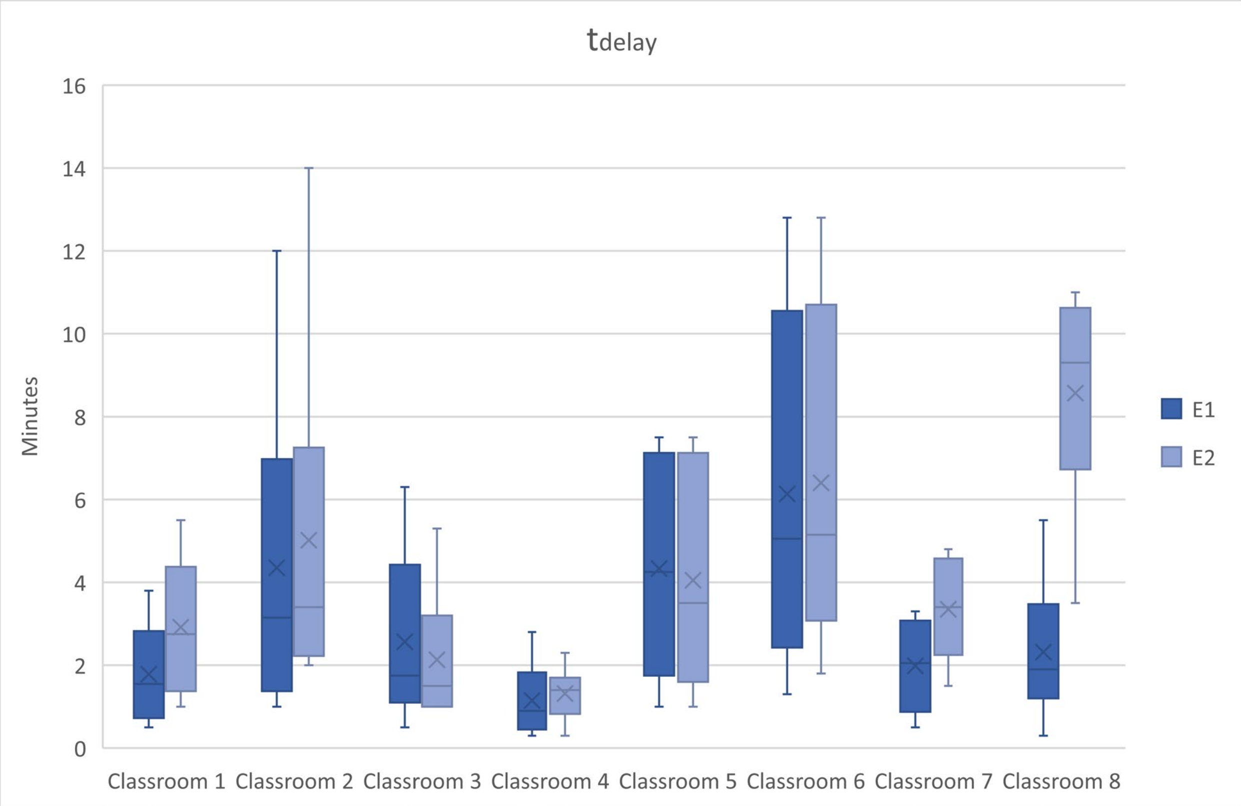


Figure 9. Boxplot of t_{delay} in primary schools at the 8 measuring locations for the different locations of emission (E1 and E2).

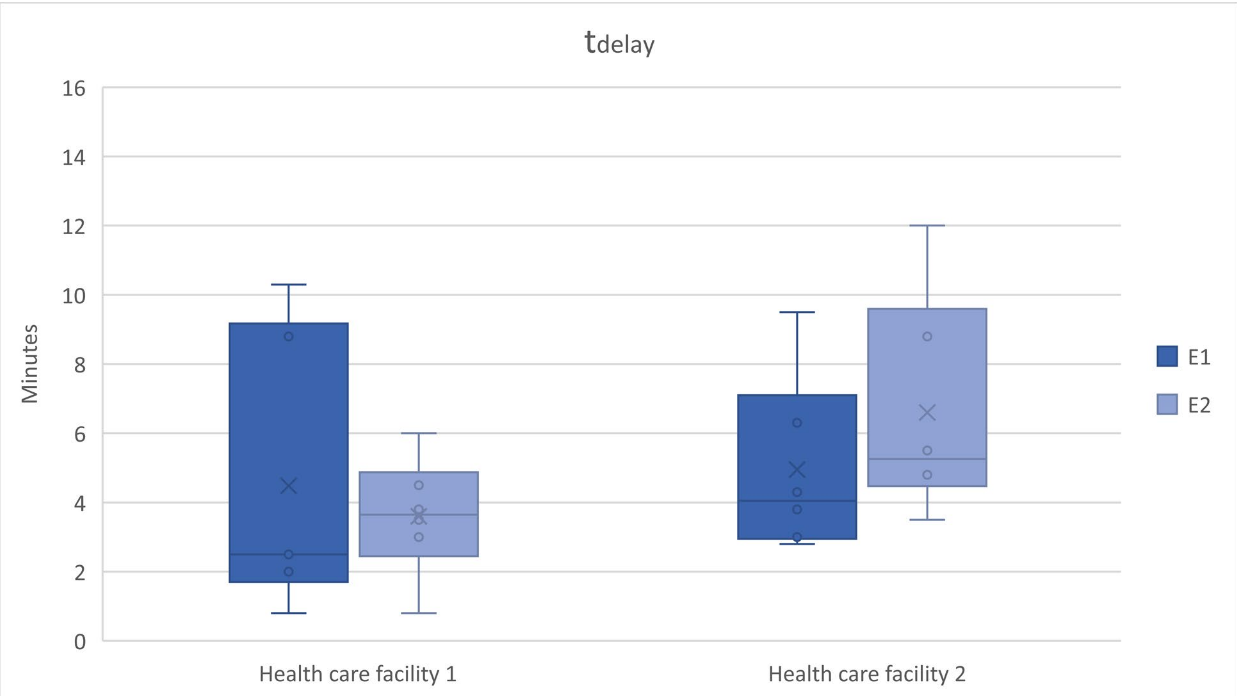
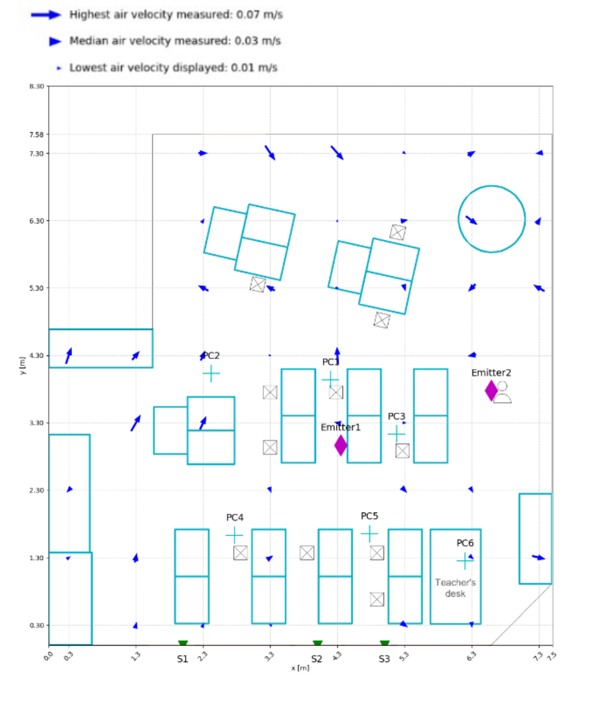


Figure 10. Boxplot of t_{Delay} in long term care facilities at the 2 measuring locations for the different locations of emission (E1 and E2).

Apart from particle measurements, air flow measurements were performed for 7 classrooms and 2 long term care facilities. The heights of the measurement positions were the same as the particle counters during the particle measurements. This enables an comparison between the two measurement methods. For the detailed description of the air flow measurements see Annex A – I. In Figure 11, the vectors of the airflow at a height of 1 meter are displayed for each location. Air velocities lower than 0.01 m/s are not displayed in the figures.

<table>
<tr><th>Class room 1</th><th>Class room 2</th></tr>
<tr><td>Range = 0.01 – 0.07 m/s</td><td>Range = 0.01 – 0.07 m/s</td></tr>
<tr><td>


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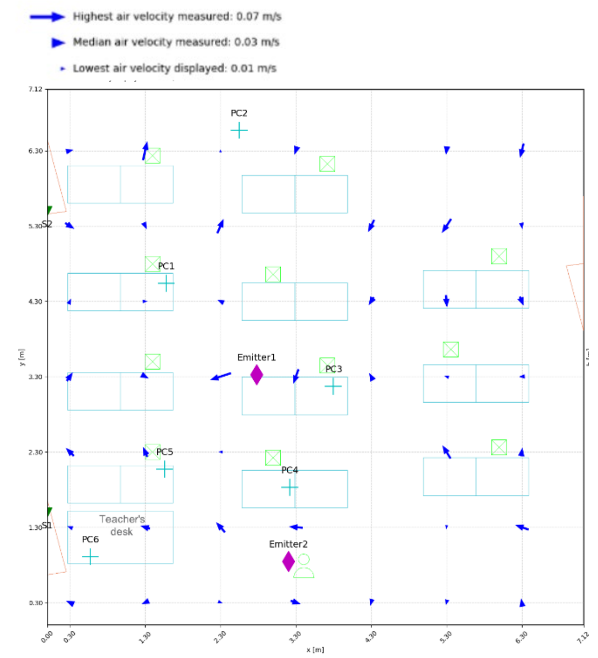
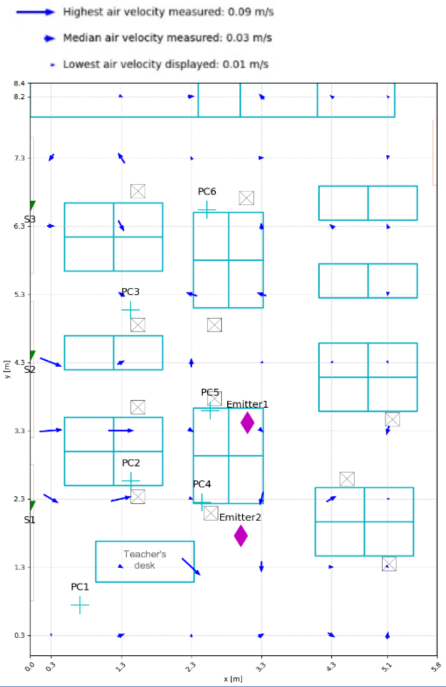
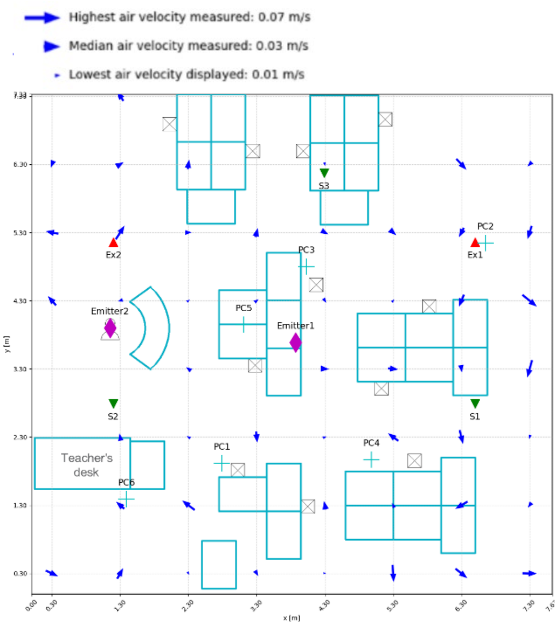
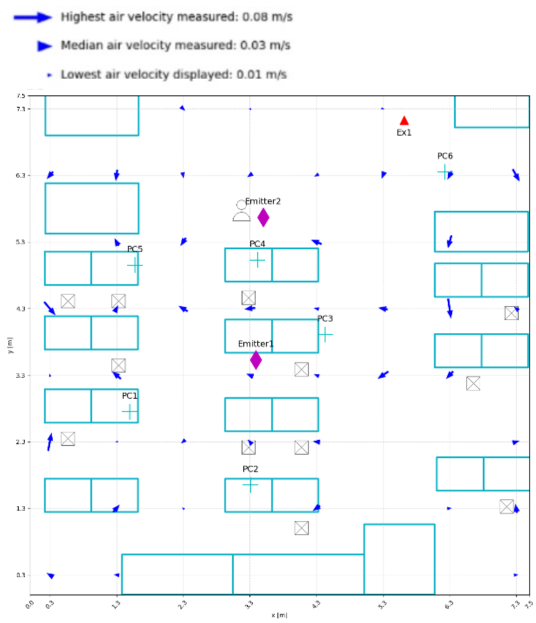
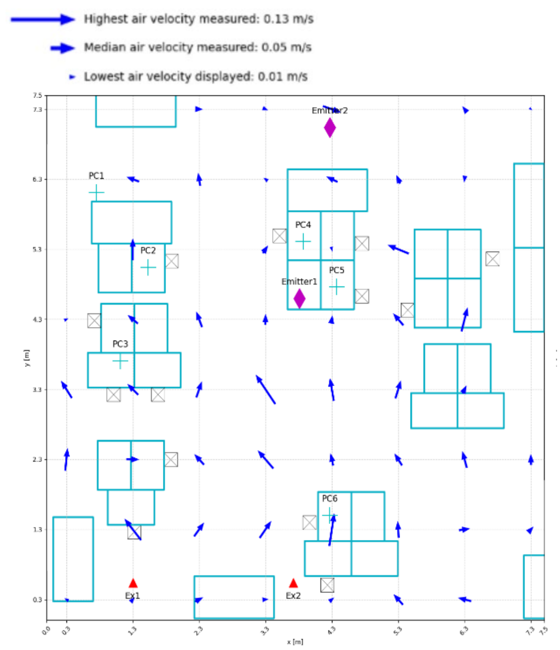


</td></tr>
</table>

Class room 3	Class room 4
Range = 0.01 – 0.09 m/s	No air flow measurements were executed for this location
	
Class room 5	**Class room 6**
Range = 0.01 – 0.07 m/s	Range = 0.01-0.08 m/s
	

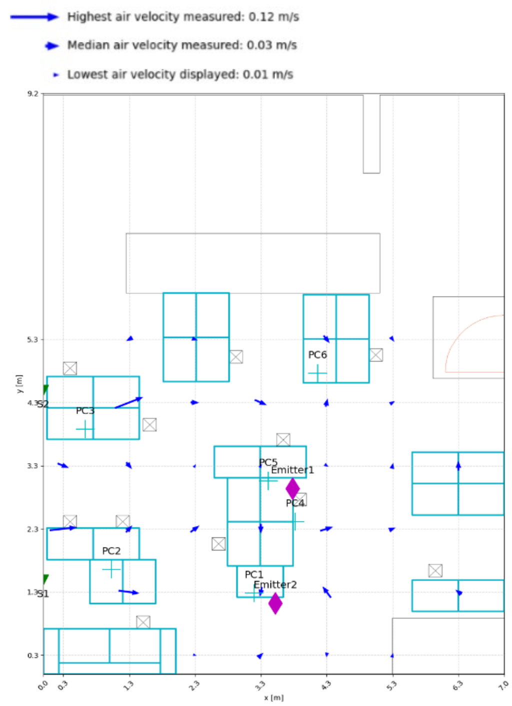
Class room 7

Range = 0.01 – 0.13 m/s



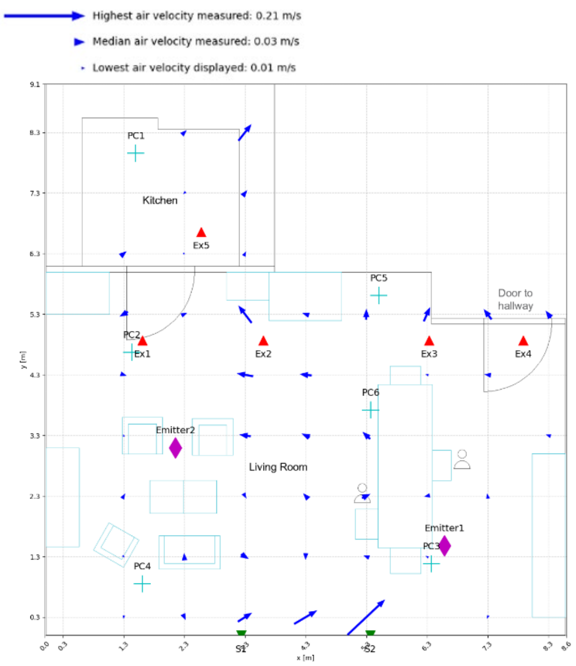
Class room 8

Range = 0.01 – 0.12 m/s



Long term care facility 1 (living room)

Range = 0.01 – 0.21 m/s



Long term care facility 2 (day care area)

Range = 0.01 – 0.07 m/s

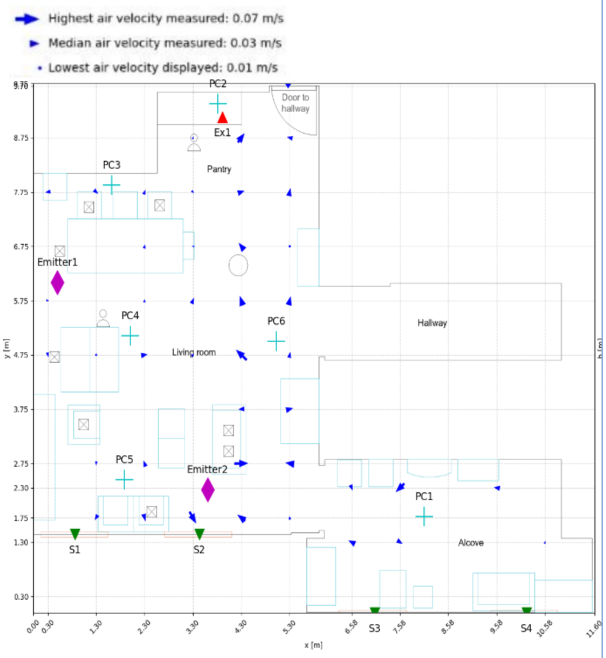


Figure 11. Vector of the air flow measured in the rooms.

