System for prediction and reduction of COVID-19 infection risk in indoor environment

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Institute of Numerical Modelling

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Introduction

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- SARS COV-2 virus will likely become endemic, it will continue to circulate in the world and can cause new waves of infections [1]
- Virus transfer routes are (1) direct transport of droplets , (2) contact of surfaces and (3) via aerosol
  - Keeping 2m distance, wearing masks and washing hands reduce the routes (1) and (2) considerably
  - Aerosol transmission (3) remains the main factor in an indoor environment [2,3]
- We have built a system for COVID-19 risk prediction which consists of
  - Model for virion transport in room
  - System for measurement of necessary model parameters

*[1] Phillips N 2021 Nature **590** 382-384*
*[2] Asadi S, Bouvier N, Wexler AS, Ristenpart WD 2020 Aerosol Science and Technology **54(6)** 635-638*
[3] Santarpia JL, Herrera VL, Rivera DN, Ratnesar-Shumate S, Denton PW, Martens JW, Fang Y, Conoan N, Callahan MV, Lawler JV, Brett-Major DM 2020 MedRxiv DOI 10.1101/2020.07.13.20041632

Model of infection risk

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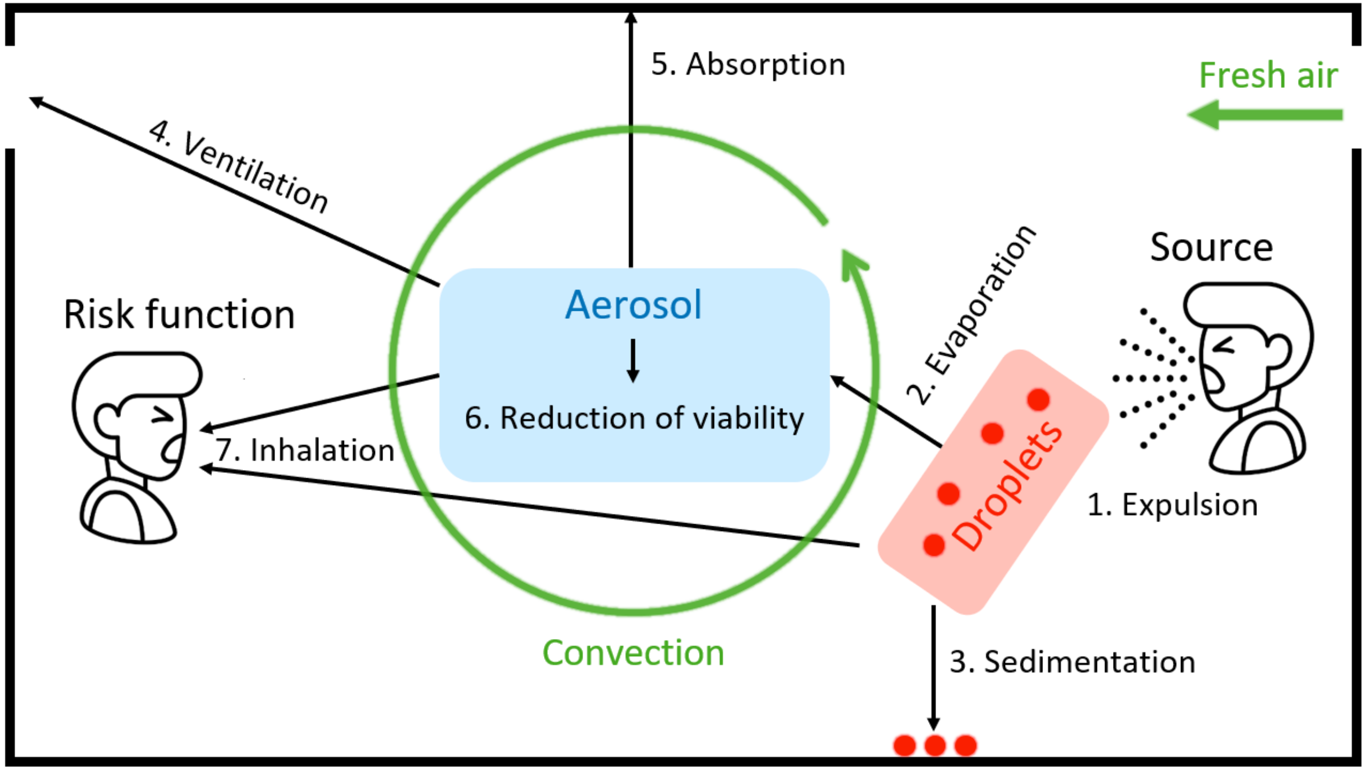
- Integral parametric model, mainly mean values > 0D (1D)



- Parameters of transfer processes 1 – 7 mainly from literature

J Virbulis et al 2021 J. Phys.: Conf. Ser. 2069 012189 DOI 10.1088/1742-6596/2069/1/012189

Room parameters

W, L, H

compute

Volume, Surface

Additional variables:

Measured
- Temperature
- Relative humidity
- CO_2 concentration

Calculated
- Droplet distribution in air (number, size)
- Number of aerosol particles
- Number of virions in aerosol
- Number of virions on surfaces

Model of infection risk

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Nr.	Process	Parameters *References*	Result
1.	Droplet expulsion	Kind (breathing, speaking, coughing, sneezing) Size distribution Concentration in mucus *Duguid JP 1946* *Schijven 2020*	Data for evaporation model
2. + 3.	Evaporation and sedimentation	Temperature ← *Chaudhuri 2020* Humidity ← *Holterman 2003*	Concentration in droplets and aerosol
4.	Ventilation	Air exchange *Foat 2020* → *Cheng 2011* →	Extract turbulent diffusion
5.	Absorption of aerosol	Surface area *Park 2001*	Reduction of concentration
6.	Reduction of viability	Time *Van Doremalen 2020*	Reduction of concentration
7.	Inhalation	Number of virions *D* $R = 1 - (1 - \alpha)^D$. *Haas 1999* *Basu 2020*	Infection risk *R* [0 – 1] (0% - 100%)

Initial virus variant

Model and measurement system

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Model parameters

- Temperature
- **Humidity**
- **Number of people**
- **Sources**
  - Speech
  - Cough
  - Sneezing
- **Ventilation**
- Room size

Effect

precents

times

orders

times

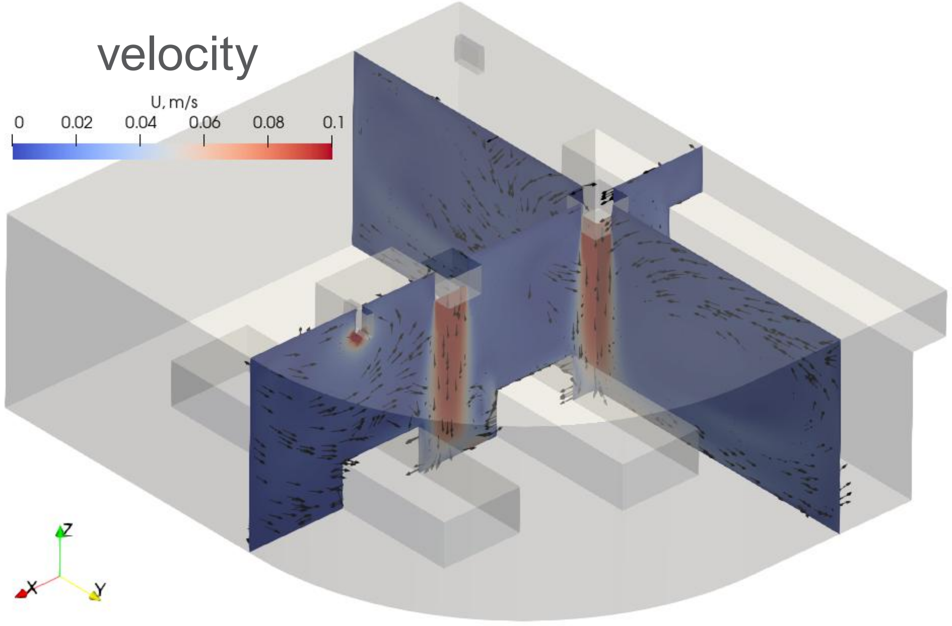
Sensors

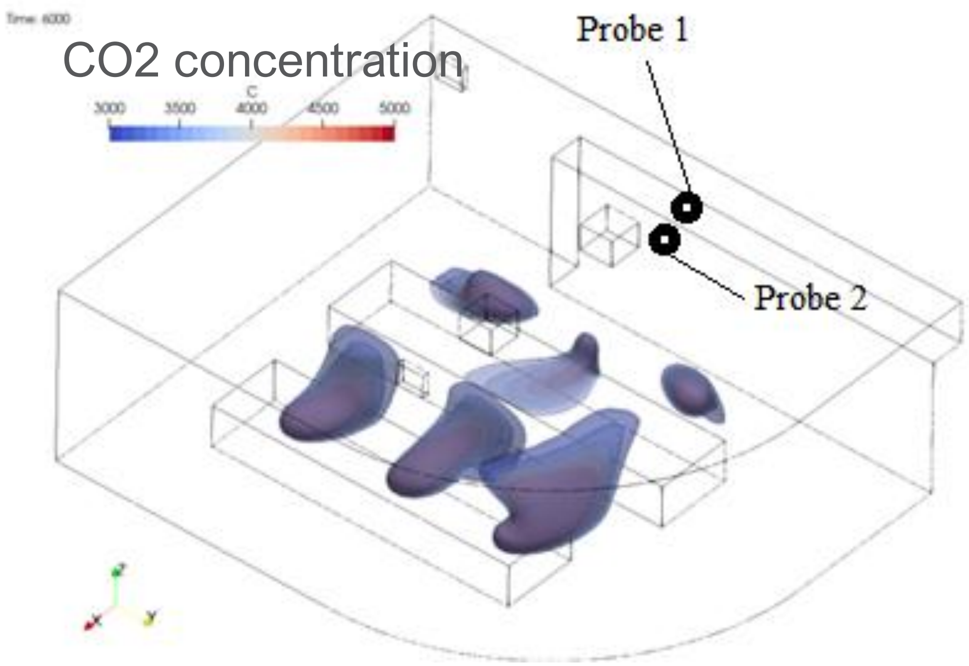
- Temperature
- Humidity
- AI ← Image sensor
- AI ← Sound sensor
- CO_2 sensor

