Ventilation and air cleaning in reducing airborne transmission

Nordic Ventilation Forum, Oct 10, 2023

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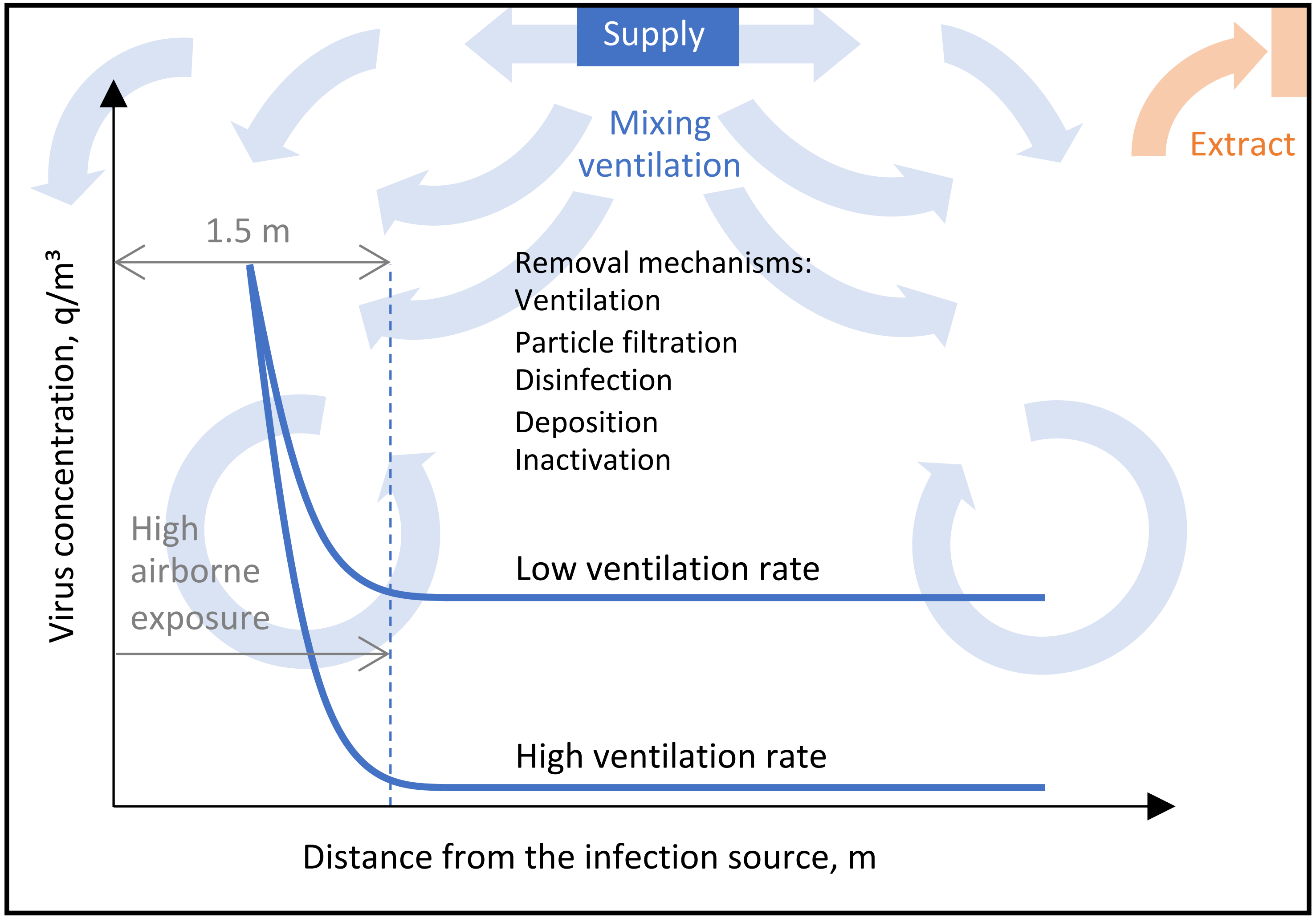
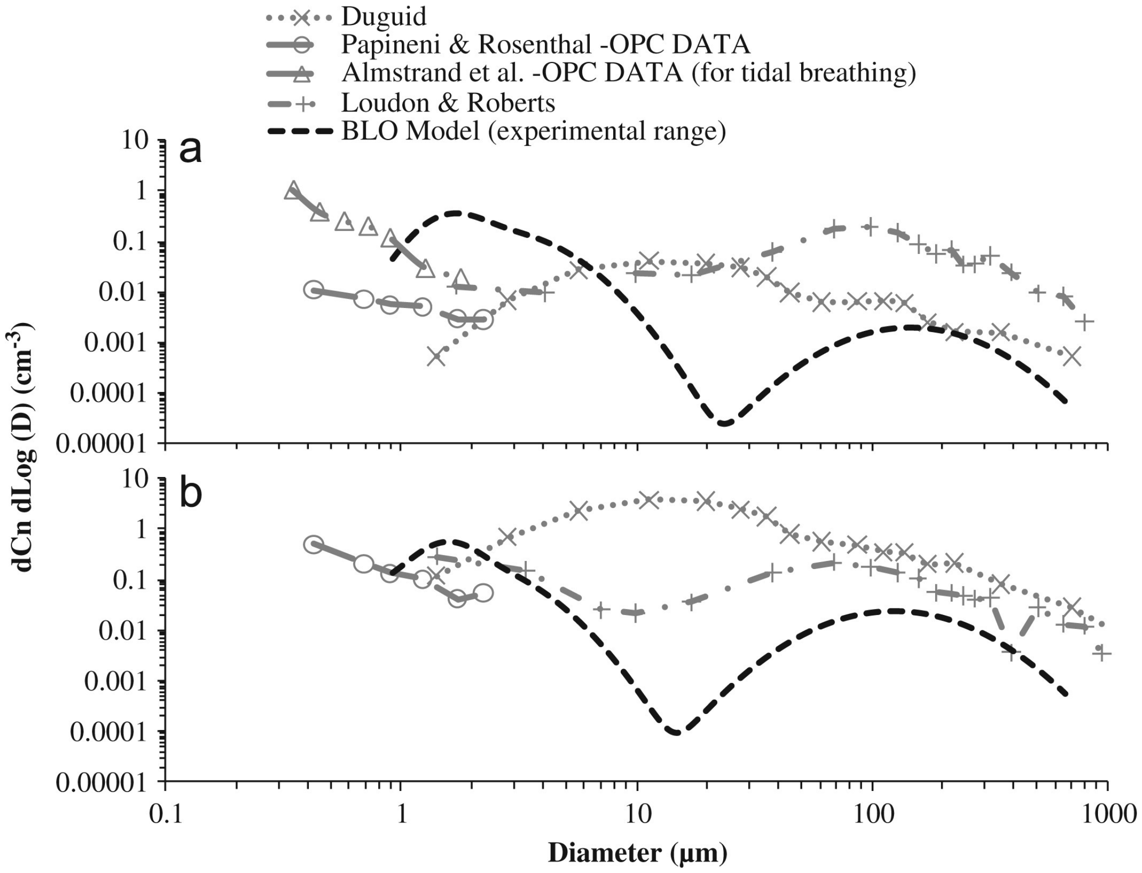
HVAC solutions vs airborne transmission