The air velocities are all 0.21 m/s at maximum. The time-averaged air velocities are below 0.05 m/s, so the average air velocity in the room is low. Specifically for classroom 7, higher air velocities are present in the room. Furthermore, the living room of the health care facility has a clear air flow from the windows inwards. Due to the low air velocities, it is challenging to determine a dominant airflow based on these measurements. This applies to both natural ventilation systems and systems with a mechanical component.

6. Conclusions

The measurements for the interventions were conducted in eight primary school classrooms and two communal living rooms in long-term care facilities. Six of the eight classrooms were equipped with natural ventilation systems. One of the spaces has mechanical supply and exhaust ventilation, and three have mechanical exhaust and natural supply ventilation.

Particle concentration measurements

Classroom 2, 5, 6 and 8 have a long 100-fold recovery time. These locations were equipped with different ventilation systems, either natural ventilation with window grills/opened windows or mechanical ventilation. For almost all locations, the 100-fold recovery time is longer for emission location E2 compared to emission location E1. This can be explained by the distance between the emitter and the particle counter which is larger for emission location E2. Due to the low air velocities that were present in the different rooms, it seems that the distance between emission point and particle counter is the most dominant factor.

Air flow measurements

From the air flow measurements, it can be concluded that the air velocities are low for all measurement locations. It is, therefore, challenging to identify a dominant air flow. For classroom 7, the air velocities are higher compared to the other classrooms. For this location, the 100-fold recovery time is also lower and the difference between the different particle counters is smaller. This could indicate that there is better mixing and dilution of the air in the room. For the other rooms, the air velocity is lower which makes the mixing and dilution less optimal, this results in longer 100-fold recovery times.

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8. Appendices

ANNEX A, RESULTS CLASSROOM 1

Experiments in-situ

WP 2, experiments phase 1

DATUM 28 July 2023

AUTEURS Ir. A. de Lange & ir. N. Lejeune

ORGANISATIE TNO

Table of contents

1. Results baseline measurement location classroom 1

The results represent the situation without any intervention to optimize the current 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 CO_2-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 the case of this location the intervention that will take place consists of replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system A and consists of openable windows and doors.

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. In this location that meant that the windows were opened during the measurements.

1.1 Characteristics of room and system

Room characteristics

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 m^2 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. 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

The ventilation system at this location is natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has three tilt and turn windows and a door which can be opened. The same applies for the exhaust of air. It should be noted that the windows were opened 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

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
	Total	N/A

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 1.2

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 were 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 CO_2 concentration in the room.

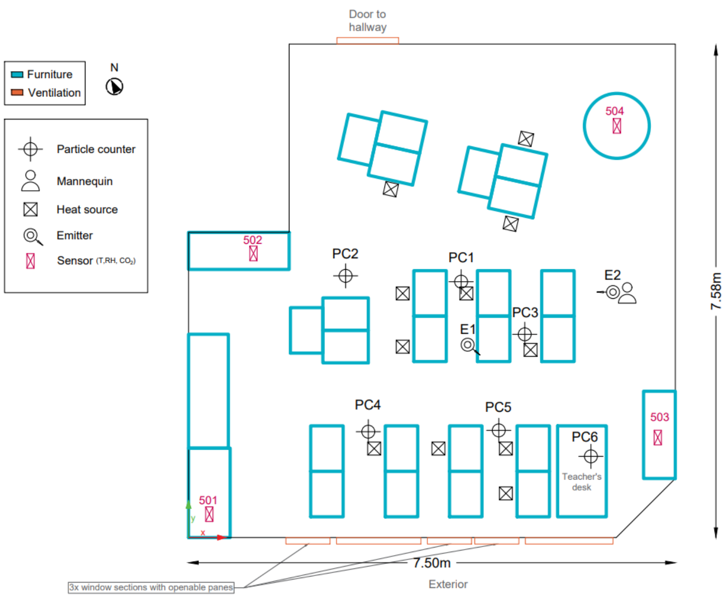


Figure 1.2 - Visualization of the classroom during the measurements.

1.3 Deviations and details compared to standard methodology

There are no real deviations from the measuring methodology during these measurements for this location. It should, however, be noted that in the standard methodology PC2 is located near the exhaust as a comparison method. This location, however, does not have an exhaust which means PC2 was located at another position.

1.4 Intervention

The intervention that will be applied in this school building consists of a balanced CO_2 controlled ventilation system with heat recovery. The heat recovery unit that will be installed has a heat recovery efficiency of 90%. The unit will be CO_2 controlled and is designed to meet de requirements for Class B of ‘PvE Frisse Scholen 2021’ and has a capacity of 950 m^3/h based on a maximum of 30 students and one teacher. This installation will be installed in all classrooms. Furthermore, all toilets, bathrooms and copy rooms will have their own mechanical exhaust system.

Other interventions in the school building are a PV-installation and the replacement of the single pane glazing with HR++ glazing.

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. Metrological data is from weerstatistieken.nl of a nearby weather station.

<table>
<tr><th colspan="5">17-06-2023</th></tr>
<tr><td rowspan="8">Surface temperature (°C)</td><td></td><td colspan="1">11:30</td><td colspan="2">15:00</td></tr>
<tr><td>Wall 1</td><td>25.5</td><td colspan="2">26.4</td></tr>
<tr><td>Wall 2</td><td>24.6</td><td colspan="2">25.5</td></tr>
<tr><td>Wall 3</td><td>25.4</td><td colspan="2">27.2</td></tr>
<tr><td>Wall 4</td><td>25.7</td><td colspan="2">27.0</td></tr>
<tr><td>Ceiling*</td><td>26.0</td><td colspan="2">27.9</td></tr>
<tr><td>Floor</td><td>25.0</td><td colspan="2">25.5</td></tr>
<tr><td>Glass surface of the windows</td><td>25.5</td><td colspan="2">28.0</td></tr>
<tr><td></td><td></td><td>Min**</td><td>Mean**</td><td>Max**</td></tr>
<tr><td>Air temperature (°C)</td><td></td><td>18.5</td><td>26.4</td><td>27.9</td></tr>
<tr><td>Relative humidity (%)</td><td></td><td>40.1</td><td>42.8</td><td>55.3</td></tr>
<tr><td>Outdoor air temperature (°C)</td><td></td><td>10.2</td><td>20.6</td><td>27.2</td></tr>
</table>

Outdoor relative humidity (%)		28	54	94
Wind	Velocity (m/s)	0.5	1.8	4.0
	Direction	North-East (52°)		

* 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).

** 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 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 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 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 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 m^3/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taken into account 25 children and one teacher, this results in a ventilation rate of 562 m^3/h (2.9 ACH) for a Class C and 796 (4.0 ACH) m^3/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} 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 E1. This indicates that at this location the decrease in the particle concentration starts sooner after the emission stopped but does not go faster. The 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.

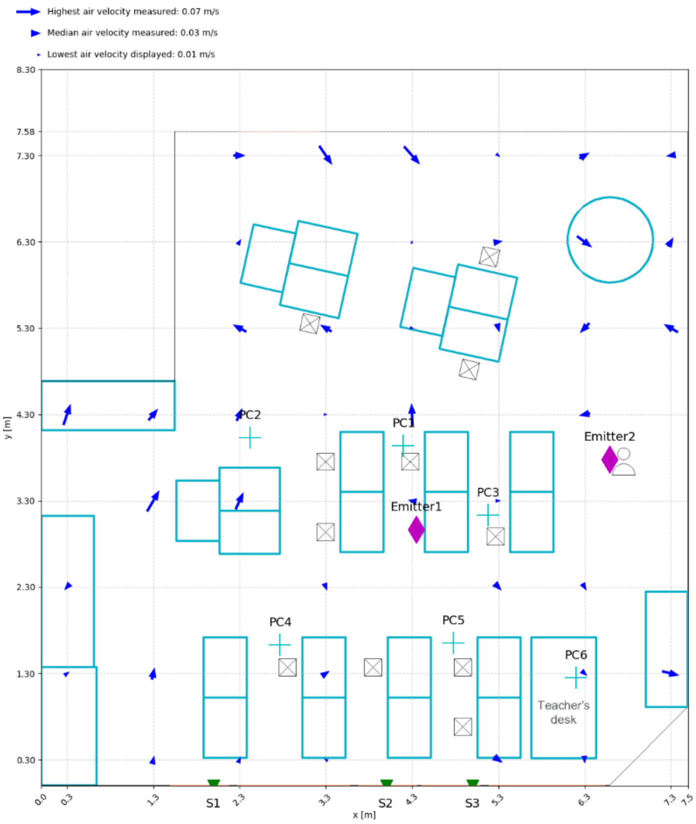
Table 2.2 - Visualization of the 100-fold increase time, 100-fold recovery time, ACH and t_{delay} mean value at all different measurement locations

		100-fold increase time (min)	100-fold recovery time (min)	Local air change rate per hour (ACH)	t_{delay} (min)
PC1	E1	10.1	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 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 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.



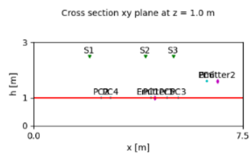


Figure 2.1 Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analysed at a height of 1.6 m, see Figure 2.2 (range 0.01 – 0.07). In this figure the air flow from the windows is more dominant (higher velocities). Furthermore, the air flow from the other side of the room is 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.

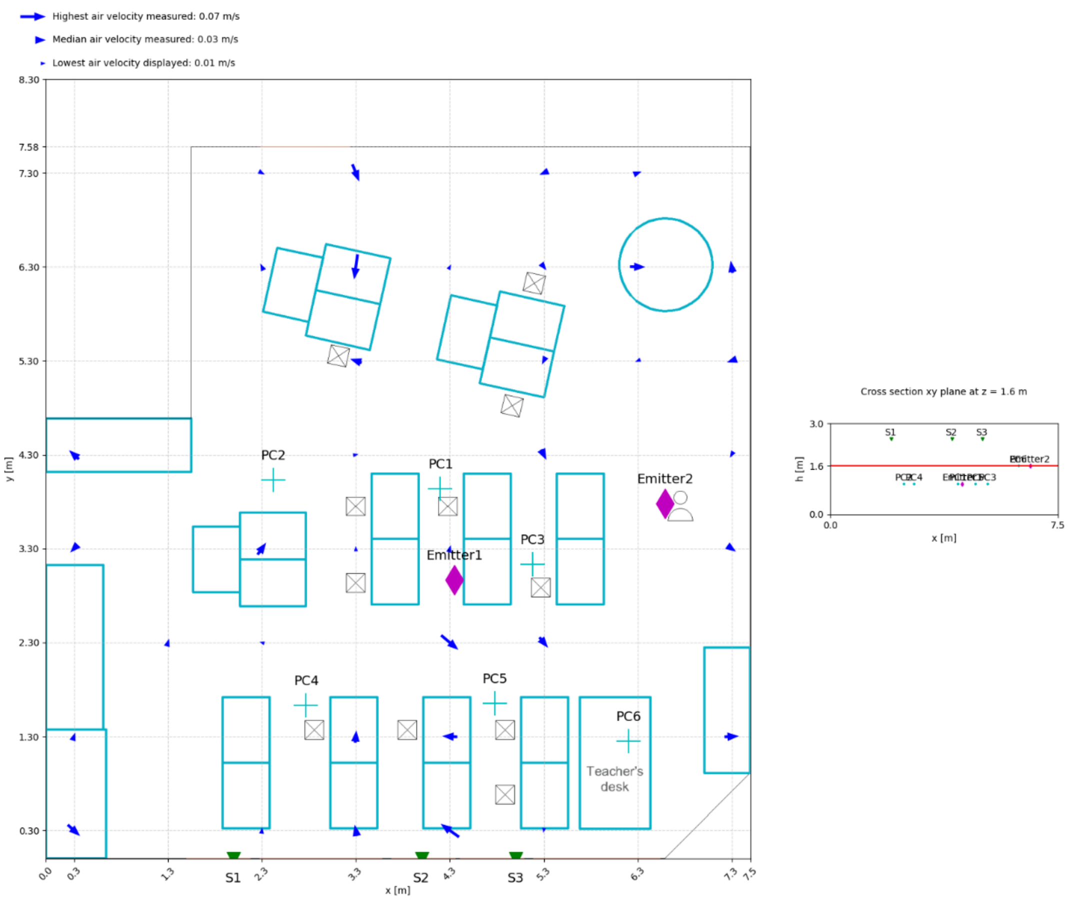


Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 Particle concentration measurements

<u>100-fold increase time</u>

The 100-fold increase time has a range of 3.6 – 23.1 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 on locations PC4 (E1) and PC6 (E2) which are both locations quite far from the emitter. In general, the closer the particle counter location to the emission location, the shorter the 100-fold increase time and vice versa.

<u>100-fold recovery time</u>

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. De 100-fold recovery time is the longest on locations PC2 (E1) and PC4 (E2). Measurements with a long 100-fold recovery time are often located far away from the emitter location.

<u>t_{delay}</u>

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. The delay was longest for PC2 (E1) and PC4 (E2), these are the locations were also the 100-fold recovery time is the longest. This underlines the notion that closer to the emission source location, the delay is small and the increase in particle concentration is quick and large.

<u>Air change per hour</u>

The ACH has a range of 2.6 – 5.3 ACH for emitter location E1 and has a range of 2.7 – 4.5 ACH for emitter location E2. These air change rates indicate, that it takes relatively long to decrease particle concentration in this classroom. These air change rates are mostly within Class C (2.9) and Class B (4.0) range according to the 'PvE Frisse Scholen' and are considered 'sufficient' and 'good' respectively.

3.2 Air flow measurements

During the air flow measurements an air flow is present towards the centre of the room. The air flow from the windows (where supply is located) is, especially at a height of 1.0 m, not dominant.

The particle concentration measurement and the air flow measurement show that there is an air flow from E1 towards PC1 and PC3 at a height of 1.0 m. This air flow could explain the relative short 100-fold increase time at PC1 and PC3, but these particle counters are also located closest to the emitter. Furthermore, PC4, PC5 and PC6 have a relative long 100-fold increase time for emitter E2. This could be related to the relative low air velocities near the window since these particle counters are all located near the windows. Related to that, from E2, the air flow in general is less dominant (lower air velocity) which could explain the (in most cases) longer 100-fold increase time and t_{delay} at the particle counters. At a height of 1.6 m, there is an air flow from emitter E1 towards PC6 which could explain the short 100-fold increase time and t_{delay}.

In conclusion, due to low air velocities a clear dominant air flow is not present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time are most likely found near the emission source location, translating into a quick increase of the particle concentration. Often, the 100-fold recovery time is low near the emission source location, indicating an efficient removal of the particle concentration at that measurement location.

ANNEX B, RESULTS CLASSROOM 2

Experiments in-situ

WP 2, experiments phase 1

DATUM 28 July 2023

AUTEURS Ir. A. de Lange & ir. N. Lejeune

ORGANISATIE TNO

Table of contents

1. Results baseline measurement location classroom 2

The results represent the situation without any intervention to optimize the current 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 CO_2-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 the case of this location the intervention that will take place consists of the use of a mobile air cleaner. Furthermore, the other intervention consist of replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system A and consists of window grills and openable doors and windows.

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. In this location that meant that the windows and the doors were closed but the window grills were opened.

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 m^2 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 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

The ventilation system at this location is natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has two natural ventilation window grills which can be opened. The same applies for the exhaust of air. It should be noted that the window grills were both open during the measurement period. The windows were 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

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

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 1.2.

For the particle counters (PC), PC1, PC3, PC4, 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 were 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 air borne 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 CO_2 concentration in the room.

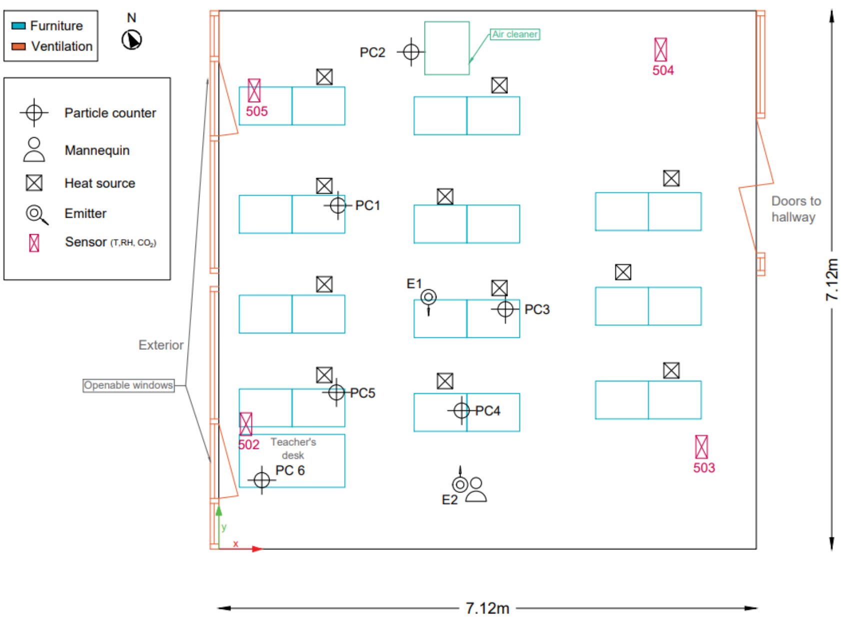


Figure 1.2 - Visualization of the classroom during the measurements

1.3 Deviations and details compared to standard methodology

The location and height of the particle counters has a deviation compared to previous measurements. The first deviation is related to the particle counters that are usually placed at a height of 1.0 m. These particle counters are during the measurement at this location placed at a height of 1.1 m. The same applies for the emitter at location E1. The second deviation is related to the location of particle counter PC2. Normally, this particle counter is placed near the exhaust but during these measurement there was no exhaust present but the particle counter was already placed at the exhaust location after the intervention.