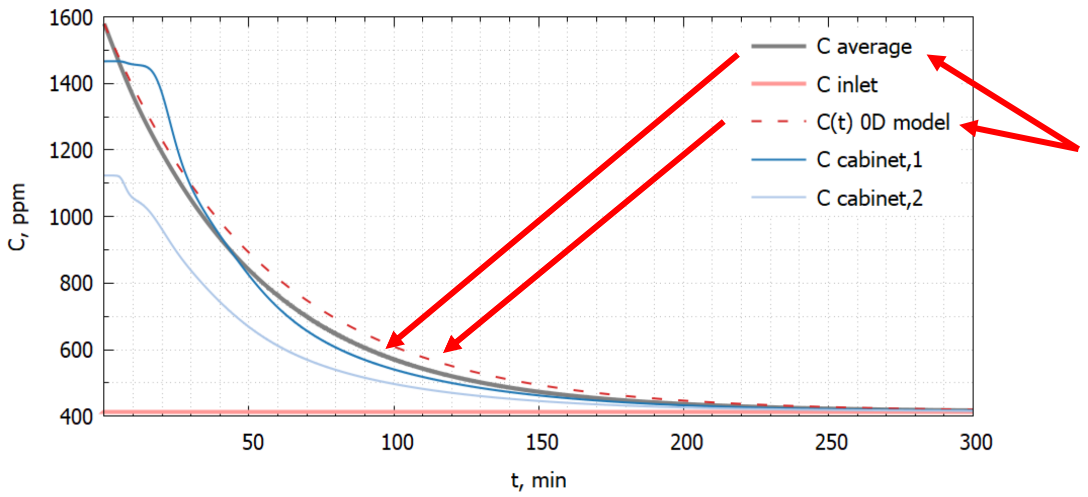
Python program
Running faster than real time on 1 core

IBPC 2021 poster Telicko et al. Section 10, ID-1299
A monitoring system for evaluation of COVID-19 infection risk

Results: 3D air flow simulations





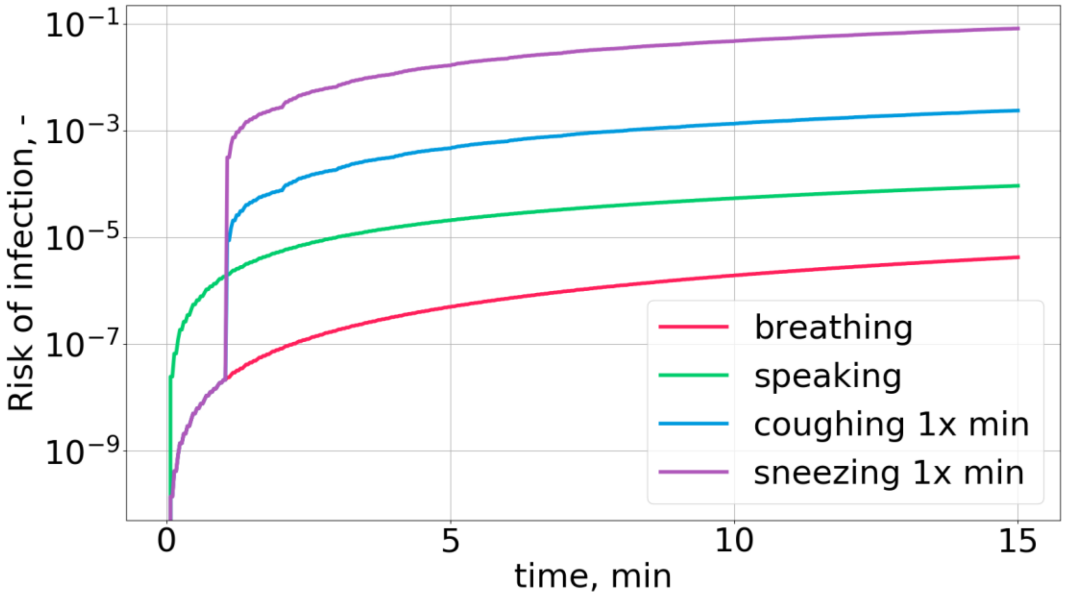


- Good agreement between CO_2 concentration in 3D model and applied integral 0D model
- 3D simulation can optimize ventilation system regarding the reduction of turbulent diffusion and decrease of droplet concentration

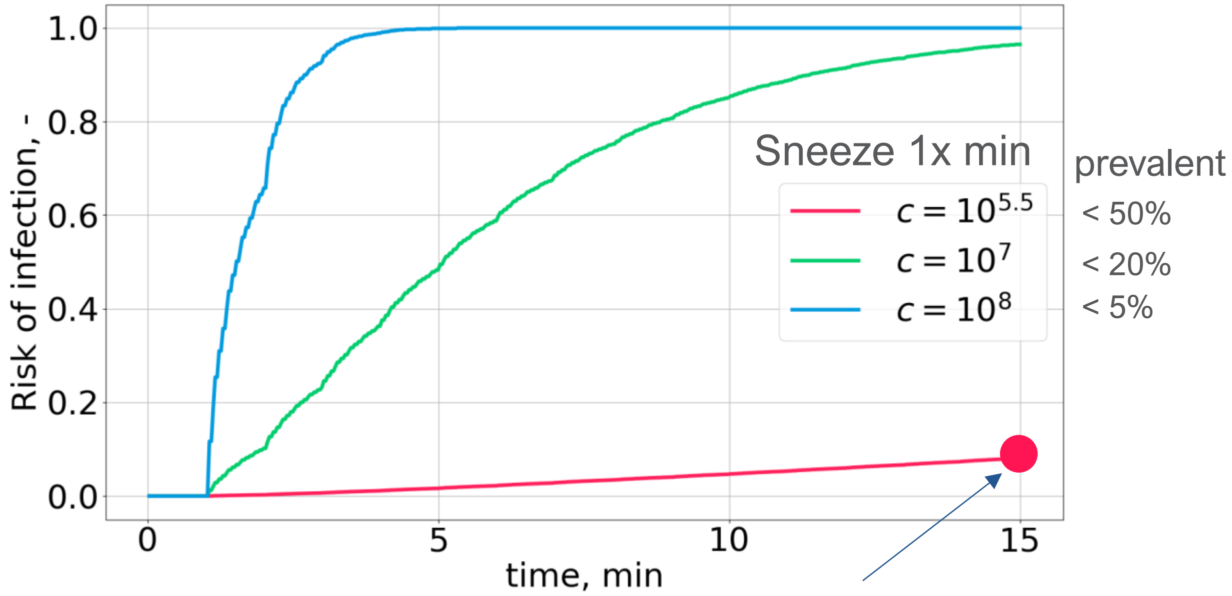
Results: basic scenarios

- Room 3x3x3 m
- T 25°C, RH 50%
- No ventilation
- No contamination at t = 0
- Enter 1 infected and 1 healthy person

Virus expulsion scenarios



Virus concentration in mucus [RNS/mL]



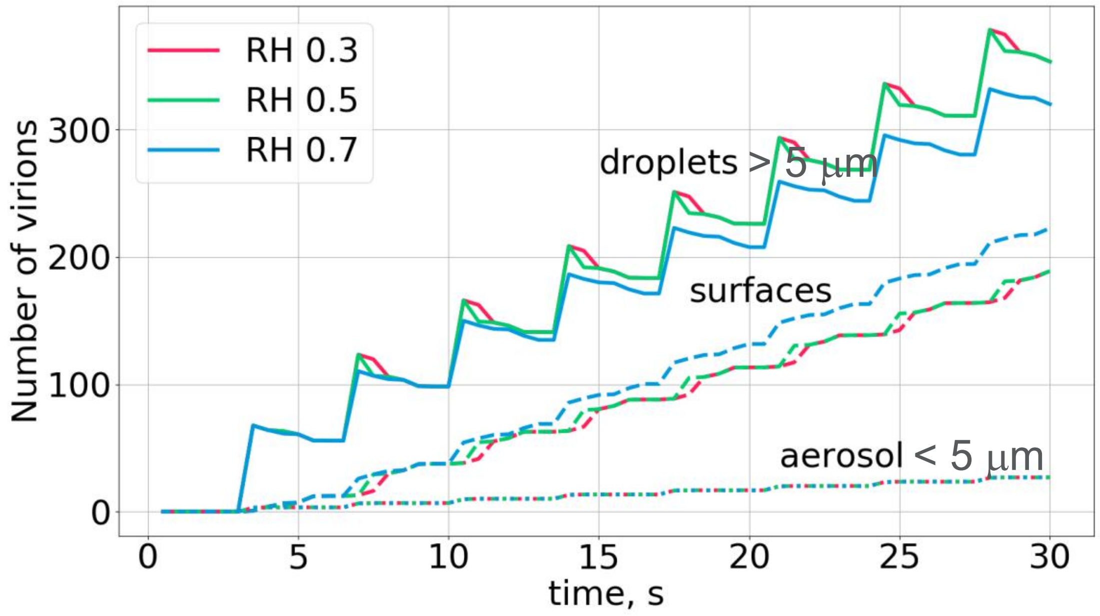
Corresponds to close contact definition – 15 min and 2 meters