- Exposure = dose is a product of the breathing rate, **concentration** and time
- Concentration control of virus containing particles: remove with **outdoor air ventilation** and **filtration** or deactivate with **UVG**
- **General ventilation** solutions for >1.5 m may be complemented with **personal ventilation** and room partitioning/zoning



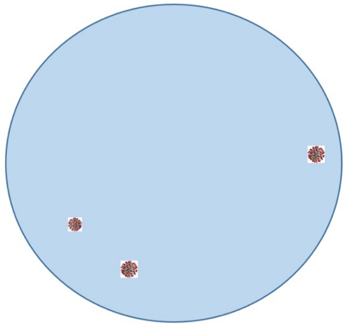
Airborne viruses



Expelled aerosol size distribution (a) speaking and (b) coughing

G.R.Johnson, L.Morawska et al. 2011 https://doi.org/10.1016/j.jaerosci.2011.07.009

- An airborne virus is not naked (0.1 □m) but is contained inside expelled respiratory fluid droplets (= droplet nuclei = virus containing aerosol)
- Most of expelled droplets > 1 □m, main interest range 1–10 □m
- ePM1 (F8) filters provide capture efficiency of 65-90% for PM1
- Therefore, already good fine outdoor air filters provide reasonable filtration efficiency for room or return air
- Easy to filtrate with high-capacity air cleaners (2…5 ach)

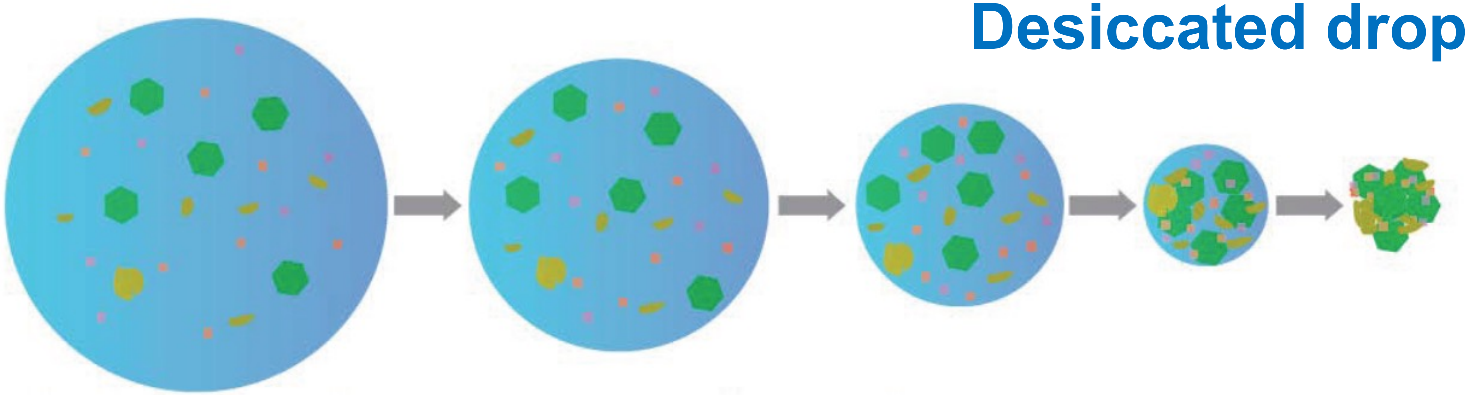


See appendix of the guidance: Criteria for room air cleaners for particulate matter
https://www.rehva.eu/activities/covid-19-guidance/rehva-covid-19-guidance

Evaporation and desiccation in the air

- Expelled droplets evaporate and desiccate in the air so that the final **droplet nuclei** shrink to roughly a half or one-third of the initial diameter

Desiccated droplet nuclei = solid particle



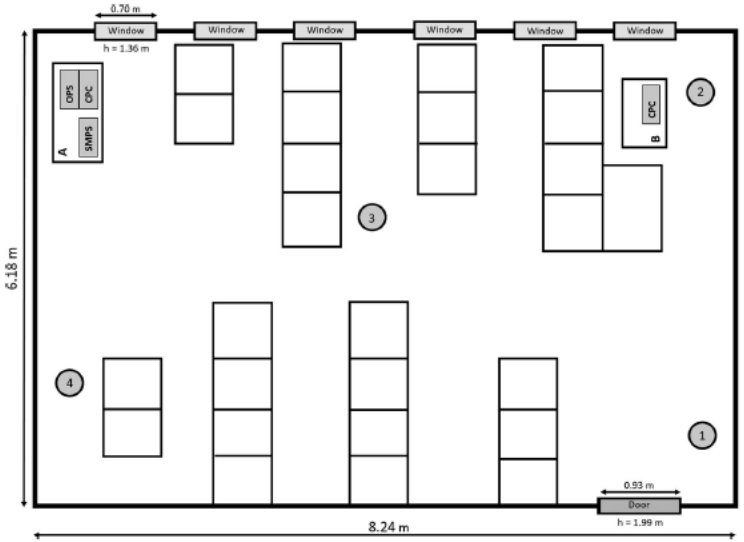
Verreault et al. (2008)

- Droplet desiccation is a fast process; 50 m droplets desiccate in about two seconds and 10 m droplets in 0.1 s (desiccated droplets still contain some fluid)
- In indoor air SARS-CoV-2 can remain active up to 3 hours and up to 2-3 days on room surfaces at common indoor conditions

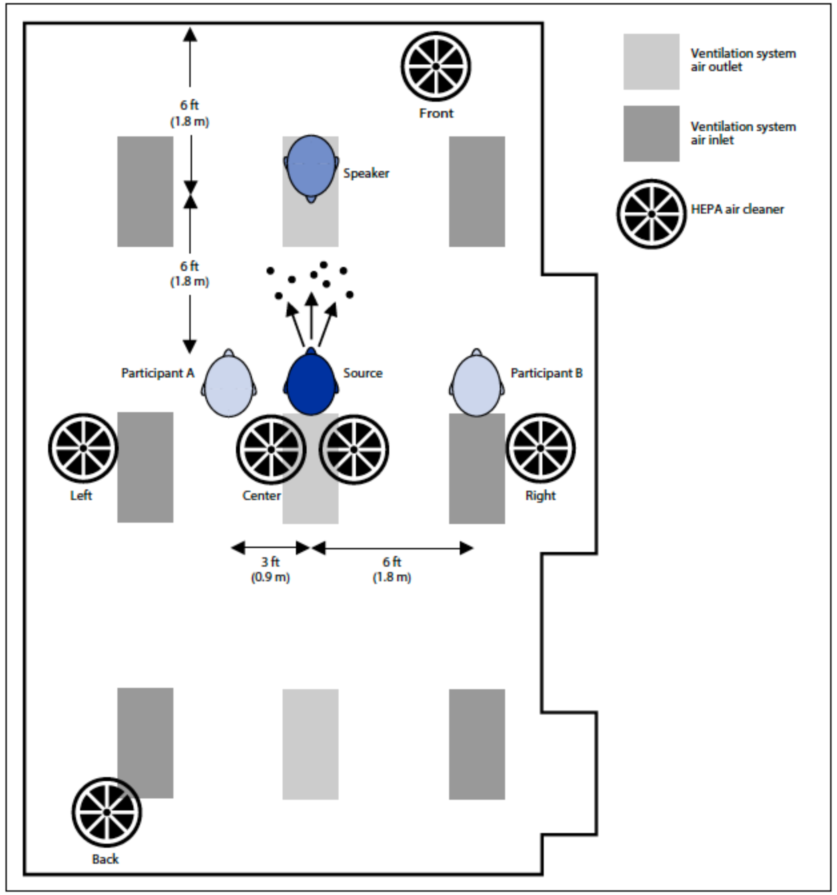
Evidence based practical solutions

- Italian schools study showed that ventilation rates of **10 L/s per person and higher reduced the likelihood of Covid-19 infection for students by 80%** compared with a classroom with natural ventilation

