Health-based target ventilation rates and design method for reducing exposure to airborne respiratory infectious diseases

Nordic Ventilation Group proposal for post-COVID target ventilation rates

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Colophon

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Health and comfort ventilation in non-residential buildings

Owing to the fact that SARS-CoV-2 and other respiratory pathogens have been shown to be effectively transmitted through the inhalation exposure route, the importance of ventilation for reducing exposure to COVID-19 and other airborne respiratory infectious diseases is widely recognised. However, no method is available to design building ventilation and other measures to protect occupants against respiratory disease transmission. The current design of ventilation according to existing indoor climate standards EN 16798-1:2019 and ISO 17772-1:2017 has been limited to the use of ventilation criteria based on the perceived air quality (odours) depending on emissions from humans and a building and on specific pollutant concentration control. This approach neglects respiratory disease transmission for which the key engineering measure is ventilation, supported, if necessary, with air filtration and air disinfection [1].

The infection risk-based ventilation design method proposed in this document provides target ventilation rates for mitigating infectious disease risk and is intended to complement existing ventilation design methods in non-residential buildings, excluding healthcare and industrial buildings. Applying these ventilation rates will reduce the spread of respiratory viruses such as SARS-CoV-2, common cold, influenza, and others, at least to the risk level where one infectious person will not infect more than one other person during the pre-symptomatic infectious period. In this method, the reproduction number is set to R=1, and it is assumed that the likelihood of infecting others is constant during the total interaction time with susceptible persons. This method is applicable for long-range airborne transmission; thus, close proximity is to be avoided, which can be done by maintaining at least 1.5 m physical distance between occupants during an epidemic. It is proposed that the target ventilation rates be applied in the design of new buildings and renovations so that the highest of health- and comfort-based ventilation rates is used as the design capacity of the ventilation system. Health-based ventilation rates may be higher than comfort ventilation rates and are required only during epidemic periods. In normal conditions – that is, outside of epidemic periods – a demand-controlled operation is recommended to comply with comfort-based values and to optimise the energy used for ventilation. Meanwhile, for demand-controlled ventilation, buildings must be provided with devices to measure indoor air quality and equipment to control air quality with ventilation or other means.

Definitions

Target ventilation rate is the required outdoor air ventilation airflow rate in **the breathing** zone determined as the highest value given by the perceived air quality (Equation 1) and infection-risk-based (Table 1 and Table 2) ventilation design methods.

Design ventilation rate is the outdoor air ventilation airflow rate supplied by the ventilation system to **the room** with an actual air distribution system, calculated as the highest value from Equations 2 and 4.

Ventilation effectiveness ε_v is the ratio of the ventilation rate with the fully mixing airflow rate and actual air distribution system with distributed contaminant source to achieve the same concentration of contaminant in the breathing zone. For fully mixing $\varepsilon_v = 1$.

Point source ventilation effectiveness ε_b describes ventilation effectiveness with a point source and is to be measured at least with two positions of source (infector). It is calculated as an average of two or more tracer gas measurements while 50% of measurement points with the highest concentration are accounted for in each measurement.

Regulation of indoor air quality may be achieved using a demand-controlled ventilation system that is operated during epidemic periods at design ventilation rates and outside the epidemic periods according to CO_2-controlled perceived air quality ventilation rates and supported with source control and outdoor air filtration.

1. Current design with perceived air-quality-based ventilation rates

EN 16798-1:2019 and ISO 17772-1:2017 specify indoor air quality and ventilation rates based on perceived air quality as the first method (6.3.2.2 Method 1). This method is applicable in indoor spaces where the criteria for indoor environments are set by human occupancy and where the production or process does not have a major impact on the indoor environment. A health-based respiratory infection risk design method is intended to complement this method so that the highest ventilation rate given by these two methods will be used to determine the system's design.

In non-residential buildings, design ventilation rates in occupied rooms are calculated based on perceived air quality by the visitors (unadapted persons) depending on the emissions from humans and building materials. The target outdoor air flow rate is calculated as follows:

$$q_{tot} = Nq_p + A_R q_B \quad (1)$$

where

q_{tot} total outdoor air ventilation rate for the breathing zone, L/s

N design value for the number of persons in the room,

q_p ventilation rate for occupancy per person, L/(s person)

A_R room floor area, m^2

q_B ventilation rate for emissions from building, L/(s m^2)

For low-polluting materials, the outdoor air ventilation rates in Equation 1 are (1 L/s = 3.6 m^3/h):

- 10 L/s per person + 1 L/s per floor area in Category I;
- 7 L/s per person + 0.7 L/s per floor area in Category II (default, representing a normal level of expectation);
- 4 L/s per person + 0.4 L/s per floor area in Category III.

When very low-polluting certified building materials are used, L/s per floor area values are by factor 2 smaller, and in the case of non-low-polluting certified building materials are by factor 2 higher.

In the case of specific pollutants, the design ventilation rates are calculated based on a mass balance equation for the substance concentration in the space, taking into account the outdoor concentration (6.3.2.3 Method 2 using criteria for individual substances). This method is not discussed in this document because it is used only very rarely.

Outdoor air ventilation rates calculated using Equation 1 apply at fully mixing air distribution. For actual air distribution solutions, the design ventilation rate supplied by the ventilation system is calculated as follows:

$$q_s = \frac{q_{tot}}{\varepsilon_v} \tag{2}$$

where

q_s design ventilation airflow rate at actual air distribution solution (L/s)

ε_v ventilation effectiveness as defined in EN 16798-3:2017, contaminant removal effectiveness in REHVA GB No 2 (-)

Ventilation effectiveness can be calculated using measured tracer gas concentrations:

$$\varepsilon_v = \frac{C_e - C_o}{C_i - C_o} \tag{3}$$

where

C_e concentration in the extract air duct

C_i average concentration at the breathing level

C_0 concentration in the supply air

Ventilation rates q_s calculated using Equation 2 should be compared with health-based infection risk ventilation target rates Q_s and the higher value should be used for ventilation system sizing as the design ventilation rate.

2. Health-based target ventilation rates for occupied spaces

Infection-risk-based outdoor air target ventilation rates for rooms occupied by humans can be calculated using the equations shown in Table 1. These airflow rates do not take into account the reduced risk caused by vaccination and apply to cases in which no face masks are being worn, no portable air cleaners are being used, and there is fully mixing air distribution and other assumptions reported in Appendix 1.

Table 1. Target outdoor air ventilation rates Q (L/s) are calculated using the number of persons in room N (-) and the room volume V (m^3).