- Different expulsion types change the infection risk by orders
  - System recognizes sources analysing the sound
- Small but inevitable infection risk by so called *super spreader*
  - We will use average concentration values

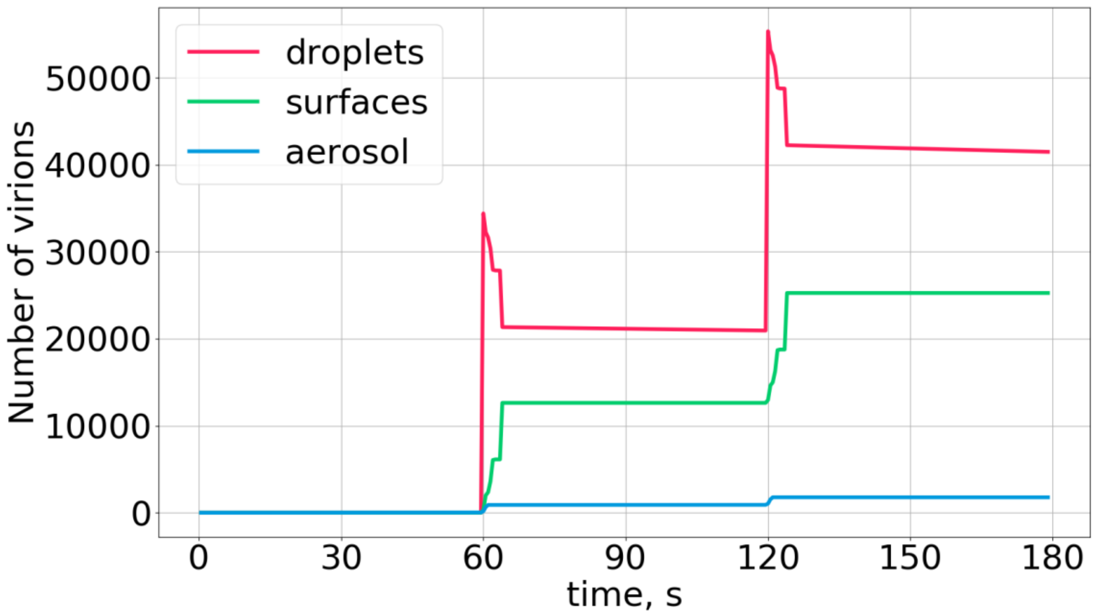
Results: basic scenarios - dynamics

(c = 10^8 is very high concentration)

Source – speech 1x 3.5 s, c = 10^8



Source – sneezing 1x min, c = 10^8

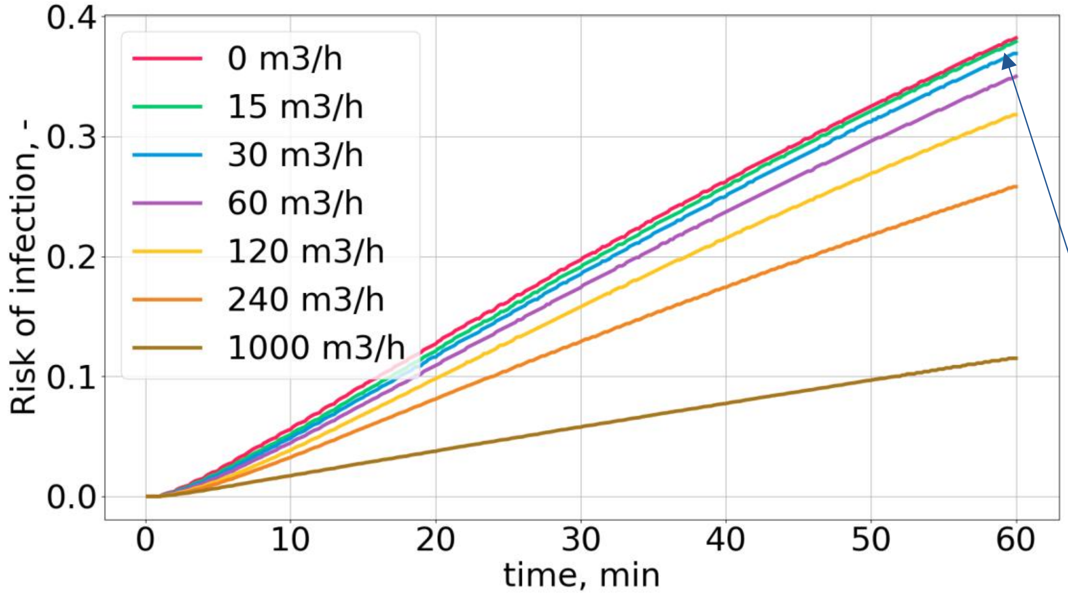


Humidity increases the sedimentation – droplets evaporate slower and sediment faster

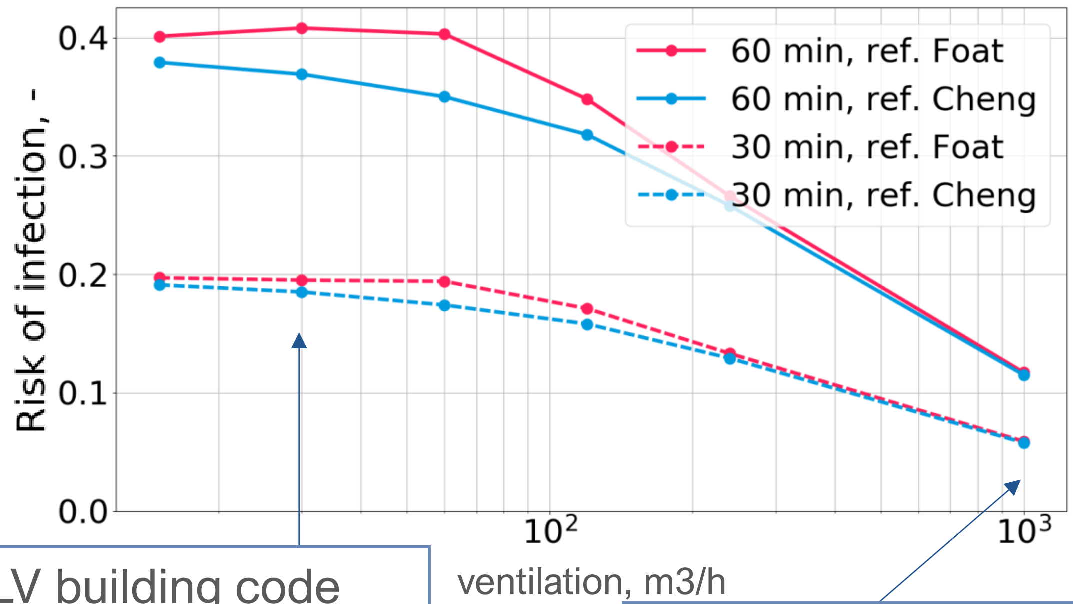
Turbulent diffusion ensures the existence of considerable part of virions in droplets > 5 μm for long time

Results: basic scenarios - ventilation

Source: coughing 1x min, c=10^7 RNS/mL (high concentration, <20% of infected)