Buonanno et al. 2022
https://doi.org/10.3389/fpubh.2022.1087087



https://doi.org/10.1080/02786826.2021.1877257

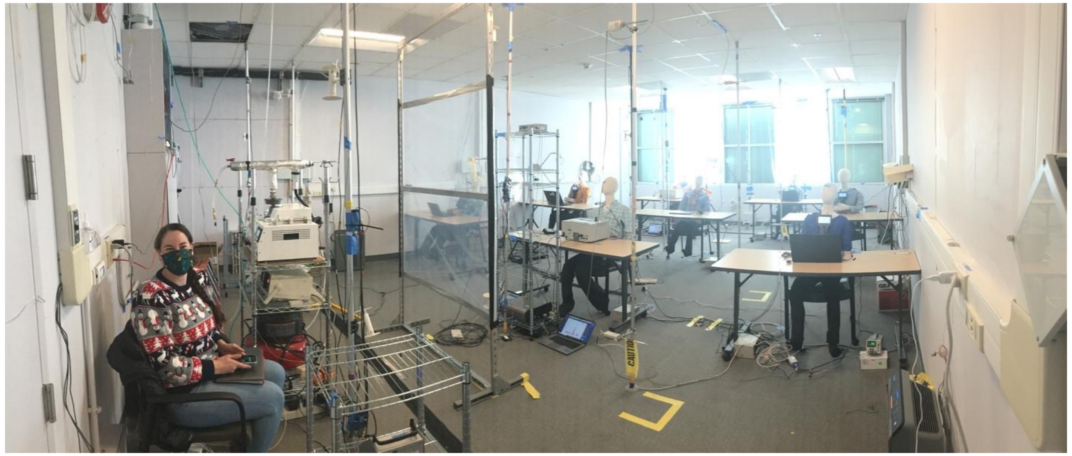


https://www.cdc.gov/mmwr/volumes/70/wr/mm7027e1.htm

- Classroom studies suggest to use at least **2 air cleaners with air change rate of about 5 ach**
- Equals to the air change rate of an adequate ventilation (i.e. in such a case will double the virus removal rate)
- Will not replace, but supports outdoor air ventilation – CO_2 monitors recommended to follow IAQ
- Finnish laboratory and CFD studies show 50% of reduction with air cleaners in offices (ILMIRA-project 2023, Kosonen et al. 2023)

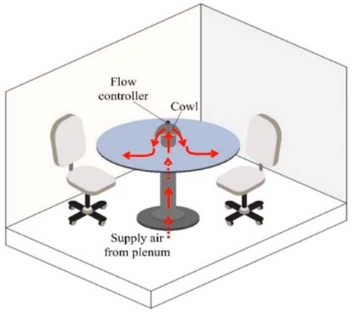
Evidence based practical solutions

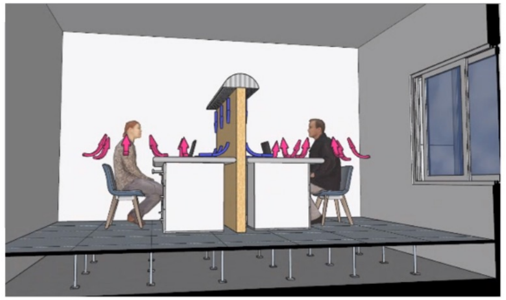
- Many studies about personal ventilation
- Personal or targeted ventilation may be combined with partitioning/zoning – **ventilation effectiveness can be improved by a factor of 1.4 to 10** depending on the local partition configuration, exhaust location and flow rate (Dygert and Dang 2012)
- Practical applications still limited – a lot of research in progress

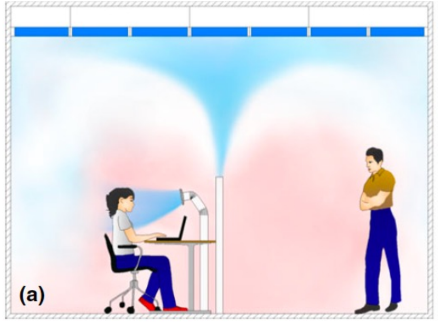


Classrooms & meeting rooms
https://onlinelibrary.wiley.com/doi/10.1111/ina.12917

https://newsletter.konzerthaus-dortmund.de/Pressemails/2020-21/Pressemitteilung/2021.01.11_Zusammenfassung_Aerosol-CO2-Messungen_Konzerthaus-Dortmund.pdf?utm_source=newsletter&utm_medium=email&utm_content







REHVA Task force on targeted ventilation

GUIDANCE

REHVA COVID guidance

https://www.rehva.eu/activities/covid-19-guidance

REHVA COVID ventilation calculator

https://www.rehva.eu/covid19-ventilation-calculator

WHO ventilation roadmap

https://www.who.int/publications/i/item/9789240021280

POLICY FORUM

INFECTIOUS DISEASE

A paradigm shift to combat indoor respiratory infection

Building ventilation systems must get much better

By Lidia Morawska, Joseph Allen, William Bahnfleth, Philomena M. Bluyssen, Atze Boerstra, Giorgio Buonanno, Junji Cao, Stephanie J. Dancer, Andres Floto, Francesco Franchimon, Trisha Greenhalgh, Charles Haworth, Jaap Hogeling, Christina Isaxon, Jose L. Jimenez, Jarek Kurnitski, Yuguo Li, Marcel Loomans, Guy Marks, Linsey C. Marr, Livio Mazzarella, Arsen Krikor Melikov, Shelly Miller, Donald K. Milton, William Nazaroff, Peter V. Nielsen, Catherine Noakes, Jordan Peccia, Kim Prather, Xavier Querol, Chandra Sekhar, Olli Seppänen, Shin-ichi Tanabe, Julian W. Tang, Raymond Tellier, Kwok Wai Tham, Pawel Wargocki, Aneta Wierzbicka, Maosheng Yao

There is great disparity in the way we think about and address different sources of environmental infection. Governments have for decades promulgated a large amount of legislation and invested heavily in food safety, sanitation, and drinking water for public health purposes. By contrast, airborne pathogens and respiratory infections, whether seasonal influenza or COVID-19, are addressed fairly weakly, if at all, in terms of regulations, standards, and building design and operation, per-

have been enacted for all aspects of food and water processing, as well as wastewater and sewage. Public health officials, environmental health officers, and local councils are trained in surveillance, sampling, and investigation of clusters of potential food and waterborne outbreaks, often alerted by local microbiology laboratories. There are published infection rates for a large range

"...healthy indoor environments with a substantially reduced

was on thermal comfort, odor control, perceived air quality, initial investment cost, energy use, and other performance issues, whereas infection control was neglected. This could in part be based on the lack of perceived risk or on the assumption that there are more important ways to control infectious disease, despite ample evidence that healthy indoor environments with a substantially reduced pathogen count are essential for public health.