Space category	Ventilation rate, L/s
Classroom	$Q = 10(N-1) - 0.24V$
Office	$Q = 23(N-1) - 0.24V$
Assembly hall	$Q = 30(N-1) - 0.24V$
Meeting room	$Q = 40(N-1) - 0.24V$
Restaurant	$Q = 40(N-1) - 0.24V$
Gym	$Q = 70(N-1) - 0.24V$

Target outdoor air ventilation rates calculated using the equations in Table 1 apply at fully mixing air distribution. For an actual air distribution solution, the design ventilation rate supplied by the ventilation system is calculated as follows:

$$Q_s = \frac{Q}{\varepsilon_b} \tag{4}$$

where

Q_s design ventilation airflow rate at actual air distribution solution (L/s)

ε_b point source ventilation effectiveness for the breathing zone (-)

Point source ventilation effectiveness can be calculated as an average of two or more tracer gas measurements with different source locations, while 50% of measurement points with the highest concentration are accounted for in each measurement *j*:

$$\varepsilon_b^j = \frac{C_{je} - C_{jo}}{C_{jb} - C_{jo}} \tag{5}$$

$$\varepsilon_b = \frac{\sum_j \varepsilon_b^j}{m} \tag{6}$$

where

ε_b^j point source ventilation effectiveness of measurement *j*

ε_b point source ventilation effectiveness

C_{je} measurement *j* concentration in the extract air duct

C_{jb} measurement *j* concentration at the breathing level that is calculated as an average concentration of 50% of the measurement points having the highest concentrations (local air quality index in REHVA GB No 2)

C_{j0} concentration in the supply air

m total number of measurements with different point source locations

The ventilation effectiveness ε_b can be determined using the contaminant point source (corresponding to an infector) so that at least two locations of the point source are measured or CFD-simulated. Point source ventilation effectiveness differs from the ε_v in Equation 2, which is determined using the distributed contaminant source corresponding to normal occupancy of all occupants and concentration C_i calculated as an average of all measurement points at the breathing level. For the cross-infection risk assessment, to take into account potentially higher concentration near the point source, the concentration C_{jb} is calculated in each measurement from half of the measurement points having the highest concentrations. However, the measurement points closer than 1.5 m to the source should not be used. Two or more measurements with different point source location must be conducted and ε_b value is calculated as an average of these measurements. Generally, ventilation effectiveness depends on air distribution, source location, heat gains etc., and the values representing typical occupant locations and the largest expected deviations from distributed source results should be determined either experimentally or by CFD simulation.

In the case of fully mixing air distribution, C_{jb} is equal everywhere in the breathing zone and in the extracted air, resulting in $\varepsilon_b = \varepsilon_v = 1.0$. This may well apply to rooms up to 50 m^2 with mixing ventilation. In larger rooms and rooms with partitions, infectious quanta emission is expected to spread in such a way that higher and lower concentration zones will be formed. This is taken into account when using C_{jb} values that neglect 50% of measurement points with lower

concentrations. In large rooms, ε_b values may be reduced to 0.8 or even to 0.5 in rooms >200 m^2. Advanced air distribution solutions, such as displacement, occupant-targeted, and personal ventilation, have the potential to reach $\varepsilon_b > 1.0$.

Portable air cleaners may compensate for a part of the infection-risk-based outdoor air ventilation rate. Portable air cleaners will be placed in such a way as to enable air to be distributed evenly to the breathing zone (mixing by air cleaners may also improve ventilation efficiency) in the room or zone with volume V. For a portable air cleaner, the filtration removal rate k_f (1/h) is calculated based on the rate of airflow through the filter Q_f (m^3/h), the ePM1 removal efficiency of the filter η_f (-), and the room volume V (m^3):

$$k_f = \frac{Q_f \eta_f}{V} \tag{7}$$

For portable cleaners with a high-efficiency particle air (HEPA) filter, the clean air delivery rate (CADR, m^3/h) can be used to calculate the filtration removal rate as $k_f = CADR/V$. Outdoor air ventilation rates with portable air cleaners for common spaces can be calculated using the equations shown in Table 2.

Table 2. Target outdoor air ventilation rates Q (L/s) with portable air cleaners are calculated based on the number of persons in the room N (-) and the volume of the room V (m^3).

Space category	Ventilation rate, L/s
Classroom	$Q = 10(N-1) - (0.87 + k_f)\, V/3.6$
Office	$Q = 23(\mathrm{N}-1) - (0.87 + k_f)\, V/3.6$
Assembly hall	$Q = 30(N-1) - (0.87 + k_f)\, V/3.6$
Meeting room	$Q = 40(N-1) - (0.87 + k_f)\, V/3.6$
Restaurant	$Q = 40(N-1) - (0.87 + k_f)\, V/3.6$
Gym	$Q = 70(N-1) - (0.87 + k_f)\, V/3.6$

For high-capacity portable air cleaners it is possible for the outdoor air ventilation rate Q to become negative, indicating that air cleaners and deposition and decay removal mechanisms are sufficient to remove the virus. However, the design outdoor air ventilation rate must always be equal to or larger than the value based on Equation 2.

3. Demand-controlled operation of ventilation systems

3.1. Health-based ventilation control

During epidemic periods such as those caused by seasonal influenza or COVID-19, the change from normal operation to design outdoor air ventilation airflow rates (the higher value of Equations 2 and 4), must be managed manually because respiratory pathogen sensors are currently not available for automatic control. Design ventilation airflow rates are required during regular operation hours of the ventilation system. In ventilation systems controlled according to room CO_2 and temperature sensors, this can be done using the CO_2 setpoint change to 550 ppm. With a 550-ppm setpoint, ventilation will be operated during regular operating hours continuously at full speed in rooms with normal occupant density and at reduced speed in rooms with lower occupancy.

3.2. Comfort ventilation control

Outside the epidemic periods, ventilation systems are to be operated according to perceived air quality design ventilation rates (Equation 2). It is recommended that buildings be equipped with measuring and control devices for the regulation of indoor air quality (IAQ). The direct measurement of indoor air pollutants is impracticable and generally requires sampling. Therefore, as an alternative, CO_2 concentration can be continuously monitored as a proxy for ventilation and IAQ. Low-cost sensors are also available for particulate matter $PM^2_{.5}$ monitoring. These are especially needed in natural ventilation and hybrid ventilation systems where outdoor air filtration may depend on the operation mode.

CO_2 concentration monitoring as a proxy for IAQ monitoring can be applied using the following preconditions:

- Source control must be applied for pollution sources from building materials and interior through the use of low polluting building materials as defined in EN 16798-1:2019;
- Ventilation systems must be equipped with fine particle filters of ePM1 or $ePM^2.5$ as specified in EN 16798-3:2017;
- No specific sources of pollutants (other than building emissions) to meet WHO guideline values for indoor and outdoor air pollutants as defined in EN 16798-1:2019;
- The CO_2 sensor must be positioned in such a way as to enable it to measure the room concentration, not the concentration of supply air – for instance, the position on the wall must be selected so that supply air jets attached to the ceiling and wall do not reach the sensor.

These four preconditions, together with correct CO_2 setpoints, ensure that gas-phase pollutants and particulate matter will remain below limit values. Commonly available temperature and CO_2 sensors and controllers can be used to regulate IAQ (Figure 1). In natural and hybrid ventilation systems, in which operation modes without outdoor air filtration with fine particle filters exist, CO_2 concentration monitoring will be complemented with $PM^2_{.5}$ monitoring.