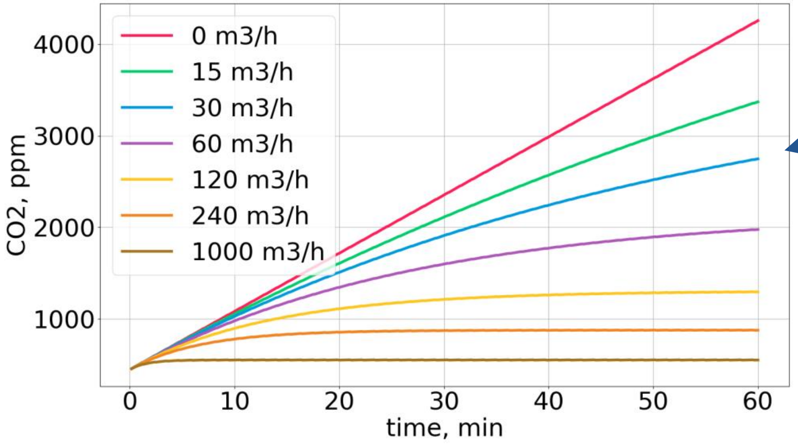


Turbulent diffusion from



LV building code
15 m^3/h / person

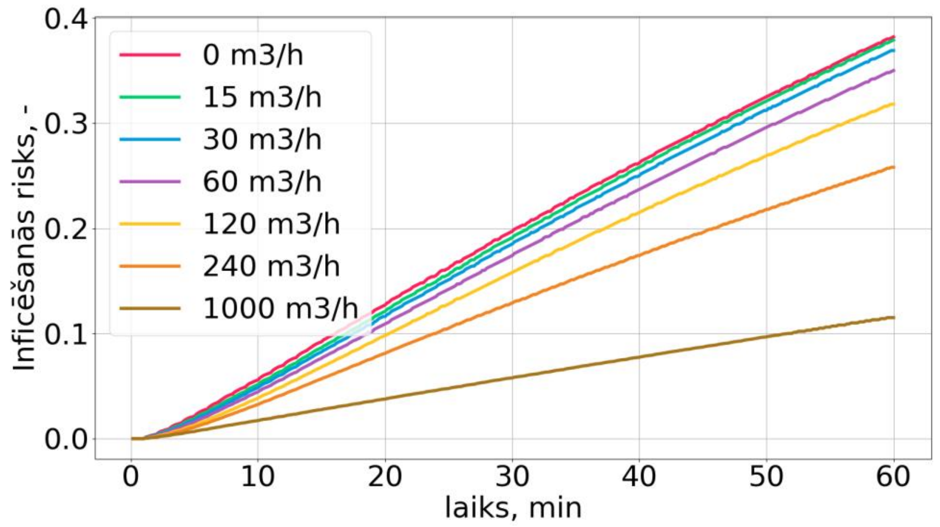
Fully open window

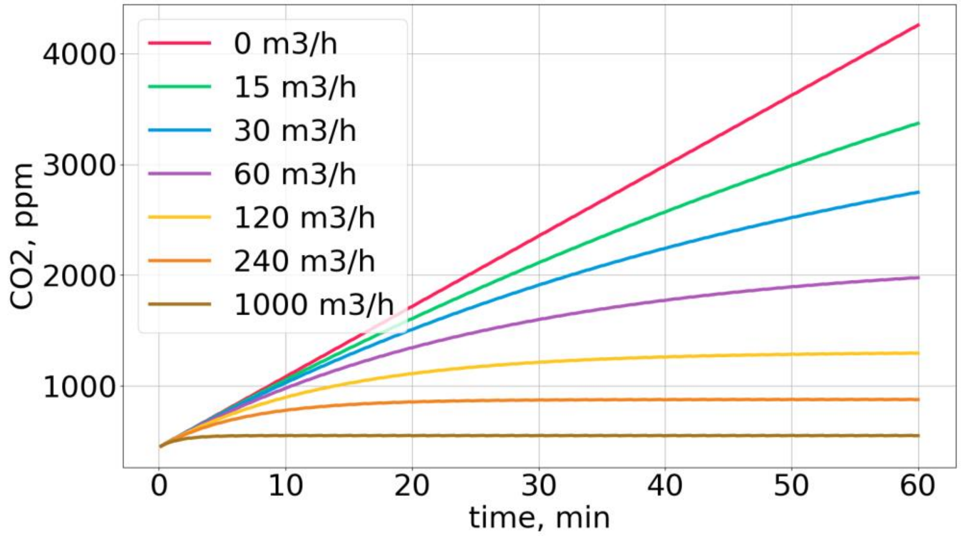


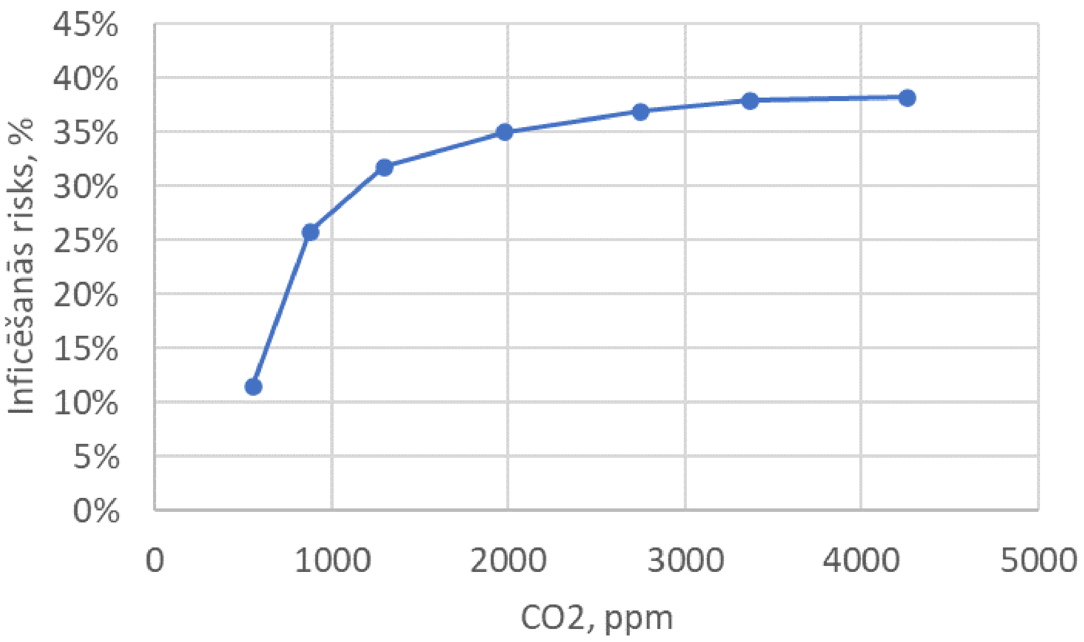
Average ventilation intensity do not reduce the infection risk as large droplets remain in air longer due to increased turbulence

Results: CO_2 vs. Infection risk

Avots: klepo 1x min, c=10^7 RNS/mL (augsta koncentrācija, <20% no slimajiem)





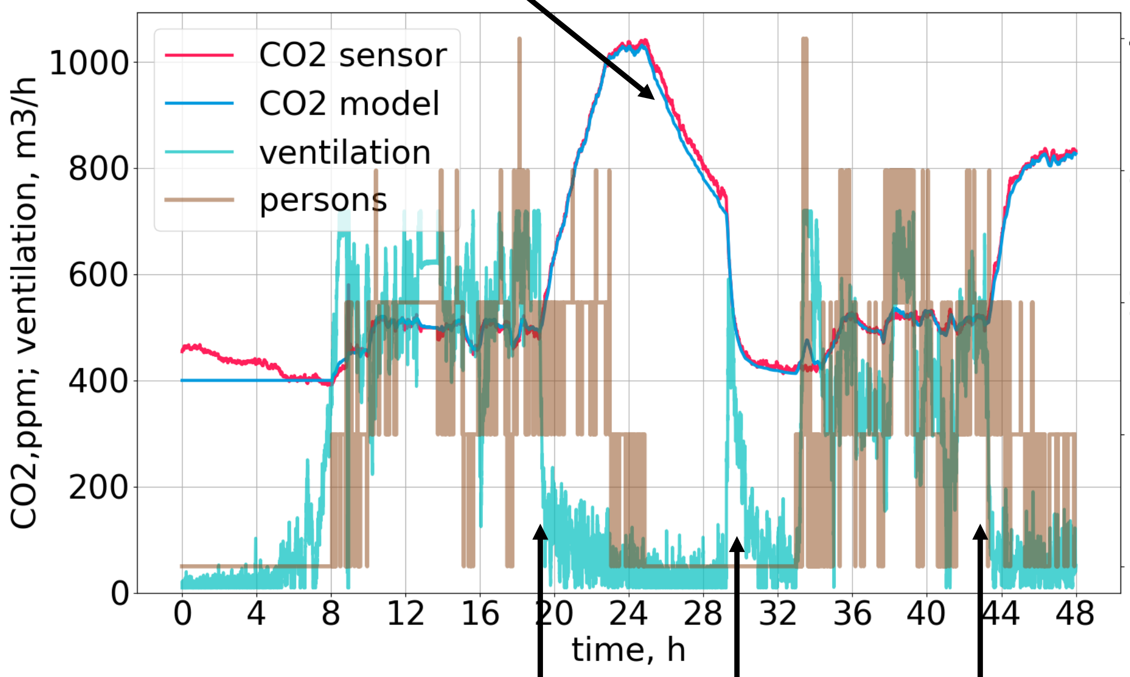


Infection risk decrease considerably for very low CO2 concentrations (~500 ppm)

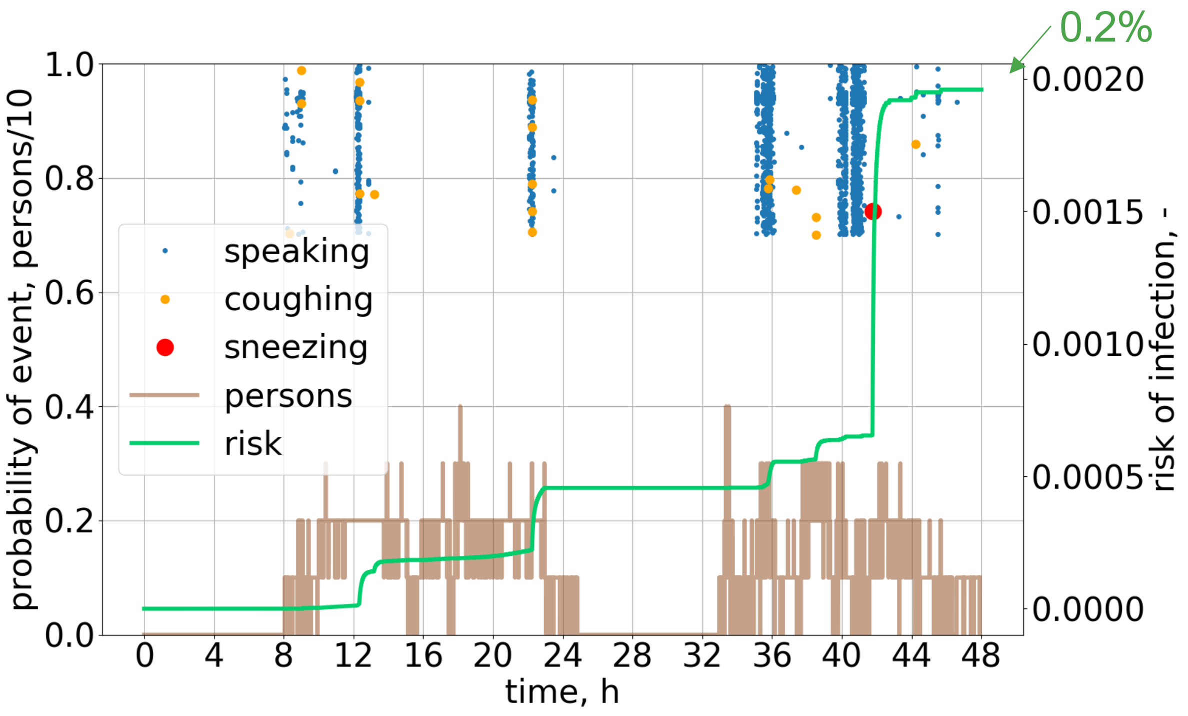
Results: operational environment

Room 523, Jelgavas 3, Riga, University of Latvia (12.01-14.01.2021) Size 7.9x6.2x3.5m, 360 m^3/h