It is now known that respiratory infections are caused by pathogens emitted through the nose or mouth of an infected person and transported to a susceptible host. The pathogens are enclosed in fluid-based particles aerosolized from sites in the respiratory tract during respiratory activities such as breathing, speaking, sneezing, and coughing. The particles encompass a wide size range, with most in the range of submicrometers to a few micrometers (1).

Although the highest exposure for an individual is when they are in close proximity, community outbreaks for COVID-19 infection in particular most frequently occur at larger distances through inhalation of airborne virus-laden particles in indoor spaces shared with infected individuals (2). Such airborne transmission is potentially the dominant mode of transmission of numerous respiratory infections. There is also strong evidence on disease transmission—for example, in restaurants, ships, and

Building and Environment 206 (2021) 108387

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journal homepage: www.elsevier.com/locate/buildenv

Respiratory infection risk-based ventilation design method

Jarek Kurnitski [a,b], Martin Kiil [a,*], Pawel Wargocki [c], Atze Boerstra [d,e], Olli Seppänen
Bjarne Olesen [c], Lidia Morawska [g,h]

REHVA COVID-19 Ventilation Calculator for estimation of ventilation effect on COVID-19 airborne infection

version 2.0, September 14, 2021

This calculator is intended to desing ventilation in well-mixed indoor spaces for the event reproduction number R<1. Air cleaners, facial masks, and limited occupancy are complementary measures possible to calculate. Alternatively, the calculator may be used for the risk assessment in existing indoor spaces.

Input Parameters

	Value		Comment
No of infectious persons in the room	1	-	One infectious person is default assumption in all cases
Mask efficiency for susceptible person	0	-	0 for no facial mask, default value for a mask 0.3
Mask efficiency for infectious person	0	-	0 for no facial mask, default value for a mask 0.5
Inactivation rate of the virus	0.63	h-1	van Doremalen et al. (2020)
Deposition to surfaces	0.24	h-1	Buonnano et al. (2020b), Miller et al. (2020), could vary 0.24-1.5 h-1, depending on particle size range
Additional control measures	0	h-1	May be used to insert a removal rate of UV disinfection

Case Specific Input Parameters & Calculation for model rooms

Air cleaner Clean Air Delivery Rate: Insert CADR (product of efficiency and airflow rate) in m^3/h units (1 L/s = 3.6 m^3/h), 0 for no air cleaner

Quanta emission rate: Select a value depending on physical and communication activities, and a virus variant, as shown below

Breathing rate: Select a value depending on physical and speaking activities as shown below

No of susceptible persons in the room = total No of persons - No of infectious persons in the room

Probability of infection is the individual probability of a susceptible person; No of infected persons = probability x No of susceptible persons

R event is the event reproduction number that is defined as number of new disease cases divided by number of infectors; to control epidemic R<1 (recommended value R=0

Room	Floor area	Height	Ventilatio	Air cleane	Qunta em	No of sus	Breathing	Occupanc	Air chang	Total first	x steady s	Average c	Quanta ir	**Probabili**	**R event**
	A (m^2)	h (m)	L/(s m^2)	m^3/h	quanta/h	-	m^3/h	h	λ_v (h^{-1})	λ (h^{-1})	[]	quanta/m^3	quanta	-	-
Open plan office 1 L/s m^2	50	3	1	0	5	5	0.65	8	1.2	2.07	0.94	0.015	0.08	**0.076**	**0.38**
Open plan office 2 L/s m^2	50	3	2	0	5	5	0.65	8	2.4	3.27	0.96	0.010	0.05	**0.050**	**0.25**
2 person office 1.5 L/s m^2	16	3	1.5	0	5	1	0.65	8	1.8	2.67	0.95	0.037	0.19	**0.176**	**0.18**
Meeting room 6 pers	18	3	4	0	9	5	0.76	8	4.8	5.67	0.98	0.029	0.17	**0.160**	**0.80**
Meeting room 10 pers	25	3	4	0	9	9	0.76	8	4.8	5.67	0.98	0.021	0.13	**0.118**	**1.06**
Meeting room 20 pers	50	3	4	0	9	19	0.76	8	4.8	5.67	0.98	0.010	0.06	**0.061**	**1.16**
Classroom 4 L/s pers	56	3	2	0	3.2	24	0.6	8	2.4	3.27	0.96	0.006	0.03	**0.027**	**0.64**
Classroom 6 L/s pers	56	3	3	0	3.2	24	0.6	8	3.6	4.47	0.97	0.004	0.02	**0.020**	**0.47**
Classroom 8 L/s pers	56	3	4	0	3.2	24	0.6	8	4.8	5.67	0.98	0.003	0.02	**0.016**	**0.38**
Restaurant 4 L/s m^2	50	3	4	0	7	9	0.71	8	4.8	5.67	0.98	0.008	0.05	**0.045**	**0.40**
Shopping 1.5 L/s m^2	50	3	1.5	0	8.4	4	1.32	8	1.8	2.67	0.95	0.020	0.21	**0.190**	**0.76**
Sports facility 3 L/s m^2	50	3	3	0	10	5	3.3	8	3.6	4.47	0.97	0.014	0.38	**0.318**	**1.59**

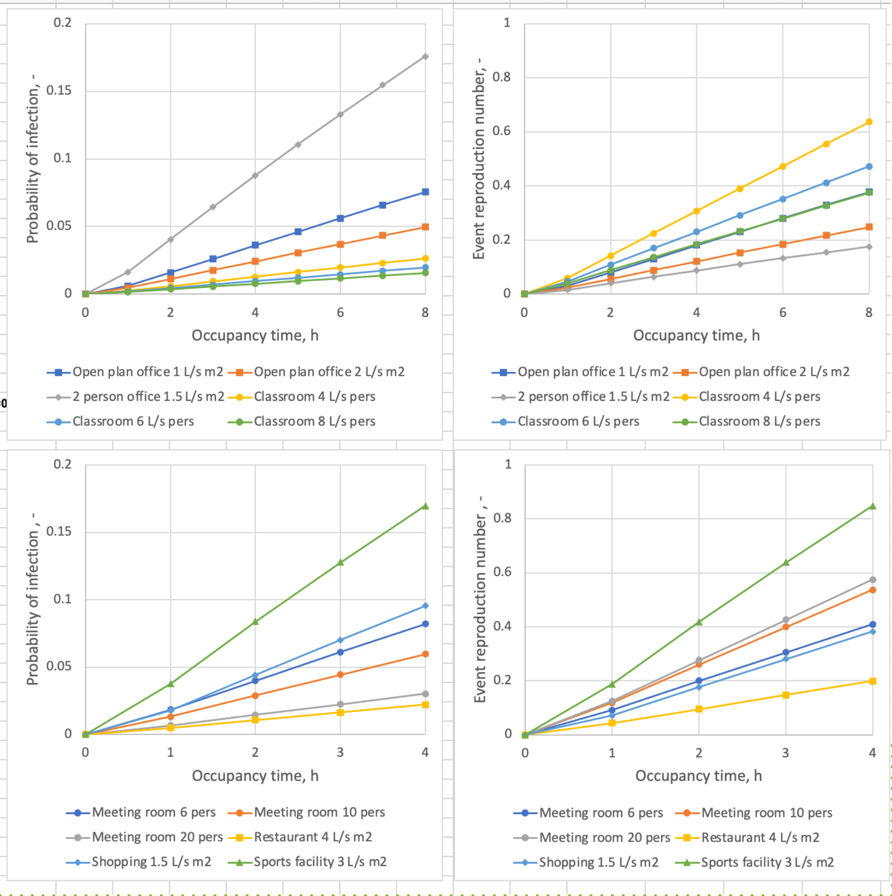
modify existing or copy new rows to add new rooms (curves are automatically drawn for existing 12 rows only)

