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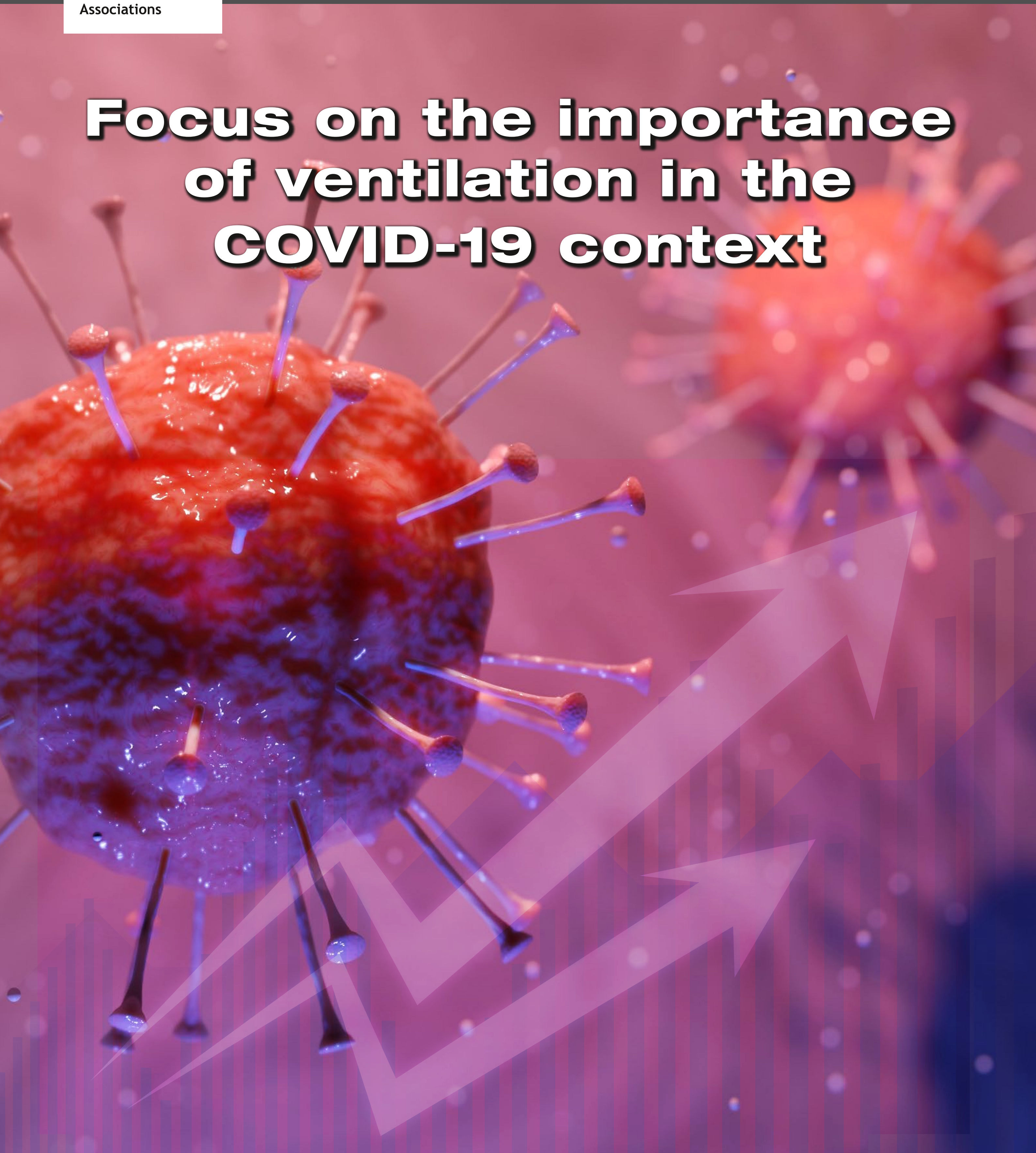
Focus on the importance of ventilation in the COVID-19 context



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COVID-19 crisis – fertile grounds for the Renovation Wave initiative?