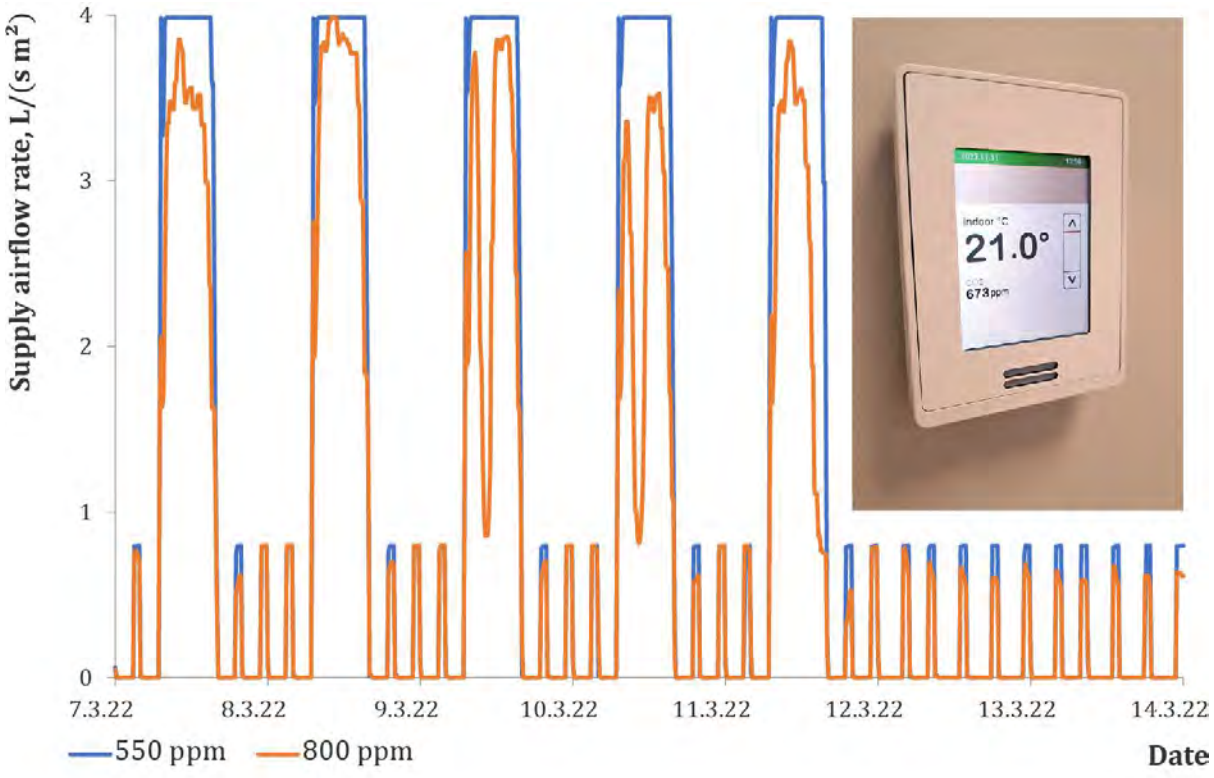

Figure 1. Example of IAQ regulation with common room CO_2 and temperature sensors in a typical classroom over the course of one week. Ventilation airflow rates with CO_2 set point of 550 ppm and 800 ppm.

In Figure 1, it can be seen that the epidemic period CO_2 setpoint change to 550 ppm has resulted in a constant air volume operation at full speed. Outside of operation hours, ventilation is switched on and off with one hour operation periods at the lowest possible fan speed in order to achieve an average 0.15 L/(s m^2) ventilation rate outside of operation hours according to EN 16798-1:2019.

CO_2 concentration setpoints can be calculated based on the perceived air quality ventilation rate per person, which is calculated from the total outdoor air ventilation rate for the breathing zone (Equation 1) and ventilation effectiveness (Equation 3):

$$q_{PAQ} = \frac{q_{tot}}{\varepsilon_v N} \tag{8}$$

where

q_{PAQ} perceived air quality ventilation rate per person (L/(s person))

q_{tot} total outdoor air ventilation rate for the breathing zone calculated with Equation 1 (L/s)

ε_v ventilation effectiveness as defined in EN 16798-3:2017 (-)

N the number of persons in the room (-)

CO_2 concentration setpoints can be calculated from metabolic CO_2 generation and CO_2 volume balance:

$$C = C_{out} + \frac{q_{CO2}}{q_{PAQ}} \frac{1000}{3.6} \quad (9)$$

where

C CO_2 concentration setpoint value (ppm)

C_{out} outdoor air CO_2 concentration, typically 400 ppm

q_{CO_2} CO_2 generation rate of 18 L/(h person) in classrooms, 20 L/(h person) in offices, meeting rooms, and restaurant, and 80 L/(h person) in gym

$\frac{1000}{3.6}$ 3600 and 10^6 are unit conversions from hour to second and litre to ppm

CO_2 concentration setpoint values calculated using Equation 9 depend considerably on the occupant density. Therefore, the following values for rooms with typical occupancy may be used as CO_2 setpoints:

- 800 ppm in classrooms and meeting rooms;
- 650 ppm in offices, restaurants, and gyms.

These CO_2 setpoint values satisfy Category I (EN 16798-1:2019), the perceived air quality in most conditions. The same values may also be applied in ventilation systems designed according to Category II, where indoor concentrations may exceed setpoint values during higher occupancy periods.

4. Calculated airflow rates for some rooms

The application of Infection-risk-based ventilation rate equations in Table 1 is illustrated using calculation examples for typical spaces in Table 3. Infection-risk-based ventilation rates are calculated as L/s per person and floor area as well as air change rates for selected rooms. These values are then compared with Category I and II (EN 16798-1) ventilation rates, calculated using Equation 1 with the assumption of low-polluting building materials. In the infection-risk-based ventilation rate calculation, point source ventilation effectiveness values estimated for typical mixing ventilation solutions are used. In the case of Category I and II ventilation rates, fully mixing air distribution is assumed (ε_v = 1.0) because, in this case, instead of one infector/point source, all occupants emit pollutants (human bio effluents and CO_2). Therefore, the emission source is also equally distributed and fully mixed to room air in large rooms with common mixing ventilation solutions. Meanwhile, CO_2 concentrations are calculated using an outdoor concentration of 400 ppm and CO_2 generation rates of 18 L/h in classrooms, 20 L/h in offices, meeting rooms, and restaurants and 80 L/h in the gym.

In classroom and office cases, which are highlighted in Table 3, Category I and Category II ventilation rates are higher than infection-risk-based ventilation rates. In meeting rooms and restaurants, the airflow rates are high even with reduced occupancy, indicating that these rooms require air distribution solutions with higher ventilation effectiveness to achieve a feasible ventilation design. However, in such rooms, a 1.5 m distance requirement will lead roughly to 50% occupancy (every second seat empty); therefore, the ventilation rates shown in the table with normal occupancy are not relevant.