1.4 Intervention

There are two different intervention implemented in this classroom. The first intervention is a mobile air cleaner. The ventilation capacity is based on the 'PvE Frisse scholen' and has a capacity of at least 918 m^3/h based on 30 students. The second intervention was a ventilation system that is connected to the heat pump to be able to heat and cool the room with the ventilation system. Furthermore, the glazing will be replaced in the current window frames.

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

The 100-fold recovery time is the longest at PC2 for both locations and at PC1 for emitter location E1. All these particle counter locations 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 m^3/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m^3/h (3.7 ACH) for a Class C and 796 m^3/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} 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
	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

T o 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 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.

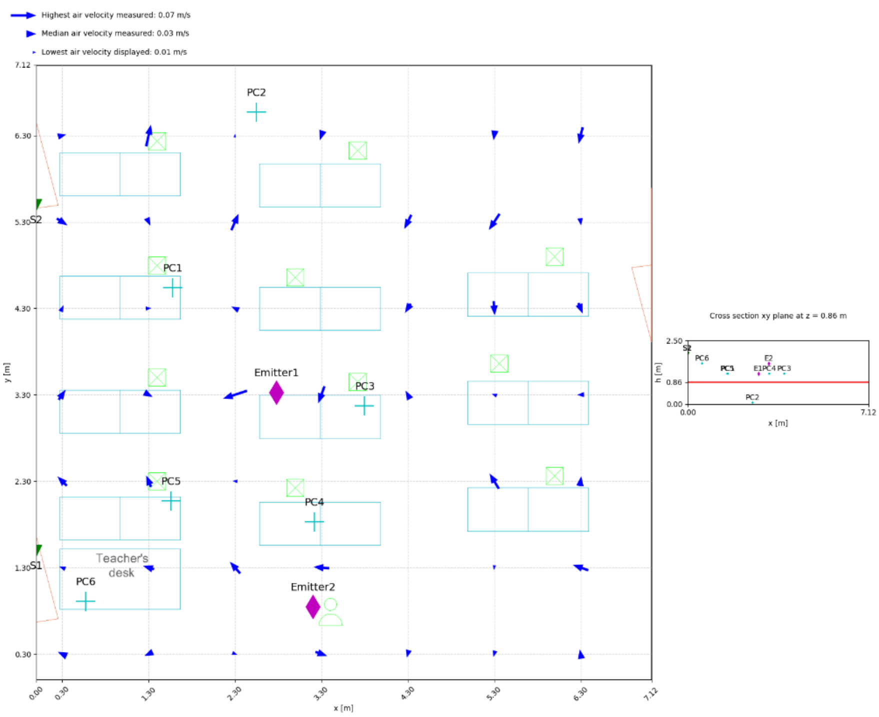


Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 0.86 m

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.

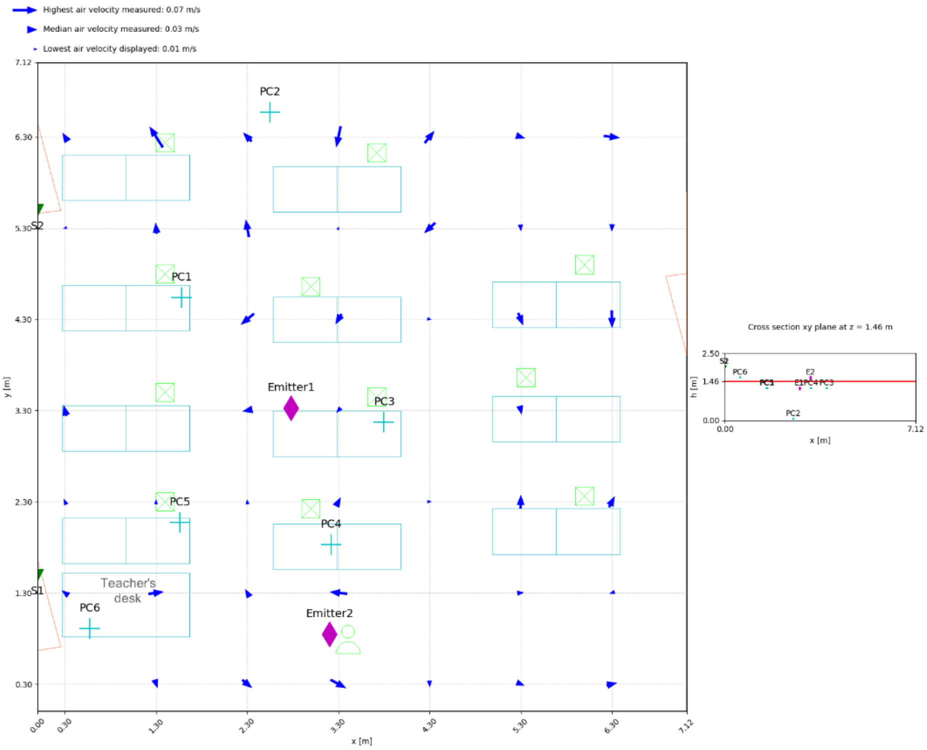


Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.46 m

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 *Particle concentration measurements*

100-fold increase time

The 100-fold increase time has a range of 0.4 – 15.7 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 on location PC2 for both emitter location E1 and E2. In general, the closer the particle counter location to the emission location, the shorter the 100-fold increase time and vice versa.

100-fold recovery time

The 100-fold recovery time has a range of 141.7 – 202.9 min for emitter location E1 and has a range of 164.4 – 1403.4 min for emitter location E2. There are, however, also 3 measurements that had negative 100-fold recovery time, indicating a very low local air exchange rate. In general, measurements located at PC1, PC2 and PC3 have a longer 100-fold recovery time. Measurements with a long 100-fold recovery time are often located far away from the emitter location.

t_{delay}

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. The delay was longest for PC2 for both emitter location E1 and E2. This is the location were also the 100-fold increase time was the longest. This underlines the notion that closer to the emission source location, the delay is small and the increase in particle concentration is quick and large.

Air change per hour

The ACH has a range of 1.4 – 2.0 ACH for emitter location E1 and has a range of 0.2 – 1.7 ACH for emitter location E2. These air change rates indicate that it takes relatively long to decrease particle concentration in this classroom. These air change rates are all not within Class C (3.7) and Class B (5.2) range according to the 'PvE Frisse Scholen' and are considered 'insufficient'.

3.2 Air flow measurements

During the air flow measurements, an air flow is present from the sides of the room towards the centre of the classroom. At a height of 1.46 m this air flow is dominant at the back of the classroom. There is no clear air flow from the window supply grills to the room at the analysed heights.

The particle concentration measurement and the air flow measurement show that there is an air flow in the direction of PC4 and PC5 from emitter E1. From the particle measurements, it can be concluded that the particle concentration moves quickly towards PC4 and PC5 from emitter location E1 (short 100-fold increase time) which can thus be validated with the air flow measurements. The 100-fold increase time is longer for the particle counters with the emission at location E2. This could be explained by the air flow measurements since the air velocities are low near emitter location E2 and the direction of the flow is unclear.

In conclusion, due to low air velocities a clear dominant air flow is not present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time are most likely found near the emission source location, translating into a quick increase of the particle concentration.

ANNEX C, RESULTS CLASSROOM 3

Experiments in-situ

WP 2, first phase of experiments

DATUM 28 July 2023

AUTEURS Ir. A. de Lange & ir. N. Lejeune

ORGANISATIE TNO

Table of contents

1. Results baseline measurement location classroom 3

The results represent the situation without any intervention to optimize the current 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 CO_2-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 the case of this location the intervention that will take place consists of the use of a mobile air cleaner. Furthermore, the other intervention that will be applied in this classroom is replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system A and consists of ventilation window grills and openable windows and doors.

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. In this location that meant that the windows and the doors were closed but the window grills were opened.

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 m^2 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
The ventilation system at this location is natural ventilation (natural supply and exhaust, system A). For air supply, the classroom has 3 window grills which can be opened. The same applies for the exhaust of air. It should be noted that the windows and emergency exit were closed during the measurement period. The window grills were open 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

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

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 1.2.

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 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 were 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 2.9 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 CO_2 concentration in the room.

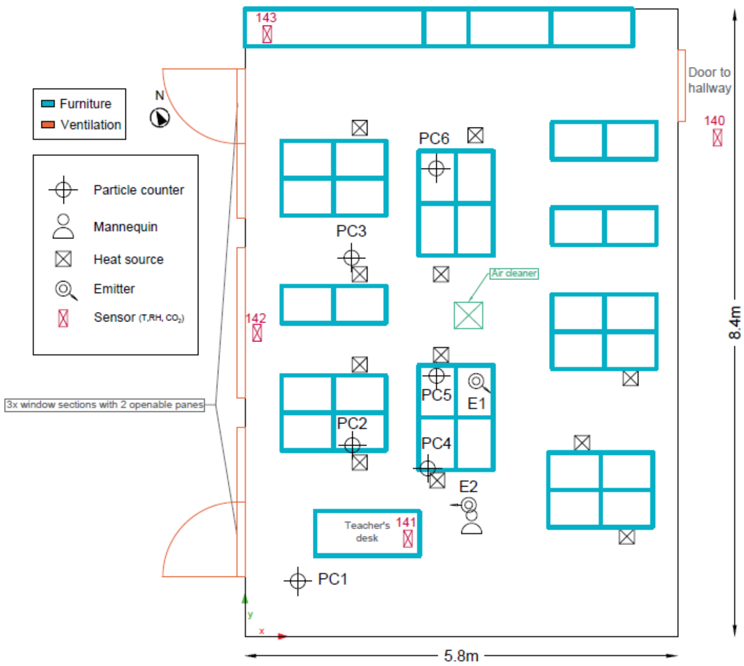


Figure 1.2 – Visualization of the classroom during the measurements.

1.3 Deviations and details compared to standard methodology

There are no real deviations from the measuring methodology during these measurements for this location. It should, however, be noted that in the standard methodology PC2 is located in the exhaust as a comparison method. This location, however, does not have an exhaust which means PC2 was located at another position.

1.4 Intervention

In this classroom two different interventions will take place. The first intervention that was implemented in this classroom was a mobile air cleaner. At power setting 2, it has a capacity of 400 m^3/h. The second intervention will be a ventilation system which 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.

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: West. 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 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 the particles more time to reach the particle counter location the particle concentration. The 100-fold increase time is the shortest for both PC2 and PC4 at emitter location E2 (9.7 – 9.1 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 is the longest near PC6 at emitter location E2, with a value of 349.1 min. The shortest 100-fold recovery time is at PC1, PC2 and PC4 for emitter location E2 (119.0, 135.0 and 123.6 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 m^3/h per person. Second, there is a Class B which results in a 'Good' air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taking into account 30 children and 1 teacher, this results in a ventilation rate of 670 m^3/h (4.3 ACH) for a Class C and 949 m^3/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} 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	189.4	1.5	3.8
	E2	8.3	119.0	2.3	1.0
PC2	E1	17.3	172.3	1.6	1.3
	E2	9.7	135.0	2.0	1.0
PC3	E1	23.6	158.3	1.7	0.5
	E2	15.7	198.6	1.4	2.0
PC4	E1	16.9	169.1	1.6	1.5
	E2	9.1	123.6	2.2	1.0
PC5	E1	21.5	166.5	1.7	2.0
	E2	17.1	155.0	1.8	2.5
PC6	E1	35.6	192.9	1.4	6.3
	E2	47.7	349.1	0.8	5.3

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. 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 , an air flow from the windows towards the center of the room is present. The air flow from the window supply grills is also visualized in Figure 2.2. A clear air flow directed downwards near the window supply grills (downdraught) 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.

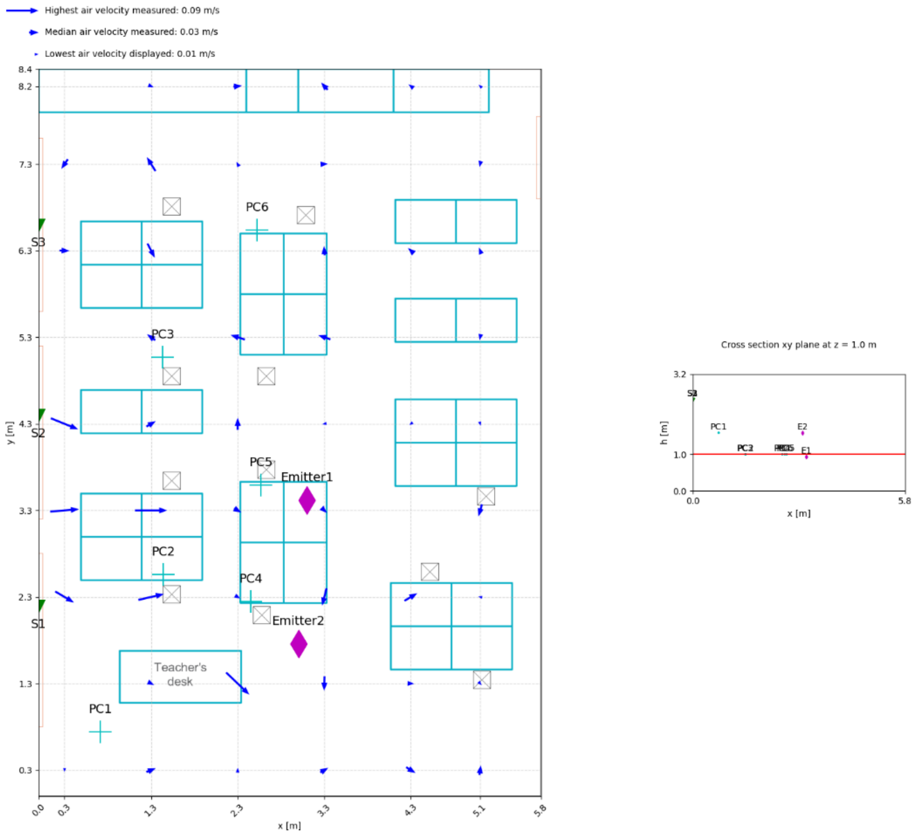


Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m

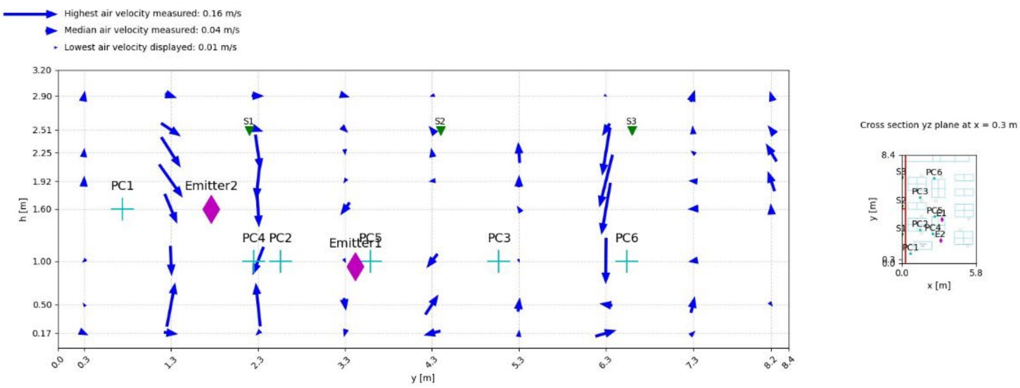


Figure 2.2 – Air flow (direction and velocity) in the YZ-plane at x = 0.3 m.

For PC1, the air flow is analysed at a height of 1.6 m, see Figure 2.3. 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.

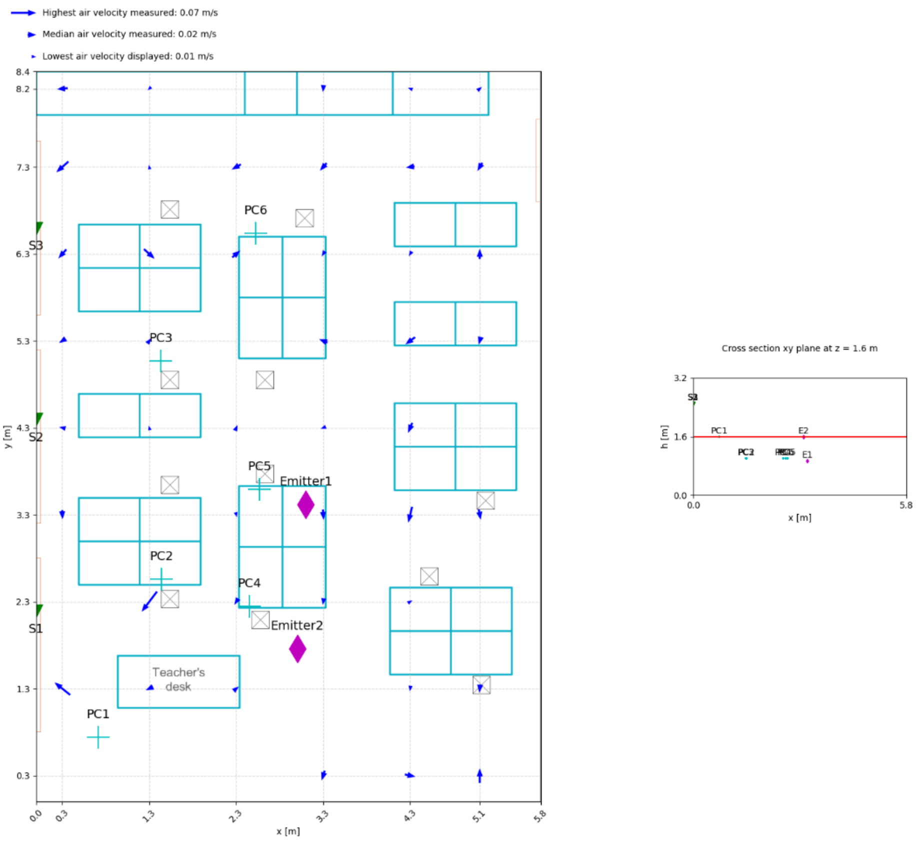


Figure 2.3 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 Particle concentration measurements

100-fold increase time

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 on location PC6 for both emitter locations. This particle counter is located far away from the emitter locations. In general, the closer the particle counter location to the emission location, the shorter the 100-fold increase time and vice versa.