Quanta emission rates (66th percentile), time weighted averages of activities

	SARS-Co	Alpha (B	Delta variant
Virus variant multiplier	1	1.4	2
	quanta/h	quanta/h	quanta/h
Classroom, infected student 10% spea	1.6	2.3	3.2

Breathing rate values

Breathing rate (time weighted average)
m^3/h
0.60



REHVA
Federation of European Heating, Ventilation and Air Conditioning Associations

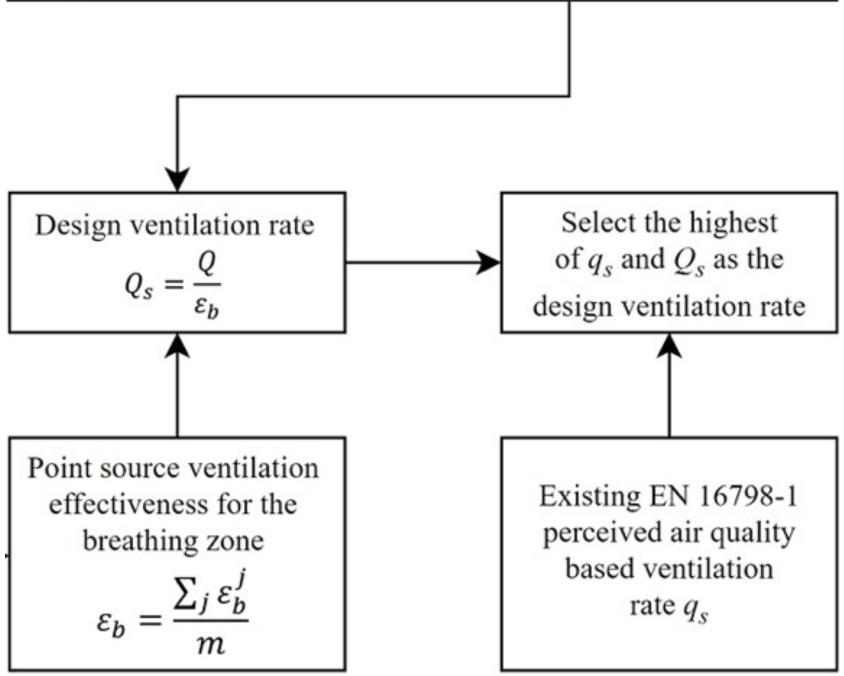
Infection risk based ventilation design

- Currently not addressed in design guides or standards however the association between sick leave and ventilation known from 2000
- Wells-Riley model modifications with quanta virus source definition most used dose response model for exposure and infections – scientific publications available
- Experimental data for SARS-CoV-2 median viral load is available
- Acceptable risk as input value in the model described with room/event reproduction number limiting the number of new disease cases
- Target ventilation as a result with fully mixing air distribution
- Case specific ventilation effectiveness of actual air distribution method
- Design value of ventilation to be selected as the highest of new infection risk-based method and existing EN 16798-1:2019 perceived air quality method

Calculation procedure

1. Calculate the target ventilation rate
2. Apply ventilation effectiveness to adjust to actual air distribution solution
3. Compare with EN 16798-1 perceived air quality based ventilation rate
4. Select the highest of these two as design ventilation rate

	Target ventilation rate, L/s
Classroom	$Q = 10(N\text{-}1) - 0.24V$
Office	$Q = 23(N\text{-}1) - 0.24V$
Meeting room	$Q = 40(N\text{-}1) - 0.24V$
Restaurant	$Q = 40(N\text{-}1) - 0.24V$
Gym	$Q = 70(N\text{-}1) - 0.24V$



NORDIC VENTILATION GROUP
Scientific collaboration

http://www.scanvac.eu/post-covid-target-ventilation-rates.html
https://www.rehva.eu/activities/post-covid-ventilation

VENTILATION IN EXISTING STANDARDS (EN 16798-1:2019)

Current ventilation criteria is based on perceived air quality by the visitors (unadapted) and occupants (adapted persons) that depend on the emissions from humans and building materials

Outdoor air flow rate:

$$q_{tot} = nq_p + A_R q_B$$

where
q_{tot} = total ventilation rate for the breathing zone, L/s
n = design value for the number of the 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 (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;

4 L/s per person + 0.4 L/s per floor area in Category III.

Cat II will lead to 2-2.5 ach in offices and 5 ach in classrooms and meeting rooms

Proposal by Nordic Ventilation Group and REHVA

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

Design ventilation rate supplied by the ventilation system:

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

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

https://www.rehva.eu/activities/post-covid-ventilation

Proposal by Nordic Ventilation Group and REHVA

Target outdoor air ventilation rates *Q* (L/s) with portable air cleaners, *N* (-) the number of persons, *V* (m^3) the room volume

Space category	Ventilation rate, L/s
Classroom	$Q = 10(N-1) – (0.87+k_f)V/3.6$
Office	$Q = 23(N-1) – (0.87+k_f)V/3.6$
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	$Q = 70(N-1) – (0.87+k_f)V/3.6$

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)

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

For HEPA filters CADR (m^3/h) can be used: $k_f = CADR/V$

https://www.rehva.eu/activities/post-covid-ventilation

Calculation examples for typical rooms

	Floor area	Room height	No of persons	Infection-risk-based ventilation: Ventilation effectiveness	Ventilation rate	Ventilation rate	Air change rate	CO_2 conc.	Comfort ventilation: 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