Table 3. Calculation example of health- and comfort-based ventilation rates in typical rooms. Infection-risk-based ventilation rates are calculated using equations shown in Table 1 and Category II and I comfort ventilation with Equation 2. CO_2 concentration is calculated from the infection-risk-based ventilation rate with Equation 8.

				Infection-risk-based ventilation					Comfort ventilation	
	Floor area	Room height	No of persons	Ventilation effectiveness	Ventilation rate	Ventilation rate	Air change rate	CO_2 conc.	Cat. II ventilation	Cat. I ventilation
	m^2	m	N, -	ε_b, -	L/(s pers)	L/(s m^2)	1/h	ppm	L/(s m^2)	L/(s m^2)
Small classroom	31.6	3.5	13	1.00	7.2	3.0	3.0	1097	3.6	5.1
Classroom	42.5	2.9	25	0.91	9.2	5.4	6.7	941	4.8	6.9
Classroom	56.5	2.9	25	0.90	8.9	3.9	4.9	962	3.8	5.4
reduced occ.	56.5	2.9	20	0.90	8.4	3.0	3.7	999	3.2	4.5
Large teaching space	129.5	2.9	50	0.60	13.3	5.1	6.4	776	3.4	4.9
reduced occ.	129.5	2.9	40	0.60	12.5	3.8	4.8	801	2.9	4.1
2-person office	21.0	2.6	2	1.00	4.9	0.5	0.6	1535	1.4	2.0
Open-plan office	56.7	2.6	6	0.80	16.5	1.7	2.4	736	1.4	2.1
Open-plan office	173.0	2.6	17	0.60	25.4	2.5	3.5	619	1.4	2.0
Meeting room	29.2	2.6	10	1.00	34.2	11.7	16.2	563	3.1	4.4
reduced occ.	29.2	2.6	6	1.00	30.3	6.2	8.6	584	2.1	3.1
Meeting room	52.5	3.2	24	0.80	45.8	20.9	23.6	521	3.9	5.6
reduced occ.	52.5	3.2	12	0.80	41.6	9.5	10.7	534	2.3	3.3
Restaurant	259.5	2.9	154	0.60	64.3	38.1	47.3	486	4.9	6.9
reduced occ.	259.5	2.9	50	0.60	59.3	11.4	14.2	494	2.0	2.9
Gym	173.5	3.5	12	0.60	86.5	6.0	6.2	657		
School gym	217.5	6.0	25	0.50	109.1	12.5	7.5	604		

Appendix 1: Infection-risk-based ventilation rates

Required outdoor air ventilation rate in the steady state at a given infection risk probability and fully mixing air distribution can be calculated as follows [2]:

$$Q = \frac{(1-\eta_i) I q Q_b (1-\eta_s) \mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k + k_f + k_{UV}\right) V \tag{10}$$

where

Q outdoor air ventilation rate (m^3/h)

p probability of infection for a susceptible person (-)

q quanta emission rate per infectious person (quanta/(h pers))

Q_b volumetric breathing rate of an occupant (m^3/h), see Table 1

I number of infectious persons (-), default value I = 1

η_s facial mask efficiency for a susceptible person (-)

η_i facial mask efficiency for an infected person (-)

D duration of the occupancy (h)

λ_{dep} deposition onto surfaces (1/h)

k virus decay (1/h)

k_f filtration by a portable air cleaner (1/h)

k_{UV} disinfection by upper room ultraviolet germicidal irradiation UVGI (1/h)

V volume of the room (m^3)

This general equation includes other potential virus removal mechanisms in addition to outdoor air ventilation, such as air cleaners, UVGI, and facial masks, which may not be present in many situations. In the case of one infectious person, no facial masks, and no air cleaners and UVGI, Equation 10 simplifies this to the following:

$$Q = \frac{q Q_b \mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k\right) V \tag{11}$$

If a portable air cleaner is used, the filtration removal rate (k_f) is calculated based on the airflow rate through the filter (Q_f), the removal efficiency of the filter (η_f), and room volume V:

$$k_f = \frac{Q_f \eta_f}{V} \tag{12}$$

For portable cleaners with a high-efficiency particle air (HEPA) filter, the clean air delivery rate (CADR, m^3/h) can be used to calculate the filtration removal rate as k_f = CADR/V. The removal efficiency of filters and the CADR are particle-size dependent. These parameters will be estimated based on the size range of 0.3–0.5 μm [3].

The following default values have been used for mask efficiency, other removal mechanisms, quanta emission rates, and breathing rates:

- facial cloth mask efficiency [4] for a susceptible person η_s = 0.3
- facial cloth mask efficiency for an infected person η_i = 0.5
- fraction of the local population who are vaccinated f_v = 0
- surface deposition loss rate [5] λ_{dep} = 0.24 1/h
- virus decay [6] k = 0.63 1/h
- quanta emission rate time average values calculated in Appendix 2, i.e. q = 4 quanta/(h pers) in classrooms, 6 quanta/(h pers) in offices and gyms, and 10 quanta/(h pers) in meeting rooms and restaurants
- number of infectious persons in the room I = 1 pers
- breathing rate time averaged values Q_b = 0.60 m^3/h in offices, Q_b = 0.57 m^3/h in classrooms, Q_b = 0.65 m^3/h in meeting rooms and restaurants and Q_b = 1.9 m^3/h in gyms
- occupancy duration D = 2, 6, and 9 hours in meeting rooms, classrooms, and offices, respectively
- interaction time of an infectious individual is in the vicinity of susceptible persons, including traveling, lunches, and other out-of-home activities, 22.5 h in offices and 16 h in schools over 2.5 days of the pre-symptomatic infectious period

An acceptable individual probability p for a specific room can be calculated based on the event reproduction number R, defined as the number of new disease cases divided by the number of infectors $R = N_c/I$. Considering that the number of new cases $N_c = p\,N_s$ an acceptable individual probability for a specific room can be calculated as follows:

$$p = \frac{RI}{N_s} = \frac{RI}{(N-I)(1-f_v\eta_v)} \tag{13}$$

where

R event reproduction number (-)

N_s the number of susceptible persons in the room, $N_s = N - I$ if no vaccinated/immune persons

f_v fraction of the local population who are vaccinated, f_v = 0 for no vaccination (-)

η_v the efficacy of the vaccine against becoming infectious, η_v = 1 for ideal protection (-)

Acceptable R during one room-occupancy event can be based on the assumption that the likelihood of infecting others (i.e. the number of infections per unit time) is approximately constant over the infectious period. In such cases, an infectious person will not infect more than one person during the infectious period:

$$\frac{R}{R_0} \cong \frac{D}{D_{inf}} \quad \Longrightarrow \quad R \leq \frac{D}{D_{inf}} \quad \text{when} \quad R_0 \leq 1 \tag{14}$$

where:

R event reproduction number, i.e. number of people who become infected per infectious occupant

D room occupancy period, i.e. length of time when both infectious and susceptible persons are present in the room at the same time (h)

D_{inf} the total interaction time when an infectious individual is in the vicinity of any susceptible persons during the whole pre-symptomatic infectious period (h)

R_0 basic reproduction number that describes the spread of an epidemic in the population (-)

The pre-symptomatic infectious period ends typically at the onset of symptoms, when the infectious person self-isolates at home or is otherwise 'removed' from contact with susceptible individuals. This period may last some days, on average approximately 2 days for influenza and 2½ days for SARS-CoV-2. For example, if an infectious person is in the vicinity of susceptible persons (e.g. on public transport, at work/school) for 20 hours altogether during the infectious period, then he or she must not infect more than $R = 1/20 = 0.05$ persons per hour, on average, in order to remain within the limit of $R_o \leq 1$.