This RJ special on COVID-19 issues includes several articles from various experts around Europe. They all want to share with you their knowledge and experience in this field. There are some very practical articles informing you about the use of UV-C or handling the recirculation issue. Also, several articles on calculating the risk of infection which provide basic information. These calculation procedures should be understood as tools to compare certain ventilation strategies to support experts in advising on the best ventilation strategy. Several articles demonstrate this effectively.

In this context I have to mention the REHVA services on COVID-19 which have been made available since April 2020. The REHVA website offers you the last updated and peer reviewed information [1]. Via this link you can find guidance and FAQ information that can be downloaded, information on the new REHVA COVID-19 ONLINE COURSE and accessible webinars on COVID-19.

I am aware that COVID-19 crisis is currently at the forefront of our attention. Against this background the professional community should revisit the basis of the current ventilation requirements and the design of our ventilation systems. This is work to be done by the REHVA Technology and Research Committee (TRC) with support of the REHVA members. Results of this work should be shared with relevant CEN and ISO technical committees to update the current standards in this field.

Yes, there is a COVID-19 crisis, but we should not forget that the currently we are on a verge of a climate crisis. I refer to a comprehensive Report Zero Carbon Buildings 2050 Summary Report CE Delft, the Netherlands (see page 83) where it is stated that the current policies focusing on incentives and information are not enough to achieve full decarbonisation of the residential building sector. Additional regulatory and pricing policies as well as instruments that support the deployment of innovation, are needed to reach the full emission reduction potential. The areas that have the largest GHG emission reduction potential are:

- Reducing energy demand by improving the energy performance of the existing building envelope
- Switching to zero-carbon fuels for heating, including a switch in heating systems
- Reducing embedded carbon in construction and renovation materials

For those interested in the development of the European policy, I also refer to a recent BPIE report titled: A Guidebook to European Building Policy, giving an overview of key EU legislation aimed at transforming and decarbonising the European building stock.

Energy gains and economic growth: The Renovation Wave Initiative

The European Commission: Renovation is a major opportunity for economic growth as it provides jobs and boosts the construction sector, which is largely dominated by local businesses, while strengthening Europe's industrial competitiveness. Building renovation is therefore central to the post-COVID-19 economic recovery, and was specifically referred to in the recovery plan published by the European Commission on 27 May 2020.

The renovation wave initiative, as presented this October, will build on measures agreed under the Clean energy for all Europeans package, notably the requirement for each EU country to publish a long-term building renovation strategy (LTRS) [2], other aspects of the amending Directive on the Energy Performance of Buildings ((EU) 2018/844), and building-related aspects of each Member State's national energy and climate plans (NECP) [3]. ■

JAAP HOGELING
Editor-in-Chief
REHVA Journal

[1] https://www.rehva.eu/activities/covid-19-guidance
[2] https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/long-term-renovation-strategies_en
[3] https://ec.europa.eu/info/energy-climate-change-environment/overall-targets/national-energy-and-climate-plans-necps_en

COVID-19 and recirculation




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Keywords: COVID-19 and recirculation: air quality, health, building level, room level, ventilation efficiency, airborne transmission

Introduction

Recirculation is an important topic in the advice to anticipate the spread of viruses in buildings and spaces [1,2]. However, the advice on recirculation also raises some questions. A generic advice cannot always be translated one-to-one in a specific situation. In this short article we would like to explain the backgrounds of the proposed advices (as found in, e.g. [1] and [2]) in more detail. With this we hope that a (large) part of the questions that may still remain can be answered and we also hope that this will make it easier to consider one's own situation and to take the possible desired measures.

First the definition: Recirculation is the reintroduction of exhaust air into the room or building. This recirculated air is then often first mixed with (clean) outside air, the ventilation component (see **Figure 1**). Normally, through a high recirculation rate, the aim is to provide heat or cold via the supply air, without the need for a high ventilation rate. This avoids the need to condition a large amount of (ventilation) outside air. It results in energy savings, often in combination with