Knowing the number of people and CO_2 concentration, the intensity of ventilation in model is adapted using PID control algorithm



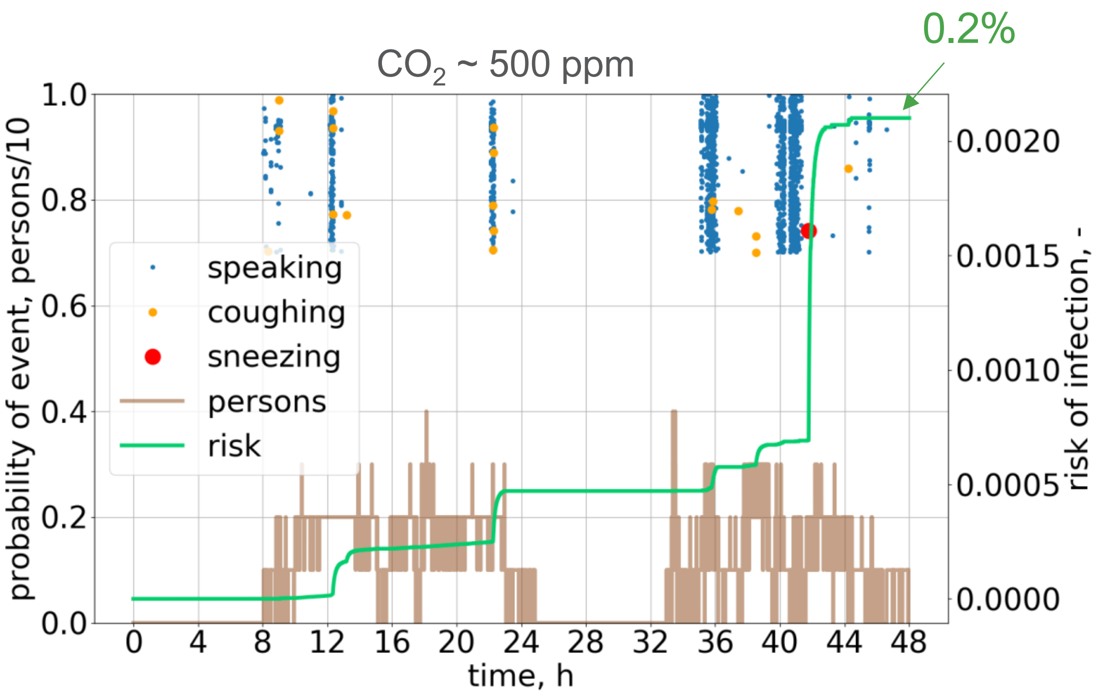
Ventilation: OFF 19:00 ON 5:00 OFF 19:00



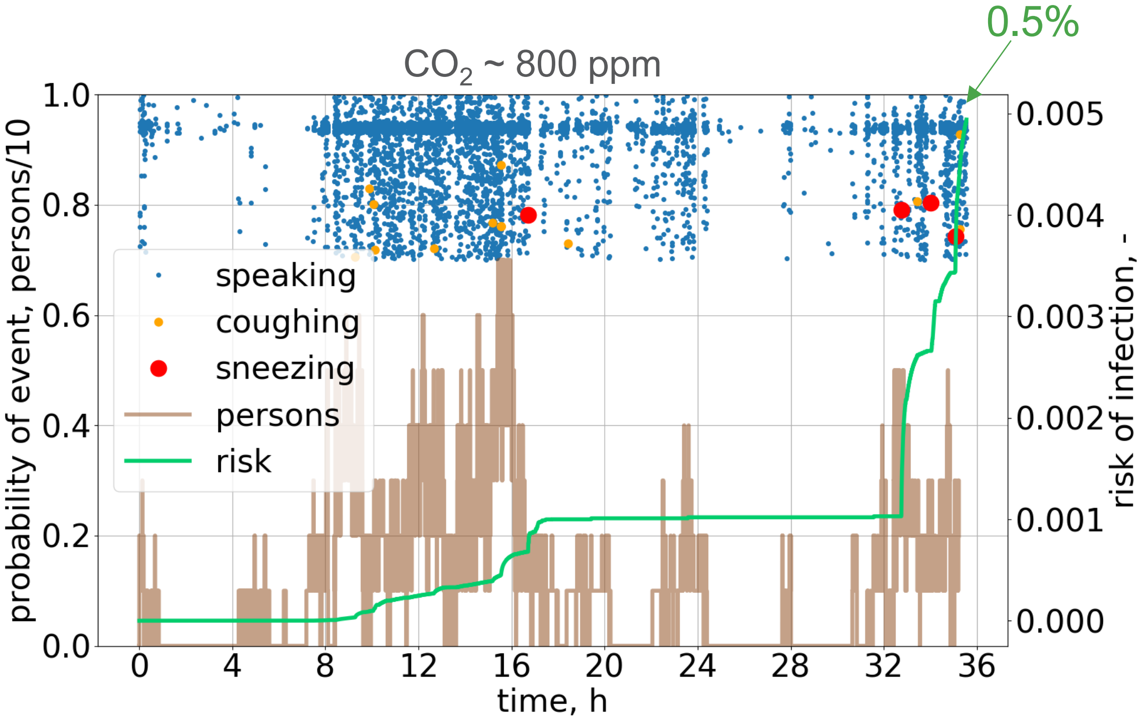
- Good agreement between modelled and measured CO2 values
- Infection risk was slightly changed due to more precise ventilation intensity

Results: different rooms

Room 523, Jelgavas 3, Riga, University of Latvia, 12.01-14.01.2021, size 7.9x6.2x3.5m



Room 101, Building A1, Pilsonu 13, Riga, P. Stradins Clinical University Hospital, 08.03-09.03.2021, size 9.5 x 3.0 x 3.0 m

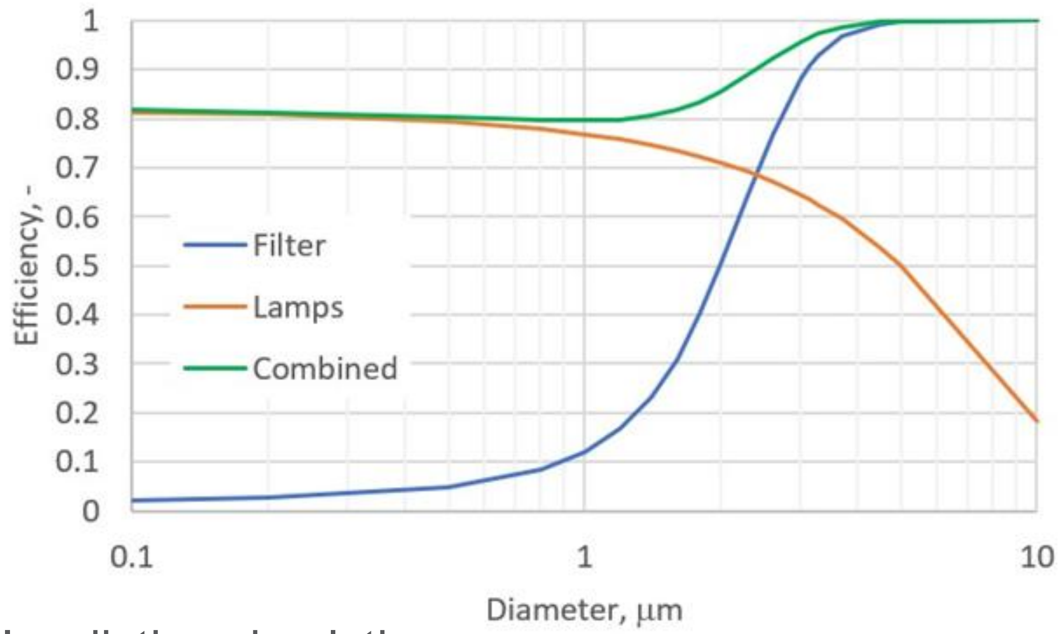


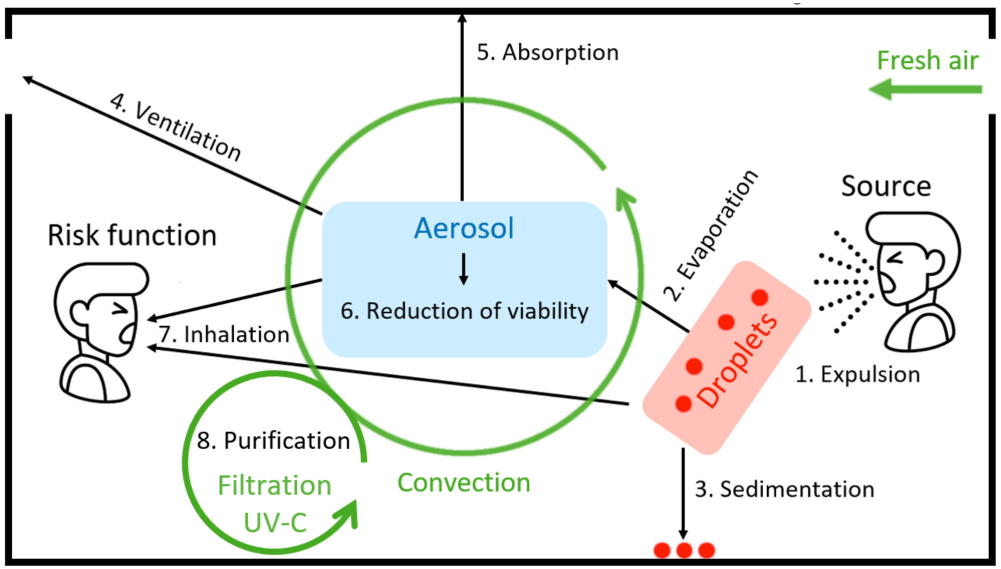
- Less people
- Larger room
- Less speaking
- Less sneezing