In highlighted cases, EN 16798-1 ventilation rate is higher

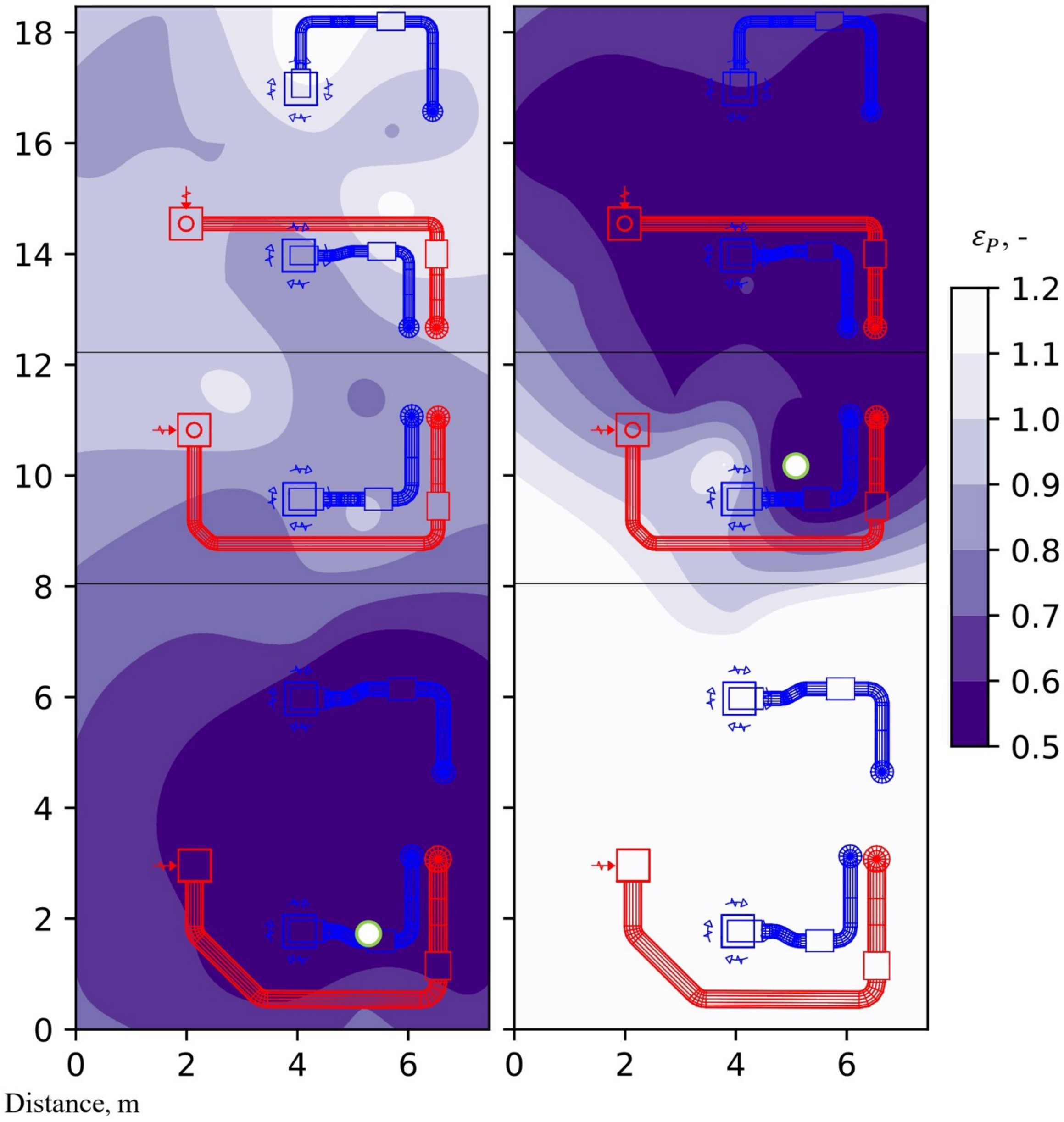
Ventilation effectiveness

- To be determined with the point source (=infector)
- Existing values do not apply because measured with distributed source (=normal occupancy)

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

$$\varepsilon_P = \frac{C_e - C_o}{C_i - C_o}$$

- Tracer gas measurement and ε_b calculation procedure provided in the document

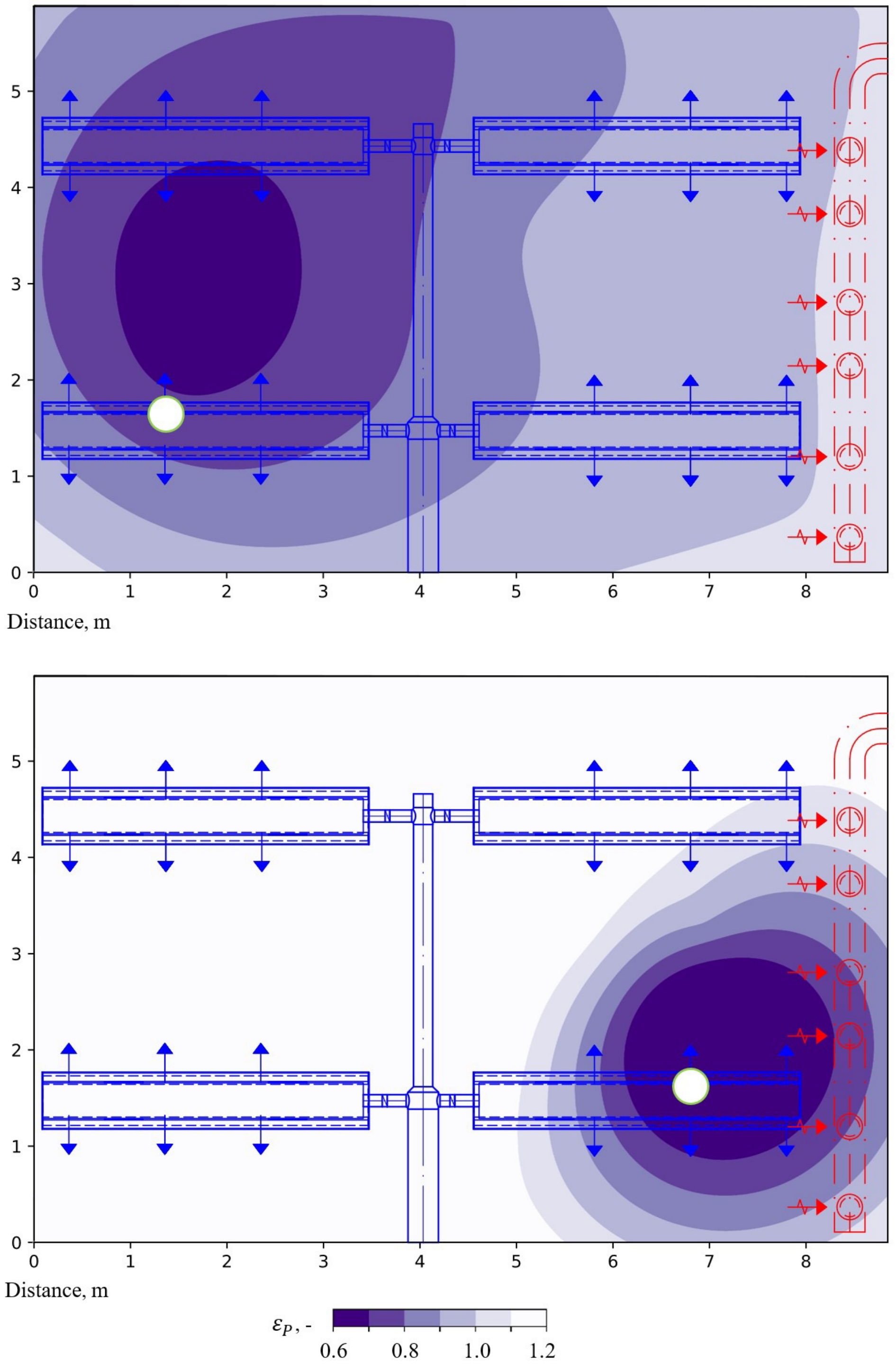


Large teaching space of 130 m^2 with 4 L/(s m^2) ventilation: ε_b^1=0.76 (left) and ε_b^2=0.77 (right) and the average value of two measurements ε_b=0.76

VENTILATION EFFECTIVENESS

- Example of tracer gas measurement in the meeting room of 52.5 m² with active chilled beams and 3.0 L/(s m²) ventilation
- Local air quality index values with left and right locations of point source
- Concentrations/ventilation effectiveness depends on the source location

- Mixing ventilation is not necessarily mixing ventilation with the point emission source