It should be noted that when there are a very low number of susceptible persons in the room (such as in an office with only a few individuals working there), Equation 8 produces high values for the individual probability which may be additionally limited to some value, for instance, $p \leq 0.1$. This is currently not done in Table 1 and Table 2; hence, in offices where $R = 9/22.5 = 0.4$, individual probability will be higher than 0.1 if the number of occupants is 4 or fewer.

It is possible to simplify Equation 5 and 6 by using the Taylor approximation of an exponential $e^n \cong 1 + n$ at low doses that allow for the rewriting of Wells-Riley equation $p = 1 - e^{-n}$ as follows:

$$n \cong \frac{1}{1-p} - 1 \tag{15}$$

where

n quanta inhaled by the occupant (quanta)

Taylor approximation provides reasonable accuracy at low p values, for instance, 2.4% at p = 0.05 and 4.7% at p = 0.1. By using another approximation $1/(1-p) = \cong 1 + p$ that applies if $|p| \ll 1$, Equation 10 can be rearranged as follows:

$$Q = \frac{(1-\eta_i) q Q_b (1-\eta_s) \mathrm{D} N_s}{R} - \left(\lambda_{dep} + k + k_f + k_{UV}\right) V \tag{16}$$

This equation enables us to calculate infection-risk-based ventilation rates in a simple fashion when substituting default values of quanta emission rate, breathing rate, and occupancy duration.

Calculation example of an open-plan office

Consider an open-plan office of 6 persons, a 50 m^2 floor area, and a room height of 2.6 m, where impinging jet ventilation with ventilation effectiveness ε_b=1.2 is used.

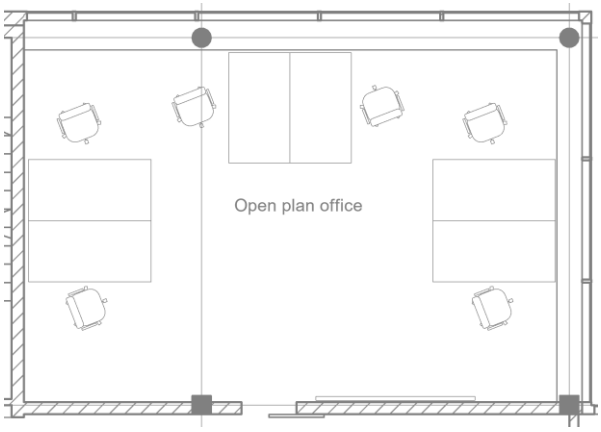

Figure 2. Floor plan of an open-plan office with 6 workplaces.

The following input data is used in the calculation of the required ventilation rate:

- surface deposition loss rate λ_{dep} = 0.24 1/h
- virus decay k = 0.63 1/h
- quanta emission rate q = 6 quanta/(h pers)
- number of infectious persons in room I = 1 pers
- breathing rate in offices and classrooms Q_b = 0.60 m^3/h
- occupancy duration D = 9 hours
- an infectious individual is in the vicinity of susceptible persons for 22.5 h over the course of a 2.5-day infectious period

Acceptable event reproduction number R can be calculated using Equation 14:

$$R \leq \frac{D}{D_{inf}} = \frac{9}{22.5} = 0.4$$

An acceptable individual probability p is calculated using Equation 13:

$$p = \frac{RI}{N_s} = \frac{0.4 \times 1}{6 - 1} = 0.08$$

The ventilation rate for fully mixing air distribution is calculated using Equation 11:

$$Q = \frac{qQ_b\mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k\right)V = \frac{6 \times 0.60 \times 9}{ln\left(\frac{1}{1-0.08}\right)} - (0.24 + 0.63)130 = 298.4\ \mathrm{m^3/h} = 76.5\ \mathrm{L/s}$$

The same value calculated using a simplified equation in Table 1 is slightly higher, showing a deviation of 5.9%:

$$Q = 22.5(6 - 1) - 0.242 \times 130 = 81.1\ \mathrm{L/s}$$

The ventilation rate 81.1 L/s corresponds to 1.6 L/(s $\mathrm{m^2}$), which is in between Category I and II ventilation rates with low-polluting materials of 2.2 and 1.5 L/(s $\mathrm{m^2}$) calculated using Equation 1. Fully mixing ventilation airflow rate is recalculated to impinging jet ventilation with higher ventilation effectiveness using Equation 4:

$$Q_s = \frac{Q}{\varepsilon_b} = \frac{81.1}{1.2} = 67{,}6\ \mathrm{L/s}$$

Ventilation rate 67.6 L/s corresponds to 11.3 L/s per person or 1.4 L/(s $\mathrm{m^2}$).

Appendix 2: Detailed information regarding quanta emission values and breathing rates

Quanta emission rates can be derived from the exhaled droplet volume emission rate (mL/h), the viral load (RNA/ml), and the quanta-response relationship (quanta/RNA) and can be calculated based on the following expression:

$$q = c_v \cdot c_i \cdot V_{exh} \tag{17}$$

where

q quanta emission rate per infectious person (quanta/(h pers))

c_v viral load in the respiratory tract (RNA/mL)

c_i the quanta-response relationship is defined as the ratio between one infectious quantum and the infectious dose expressed in viral copies, i.e. the number of viral RNA copies required to infect at least 63.21% of susceptible persons (quanta/RNA)

V_{exh} the total volume of respiratory droplets exhaled per unit time (mL/h)

The droplet volume emission rate can be calculated using the following model [7]:

$$V_{exh} = 3600 \cdot 10^6 \cdot \sum_{i=1}^{6} P_{i,br,sp,si} \cdot V_i\,(D) \tag{18}$$

where

P_i particle emission rate in the i^{th} bin of six aerosol droplet diameters during expiratory activities as measured by Fleischer [8] and presented in Table 4 (particles/s)

$V_i(D)$ is the total volume from each size bin (mL)

Table 4. Total dry volume of aerosols per litre of exhaled breath during various respiratory activities (br - breathing sp – speaking, and si – singing).