→ Lower risk

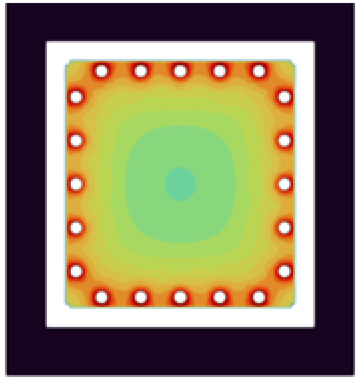
Results: Purification device added

Combined device proposed: coarse M5 filter +UV-Lamps

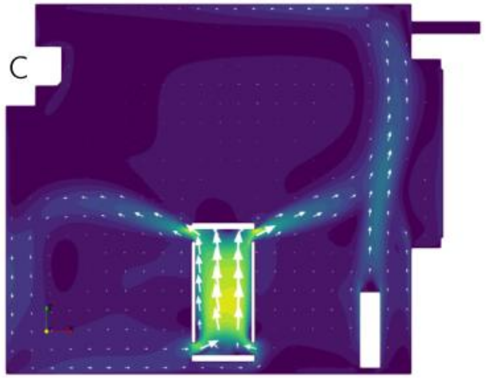




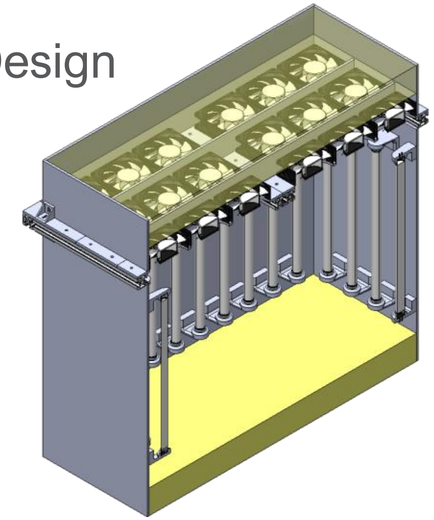
Irradiation simulation



CFD simulation



Design

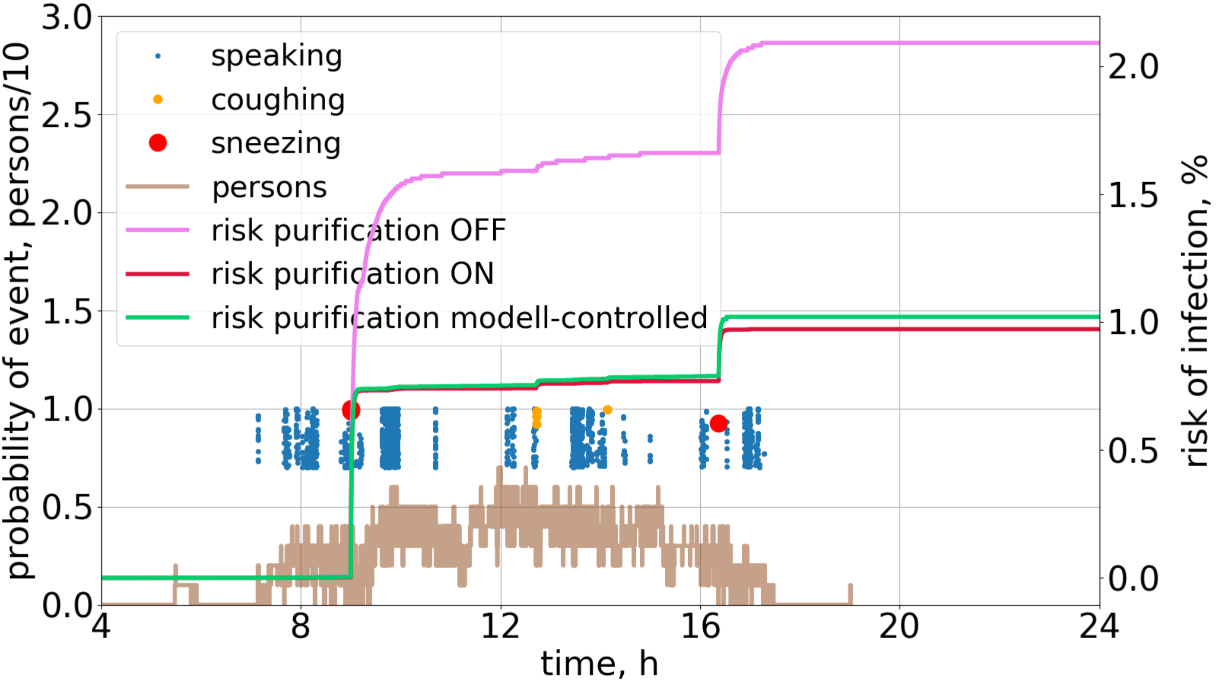


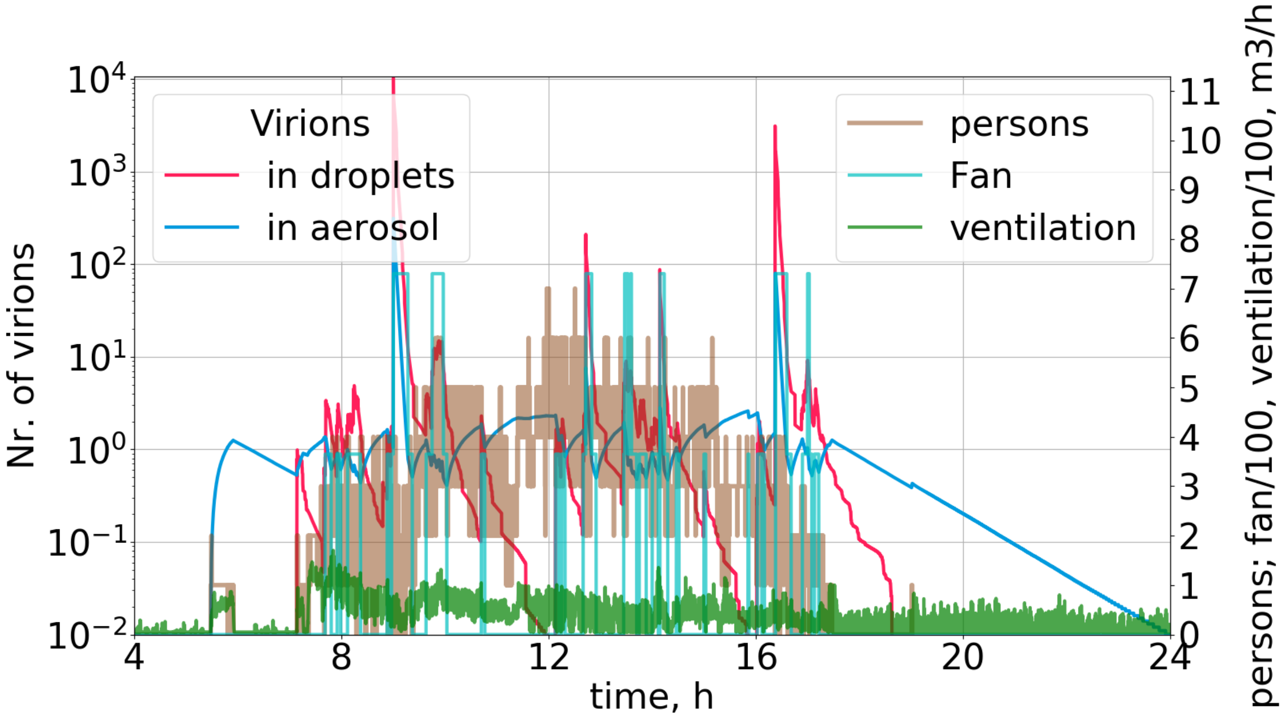
Outer dimensions: 615x657x840 mm^3

Prototype

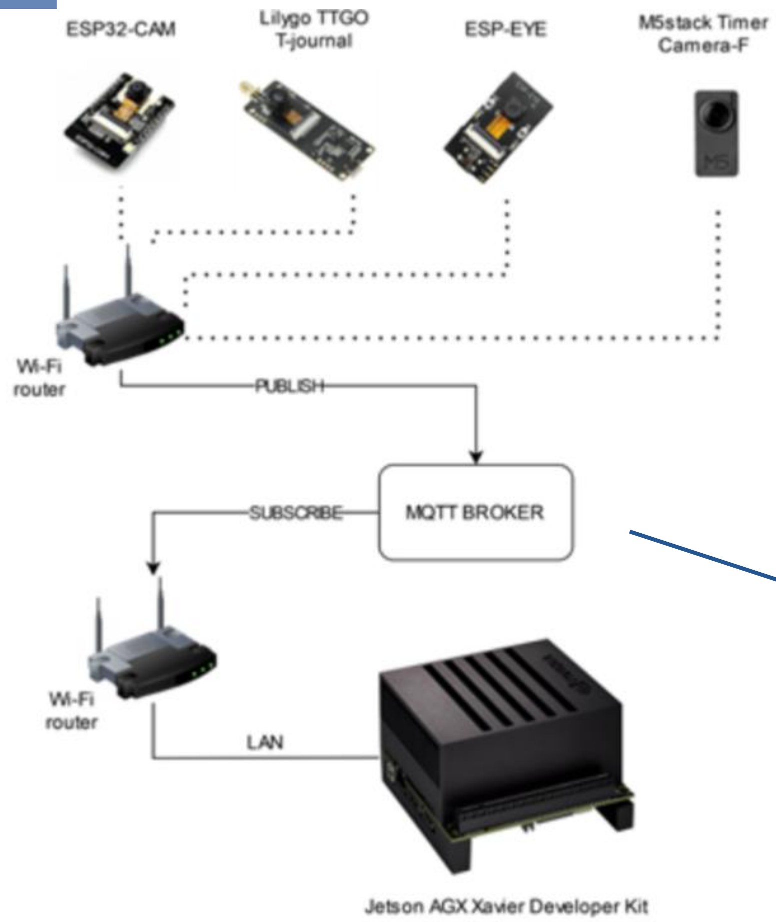
Results: effect of purification

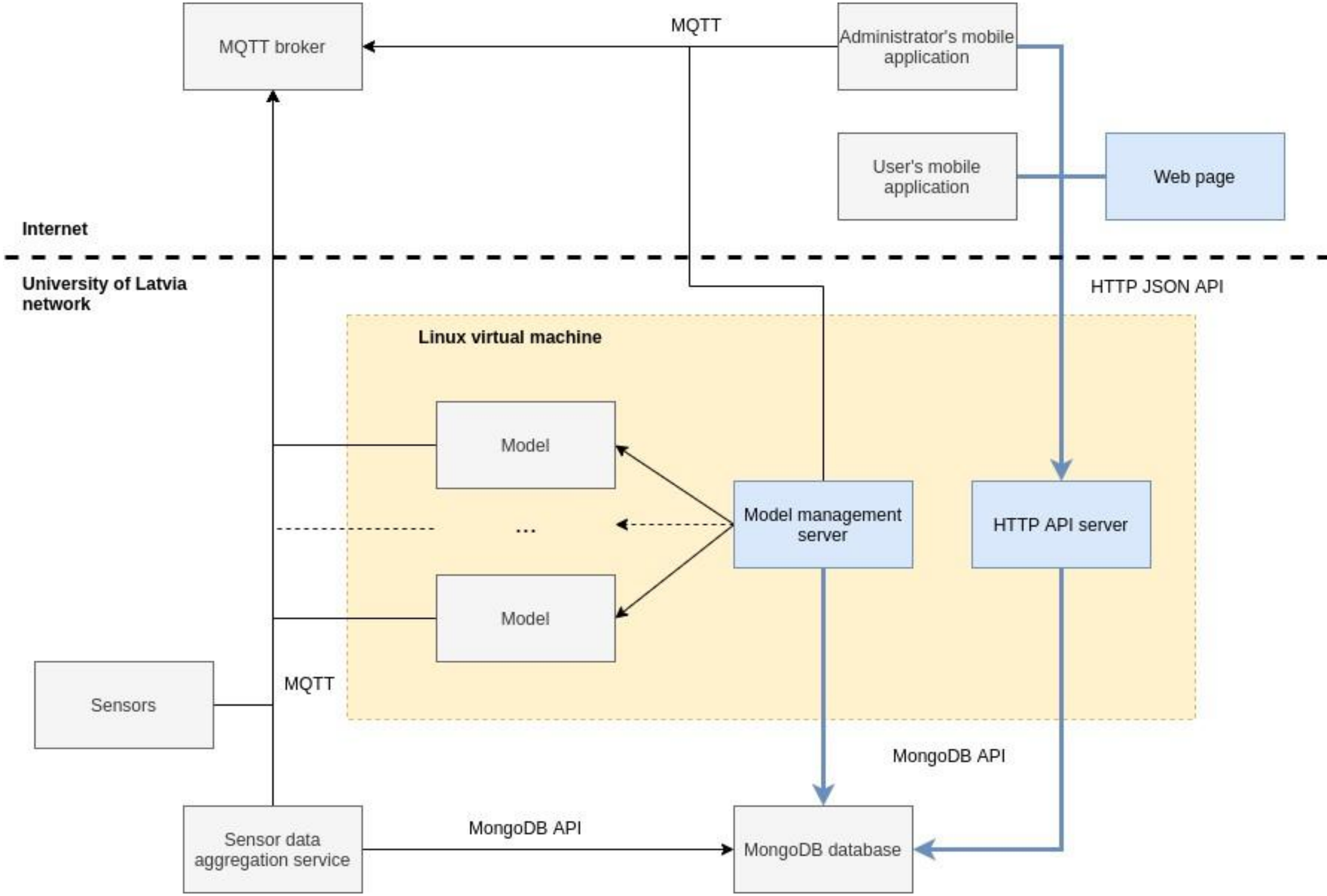
A real operational scenario on 21.02.2023 in Office 523 of the Science building, Jelgavas str 3, Riga (without a purification device) is compared to scenarios