100-fold recovery time

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. De 100-fold recovery time is the longest on location PC6 for both emitter locations. This indicates that both the 100-fold increase time and the 100-fold recovery time are the longest at PC6. Measurements with a long 100-fold recovery time are often located far away from the emitter location.

t_{delay}

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. The delay was longest for PC6 for both emitter locations. This is the location that is located furthest from the emission locations and also had the longest 100-fold increase time and 100-fold recovery time.

Air change per hour

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. These small air change rates indicate that it takes relatively long to decrease the particle concentration in this classroom. The air change rates do not meet the requirements for both Class C (4.3) and Class B (6.1) according to the 'PvE Frisse Scholen', so they are not considered 'sufficient'.

3.2 Air flow measurements

During the air flow measurement an air flow is present from the windows towards the centre of the room. Furthermore, the flow from the windows is directed downwards (downdraught). This air flow is more dominant (higher velocities present) for a height of 1.0 m than at a height of 1.6 m.

The particle concentration measurement and the air flow measurement show that the air velocities are higher near the windows than at the other side of the classroom. The 100-fold increase times are, in general, longer for particle counters at emission location E1 compared to emission location E2. This could be explained by the air velocities since these are lower near emission location E1 compared to emission location E2, meaning it would take longer until the particles reach the particle counters. The 100-fold increase time and 100-fold recovery time is longest at PC6, this particle counter is located at the back of the classroom where air velocities are low. This particle counter is also located relative far away from both emission locations.

In conclusion, due to low air velocities a clear dominant air flow is not present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time provide are most likely found near the emission source location, translating into a quick increase of the particle concentration. Often, the 100-fold recovery time is low near the emission source location, indicating an efficient removal of the particle concentration at that measurement location.

ANNEX D, RESULTS CLASSROOM 4

Experiments in-situ

WP 2, experiments phase 1

DATUM 28 July 2023

AUTEURS Ir. A. de Lange & ir. N. Lejeune

ORGANISATIE TNO

Table of contents

1. Results baseline measurement location classroom 4

The results represent the situation without any intervention to optimize the current 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 CO_2-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 the case of this location the intervention that will take place consists of a new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system A and consists of openable windows and doors.

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. In this location that meant that the windows were opened and the door was closed.

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 m^2 and was located on the ground floor. The 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

The ventilation system at this location is 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. 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

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

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 1.2.

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 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.

For this location, the air flow (vector: velocity and direction) measurements were not executed.

There were also sensors for measuring temperature, humidity and CO_2 concentration in the room.

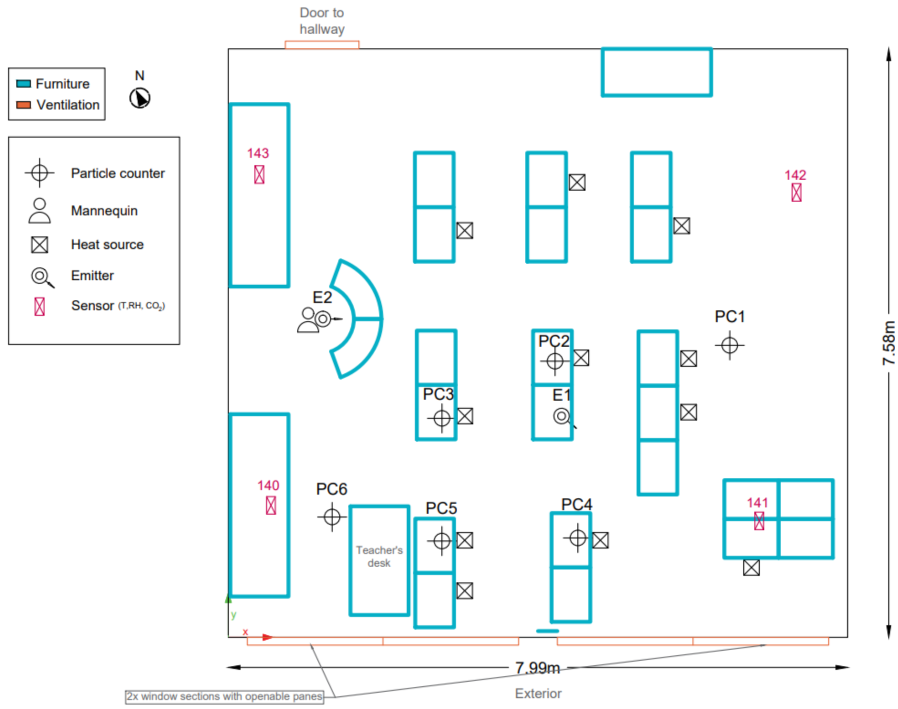


Figure 1.2 - Visualization of the classroom during the measurements

1.3 Deviations and details compared to standard methodology

The main deviation for this location is the malfunction of the air flow measurement system. This means that no air flow measurements have been executed prior to the intervention. This will, therefore, be excluded from the analysis. Another deviation is that there was a power cut from 13:02 till 13:14, this resulted in a few missing data points during the particle concentration measurements. Finally, one of the static heat sources broke down during the particle concentration measurements meaning a part of the measurements was executed with 10 instead of 11 heat sources.

1.4 Intervention

The intervention that will be applied in this school building consists of a balanced CO_2 controlled ventilation system with heat recovery. The heat recovery unit that will be installed has a heat recovery efficiency of 90%. The unit will be CO_2 controlled and is designed to meet de requirements for Class B of 'PvE Frisse Scholen 2021' and has a capacity of 950 m^3/h based on a maximum of 30 students and one teacher. This installation will be installed in all classrooms. Furthermore, all toilets, bathrooms and copy rooms will have their own mechanical exhaust system.

Other interventions in the school building are a PV-installation with 50 PV panels.

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.

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 weather station Rotterdam.

<table>
<tr><th colspan="5">16-06-2023</th></tr>
<tr><td rowspan="8">Surface area temperature (°C)</td><td></td><td>11:00</td><td colspan="2">16:00</td></tr>
<tr><td>Wall 1</td><td>24.6</td><td colspan="2">N/A*</td></tr>
<tr><td>Wall 2</td><td>24.3</td><td colspan="2">N/A</td></tr>
<tr><td>Wall 3</td><td>24.7</td><td colspan="2">N/A</td></tr>
<tr><td>Wall 4</td><td>24.0</td><td colspan="2">N/A</td></tr>
<tr><td>Ceiling</td><td>24.9</td><td colspan="2">N/A</td></tr>
<tr><td>Floor</td><td>23.3</td><td colspan="2">N/A</td></tr>
<tr><td>Glass surface of the windows</td><td>25.5</td><td colspan="2">N/A</td></tr>
<tr><td></td><td></td><td>Min**</td><td>Mean**</td><td>Max**</td></tr>
<tr><td>Air temperature (°C)</td><td></td><td>23.5</td><td>25.9</td><td>27.6</td></tr>
<tr><td>Relative humidity (%)</td><td></td><td>39.0</td><td>42.3</td><td>47.4</td></tr>
<tr><td>Outdoor air temperature (°C)</td><td></td><td>11.8</td><td>19.7</td><td>26.3</td></tr>
</table>

Outdoor relative humidity (%)		30	54	98
Wind	Velocity (m/s)	0.8	2.3	5.0
	Direction	North-East (4°)		

*There were no air flow measurements at this measurement location so there were no measurements during the afternoon.

** 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 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-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 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 m^3/h per person. Second, there is a Class B which results in a ‘Good’ air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m^3/h (3.1 ACH) for a Class C and 796 m^3/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} 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
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

Due to a malfunction in the measurement equipment, the air flow vectors at this location could not be measured.

3. Conclusions

Performance of the ventilation system before interventions is as follows.

3.1 Particle concentration measurements

100-fold increase time

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 PC2 (E1) and PC1 (E2). Often, the closer the particle counter location to the emission location, the shorter the 100-fold increase time. However, this does not apply for each case, PC2 (for example) is located close to E1 but has a relative long 100-fold increase time.

100-fold recovery time

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. De 100-fold recovery time is the longest on location PC5 (E1) and PC4 (E2). In general, it seems that the particle counters located near the windows have a longer 100-fold recovery time.

t_{delay}

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. The delay was longest for PC2 for both emitter locations, this location also has a relatively long 100-fold increase time. These findings do not support the finding that the delay is shorter when the particle counter is located close to the emitter.

Air change per hour

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. These air change rates indicate that it takes relatively long to decrease the particle concentration in the classroom. The air change rate are mostly within Class C (3.1) range according to the ‘PvE Frisse Scholen’ and are considered ‘sufficient’.

3.2 Air flow measurements

Due to a malfunction in the measurement equipment, the air flow vectors at this location could not be measured.

ANNEX E, RESULTS CLASSROOM 5

Experiments in-situ

WP 2, experiments phase 1

DATUM 28 July 2023

AUTEURS Ir. A. de Lange & ir. N. Lejeune

ORGANISATIE TNO

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1. Results baseline measurement location classroom 5

The results represent the situation without any intervention to optimize the current 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 CO_2-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 the case of this location the intervention that will take place consists of Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system D and consists of two mechanical supply grills and 2 mechanical exhaust grills.

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. In this location that meant that the windows and the doors were closed.

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 m^2 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

The ventilation system at this location is 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. 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.

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

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

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 1.2.

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 0.37 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 CO_2 concentration in the room.

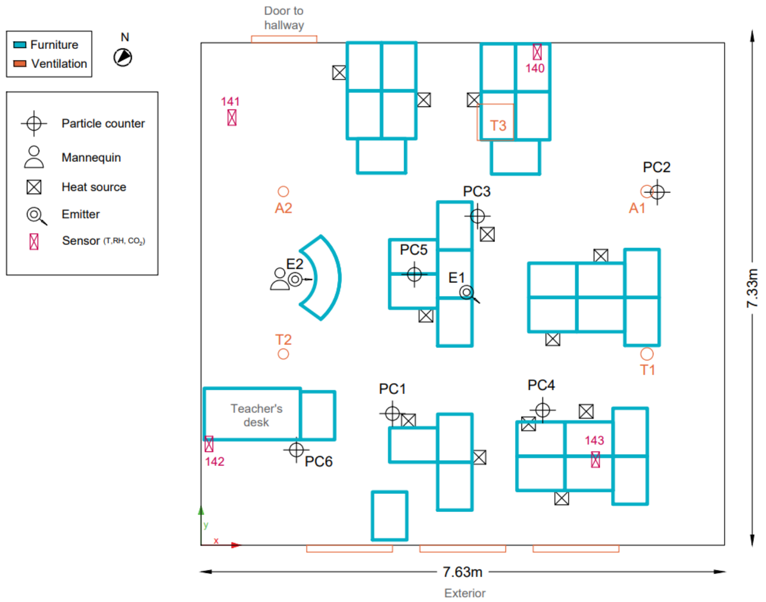

Figure 1.2 - Visualization of the classroom during the measurements

1.3 Deviations and details compared to standard methodology

A small deviation was that one of the heat sources boxes that was used broke down during the measurements. Therefore, only 11 static heat sources were used during most of the measurement period.

1.4 Intervention

The intervention that will be applied in this school building consists of a balanced CO_2 controlled ventilation system. The unit will be CO_2 controlled and is designed to meet de requirements for Class B of 'PvE Frisse Scholen 2021' and has a capacity of 918 m^3/h based on 29 students and one teacher. This installation will be installed in all classrooms.

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 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 is the longest at location PC2 for both emitter location E1 and E2 (32.8 - 63.7 min). This particle counter is locate 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 particle counters are both located relatively close to the emitter which means that the particle concentration can increase faster.

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 m^3/h per person. Second, there is a Class B which results in a ‘good’ air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taking into account 30 children and 2 teachers, this results in a ventilation rate of 691 m^3/h (3.5 ACH) for a Class C and 979 m^3/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} 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
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.

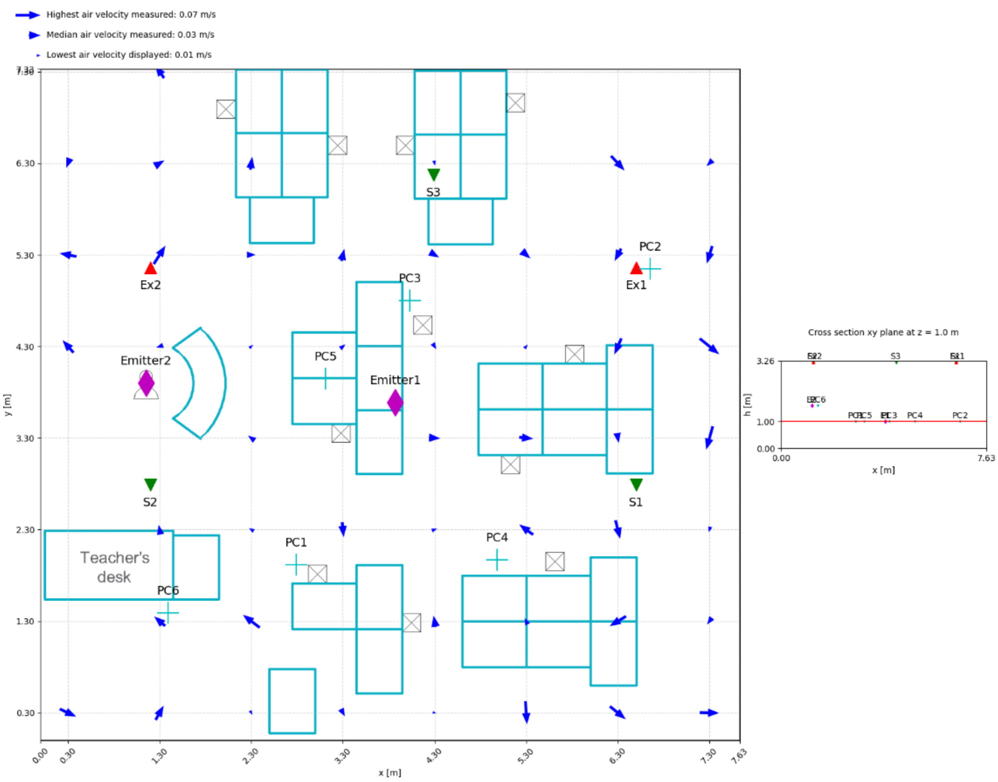

Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m.

For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 2.2 (range 0.01 – 0.09). 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.

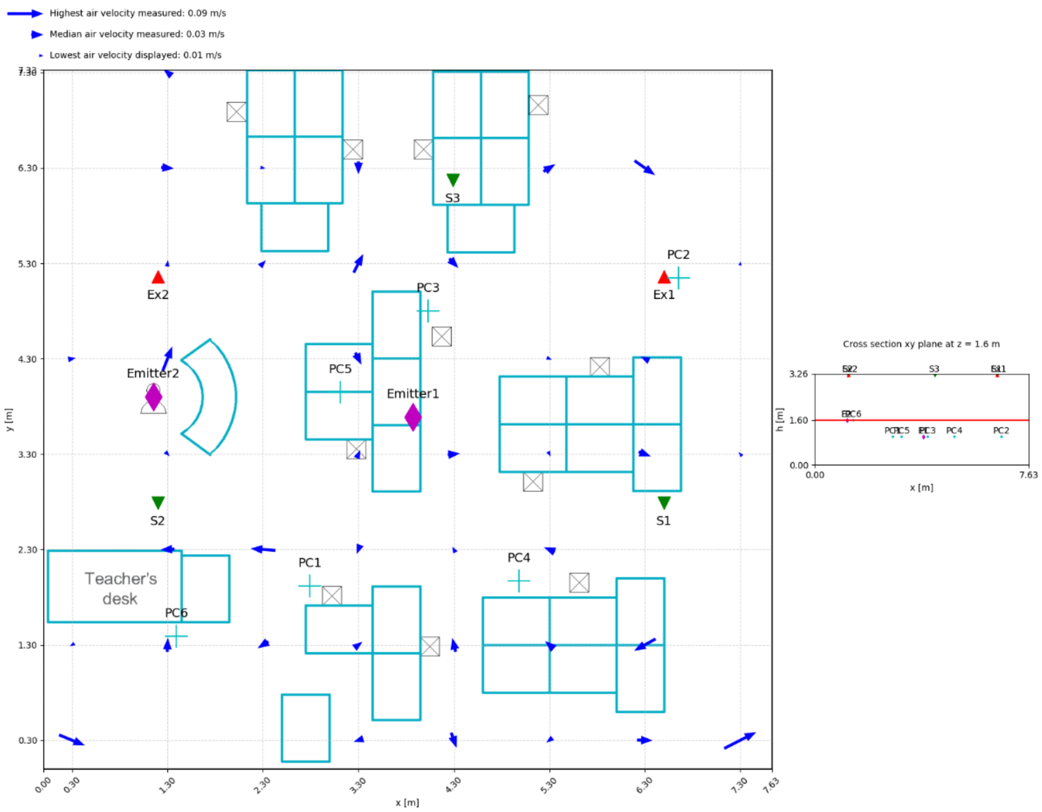

Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m.

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 Particle concentration measurements

<u>100-fold increase time</u>

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 on locations PC2 (E1) and PC2 (E2) which is the measurement location close to the exhaust. In general, the closer the particle counter location to the emission location, the shorter the 100-fold increase time and vice versa.

<u>100-fold recovery time</u>

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. De 100-fold recovery time is the longest on locations PC2 (E1) and PC4 (E2). Measurements with a long 100-fold recovery time are often located far away from the emitter location.

<u>t_{delay}</u>

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. The delay was longest for PC2 for both emitter locations. This is the location at the exhaust which also had long 100-fold increase time and 100-fold recovery time. In general, the closer the particle location to the emission location, the shorter the t_{delay} and vice versa.

<u>Air change per hour</u>

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. These small air change rates indicate that it takes relatively long to decrease the particle concentration in this classroom. These air change rates do not 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’.

3.2 Air flow measurements

During the air flow measurement, the highest air velocities are at the sides of the classroom and the lowest are located in the centre of the classroom. Furthermore, there are no dominant air flows visualized 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.

In conclusion, due to low air velocities it is most likely that no dominant air flow is present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time provide are most likely found near the emission source location, translating into a quick increase of the particle concentration. Often, the 100-fold recovery time is low near the emission source location, indicating an efficient removal of the particle concentration at that measurement location.