Size bin (µm)	$P_{i,br}$	$P_{i,sp}$	$P_{i,si}$
0.30–0.50	550	1 800	10 100
0.50–1.00	220	700	6 000
1.00–3.00	80	200	2 300
3.00–5.00	2	0	4
5.00–10.00	0	2	3
10.00–25.00	0	0	2

Viral RNA in different-sized respiratory aerosols emitted by infected patients has been measured by Coleman [9], providing a foundation for one to calculate the viral copies $c_{v,(D_{dry}\leq 5\ \mu\mathrm{m})}$ contained in fine dehydrated aerosols based on the balance equation of RNA copies:

$$c_{v,breath,eq(\leq 5\ \mu\mathrm{m})} = 8.7 \cdot c_{v,0} \tag{19}$$

$$c_{v,speak,eq(\leq 5\ \mu\mathrm{m})} = 78.7 \cdot c_{v,0} \tag{20}$$

$$c_{v,sing,dry(\leq 5\ \mu\mathrm{m})} = 26.0 \cdot c_{v,0} \tag{21}$$

For the viral load $c_{v,o}$ in the sputum, an average viral load of $10^8\ \frac{\mathrm{RNA}}{\mathrm{mL}}$ can be used, which is close to the median viral load for non-vaccinated (median $10^{8.1}\ \frac{\mathrm{RNA}}{\mathrm{mL}}$) and vaccinated individuals (median $10^{7.8}\ \frac{\mathrm{RNA}}{\mathrm{mL}}$) [10].

The quanta-RNA relationship 1 quanta=$14 \cdot 10^4$ RNA copies have been reported by Sender [11], who analysed human challenge data reported for a wild pre-alpha variant. Based on the quanta-RNA relationship for the original Wuhan strain, the quanta-RNA for several successive strains can be defined [12] as shown in Table 5.

Table 5. Estimated quanta-RNA relationship for various strains of SARS-CoV-2.

Strain of SARS-CoV-2	**Infectivity compared to the variant in the previous row**	$c_i\ (\frac{\mathbf{quanta}}{\mathbf{RNA}})$	**Virus variant quanta multiplier (-)**
Original (Wuhan)	-	14 000	1.0
Alpha (B.1.1.7)	+90%	7 400	1.9
Delta (B 1.617.2)	+150%	5 000	2.8
Omicron (B.1.1.529)	+420%	1 200	11.7

When comparing the quanta-emission rates (quanta/h) to those in the previous model proposed by Buonanno [13], there are differences more than tenfold even for the same expiratory activities and viral load [12], as shown in Table 6. This significant difference is caused by the difference between the values used to describe the quanta-RNA relationship c_i. Buonanno used $c_i = 2 \cdot 10^{-2}\ (\frac{\mathrm{quanta}}{\mathrm{RNA}})$, based on data for SARS-CoV-1, meaning that at least 200 viral copies would need to be ingested in order to infect at least 63.2% of the susceptible population, compared to 14,000 viral copies of the original SARS-CoV-2 strain.

Table 6. Average quanta emission rates (quanta/h) for SARS-CoV-2 original strain.

Activity	Buonanno et al. [1] Viral load 10^7 RNA/mL	Viral load 10^7 RNA/mL	Viral load 10^8 RNA/mL
Breathing	0.72	0.01	0.13
Speaking	9.7	0.38	3.8
Singing	62	0.90	9.0

[1] In the case of Buonanno, we refer to 66th percentile values. In this document, in the case of a viral load of 10^7 RNA/mL and 10^8 RNA/mL we refer to 35th and 56th percentile values, respectively.

Quanta emission rate values at viral load 10^8 RNA/mL for Delta and Omicron variants, calculated in Table 7 by applying the virus variant multipliers from Table 5, are comparable with the common cold/rhinovirus values ranging q = 1…10 quanta/h [14]. Significantly lower values such as q = 0.2 quanta/h have been reported for influenza [15].

Table 7. Virus-disease-specific values. All values in this table are approximative, with large uncertainty bands. Values of quanta emission rates are 56th percentiles, except for the 'superspreader', which is a 95% percentile for standing & speaking. The term '10% speaking' means that infected individuals speak 10% of the time on average.

Virus strain	SARS-CoV-2 original	Delta variant †	Omicron variant †	Seasonal influenza (flu)	Rhinovirus (common cold)	Measles
Infectious period, D_i [1] [days]	2.5	2.5	2.5	2	3	4
Vaccine effectiveness, η_v [2]	0.94	0.94	0.85	0.4	-	0.97
Virus inactivation (decay) rate, λ_d [1/h]	0.63	0.63	0.63	0.80	est. 0.63	est. 0.63
Quanta emission rate, q_e [quanta/h] [3]						
Hospital, resting patient	0.13	0.36	1.5	0.035	0.21	3.1
Classroom, 5% speaking	0.31	0.9	3.7	0.19	2	18
Office work, 10% speaking	0.50	1.4	5.8	0.24	2	
Restaurant, 20% speaking	0.86	2.4	10.1	0.29	2	
Meeting, 20% speaking	0.86	2.4	10.1	0.34	2	
Sport, 50% heavy exercise, 50% resting	0.51	1.4	5.9	-	-	
Singing	9.0	25	105	-	-	-
Superspreader	90	250	1050	4.10	23	6400

[1] Time until the person self-isolates due to the onset of severe symptoms

[2] Vaccine effectiveness against infection. For all SARS-CoV-2 variants, vaccine effectiveness is for at least 3 doses of mRNA-type vaccine. For influenza, this requires a seasonal booster. For measles, at least 2 doses

[3] All quanta emission rates are estimated based on median values

Volumetric breathing rates depend on the activity [16] being undertaken, as shown in Table 8. Time-averaged breathing rates for specific rooms, calculated from Table 8 values, are shown in Table 9.

Table 8. Volumetric breathing rates.

Activity	**Breathing rate Q_b, m^3/h**
Default sedentary activity, non-speaking	0.54
Talking	1.10
Light exercise	1.38
Heavy exercise	3.30

Table 9. Time-averaged breathing rates for specific rooms.

Room	**Breathing rate Q_b, m^3/h**
Classroom, infected student 5% speaking	0.57
Office work, 10% speaking	0.60
Meeting, 20% speaking	0.65
Restaurant, 20% speaking	0.65
Shopping, 10% speaking	1.35
Sport, 50% heavy exercise, 50% resting	1.92

Appendix 3: Example of the point source ventilation effectiveness measurement

Two air distribution systems with duct diffusers, as shown in Figure 3, were measured, following the local air quality index measurement procedure specified in REHVA GB No 2, in an open-ceiling mock-up classroom with a room height of 3.8 m and floor area of 5.2 × 8.7 m (45 m^2). Both cases had two duct diffusers with downward and side nozzles (240°), but in the case of D240°↓V1, extract air devices were installed in one corner of the classroom ceiling and D240°↓V2 had six equally distributed extracts on the ceiling. A ventilation rate of 240 L/s (5.3 L/(s m^2), 5 1/h), supply air temperature of 18°C, and room temperature of 22°C were used in all measurements.