with continuous purification (100% of time at 700 m3/h) and model-controlled purification (8.7% of time). The purification device reduces the risk by ~50% or would save 99% energy of comparable ventilation heat losses.





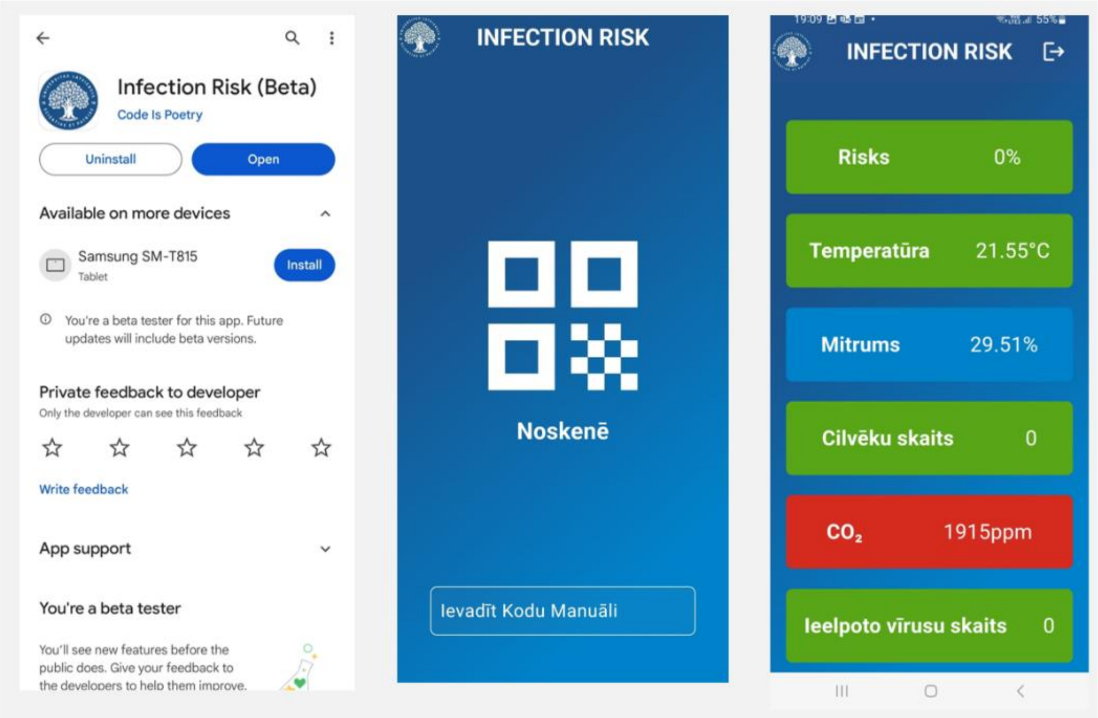
Results: server system & mobile application



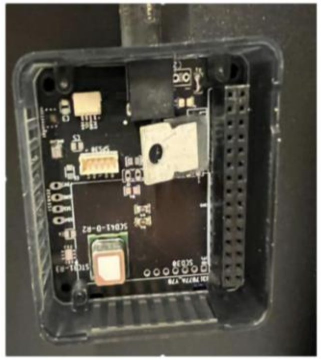


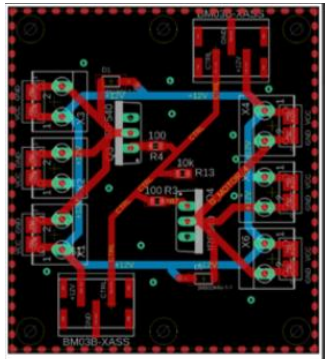
Results: mobile & web applications

Administration, user and web apps



Existing prototype





SISTĒMA VĪRUSINFEKCIJU IZPLATĪBAS SAMAZINĀŠANAI TELPĀS

LATVIJAS UNIVERSITĀTE

Zinātība

NOZARE

VESELĪBAS AIZSARDZĪBA (inficēšanās risku samazināšana, gaisa kvalitātes kontrole telpās).