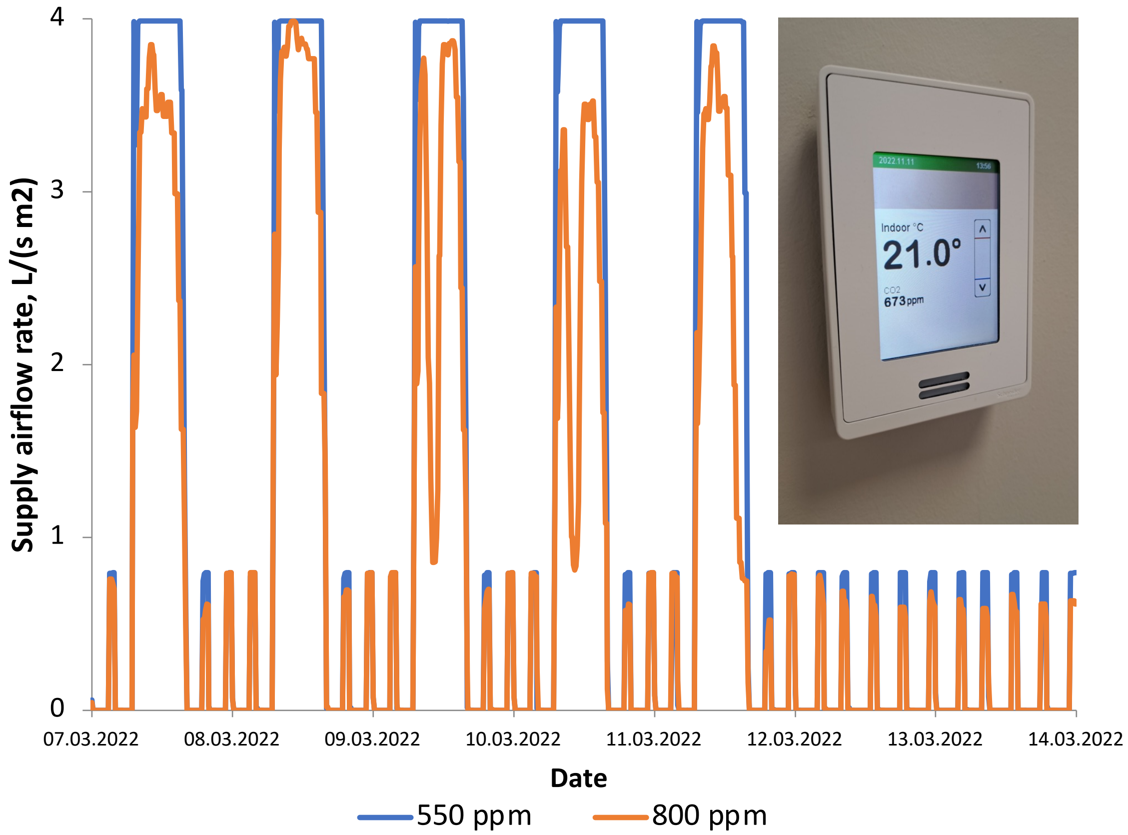
Demand-controlled operation

Epidemic periods:

- CO_2 setpoint 550 ppm

Outside epidemic periods:

- operation according to perceived air quality design ventilation rate
- recommended CO_2 setpoints:
  - 800 ppm in classrooms and meeting rooms
  - 650 ppm in offices, restaurants, and gyms



Ventilation airflow rates in a typical classroom with CO_2 set point of 550 ppm and 800 ppm

Proposed implementation in EN 16798-1 revision

- Infection-risk based target ventilation rates for fully mixing air distribution – generic equation:

$$Q = q_q(N-1) - q_r V$$

where

Q	target outdoor air ventilation rate (L/s)
q_q	quanta emission specific ventilation rate for occupancy per person (L/(s person))
q_r	removal rate of virus decay and deposition (L/(s m^3))
N	the number of persons in the room
V	room volume (m^3)

- q_q (viral load and risk level) and q_r (removal mechanisms) are virus specific parameters

Proposed implementation in EN 16798-1 revision

- Tabulated values for virus specific ventilation parameters q_q and q_r

Space category	q_q, L/(s person)	q_r, L/(s m^3)
Classroom	10	$0.24 + k_f/3.6$
Office	23	$0.24 + k_f/3.6$
Assembly hall	30	$0.24 + k_f/3.6$
Meeting room	40	$0.24 + k_f/3.6$
Restaurant	40	$0.24 + k_f/3.6$
Gym	70	$0.24 + k_f/3.6$

- In the case of no air cleaner, $k_f = 0$
- There are no IEQ categories in this case
- Tabulated values may be provided in the national annex

Proposed implementation in EN 16798-1 revision

- Design ventilation rate supplied by the ventilation system Q_s is calculated with point source ventilation effectiveness ε_b for the breathing zone:

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

- ε_b is to be calculated as an average of two or more tracer gas measurements with different source locations (or CFD simulations):

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

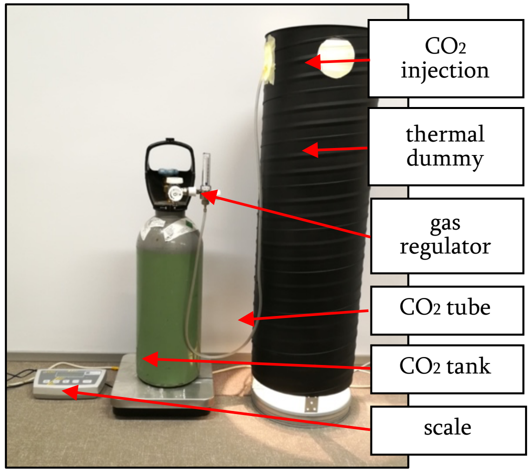
$$\varepsilon_b = \frac{\sum_j \varepsilon_b^j}{m}$$

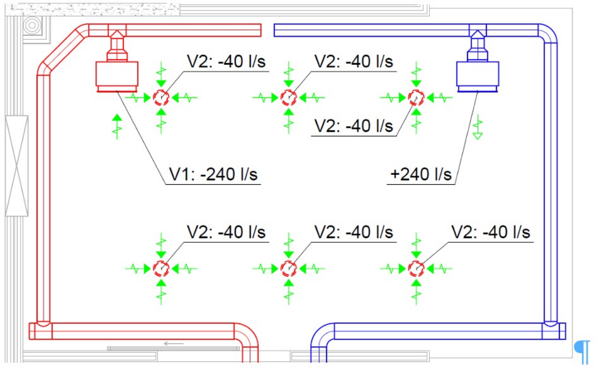
- or with more dedicated method

where

ε_b^j	point source ventilation effectiveness of measurement *j*
ε_b	point source ventilation effectiveness for the breathing zone
C_{je}	measurement *j* concentration in the extract air duct
C_{jb}	measurement *j* concentration at the breathing level
C_{j0}	concentration in the supply air
m	total number of measurements with different point source locations