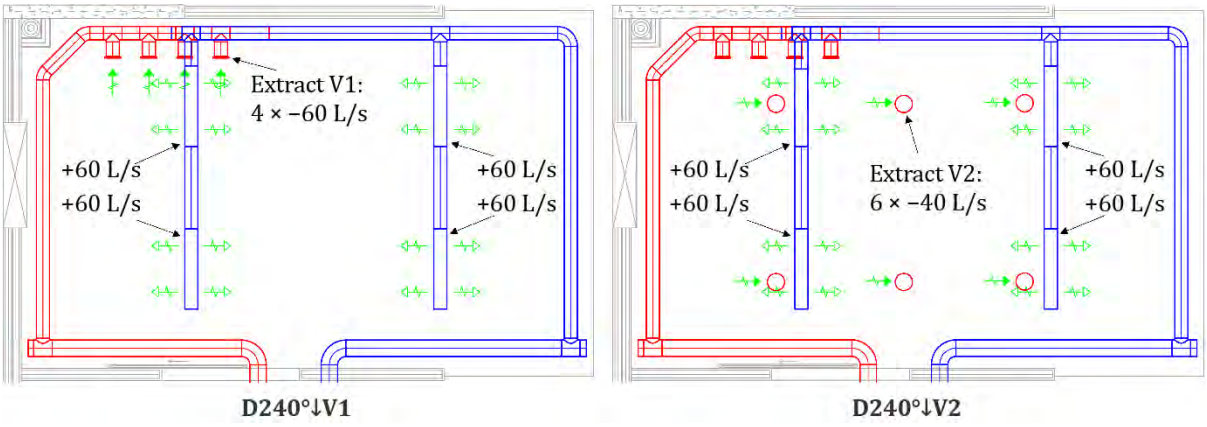

Figure 3. A comparison of two air distribution systems with duct diffusers. D240°↓V1 has four extract air devices in one corner of the classroom ceiling and D240°↓V2 has six ceiling extracts.

For both air distribution systems, three locations of point source E2, E5, and E8, as shown in Figure 4, were measured. Point source locations were selected not from the middle of the room but from the desk row, meaning there was a longer distance from which to extract air devices. CO_2 as a tracer gas with a continuous dose method was used. CO_2 concentrations were measured with 15 calibrated dataloggers K1-K15 on the desks (breathing plane, h=1.1 m). One logger was in the supply air duct for outdoor air reference concentration and another in the extract air duct for D240°↓V1 with a single extract location. In D240°↓V2, six loggers were used in each extract point, and extract airflow rate weighted, average extract air CO_2 concentration was calculated. For illustrative purposes, to draw colour plots of CO_2 concentration, an additional 8 loggers P1–P8 were used in the perimeter at the same height of h=1.1 m.

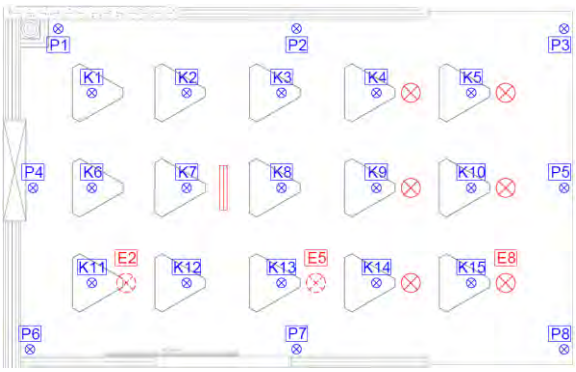

Figure 4. Location of the measurement points and a photo of the mock-up room. Breathing plane measurement points K1–K15 at 1.1 m height, source positions E2, E5, and E8, and perimeter measurement points P1–P8, which were used solely for illustrative purposes.

Tracer gas was injected continuously during the test by using a CO_2 bottle connected to a dummy as a contaminant source (Figure 5). Inside the dummy, the tracer gas tube was directed downwards to achieve good mixing, and it was ensured that no tracer gas was released from the bottom opening of the dummy. Therefore, the plume of the dummy released mixed tracer gas to the room from upper openings. For illustrative purposes, air change efficiency was also measured, which was done using the concentration decay method. In this case, the tracer gas was released to a room and mixed well with a fan before the decay measurement was conducted.

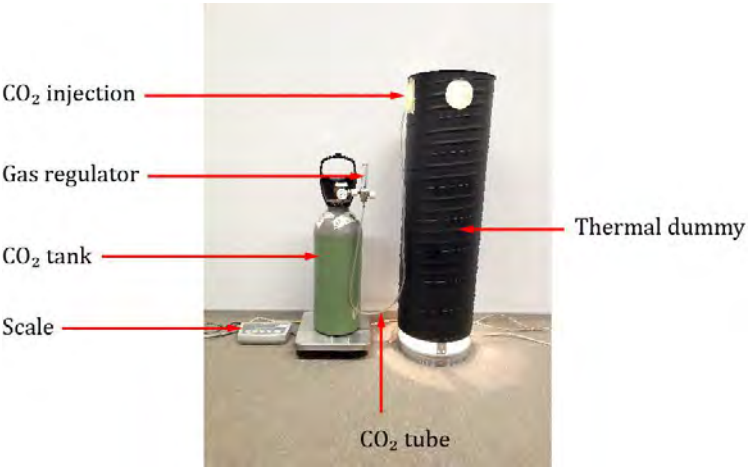

Figure 5. CO_2 bottle connected to a dummy used as a contaminant source.

The local air quality index was calculated for each measurement point K1–15 as follows:

$$\varepsilon_P = \frac{C_e - C_o}{C_P - C_o} \tag{22}$$

where

ε_p local air quality index at the measurement point P

C_P steady state concentration at the measurement point P

The local air quality index (Equation 22) is similar to that used in Equation 5, the only difference being that the concentration from a specific measurement point is used. The results are shown in Table 10, where an average of all measurement points is calculated for illustrative purposes (ventilation effectiveness according to Equation 3).

Table 10. The local air quality index calculated with Equation 22 for two studied air distribution systems with three locations of the point source (2 × 3 = 6 measurements). Measurement points that are closer than 1.5 m to the source are highlighted and excluded from calculation in Table 11.

	D240°↓V1			**D240°↓V2**		
	E2 source	**E5 source**	**E8 source**	**E2 source**	**E5 source**	**E8 source**
K1	1.05	0.96	1.01	1.09	0.90	1.51
K2	1.10	0.98	1.03	1.06	0.95	1.29
K3	1.01	0.89	0.96	1.10	1.07	1.13
K4	0.94	0.82	0.85	1.10	1.27	1.03
K5	0.99	0.93	0.87	1.23	1.30	0.76
K6	1.04	1.02	1.10	1.11	0.88	1.58
K7	1.10	1.00	1.03	1.00	0.92	1.40
K8	1.23	1.06	0.94	1.14	1.16	1.13
K9	1.12	1.01	0.89	1.24	1.16	1.02
K10	1.21	1.10	0.98	1.29	1.22	0.78
K11	1.04	1.04	1.07	1.02	1.08	1.46
K12	1.04	0.76	0.78	0.88	1.25	1.25
K13	1.10	0.80	0.76	1.00	2.03	1.20
K14	1.18	0.77	0.65	1.15	2.31	1.02
K15	1.11	1.04	0.57	1.14	1.63	0.75
AVG K1-K15	1.09	0.95	0.90	1.10	1.28	1.15

The calculation of point source ventilation effectiveness is presented in Table 11. Measurement points closer than 1.5 m to the source (highlighted in Table 4) are excluded and all other values are sorted in ascending order. From 50% of the points with the lowest values (highlighted in Table 11), an average is calculated. Finally, ventilation effectiveness ε_b is calculated as an average of results from three locations of the source.