PIELIETOJUMS

Vīrusinficēšanās (Covid-19 u.c.) risku automatizēts monitorings, individuāla informēšana par to un risku samazināšana telpās.

MĒRĶIS

Ar iespējami minimālu energopatēriņu nodrošināt no inficēšanās drošu vidi cilvēkiem dažāda lietojuma telpās.

RISINĀJUMS

Būtiski samazināts aerosolu pārnesto vīrusu inficēšanās risks telpās (birojos, klasēs, auditorijās, publiskās telpās, slimnīcu telpās un tml.), kā arī cilvēku personificēta individuāla informēšana par inficēšanās risku.

APRAKSTS

DROŠĀS TELPAS SISTĒMA ietver:

- Vīrusu inficēšanās riska monitoringa sistēmu, kas sastāv no fizikālo parametru (CO_2, temperatūra, mitrums un potenciāli arī citi fizikālie parametri) mērījumu, cilvēku skaita un trokšņu identifikācijas mikroelektroniskām iekārtām un uz neironu tīkliem bāzētas programmatūras (sensori, mikroelektronika, programmatūra).
- Kompaktu autonomi darbināmu gaisa attīrīšanas/dezinficēšanas iekārtu, kas sastāv no UV-C lampām, gaisa filtriem, ventilatoriem, un elektroniskā vadības bloka, kas ievietoti metāla korpusā.
- Datu bāzes uz sistēmas servera un lietotāju un administratora mobilajām aplikācijām drošās telpas un gaisa dezinfcēšanas sistēmas vadībai un sistēmas klientu individuālai informēšanai.

PRIEKŠROCĪBAS

- Vīrusu un citu aerosolu pārnesto infekciju risku kontrole un būtiska samazināšana telpās.
- Automātiska cilvēku individuāla informēšana un brīdināšana par apstākļiem un gaisa kvalitāti telpā.
- Vīrusinfekcijas izplatības samazināšanas sistēmu vairākās telpās un ēkās centarlizēta pārvaldība
- Energoefektivitāte (iekārtas tiek darbinātas tikai atbilstoši nepieciešamībai pieaugot riskam).
- Nav lielo enerģijas zudumu, kas saistīti ar vīrusu infekcijas risku samazināšanai nepieciešamo intensīvo telpas ventilāciju ar gaisa apmaiņas kārtu virs 5 gaisa tilpumi stundā.
- Automātiskā vadība uz mērījumu un adaptēta riska modeļa bāzes.
- Autonomā pieslēgšana (var darbināt neatkarīgi vienā vai vairākās telpās).
- Uzdotas gaisa kvalitātes uzturēšana telpā.

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LU-2023-008

Conclusions

- The model, combined with the measurement system, enables real-time prediction of infection risk
  - can be used to increase the safety in an indoor environment.
- The parameter studies reveal that infection risk
  - slightly increases at lower humidity levels
  - decreases with more intensive ventilation.
- The coughing, but especially the sneezing events, strongly increase the risk of infection in the room
  - distinguishing these events is very important for effective risk assessment.
- A method to estimate unknown ventilation intensity has been proposed and successfully tested.
- A purification device prototype has been developed and integrated into the system
- Mobile and web apps have been created for convenient, real-time monitoring of infection risk

Thanks to

Jevgēņijs Teļičko, Maija Sjomkāne, Daniels Vidulejs, Maksims Surovovs, Andris Jakovičs, Andrejs Sabanskis

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«Tracing, testing and treatment of Covid-19 patients»

VPP Valsts pētījumu programma

PAULA STRADIŅA KLĪNISKĀ UNIVERSITĀTES SLIMNĪCA

LATVIJAS UNIVERSITĀTE ANNO 1919 UNIVERSITY OF LATVIA

BMC Latvijas Biomedicīnas pētījumu un studiju centrs

European Regional Development Fund, Project "System for prediction and reduction of COVID-19 infection risk in indoor environment" No. 1.1.1.1/21/A/046.

NATIONAL DEVELOPMENT PLAN 2020

EUROPEAN UNION European Regional Development Fund

INVESTING IN YOUR FUTURE

Appendix - Model

2. Evaporation

The evaporation mass flux has two components:

$$\frac{dm_1}{dt} = -4\pi\rho_v D_v R_s \ln(1 + B_M)$$

$$\frac{dm_2}{dt} = -4\pi\rho_v \alpha_g R_s \ln(1 + B_T)$$

where B_M and B_T are the Spalding mass and heat transfer numbers

$$BM = \frac{Y_{1,s} - Y_{1,\infty}}{1 - Y_{1,s}}$$

$$BT = \frac{C_{p,l}}{h_{fg}} \cdot (T_s - T_\infty)$$

The energy balance is governed by

$$mc_{p,l}\frac{\partial T_s}{\partial t} = -k_g A_s \frac{\partial T}{\partial r} + h_{fg}\frac{dm_1}{dt} - e_l \frac{dm_2}{dt}$$

7. Risk function

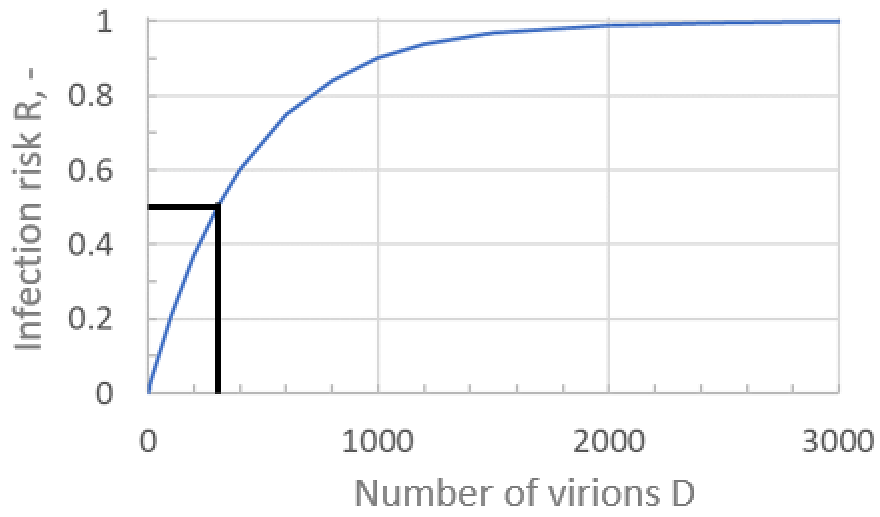
risk of infection R is[4] **Haas 1999**

$$R = 1 - (1 - \alpha)^D.$$

COVID-19 ID50% ir ~300 virions

Basu 2020

$\alpha = 0.0023$



Appendix - Model

3. Sedimentation

$$v_{sed} = \sqrt{\frac{4\,\rho_{water}\,g\,D}{3\,\rho_{air}\,C_D}}$$

$$C_D = \left(\left(\frac{24}{Re}\right)^{0.52} + 0.32^{0.52}\right)^{\frac{1}{0.52}}$$

$$Re = \frac{\rho_{air}\,D\,v_{sed}}{\nu}$$

until the floor is reached or a droplet reaches its final size. When the final size is reached, droplet dynamics are calculated by solving a one-dimensional (vertical room dimension) convection-diffusion equation where convection is described by the sedimentation velocity given above and the diffusion accounts for the turbulent mixing of air in the room. Solving equations for every expelled particle group is not possible in the real-time operational model, therefore the solution is performed beforehand for all pair combinations of 16 diameters and 16 turbulent diffusivities. The calculated temporal distributions in the height of 1.2 m are last squares fitted using combination of two exponents and interpolated for any combination of particle diameter and turbulent diffusivity. The turbulent diffusion coefficient K is calculated from room volume V and ventilation Q according to [22].

$$K = 16.7\,Q/V$$

The droplets are assumed sedimented if their concentration at the inhalation height of 1.2 m $\leq$ 0.1% of the initial concentration .

Appendix - Model

5. Absorbtion

Wall sedimentation

Sedimentation of small airborne particles on surfaces is calculated according to [23]. The mechanism for this sedimentation is Brownian diffusion through the laminar boundary layer. Contrary to the vertical sedimentation, which is faster for larger particles, Brownian diffusion is more pronounced for smaller particles. The rate of wall loss for total particle number *N* is defined as

$$\frac{dN}{dt} = -\beta\, N.$$

The wall loss rate coefficient

$$\beta = \frac{D_{Br}\, A}{d_{BL} V}$$

depends on surface area *A*, volume *V*, thickness of the laminar boundary layer d_{BL} (assumed 1 cm) and diffusion coefficient

$$D_{Br} = \frac{k_B T\, C_{slip}}{6\, \pi \nu R}$$

where

$$C_{slip} = 1 + \frac{l}{R}\left(1.26 + 0.418\, e^{\frac{-0.867\, R}{l}}\right)$$

l is free path length and *R* is particle radius.

6. Viability correction

The viability of the virus in aerosols and small droplets decreases in the time [25]. The model assumes the following dynamics:

$$N^{i+1} = N^{i}\, e^{-1.64e-4\, dt}$$

where the constant in the exponent is obtained by digitalizing the experimental data in Fig. from [25].

7. Inhalation

The person for whom the infection risk is calculated inhales 0.4 l/s of air with an average room concentration of aerosols and the concentration of droplets at the height of 1.2 m. Between 19% and 95% of inhaled particles are absorbed depending on their size [26]. Therefore a number of virions enter the organism and this number is used to calculate the risk of infection.