Deliverable Work package 2

ANNEX F, RESULTS CLASSROOM 6

Experiments in-situ

WP 2, experiments phase 1

DATUM 28 July 2023

AUTEURS Ir. A. de Lange & ir. N. Lejeune

ORGANISATIE TNO

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1. Results baseline measurement location classroom 6

The results represent the situation without any intervention to optimize the current 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 CO_2-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 the case of this location the intervention that will take place consists of Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system C and consists of 3 natural ventilation air grills in de windows and an exhaust ceiling grill.

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. In this location that meant that the windows and the doors were closed but two of the three window grills were opened.

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 m^2 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 circa 20 students and 1 teacher. A visualization of the room can be seen in Figure 1.1.

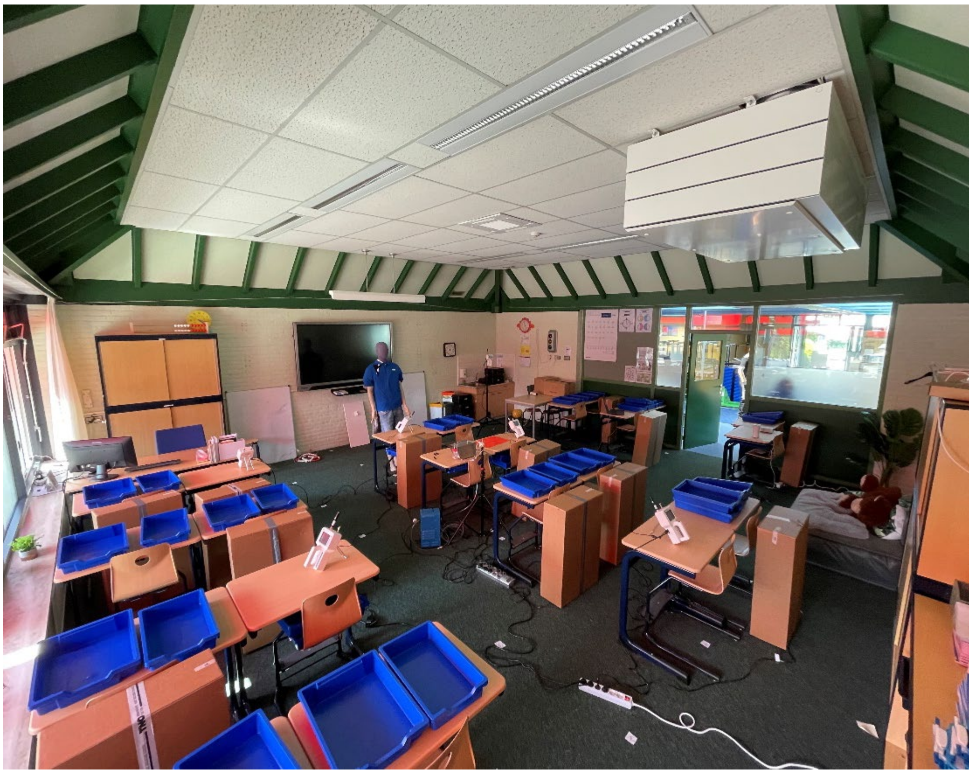

Figure 1.1 - Visualization of the classroom during the measurements

Ventilation system in the room

The ventilation system at this location is ventilation system C (natural supply and mechanical exhaust). For air supply, the classroom has three natural ventilation air grilles in the windows which can be opened. For the exhaust of air, the room has one mechanical ceiling grille. It should be noted that 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.

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

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

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 1.2.

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 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 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 CO_2 concentration in the room.

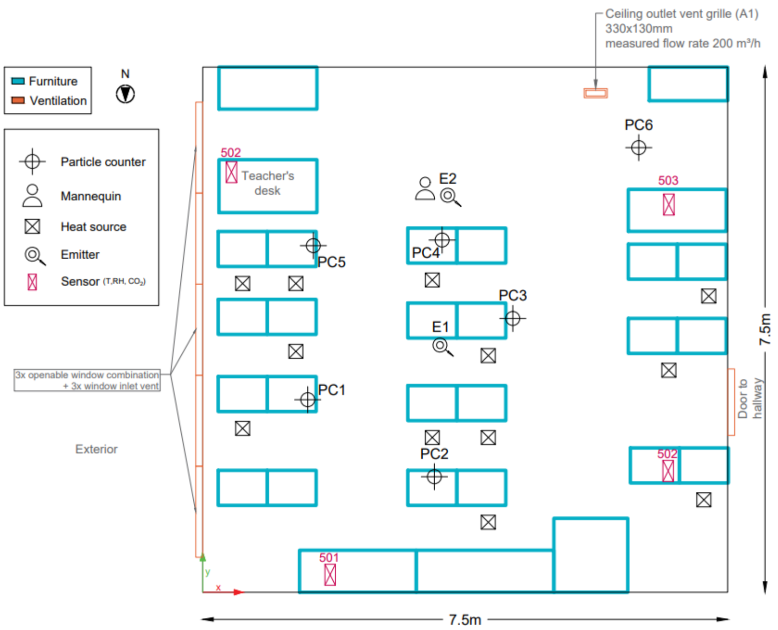

Figure 1.2 - Visualization of the classroom during the measurements

1.3 Deviations and details compared to standard methodology

There are no real deviations from the measuring methodology during these measurements for this location. It should, however, be noted that in the standard methodology PC2 is located in the exhaust as a comparison method. For this location, however, PC6 was used since the location of the exhaust was close to the location of the standing teacher.

1.4 Intervention

The intervention that will be applied in this school building consists of a balanced CO_2 controlled ventilation system. The unit will be CO_2 controlled and is designed to meet de requirements for Class C of 'PvE Frisse Scholen 2021' and has a capacity of 562 m^3/h based on 25 students and one teacher. This installation will be installed in all classrooms.

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 23.3 and 29.4 degrees Celsius throughout the day.

Table 2.1 - 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

Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time is the longest on location PC2 for both emitter location E1 and E2 (20.3 and 20.6 min). This particle counter is located at a relative far distance from both emitter locations which indicates that the particle concentration reaches these locations slower. The 100-fold increase time is the shortest for PC5 at emitter location E1 (1.4 min).

The 100-fold recovery time is the longest at location PC2 for emitter location E2 (1261.3 min). There are, however, also 4 negative values which means that the particle concentration increased during the recovery period on 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 (119.1 – 113.7 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 m^3/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m^3/h (3.5 ACH) for a Class C and 796 m^3/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} 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 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	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	1261.3	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	119.1	2.3	4.3
	E2	10.1	242.8	1.1	3.5
PC5	E1	1.4	113.7	2.4	1.3
	E2	8.3	219.9	1.2	5.0
PC6	E1	7.2	231.7	1.2	2.8
	E2	7.5	604.8	0.5	1.8

* 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 (velocity 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.

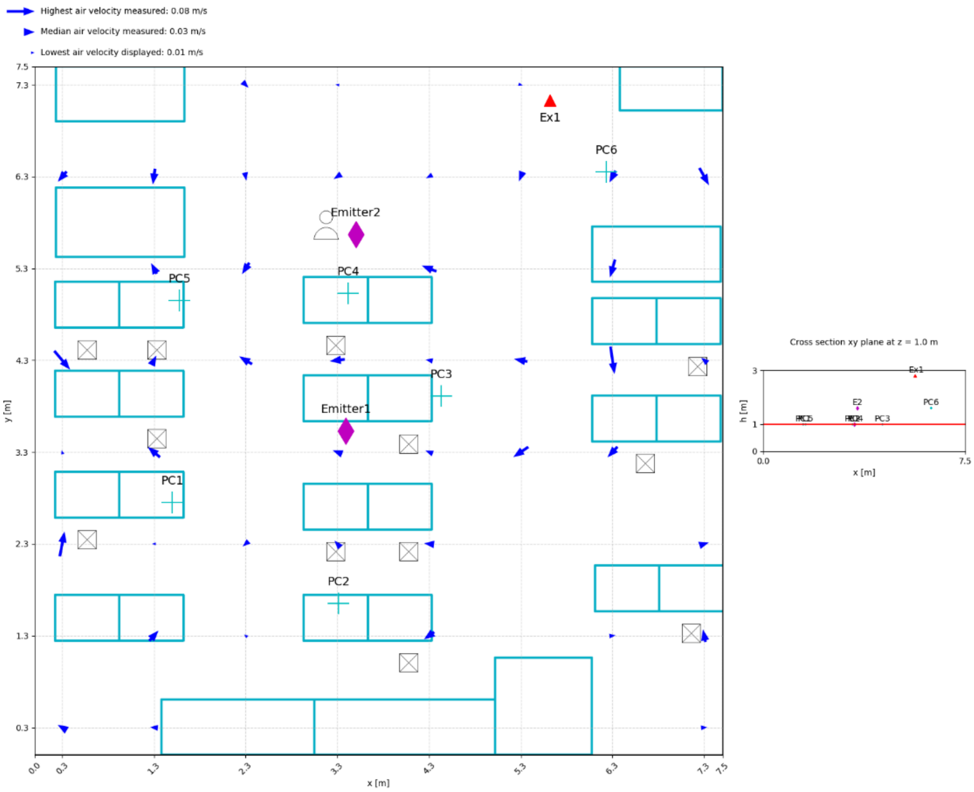

Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m

For PC6, the air flow is analyzed at a height of 1.6 m, see Figure 2.2 (range 0.01 - 0.06 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 towards the room.

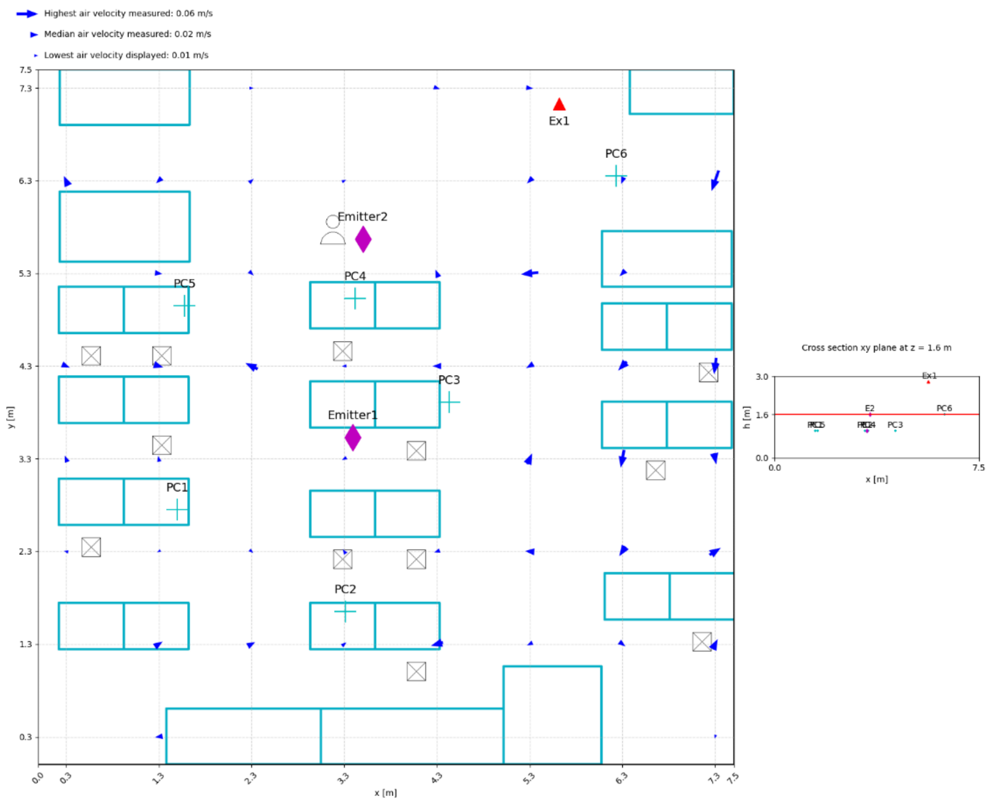

Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 Particle concentration measurements

100-fold increase time

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 on locations PC2 for both emitter location E1 and E2, which is also the particle counter located furthest from the emitter locations. In general, the closer the particle counter location to the emission location, the shorter the 100-fold increase time and vice versa.

100-fold recovery time

The 100-fold recovery time has a range of 113.7 – 446.0 min for emitter location E1 and has a range of 219.9 – 1261.3 min for emitter location E2. It should, however, be noted that there are also negative values. This means that the particle concentration increases during the recovery period, indicating a very low local air exchange rate. Measurements with a long 100-fold recovery time are often located at the back of the classroom which is further away from the emitter location.

t_{delay}

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. The delay was the longest for PC2 (E1) and for PC1 (E2), these are the locations that also had a very long 100-fold recovery time. This underlines the notion that closer to the emission source location, the delay is small and the increase in particle concentration is quick and large.

Air change per hour

The ACH has a range of 0.6 – 2.4 ACH for emitter location E1 and has a range of 0.2 – 1.2 ACH for emitter location E2. These air change rates indicate that it takes relatively long to decrease particle concentration in this classroom. These air change rates are not within both Class C (3.5) and Class B (4.9) according to the 'PvE Frisse Scholen'.

3.2 Air flow measurements

During the air flow measurement the air velocities are highest at the centre of the room. Furthermore, an air flow can be located directed from the windows towards the room. At a height of 1.6 m, the air flow is most prominent near the opposite side of the room (side of the door).

The particle concentration measurement and the air flow measurement show that there is an air flow from emitter location E1 and E2 towards PC4 and PC5 which could explain the high concentration of particles at these locations. At these locations there is also a relatively higher air velocity, in different directions, which could explain the low 100-fold recovery time. The 100-fold recovery time is longer for PC1, PC2 and PC3 for both emitter locations. These locations all seems to be located in a location were the air velocities are lower, meaning it takes relative long before the particle concentration decreases at these locations.

In conclusion, due to low air velocities it is most likely that no dominant air flow is present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time provide are most likely found near the emission source location, translating into a quick increase of the particle concentration.

ANNEX G, RESULTS CLASSROOM 7

Experiments in-situ

WP 2, experiments phase 1

DATUM	28 July 2023
AUTEURS	Ir. A. de Lange & ir. N. Lejeune
ORGANISATIE	TNO

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1. Results baseline measurement location classroom 7

The results represent the situation without any intervention to optimize the current 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 CO_2-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 the case of this location the intervention that will take place consists of Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system A and consists of openable windows and doors.

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. In this location that meant that two of the three windows were opened and the doors were closed.

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 m^2 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

The ventilation system at this location is 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. There are, furthermore, two roof outlet vents present but this is natural ventilation which exhausts air directly towards the roof (see Figure 1.1). It should be noted that the 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.

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

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 vents	
	Total	N/A

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 1.2.

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 were 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 2.5 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 CO_2 concentration in the room.

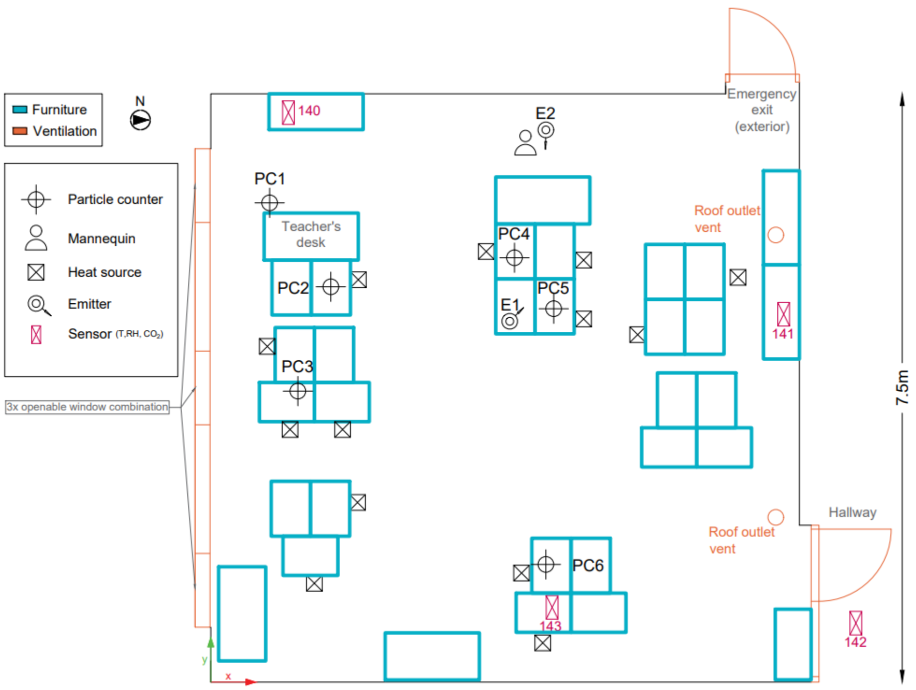

Figure 1.2 - Visualization of the classroom during the measurements

1.3 Deviations and details compared to standard methodology

There are no real deviations from the measuring methodology during these measurements for this location. It should, however, be noted that in the standard methodology PC2 is located in the exhaust as a comparison method. This location, however, does not have an exhaust which means PC2 was located at another position.

1.4 Intervention

The intervention that will be applied in this school building consists of a split air conditioning unit with balanced ventilation with heat recovery. The unit is designed to meet the requirement for Class B of 'PvE Frisse Scholen 2021' with a capacity of 30.6 m^3/h per person and is designed for a classroom with an average of 25 students and one teacher. Each classroom will have four supply vents for fresh air and four exhaust roof vents.

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. Table 2.2 gives an overview of the results for each measurement location (PC1 – PC6). 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 is takes relatively long before the particle concentration has increased a 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 1.2, since the emitter E1 is located close towards PC4 and PC5 which means that the particles reach these particle counters quickly which results in a short increase time.

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 far distance from the emitter. What is interesting to note, however, is that 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 m^3/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m^3/h (3.3 ACH) for a Class C and 796 m^3/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) but 4 measurement locations do not meet the requirements of class B.

Finally, t_{delay} was calculated for the different measurement locations. This indicates the time it takes until the particle concentration at a specific location starts to decline after the emission was stopped. The lowest 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 highest 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
	E2	23.6	79.3	3.5	3.5

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 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.