Table 11. Calculation of point source ventilation effectiveness ε_b.

	D240°↓V1			D240°↓V2		
	E2 source	**E5 source**	**E8 source**	**E2 source**	**E5 source**	**E8 source**
	0.94	0.76	0.65	0.88	0.88	0.76
	0.99	0.77	0.76	1.00	0.90	0.78
	1.01	0.82	0.78	1.00	0.92	1.02
	1.04	0.89	0.85	1.06	0.95	1.02
	1.04	0.93	0.87	1.09	1.07	1.03
	1.05	0.96	0.89	1.10	1.08	1.13
	1.10	0.98	0.94	1.10	1.16	1.13
	1.10	1.00	0.96	1.11	1.16	1.20
	1.10	1.01	0.98	1.14	1.22	1.25
	1.11	1.02	1.01	1.14	1.25	1.29
	1.12	1.04	1.03	1.15	1.27	1.40
	1.18	1.04	1.03	1.23	1.30	1.46
	1.21	1.06	1.07	1.24	1.63	1.51
	1.23	1.10	1.10	1.29	2.31	1.58
Average of 50% of measurement points with lowest values						
	1.02	0.87	0.82	1.03	1.00	0.98
Average of 2 (E5 and E8) source locations			**0.85**			**0.99**
Average of 3 source locations			**0.91**			**1.00**

Therefore, the point source ventilation effectiveness value of ε_b = 0.91 must be used for D240°↓V1 and ε_b = 1.00 for D240°↓V2 air distribution system to calculate the design ventilation rate using Equation 4.

If only two source locations E5 and E8 had been measured (in the middle of the room and at one end of the room, providing a longer distance for extraction), ε_b values would be slightly lower due to there being more unfavourable source locations: 0.85 vs 0.91 for D240°↓V1 and 0.99 vs. 1.00 for D240°↓V2, respectively.

To illustrate the concentration distributions in the room, the local air quality index values were plotted, as shown in Figure 6. These can be compared with air change efficiency values ε_a, which were determined using the concentration decay method and distributed source (Figure 7). It can be seen that D240°↓V1 achieved a higher air change efficiency (56%) than that of D240°↓V2 (50%), which corresponds exactly to fully mixing air distribution. It is important to note that fully mixing air distribution with distributed source is not necessarily a fully mixing with point source, as is the case with D240°↓V1. Despite achieving 56% air change efficiency, this air distribution system produces a lower value for the point source ventilation effectiveness (0.91). At the same time, D240°↓V2 with multiple extract points has resulted in fully mixing both with distributed and point source (ε_a = 50% and ε_b = 1.00).

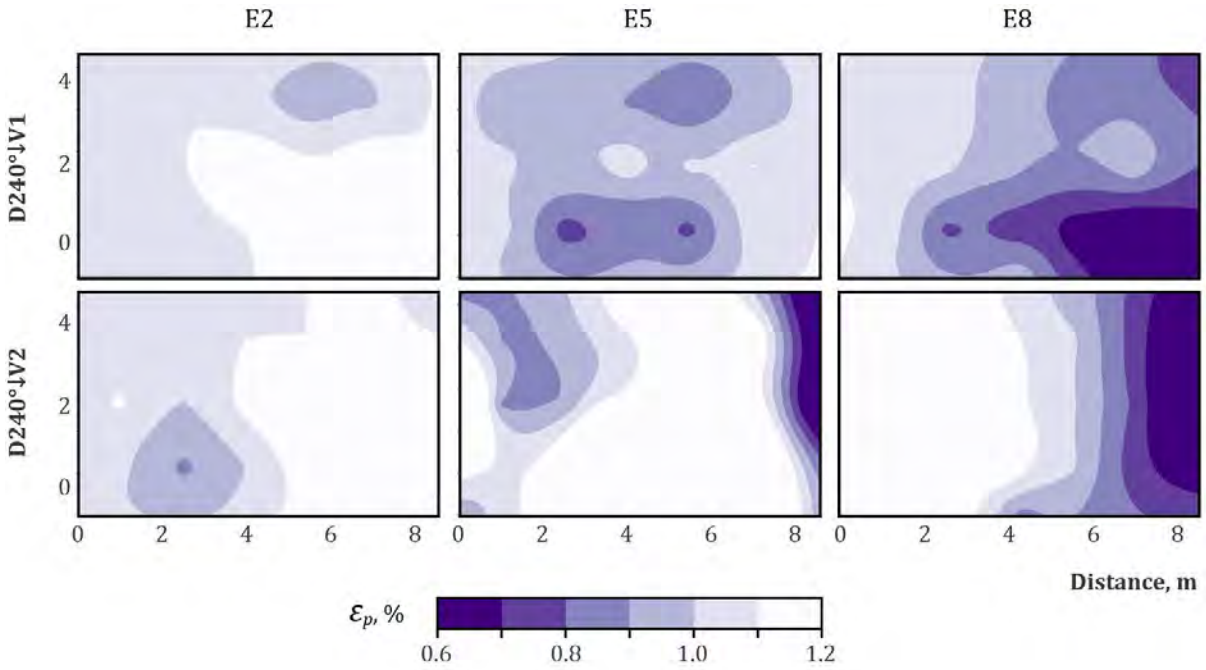

Figure 6. The distribution of local air quality index values with three locations of point source.

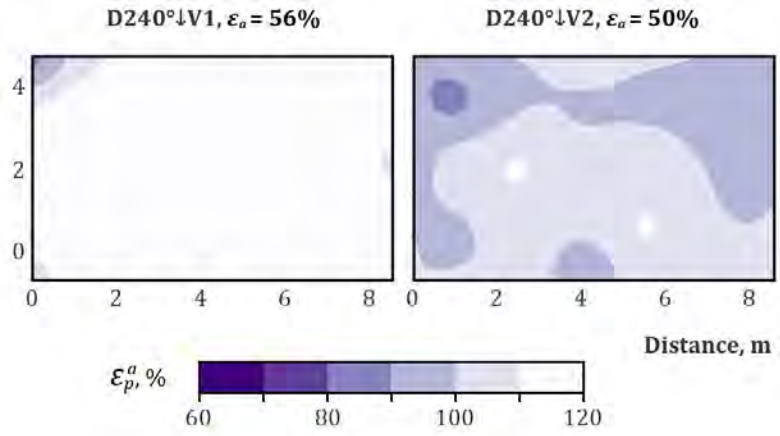

Figure 7. Air change efficiency values and the distribution of local air change index values.

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