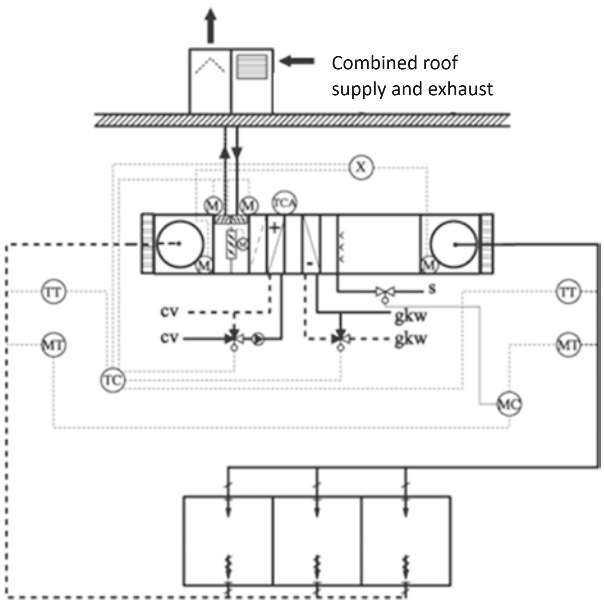


Figure 1. Example of a recirculating solution. Figure taken and translated from [3].

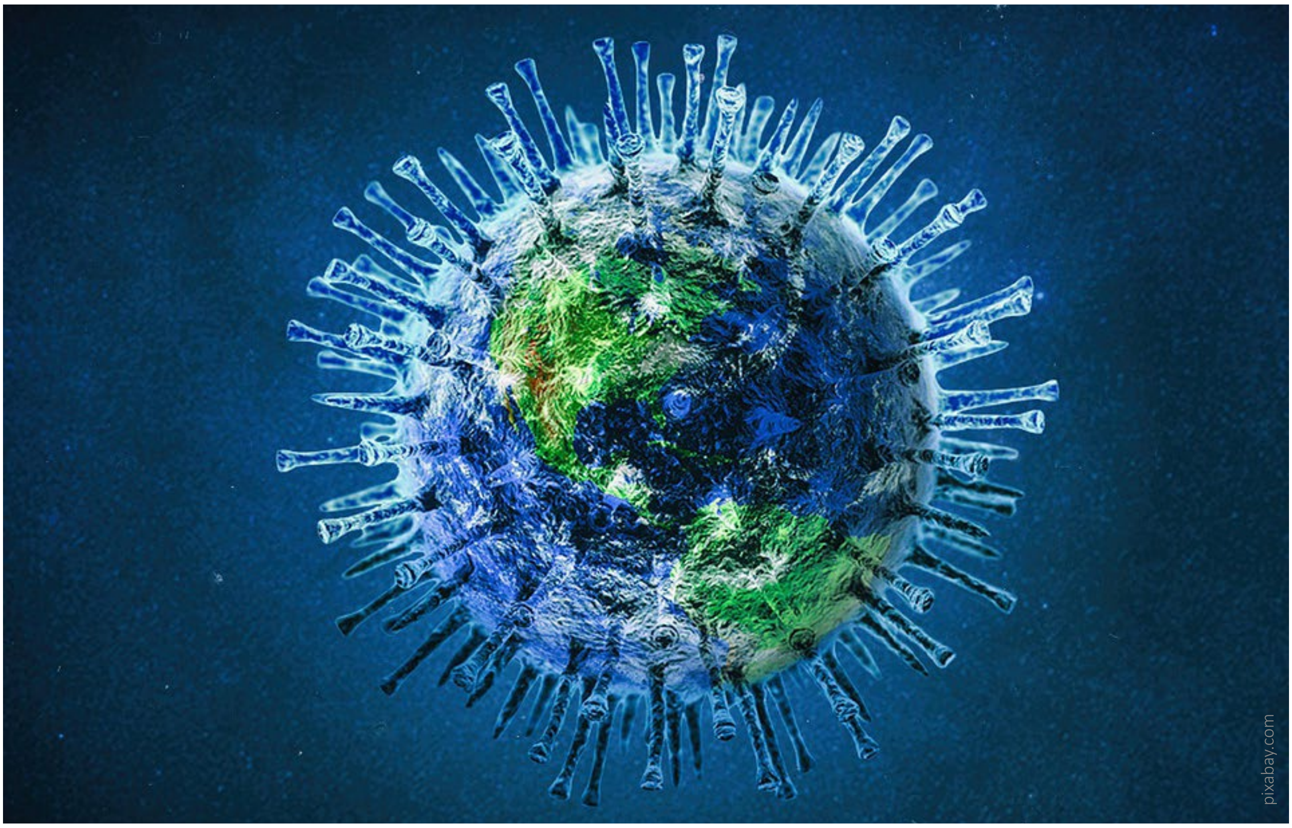
the possibility of limiting the capacity of the heating and/or cooling system. In new buildings heat recovery is a legal requirement since 2014 (EU 1253 [4]) in case of balanced ventilation. However, the desired heat transfer can be achieved without the need for recirculation, for example by means of a twin-coil system, crossflow heat exchanger or rotary heat exchanger. In practice, however, there are still many often somewhat older buildings, with mechanical supply and return, where recirculation is used as part of the air treatment system. Often it is not possible to switch off recirculation completely without creating capacity problems with regard to heating and cooling.