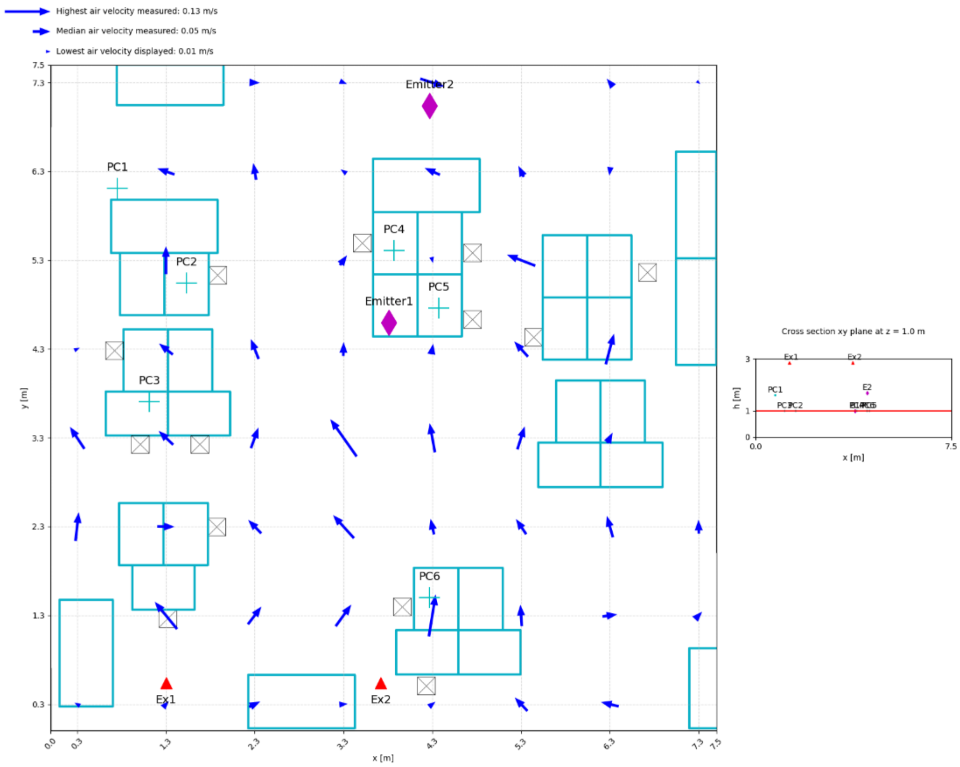

Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m

For PC1, the air flow is analyzed at a height of 1.6 m, see Figure 2.2 (range 0.01 - 0.08 m/s). In this figure, it can be seen that the air velocities are lower compared to a height of 1.0 m. The direction of the air flow is comparable for both heights, from the back of the classroom towards the center. Specifically for PC1, there seems to be an air flow from emitter location E1 that is directed towards PC1 but this is an air flow with low air velocities.

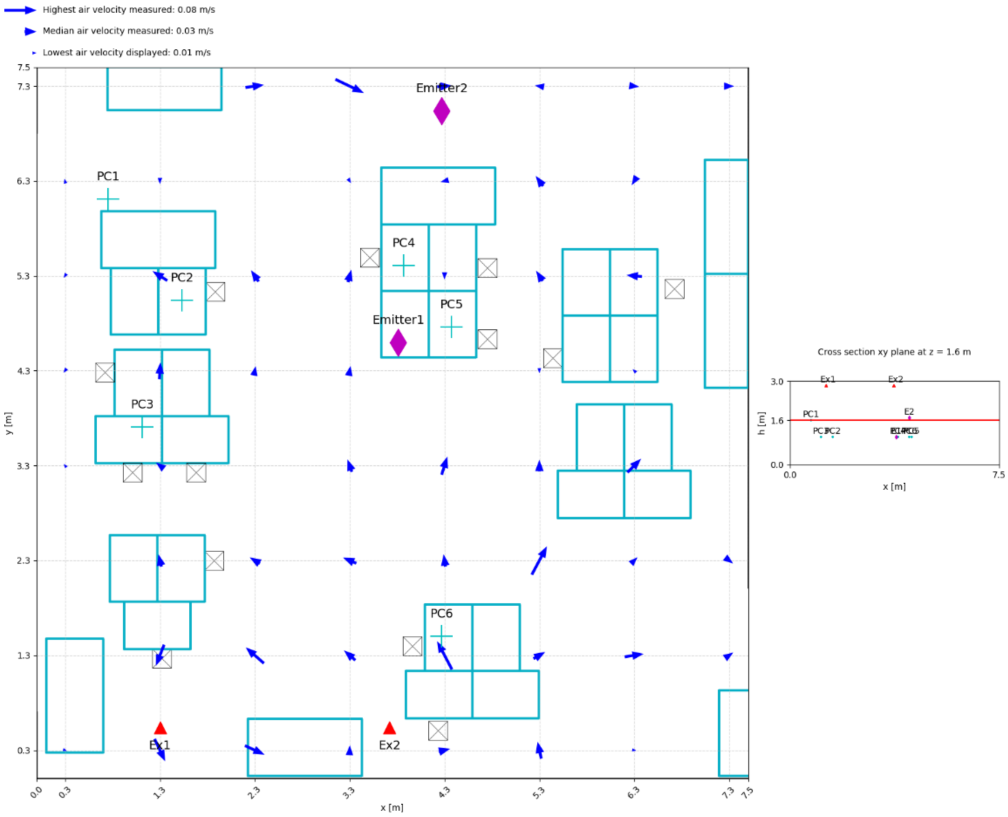

Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 Particle concentration measurements

<u>100-fold increase time</u>

The 100-fold increase time has a range of 1.3 – 25.5 min for emitter location E1 and has a range of 8.9 – 41.5 min for emitter location E2. The 100-fold increase time is the longest on locations PC2 (E1) and PC1 (E2). In general, the closer the particle counter location to the emission location, the shorter the 100-fold increase time and vice versa.

<u>100-fold recovery time</u>

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. De 100-fold recovery time is the longest on locations PC4 (E1) and PC6 (E2). The range of 100-fold recovery times is significantly larger at emitter location E2 compared to emitter location E1 and the overall 100-fold recovery times are higher.

<u>t_{delay}</u>

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. The delay was longest for PC4 (E1) and for PC3 (E2). These locations are located quite far away from the emitter location. This underlines the notion that closer to the emission source location, the delay is small and the increase in particle concentration is quick and large.

<u>Air change per hour</u>

The ACH has a range of 5.1 – 5.7 ACH for emitter location E1 and has a range of 3.5 – 5.2 ACH for emitter location E2. These air change rates indicate that it takes relatively long to decrease particle concentration in this classroom. These air change rates are all within Class C (3.3) range according to the 'PvE Frisse Scholen' and are considered 'sufficient' respectively.

3.2 Air flow measurements

During the air flow measurement an air flow is present from the back towards the centre of the room. This air flow has higher air velocities at a height 1.0 m than at a height of 1.6 m.

The particle concentration measurement and the air flow measurement show that there is an air flow from E1 towards both PC4 and PC5, these locations both have a short 100-fold increase time. Furthermore, in general, the 100-fold increase times are longer for the particle counters when emission took place at emitter location E2 compared to emitter location E1. This could be explained with the air velocities since these are lower at emitter location E2 compared to emitter location E1.

In conclusion, due to low air velocities it is most likely that no dominant air flow is present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time provide are most likely found near the emission source location, translating into a quick increase of the particle concentration.

ANNEX H, RESULTS CLASSROOM 8

Experiments in-situ

WP 2, experiments phase 1

DATUM	15 November 2023
AUTEURS	Ir. A. de Lange & ir. N. Lejeune
ORGANISATIE	TNO

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1. Results baseline measurement location classroom 8

The results represent the situation without any intervention to optimize the current ventilation system or situation.

Future interventions are divined 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 CO_2-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 the case of this location the intervention that will take place consists of Replacement: new, different or updated system (capacity, function, system typology (e.g. natural ventilation, mechanical supply and or exhaust, balanced ventilation system).

The current ventilation system or situation at this location is system A and consists of openable windows and doors.

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. In this location that meant that the windows were opened and the doors were closed.

1.1 Characteristics of room and system

Description of the room

The school is located in a suburban environment and was originally built in 1882. The classroom that was considered during this analysis, has a surface area of 64.4 m^2 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

The ventilation system at this location is 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. It should be noted that the 2 tilt and turn windows were opened 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

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

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 1.2.

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 were 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 0.17 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 occupied by students.

There were also sensors for measuring temperature, humidity and CO_2 concentration in the room.

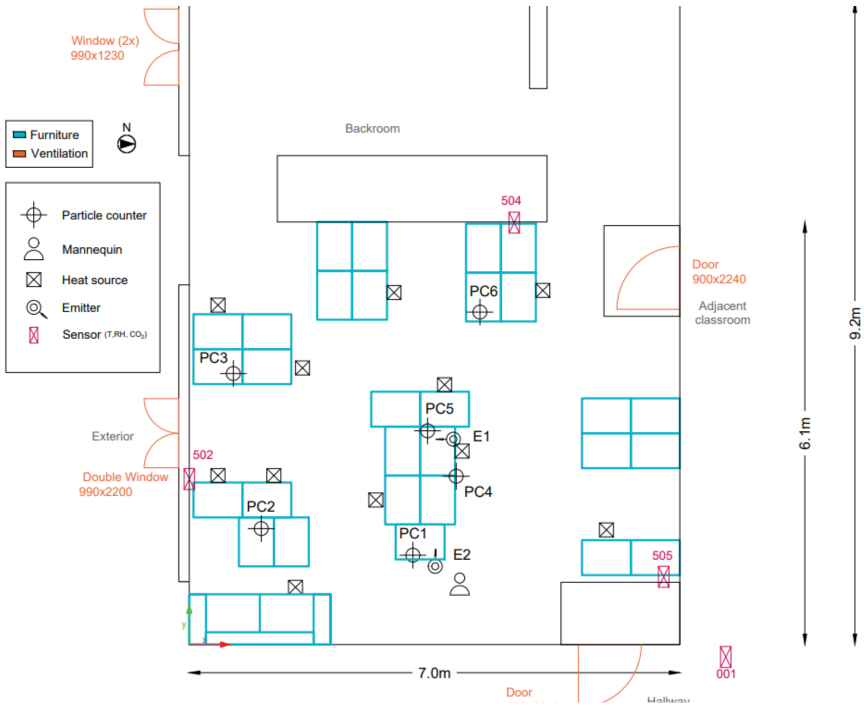

Figure 1.2 - Visualization of the classroom during the measurements

1.3 Deviations and details compared to standard methodology

There are no large deviations from the measuring methodology during these measurements for this location. It should, however, be noted that in the standard methodology PC2 is located in the exhaust as a comparison method. This location, however, does not have an exhaust which means PC2 was located at another position.

1.4 Intervention

The intervention that will be applied in this school building consists of a ventilation system which consists 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.

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 is longest for PC1 and PC2 at emitter location E2 (159.2 and 186.6 min). This means that is takes long before the particle concentration has increased a 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.

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 m^3/h per person. Second, there is a Class B which results in a 'good' air quality, this requires a ventilation rate of 30.6 m^3/h per person. When taking into account 25 children and one teacher, this results in a ventilation rate of 562 m^3/h (2.0 ACH) for a Class C and 796 m^3/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) en 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 the different measurement locations. This indicates the time it takes until the particle concentration at a specific location starts to decline after the emission was stopped. The lowest 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 highest value was measured at PC3 at emitter location E2 with a value of 10.5 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	167.5	1.6	2
	E2	159.2	N/A	N/A	11
PC2	E1	14	227.4	1.2	1.5
	E2	186.6	N/A	N/A	9.8
PC3	E1	31.3	118.3	2.3	2.8
	E2	90.6	N/A	N/A	10.5
PC4	E1	1.3	169.8	1.6	1.8
	E2	99.3	605.9	0.5	7.8
PC5	E1	2.2	370.1	0.7	0.3
	E2	81.2	770	0.4	8.8
PC6	E1	85.6	247.2	1.1	5.5
	E2	36.5	88.8	3.1	3.5

* 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 is present. 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.

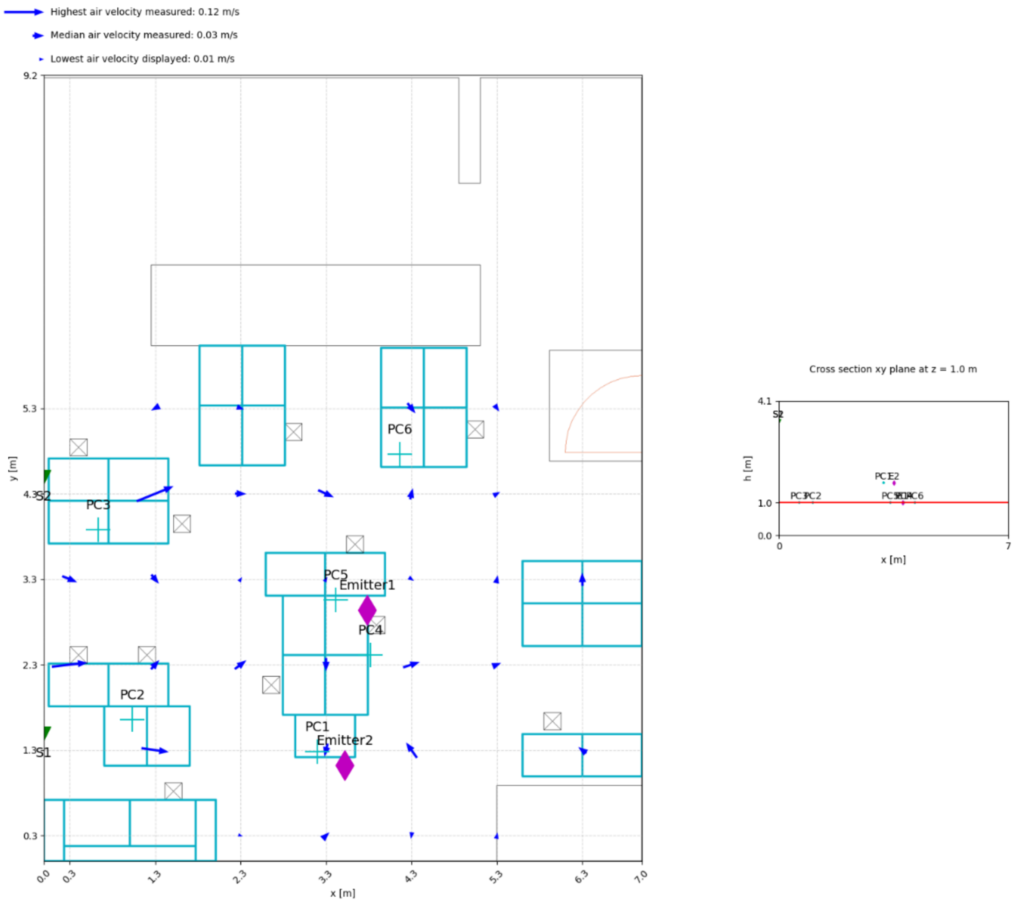

Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 1.0 m

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.

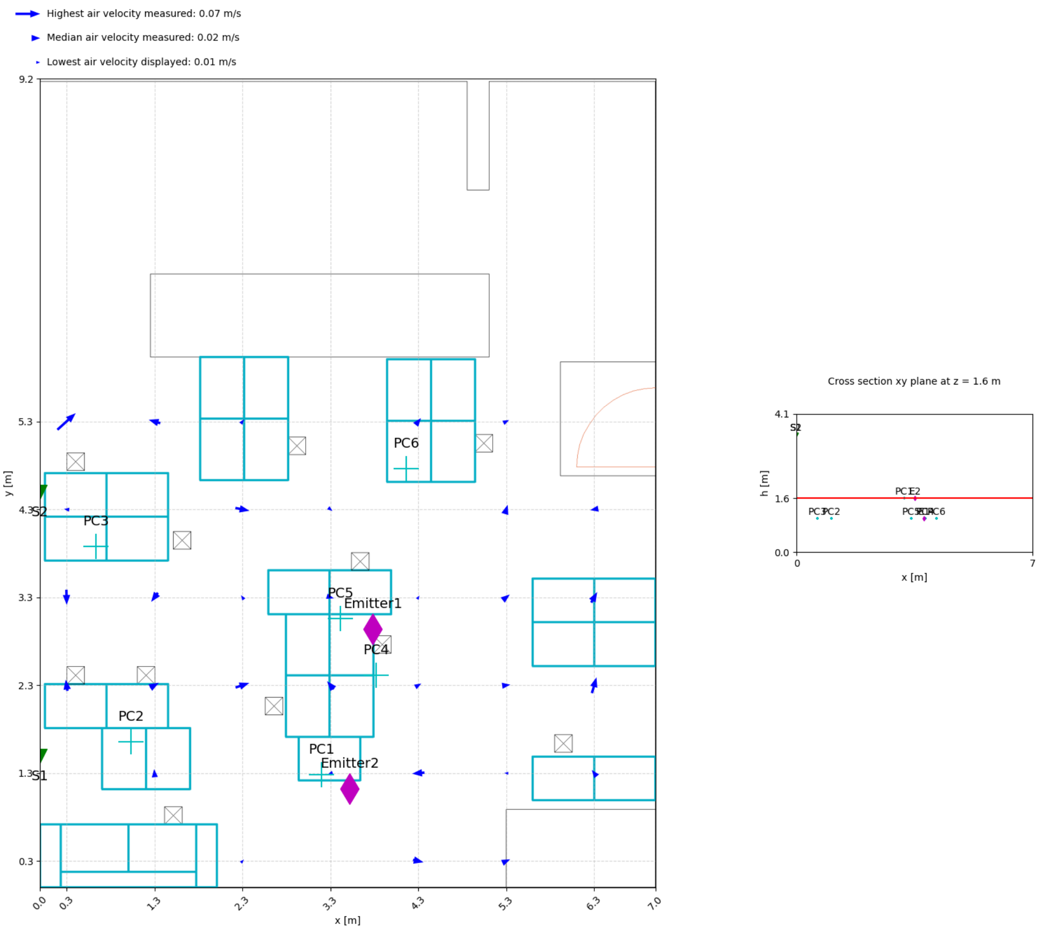

Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.6 m

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 Particle concentration measurements

100-fold increase time

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 the longest on locations PC1 and PC2 (E2). PC1 is located close to E2 but the direction of the emitter is in the other direction than PC1 which causes a long 100-fold increase time.