MORE ATTENTION TO VENTILATION EFFECTIVENESS – EXAMPLE OF THE TRACER GAS MEASUREMENT





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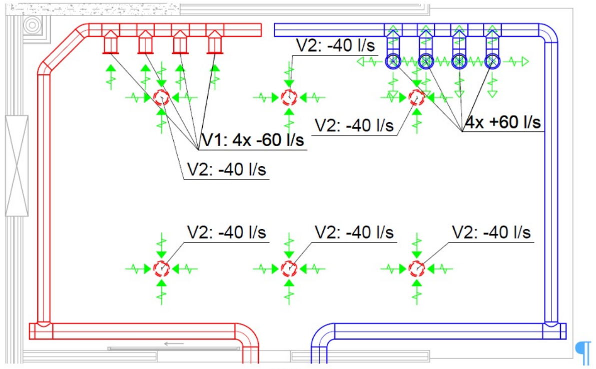
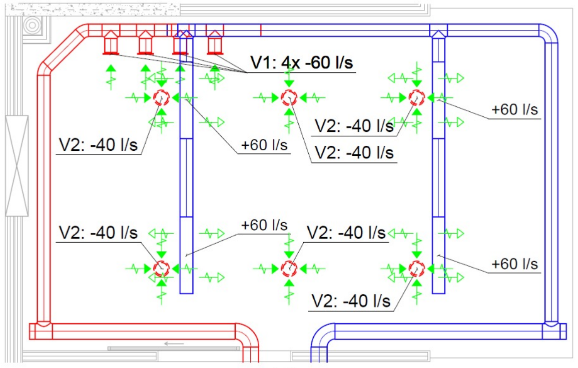
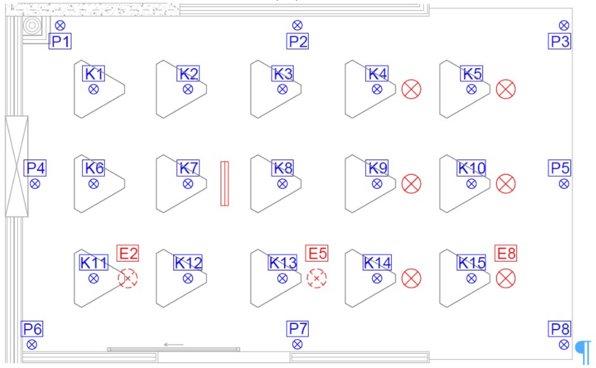


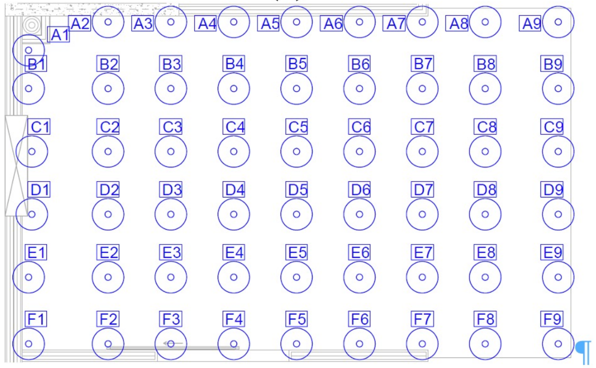
(2)



(3)



(4)



(5)


(6)

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- Advanced air distribution solutions enable to reduce ventilation rates

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$t_{room} - t_{supply} \approx 4^{\circ}C$; 240 l/s

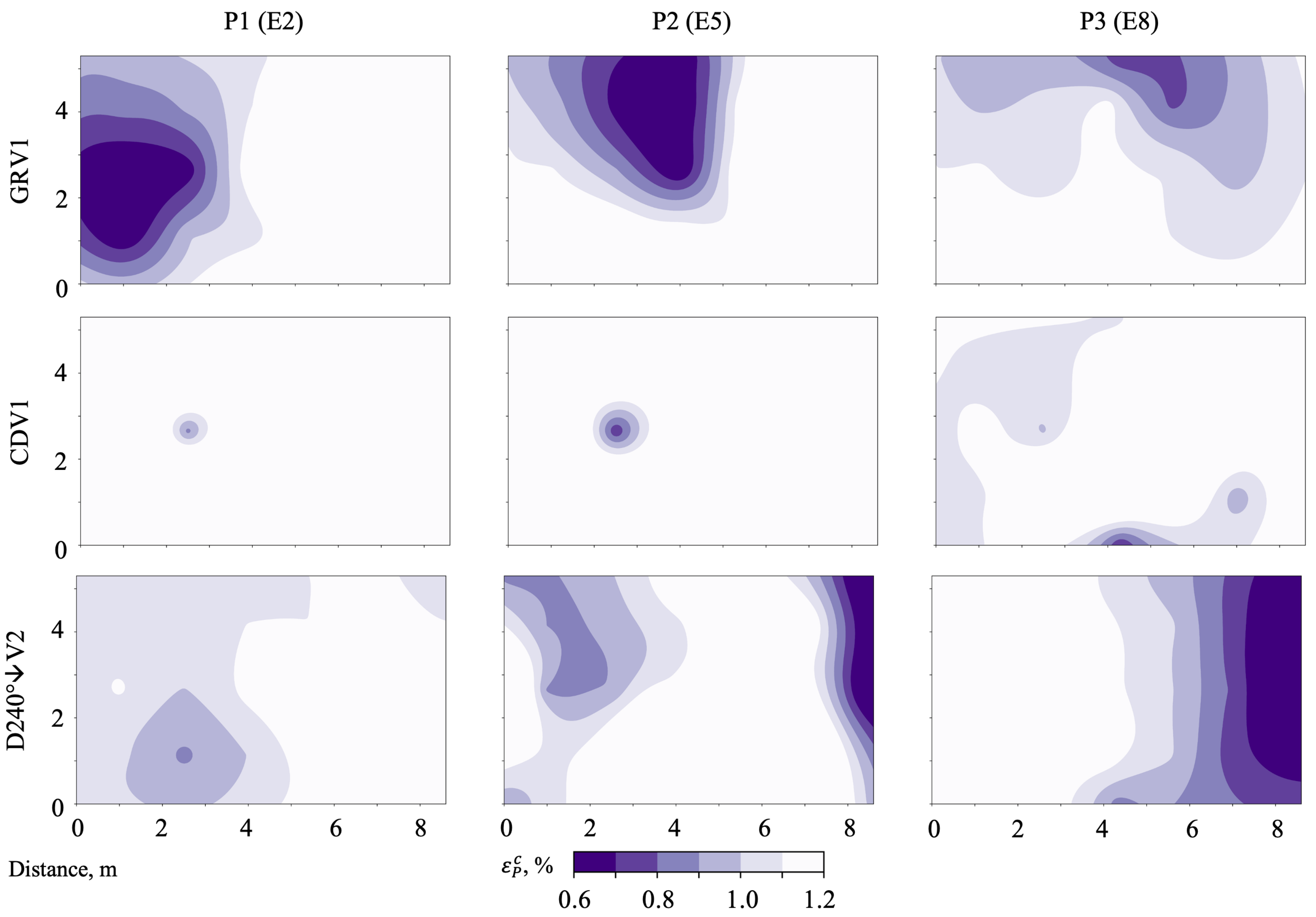
Ventilation solution used in renovation tested in laboratory

VENTILATION EFFECTIVENESS IN THE CLASSROOM MOCK UP

$$Q_{supply} = \frac{Q}{\varepsilon_b}$$

$$\varepsilon_b = \frac{C_e - C_o}{C_i - C_o}$$

Local air quality index values in the range of 0.77…1.36



$\varepsilon_b = 0.77$

$\varepsilon_b = 1.36$

$\varepsilon_b = 0.93$

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- Good improvement potential with occupant targeted and other advanced air distribution solutions

Conclusions

- Infection risk-based ventilation design method is proposed to complement EN 16798-1:2019 current method based on perceived air quality
- The highest ventilation rate given by these two methods shall be used
- The aim is not to eliminate, but considerably reduce the infection risk: infector will cause no more than one new disease case during pre-symptomatic infectious period
- In typical classrooms and offices, infection risk-based ventilation rates mostly do not exceed Category I ventilation rates, ranging in classrooms 8-13 L/s per person
- In meeting rooms, restaurants and gyms, infection-risk based ventilation rates are remarkably high, indicating that feasible ventilation design would suggest to reduce occupancy and to use advanced air distribution