Where the energetic and capacity reasons regarding heating and cooling capacity are clear, the use of recirculation is less logical from a health point of view. After all, 'polluted' air is brought back into the building. In principle, this air can also end up in places/spaces where there are no sources of pollution and thus lead to health or other complaints elsewhere in the building. The contamination can be broadly defined, CO_2, odors, particulate matter, but also germs. By only supplying outside air, i.e. ventilation, you can easily prevent these contaminants from being reintroduced into the building.

This is the underlying explanation for the advice not to use recirculation. However, we can still make a distinction. The explanation as described above focuses on building level. There is also a possibility to recirculate at room level. This is often done using secondary air circulation systems such as a fan-coil unit, split-unit or induction system. In the description below we will deal with both levels separately.

Recirculation at building level

At the building level, the use of recirculation is undesirable in the context of health in general, when talking about local sources that can affect a person's health. In the current situation it is the SARS-CoV-2 virus and therefore a precaution against COVID-19. Through recirculation at building level, it is possible that viruses produced in one room are spread throughout the building. The concentration is then of course reduced. Although at the moment the (long-range [5]) risk of infection via airborne transmission is not considered high, it is desirable to prevent this from happening from a precautionary point of view. A recent study [6], although not yet peer-reviewed, shows that the virus can be found on filters in the air handling unit when recirculation is used and therefore the risk is not a hypothetical assumption. In this case, only the RNA has been detected and not tested for viability. Not using recirculation prevents this situation from occurring. In principle, the ventilation level, i.e. the



fresh air supply, should not have to be adjusted for this if it is already sufficient. If the ventilation level is assessed as insufficient, you should increase this level, but this is independent of not using recirculation at building level. From an air treatment point of view, there could be capacity limitations at high (summer) and low (winter) outdoor temperatures. If more ventilation can be provided, this is only positive. If this is not the case, it is necessary to consider to what extent the thermal comfort is affected by the transition to an air-conditioned situation based on outdoor air solely.

With regard to particles (viruses are transported via particles/aerosols) there is the possibility to filter air. In this way you could clean the recirculated air. Often there will be some degree of filtration present in a recirculation system. However, these filters, and as a result the total air treatment system, are normally not designed to effectively remove the small (<1–2.5 micron) particles [6]. It is precisely these particles that play a role in the airborne transmission route because they can float for a long time. Placing better filters is an option, but will often not be possible due to the higher pressures in the existing air handling unit that will then be required. For microbiological contamination, if done properly, there is also the possibility to remove them by means of ultraviolet light (UVGI - ultraviolet germicidal irradiation) or ionization.

Considering the above, it is best not to use recirculation at the building level. Where it is impossible to prevent this completely due to capacity problems, it should be minimized as much as possible. Improvement of filters should be considered then, and the ventilation level should be set as high as possible. The latter to make dilution as large as possible. Specific situations (multiple infections, long-term presence, sensitive groups, e.g. nursing homes) provide emphatic reasons to avoid recirculation.

Recirculation at room level

At room level, different types of delivery systems are used to bring air into the room and to condition air. Sometimes this is combined. Especially when it concerns systems that also provide for (part of) the ventilation of the room, these should not be switched off. An induction unit is a typical example of such a system. Such a unit also provides the fresh air supply (ventilation) of the room. Ventilation is one of the most important components in the strategy to reduce the (long-range) airborne risk. The more ventilation with fresh outside air, the better. Also, many fan-coil units will have a fresh air (ventilation) component. Again, the advice is to keep these types of systems running.