100-fold recovery time

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 for emitter location E2. De 100-fold recovery time is the longest on locations PC1, PC2 and PC3 for emitter location E2, the 100-fold recovery time is negative on these locations so the particle concentration increases. The range of 100-fold recovery times is significantly larger at emitter location E2 compared to emitter location E1 and the overall 100-fold recovery times are higher.

t_{delay}

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 delay was longest on PC1 and PC3 for emitter location E2, these locations also had a long 100-fold recovery time and a long 100-fold increase time.

Air change per hour

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. These air change rates indicate that it takes relatively long to decrease particle concentration in this classroom. Only PC3 at emitter location E1 and PC6 at emitter location E2 are within the range for Class C (2.0 ACH) according to the 'PvE Frisse Scholen' and are considered 'sufficient' respectively. The other values are not sufficient for both Class C and Class B

3.2 Air flow measurements

During the air flow measurement, at a height of 1.0 m, a clear air flow was present from the windows in the direction towards the centre of the room. This air flow is not clearly present at a height of 1.6, at this height the air velocities (in general) are lower.

The particle concentration measurement and the air flow measurement show that in general the 100-fold recovery times are longer at emitter location E2 compared to emitter location E1. This could be explained by the relative long time it takes for particle concentrations to reach the particle counters from emitter location E2 due to the air flow directed away from the particle counters. Furthermore, PC1 is located directly near emitter location E2 but has a very long 100-fold increase time. This can be explained by the direction of the air flow and the direction of the emission, both are directed away from PC1.

In conclusion, due to low air velocities it is most likely that no dominant air flow is present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time provide are most likely found near the emission source location, translating into a quick increase of the particle concentration.

ANNEX I RESULTS – COMMON LIVING ROOM AND DAY CARE AREA

Experiments in-situ

WP 2, experiments phase 1

DATUM	25 September 2023
AUTEURS	Ir. A. de Lange & ir. N. Lejeune
ORGANISATIE	TNO

Table of contents

1. Results baseline measurement location living room and day care area

The results represent the situation without any intervention to optimize the current ventilation system or situation.

Future interventions are divined 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 CO_2-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 the case of this location the intervention that will take place is currently unknown so will be described in the next report.

The current ventilation system or situation at this location is system C and consists five mechanical exhaust grills for the living room and one mechanical exhaust grill for the day care area.

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. In this location that meant that the windows and the doors were closed but the window grills were opened.

1.1 Characteristics of room and system

Description of the building

The long-term care facility is located in a suburban environment and was originally built in 2013. The building has four living rooms and four day care areas. For this research, both a living room and a day care area were measured.

1. Living room

The living room that was considered during this analysis, has a surface area of 61 m^2 and was located on the first floor. The façade was orientated towards the South-West and the height of the room was 2.65 m. During the measurements, this room was designed for 10 persons, 8 clients and 2 caretakers. A visualization of the room can be seen in Figure 1.1.

Figure 1.1 - Visualization of the living room during the measurements

Ventilation system in the living room

The ventilation system at this location is mechanical ventilation (natural supply and exhaust, system C). For air supply, the classroom has two window grills. For the exhaust of air, the room has five exhaust grills. There are, furthermore, two sliding doors present in the room which can be opened. It should be noted that the window grills were opened during the measurement and the sliding doors were closed. An overview of the ventilation system can be seen in Table 1.1. It should be noted that the ventilation in this room is CO_2 controlled and the design capacity of the ventilation system is 225 m^3/h.

Table 1.1 - Overview of the ventilation system present in the living room

Ventilation system		
	Type	Measured flow rate (m^3/h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Window grille	N/A
	Window grille	N/A
	Total	**N/A**
Ventilation (exhaust)		
	Ceiling grille	15
	Ceiling grille	15
	Ceiling grille	0
	Ceiling grille	14
	Ceiling grille	36
	Total	**80**

1. Day care area

The day care area that was considered during this analysis, has a surface area of 67 m^2 and was located in the basement. The façade was orientated towards the South-West and the height of the room was from 2.4 - 2.65 m. During the measurements, this room was designed for 10 persons, 8 clients and 2 caretakers. A visualization of the room can be seen in Figure 1.2.

Figure 1.2 - Visualization of the day care area during the measurements

Ventilation system in the day care area

The ventilation system at this location is mechanical ventilation (natural supply and exhaust, system C). For air supply, the classroom has four window grills. For the exhaust of air, the room has one exhaust grille. It should be noted that two of the window grills were opened during the measurement period to represent the real situation. An overview of the ventilation system can be seen in Table 1.2. It should be noted that the ventilation in this room is, contrary to the living room, not CO_2 controlled.

Table 1.2 – Overview of the ventilation system present in the day care area

Ventilation system		
	Type	Measured flow rate (m^3/h)
D (Mechanical supply and exhaust)		
Ventilation (supply)		
	Window grille	N/A
	Window grille	N/A
	Window grille	N/A
	Window grille	N/A
	Total	N/A
Ventilation (exhaust)		
	Ceiling grille	15
	Total	**15**

1.2 Description of standard methodology

Two different measurements were performed in both rooms, particle concentration measurements and air flow measurements. During both measurements, heat sources were present to represent the patients and caretakes in the room. The caretakers were represented as a mannequin with a heating blanket that emits 64 watt. There were, furthermore, seven static heat sources that each emit 80 watt representing the clients in the classroom. These static heat sources were only included in the day care area. 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 and Figure 1.4, for the living room and day care area respectively.

For the particle counters (PC) PC3, PC4 and PC5 were located at 1.2 m height since this represents the breathing zone of sitting clients. PC1 and PC6 is located at a height of 1.7 m since this represents the breathing zone of a standing care taker. PC2 was located near an exhaust point of the room. The emission of the particles took place at two different positions (E1 and E2), both at a height of 1.2 m.. Different particle sizes were 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 four different heights from 0.37 to 2.08 m. For these measurements, a grid of 1.0 x 1.0 m was created which in total resulted in 55 measurement points for both the living room and the day care area.

There were also sensors for measuring temperature, humidity and CO_2 concentration in the room.

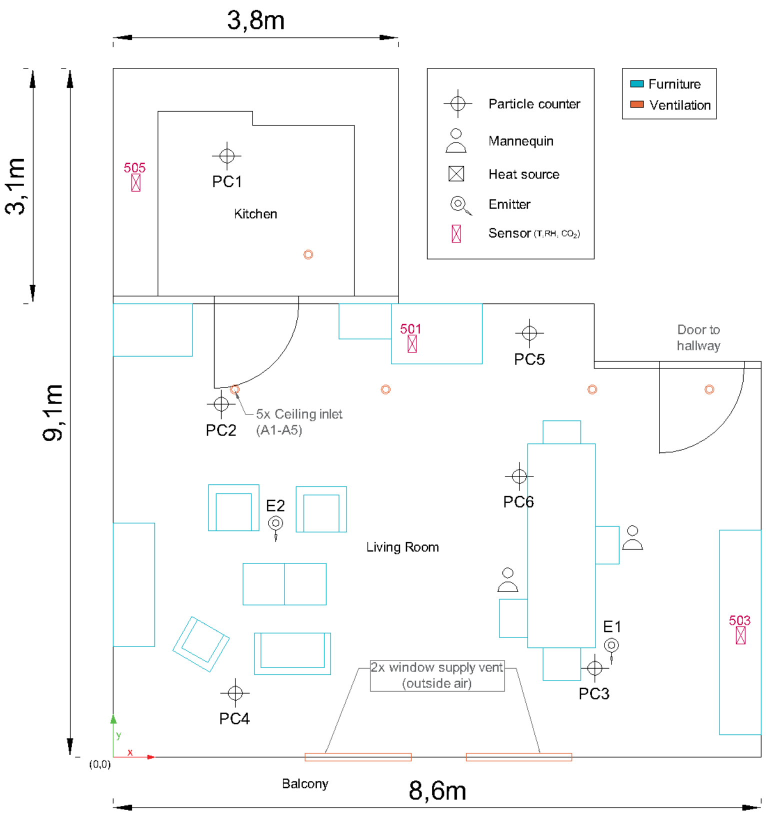

Figure 1.3 - Visualization of the living room during the measurements

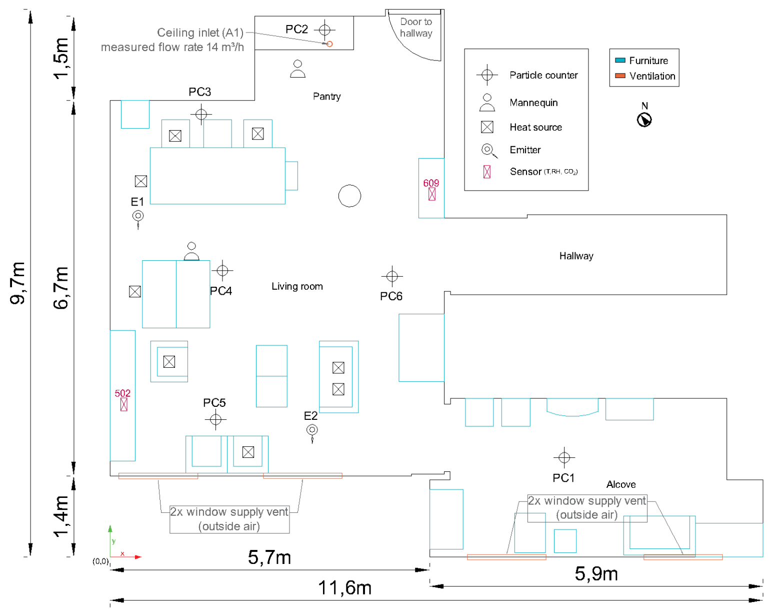

Figure 1.4 - Visualization of the day care area during the measurements

1.3 Deviations and details compared to standard methodology

This measurement was performed prior to other measurements and in a care facility instead of a school. This means that there are small deviations in terms of the height of the particle emitters and particle counters. Furthermore, during the measurements in the classroom a nozzle was added to the particle emitter to create more realistic emission of particles. This was, however, not yet included during these measurements. Lastly, for the living room, no static heat sources were added (only two mannequins).

1.4 Intervention

This will be described in the next report since it is currently unknown.

2. Results (before intervention)

Indoor & outdoor conditions

1. Living room

The indoor and outdoor conditions during the measurements can be seen in Table 2.1. The room temperature was between 18.7 and 22.7 °C throughout the day.

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

<table>
<tr><th colspan="5">12-04-2023</th></tr>
<tr><td rowspan="8">Surface area temperature (°C)</td><td></td><td colspan="2">10:30</td><td>18:00</td></tr>
<tr><td>Wall 1</td><td colspan="2">19.3</td><td>19.3</td></tr>
<tr><td>Wall 2</td><td colspan="2">20.0</td><td>20.6</td></tr>
<tr><td>Wall 3</td><td colspan="2">20.1</td><td>20.4</td></tr>
<tr><td>Wall 4</td><td colspan="2">17.8</td><td>18.5</td></tr>
<tr><td>Ceiling</td><td colspan="2">21.4</td><td>23.0</td></tr>
<tr><td>Floor</td><td colspan="2">20.2</td><td>21.1</td></tr>
<tr><td>Glass surface of the windows</td><td colspan="2">18.9</td><td>19.4</td></tr>
<tr><td></td><td></td><td>Min*</td><td>Mean*</td><td>Max*</td></tr>
<tr><td>Air temperature (°C)</td><td></td><td>18.7</td><td>21.3</td><td>22.7</td></tr>
<tr><td>Relative humidity (%)</td><td></td><td>31.2</td><td>40.6</td><td>53.6</td></tr>
<tr><td>Outdoor air temperature (°C)</td><td></td><td>6.2</td><td>9.4</td><td>12.7</td></tr>
<tr><td>Outdoor relative humidity (%)</td><td></td><td>51</td><td>73</td><td>97</td></tr>
<tr><td>Wind</td><td>Velocity (m/s)</td><td>3.5</td><td>7.7</td><td>10</td></tr>
</table>

	Direction	South – South - West (196°)

* The mean value is calculated by taking the average values one sensor between 11:00-20:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2. Day care area

The indoor and outdoor conditions during the measurements can be seen in Table 2.2. The room temperature was between 19.0 and 21.6 °C throughout the day.

Table 2.2 - Conditions during the measurement period. Wall 1: North-West, Wall 2: North-East, Wall 3: South-East, Wall 4: South-West. Metrological data is from weerstatistieken.nl of a nearby weather station.

12-04-2023				
Surface area temperature (°C)		*10:30*		*18:00*
	Wall 1	21.2		N/A
	Wall 2	21.8		22.0
	Wall 3	22.1		22.2
	Wall 4	21.9		23.4
	Ceiling	23.1		23.1
	Floor	22.1		22.6
	Glass surface of the windows	20.9		23.6
		Min*	Mean*	Max*
Air temperature (°C)		19.0	20.3	21.6
Relative humidity (%)		33.6	48.2	55.5
Outdoor air temperature (°C)		6.2	9.4	12.7
Outdoor relative humidity (%)		51	73	97
Wind	Velocity (m/s)	3.5	7.7	10
	Direction	South – South - West (196°)		

* The mean value is calculated by taking the average values one sensor between 11:00-20:00. Minimum and maximum are the smallest and largest value for all sensors combined in the given time period.

2.1 *Particle concentration measurements*

2.1.1 Living room

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 2.3 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time is the longest at location PC2 for emitter location E2 (67.1 min). For emitter location E1 the 100-fold increase time is also the longest at emitter location E2 (45.8 min). This particle counter is placed near the exhaust which means the particle concentration increases gradually. The 100-fold increase time is shortest at PC3 near emitter location E1 (2.1 min). PC3 is located near the emitter which means the particle concentration can increase faster. PC6 has the shortest 100-fold increase time for emitter location E2, this particle counter is located far from the emitter.

The 100-fold recovery time is dependent on the location of the particle emitter. The 100-fold recovery time is for all particle counters, except PC4, shorter at emitter location E1 than at emitter location E2. This means thar the particle concentration decreases faster when the particles are emitted at location E1 than at location E2. The 100-fold recovery time is very similar at both emitter locations for PC2 (235.2 – 236.7 min), this is the particle counter located near the exhaust were the decrease goes more gradually. The 100-fold recovery time is longest for PC4 for both emitter locations (N/A - 324.2 min). For emitter location E1, the particle concentration increased during the recovery period which results in a negative value for the 100-fold recovery time (this is shown as N/A).

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. These values are calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For care facilities the results are compared with 'Bouwbesluit 2012'. For newly build the requirement is 1.33 ACH (234 m^3/h); with an occupation of 10 persons. For existing build the requirements is 0.71 ACH (124 m^3/h); with an occupation of 10 persons. When these values are compared with the ACH values in Table 2.3, it can be seen that for emitter location E1 PC2 and PC4 do not meet the requirements for newly build care facilities. For emitter location E2, PC1, PC2 and PC4 do not meet the requirements for newly build care facilities.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} is the longest for PC4 emitter location E1 (10.3 min). This location also had a very 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. The t_{delay} is shortest for PC3 emitter location E1 (0.8 min). This means that at this location the decrease of the particle concentration starts quickly after the emission stopped.

Table 2.3 - 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	34.7	160.8	1.7	2.5
	E2	44.8	203.7	1.3	4.5
PC2	E1	45.8	236.7	1.2	8.8
	E2	67.1	235.2	1.2	6.0
PC3	E1	2.4	79.3	3.5	0.8
	E2	16.3	142.6	2.0	3.5
PC4	E1	34.1	N/A*	N/A	10.3
	E2	38.0	324.2	0.9	3.0
PC5	E1	9.3	91.3	3.0	2.0
	E2	12.3	148.6	1.9	3.8
PC6	E1	9.6	93.6	3.0	2.5
	E2	7.1	146.5	1.8	0.8

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

2.1.2 Day care area

The different variables that were discussed in chapter 3 are calculated for each measurement location and set-up. Table 2.4 gives an overview of the results for each measurement location (PC1 – PC6). The 100-fold increase time is the shortest at PC2 for emitter location E1 (7.8 min). This particle counter is, however, not location near the emitter. The 100-fold increase time is longest for emitter location E2 for both PC1 and PC2. PC2 is located near the exhaust of the room which means the increase in the particle concentration goes more gradually. There is a large difference for PC2 between emitter location E1 and emitter location E2. This could be related to the large difference is distance between PC2 and both emitter location.

The 100-fold recovery time is dependent on the location of the particle emitter. The 100-fold recovery time is longest for PC6 at emitter location E2 (3643 min). The 100-fold recovery time is also long for emitter location E2 PC2, this location also has the longest 100-fold increase time. The 100-fold recovery time is shortest at PC4 emitter location E2 (78.5 min) and PC5 emitter location E2 (90 min). Both particle counters are located close to the emitter.

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. These values are calculated to be able to compare the current performance of the ventilation system with the Dutch Building regulations. For care facilities the results are compared with 'Bouwbesluit 2012'. For newly build the requirement is 1.34 ACH (234 m^3/h); with an occupation of 10 persons. For existing build the requirements is 0.71 ACH (124 m^3/h); with an occupation of 10 persons. When these values are compared with the ACH values in Table 2.4, it can be seen that for emitter location E2 PC2 and PC6 do not meet the requirements for newly build care facilities, all other values meet the requirements.

Finally, t_{delay} was calculated for all measurement locations. t_{delay} is the longest for PC2 at emitter location E2, the 100-fold increase time was also the longest at this location. t_{delay} is shortest for PC4 emitter location E1 (2.8 min) and PC5 at emitter location E2 (3.5 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.