Where a system does not contribute to ventilation, the advice becomes more difficult. A split-unit is a typical example of a system at room level that often does not contribute to the ventilation of a room. However, it can be essential in the conditioning of the room to achieve pleasant thermal conditions. In the recent period, the advice from the RIVM (Dutch National Institute for Public Health and the Environment), REHVA, [2], etc. on whether or not to use such a unit has been somewhat diffuse. In principle, the advice is not to use such a unit. The starting point for this advice at room level is that we want to prevent the direct transmission of the virus through airflow between people. The problem here is that this advice is easily stated in a generic way, but that the interpretation is very case-specific and often difficult to assess.

Transmission by airflow between persons can occur when a (direct) airflow between persons in a room can occur. In practice, supply grilles and systems such as a split unit will be designed and placed in such a way that a mixing situation arises in a room. Whether or not the split-unit is switched on will then not change much to the mixing situation. This means that it is not to be expected that this will result in a stable airflow between two people. In certain cases, however, it is possible that by turning on the unit, circulation flows (vortices) will be created in the room, which may develop into such a flow of air between people. The case in the restaurant in

China [7] shows the possibility of this. This concerned a unit on the wall that created a standing room air recirculation flow via the ceiling. It should be noted that in this example, the ventilation level in the restaurant was very low. With respect to COVID-19, for a ceiling unit the direction of flow could be set parallel to the ceiling, preferably in all directions, so that mixing is optimized and no recirculation flow can develop similar to the situation as sketched for the restaurant in China [8,9]. It must be stressed that the main point of departure is always a well-functioning ventilation system and sufficient ventilation of the room.

Often it will not be easy to gain insight into the air flow that is created in a room. Smoke for visualization is a useful tool, but it is better to leave the assessment to an expert such as a building services consultant. Another important note is that if the system remains on, the ventilation must remain in order in all cases. With a working system, cooling will probably give the impression that the air has to be ventilated a little less, because the air can also be assessed as 'fresh' from an air quality point of view [10]. This is not desirable. Ventilation in this case, and in fact always, is first and foremost intended to keep the air quality high.

Ventilation principles

In addition to the importance of sufficient ventilation, for the sake of completeness we would also like to briefly discuss ventilation efficiency for room ventilation solutions. There are two main principles: mixing ventilation and displacement ventilation. In **Figure 2**, the principles are visualized schematically.

In principle, displacement ventilation is a more efficient form of ventilation. This means that with the same amount of air contaminants are removed more efficiently, so that their concentration in the room, in the breathing zone, is lower.

The interesting point, however, is that for the issue of aerosols this does not necessarily has to be the case. This is presented in a study by Nielsen et al. [12] in which they compare the inhaled concentration with the exhaust concentration. **Figure 3** gives a summary of some examples in which de inhaled concentration is compared to the concentration at the exhaust. In this case the persons ('source', 'receiver') are positioned 0.35 m apart from each other.

Figure 3 shows that in this case displacement ventilation (C_{max}/ C_R = 4.0–7.3; C_R: exhaust concentration of contamination, C_{max}: inhaled concentration of the 'receiver') performs less well than a mixing ventilation solution (C_{max}/ C_R = 1.7–2.1). The explanation for this is that, at a relatively short distance, the breath of the 'source' person can break through the boundary layer of the 'receiving' person. Displacement ventilation appears to be more sensitive to this than a mixing