Table 2.4 - 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	34.1	204	1.4	9.5
	E2	49.7	105	2.6	5.0
PC2	E1	17.9	148	1.9	6.3
	E2	43.1	N/A*	N/A	12
PC3	E1	33.1	94	2.9	3
	E2	13.1	85	3.3	4.8
PC4	E1	10.5	160	1.7	2.8
	E2	14.3	78.5	3.5	5.5
PC5	E1	15.6	119	2.3	3.8
	E2	9.3	90	3.1	3.5
PC6	E1	7.8	90	3.1	4.3
	E2	28.3	3.643	0.1	8.8

* 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 PC3, PC4 and PC5 the measurements have been analyzed at a height of 0.94 m. For PC1 and PC6, the measurements have been analyzed at a height of 1.51 m.

2.2.1 Living room

The direction and velocity of the air flow at a height of 0.94 m can be seen in Figure 2.1 (range 0.01 – 0.21 m/s). The average air velocity in the room is 0.03 m/s. There is only a small area (near the windows) were the max air velocity is achieved of 0.21 m/s.

In Figure 2.1 an air flow from the windows towards the exhaust points of the room is present. There is an air flow in the direction of emitter location E1 and DT3 from the windows.

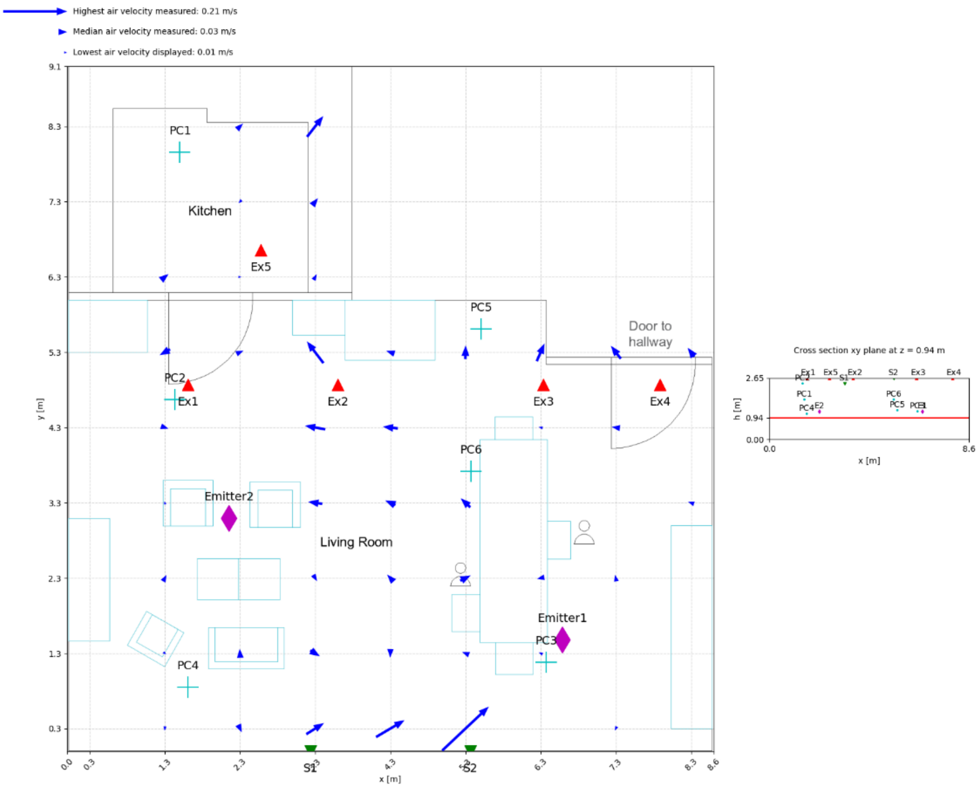

Figure 2.1 - Air flow (direction and velocity) in the XY-plane at a height of 0.94 m.

For PC1 and PC6, the air flow is analyzed at a height of 1.51 m, see Figure 2.2 (range 0.01 – 0.21 m/s). Once again, there is an air flow from the windows inwards towards the exhausts. There is also an air flow from the location of the exhausts towards the kitchen. Specifically for the particle counters, it is hard to see a dominant air flow for both PC1 and PC6. An air flow with low velocities from emitter location E1 in the direction of PC6 is present. Furthermore, an air flow can be seen directed from exhaust (Ex2) in the direction of the kitchen and PC1.

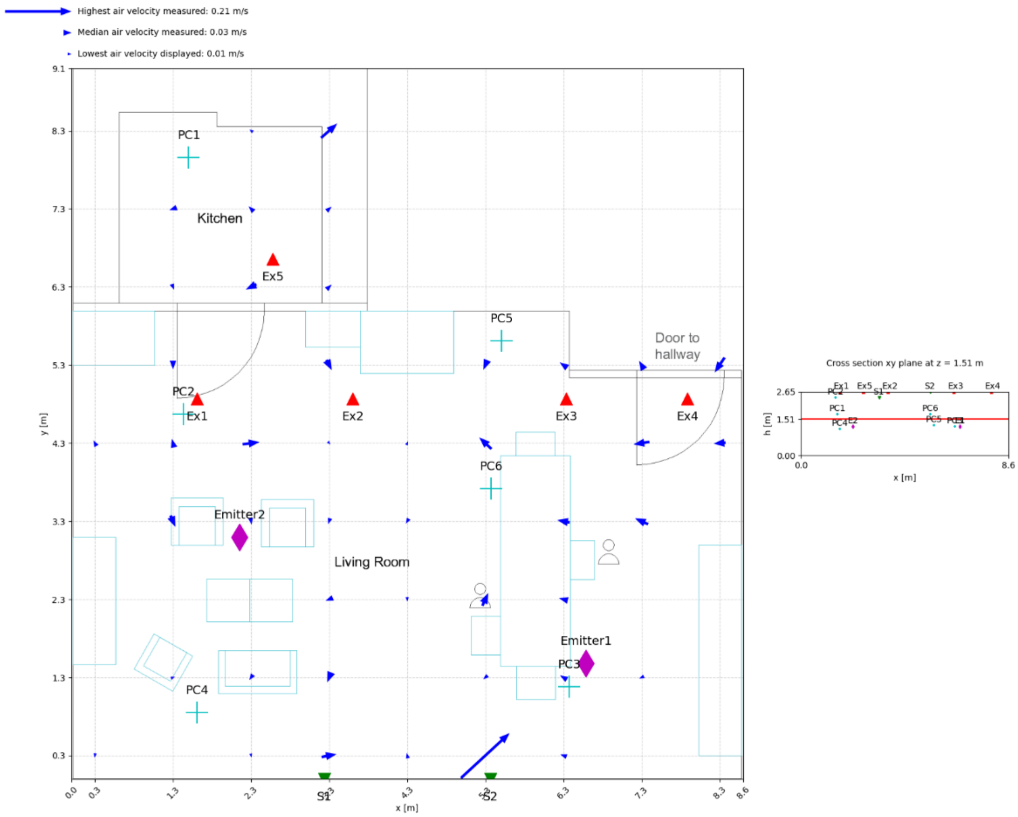

Figure 2.2 - Air flow (direction and velocity) in the XY-plane at a height of 1.51 m.

2.2.2 Day care area

The direction and velocity of the air flow at a height of 0.94 m can be seen in Figure 2.3 (range 0.01 – 0.07 m/s). There is no clear air flow in the day care area, the air velocity are highest between the windows and the exhaust but a dominant air flow is not obtained from the results. There seems to be an air flow directed away from emitter location E2. Furthermore, the air velocities are low at PC4 and PC5 and air flow is directed away from these particle counters.

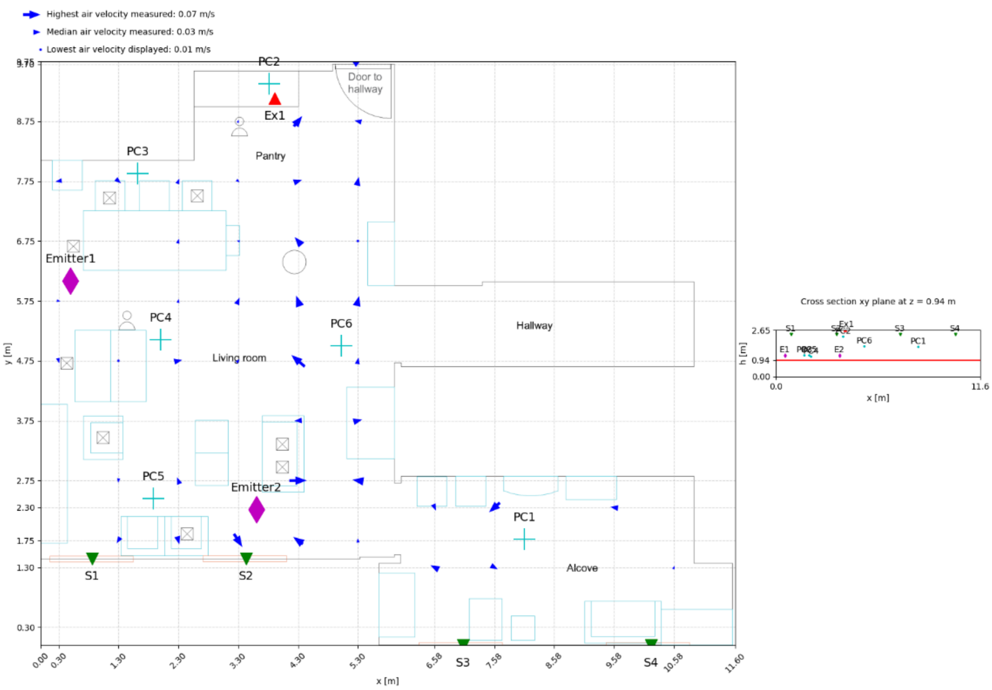

Figure 2.3 - Air flow (direction and velocity) in the XY-plane at a height of 0.94 m.

For PC1 and PC6, the air flow is analyzed at a height of 1.51 m, see Figure 2.4 (range 0.01 - 0.1 m/s). For this height, the air flow is (once again) hard to determine. Specifically for the particle counters, an air flow with low air velocities from emitter location E2 towards the window is present, this air flow is directed away from PC6.

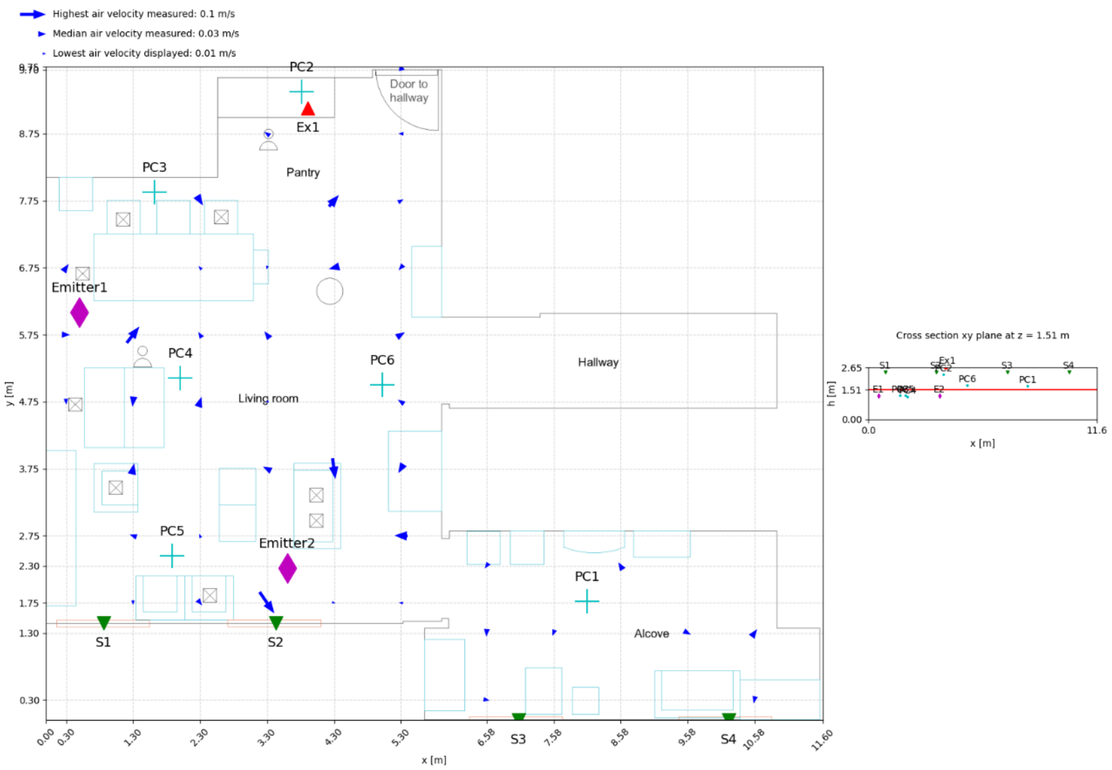

Figure 2.4 - Air flow (direction and velocity) in the XY-plane at a height of 1.51 m.

3. Conclusions

Performance of the ventilation system before interventions is described through the outcome parameters.

3.1 Living room

3.1.1 Particle concentration measurements

100-fold increase time

The 100-fold increase time has a range of 2.4 – 45.8 min for emitter location E1 and has a range of 7.1 – 67.1 min for emitter location E2. The 100-fold increase time is the longest on location PC2 for both emitter location E1 and E2. This is the measurement location close to the exhaust. In general, the closer the particle counter location to the emission location, the shorter the 100-fold increase time and vice versa. An exception on this rule is PC6, E2, this location has a short 100-fold increase time (7.1 min) but is located relatively far from the emitter.

100-fold recovery time

The 100-fold recovery time has a range of 79.3 – N/A min for emitter location E1 and has a range of 142.6 – 324.2 min for emitter location E2. The 100-fold recovery time shorter at all locations, except PC4, at emitter location E1 compared to emitter location E2. Measurements with a long 100-fold recovery time are often located far away from the emitter location.

t_{delay}

t_{delay} has a range of 0.8 – 10.3 min for emitter location E1 and has a range of 0.8 – 6.0 min for emitter location E2. The 100-fold increase time is shortest for PC3 (E1), at this location the delay was also the shortest (0.8 min). This means that the decrease of the particle concentration starts quickly after emission. In general, the closer the particle location to the emission location, the shorter the t_{delay} and vice versa.

Air change per hour

The ACH has a range of N/A – 3.5 ACH for emitter location E1 and has a range of 0.9 – 2.0 ACH for emitter location E2. These small air change rates indicate that it takes relatively long to decrease the particle concentration in this care facility. These air change rates do meet the requirement for existing buildings but do not meet all requirements for newly build care facilities.

3.1.2 Air flow measurements

The analysed air velocities were low during the air flow measurements, only near the windows there was a clear air flow present. When the particle concentration measurements and the air flow measurements are compared it can be seen that at a height of 0.94 m there is an air flow running from the window in the direction of E1 and PC3. PC3 has a short 100-fold increase time and a short 100-fold recovery time. This can, however, also be explained by the small distance between the particle counter and the emitter. For a height of 1.51 m an air flow in the direction of PC6 from emitter location E1 was present. PC6 has a short 100-fold increase time for emitter location E1, this can be explained by this air flow.

In conclusion, due to low air velocities it is most likely that no dominant air flow is present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time provide are most likely found near the emission source location, translating into a quick increase of the particle concentration. Often, the 100-fold recovery time is low near the emission source location, indicating an efficient removal of the particle concentration at that measurement location.

3.2 Day care area

3.2.1 Particle concentration measurements

<u>100-fold increase time</u>

The 100-fold increase time has a range of 7.8 – 34.1 min for emitter location E1 and has a range of 9.3 – 49.7 min for emitter location E2. The 100-fold increase time is the shortest at PC6 for emitter location E1 (7.8 min). This particle counter is not located near the emitter. The 100-fold increase time is the longest for emitter location E2 at PC2, this particle counter is placed near the exhaust.

<u>100-fold recovery time</u>

The 100-fold recovery time has a range of 90 – 204 min for emitter location E1 and has a range of 78.5 – N/A min for emitter location E2. The 100-fold recovery time is dependent on the emitter location. The 100-fold recovery time is longest for PC6 at emitter location E2 (3643 min). The 100-fold recovery time is also long for emitter location E2 PC2, this is also the location with the longest 100-fold increase time. The 100-fold recovery time is shortest at PC4 emitter location E2 (78.5 min). Measurements with a long 100-fold recovery time are often located far away from the emitter location.

<u>t_{delay}</u>

t_{delay} has a range of 2.8 – 9.5 min for emitter location E1 and has a range of 3.5 – 12.0 min for emitter location E2. The delay was longest for PC2 at emitter location E2, at this location the 100-fold increase time was also the longest. The shortest t_{delay} is at PC4 emitter location E1 (2.8 min), this location is located close to the emitter location. In general, the closer the particle location to the emission location, the shorter the t_{delay} and vice versa.

<u>Air change per hour</u>

The ACH has a range of 1.4 – 3.1 ACH for emitter location E1 and has a range of N/A – 3.5 ACH for emitter location E2. These small air change rates indicate that it takes relatively long to decrease the particle concentration in this care facility. These air change rates do meet the requirements for existing buildings according to 'Bouwbesluit 2012' but do not all meet the requirements for newly built care facilities.

3.2.2 Air flow measurements

The air velocities were low during the measurements in the day care area. There is no clear dominant air flow present in the room and there is no air flow present towards the exhaust of the room. The particle concentration measurements and the air flow measurements can be compared with each other to potentially explain the results. At a height of 0.94 m an air flow can be seen from emitter location E2 towards PC6 (away from PC4 and PC5), this is an air flow with a low velocities. Furthermore, an air flow directed away from PC3 is present which could explain the short 100-fold recovery time at this location. For a height of 1.51 m, there seems to be an air flow from emitter location E2 towards PC6 but not towards PC1, this could explain the long 100-fold increase time at this location.

In conclusion, due to low air velocities it is most likely that no dominant air flow is present. The particle spread throughout the room is therefore dependent on the proximity of the particle counter to the emission source location. A short t_{delay} and 100-fold increase time provide are most likely found near the emission source location, translating into a quick increase of the particle concentration. Often, the 100-fold recovery time is low near the emission source location, indicating an efficient removal of the particle concentration at that measurement location.