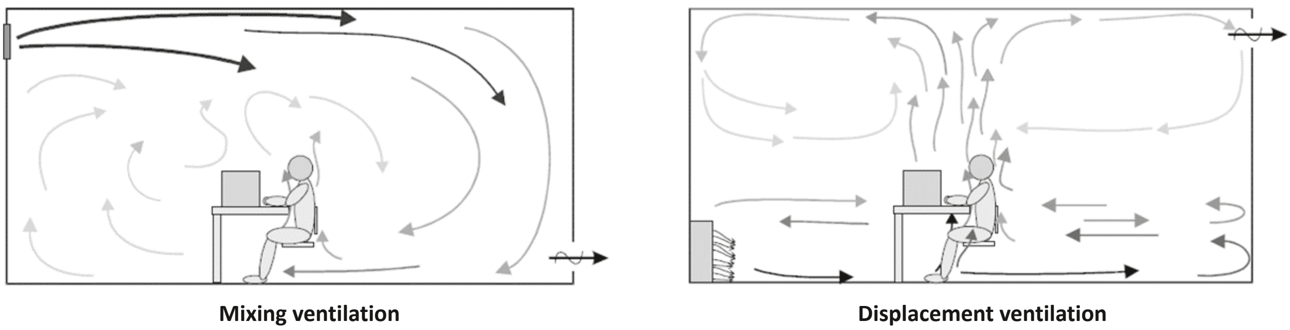


Figure 2. Schematic representation of the principle of mixing ventilation and displacement ventilation. [11]

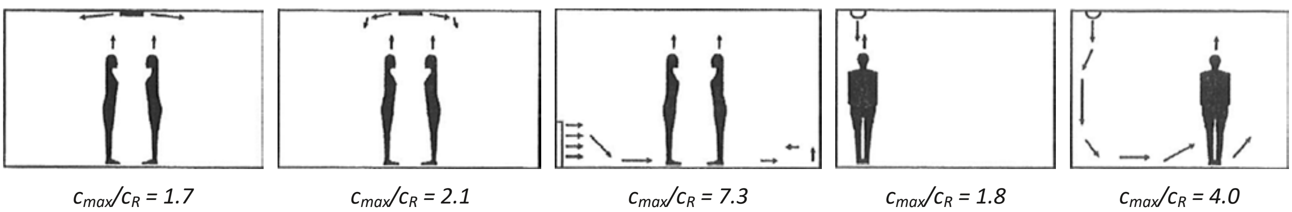


Figure 3. Comparison of different flow situations in a room expressed through the ratio of the exhaust concentration of pollution (C_R) to the inhaled concentration of the 'receiver' (C_{max}) with the emission of particles (pollution) by the other person in the room [13] (based on [12]).

situation. This is a problem at a short distance, but also at a larger distance displacement ventilation can perform less well in such a situation. The exhaled air can become trapped in a stratified, calm, layer that is characteristic for displacement ventilation. As a result, the particles can stay there longer and spread further [14]. In a mixing situation, these particles are in that case better diluted and removed.

In conclusion

With the current experiences, the importance of having a good ventilation has been shown once more. Recirculation no longer belongs in new buildings. There are good alternatives to make heat recovery possible without having to mix air. At room level, we need to be aware that decentralized systems contribute to the conditioning of the space, but that here too ventilation must remain leading. In these times of COVID-19, but also for the future, efficient ventilation is important, but in the spread of germs between people, other performance indicators for ventilation are also important. It is good to recognize them and to take them into account now, but certainly also in the future. ■

Acknowledgement

This article is (nearly) a directly translated version of the article that was prepared for TVVL Magazine (Nr.5 – October). For the initial translation DeepL has been applied.

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Upper room Ultraviolet Germicidal Irradiation (UVGI)

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Since the 1950s Upper room Ultraviolet Germicidal Irradiation (UVGI) has been used to combat pathogens on surfaces and in the air (Wells, 1955; Riley 1976). In those days it was a control measure against Tuberculosis and Measles.

In buildings UVGI can be applied in different ways:

1) UVGI in fixtures in the open air
2) in mobile robots with high intensity to destroy pathogens (the absence of humans is required)
3) in fixtures in air handling units and local air cleaning devices.

This article is directed to the UVGI in fixtures in the open air. It combats pathogens deposited on surface and floating in the air by irradiation with UVGI.

UVGI

Sunlight contains irradiation from the UV spectrum (see fig 1): long waves (UVA: 315 – 400 nm) and median waves (UVB: 280 – 315 nm). Outdoors viruses can be destroyed due to the high intensity of the UV present. The higher the UV-Index the better it can destroy the virus. Short waves are not present in natural light. It is filtered out by the atmosphere. A wavelength of 254 nm (UVC) has a relative high efficiency compared to a wavelength of 313 nm (UVB). This results in short range waves (UVC) is destroying pathogens more efficiently compared to long range waves (UVA/UVB). To obtain equal inactivation higher doses is required for UVA and UVB than UVC.

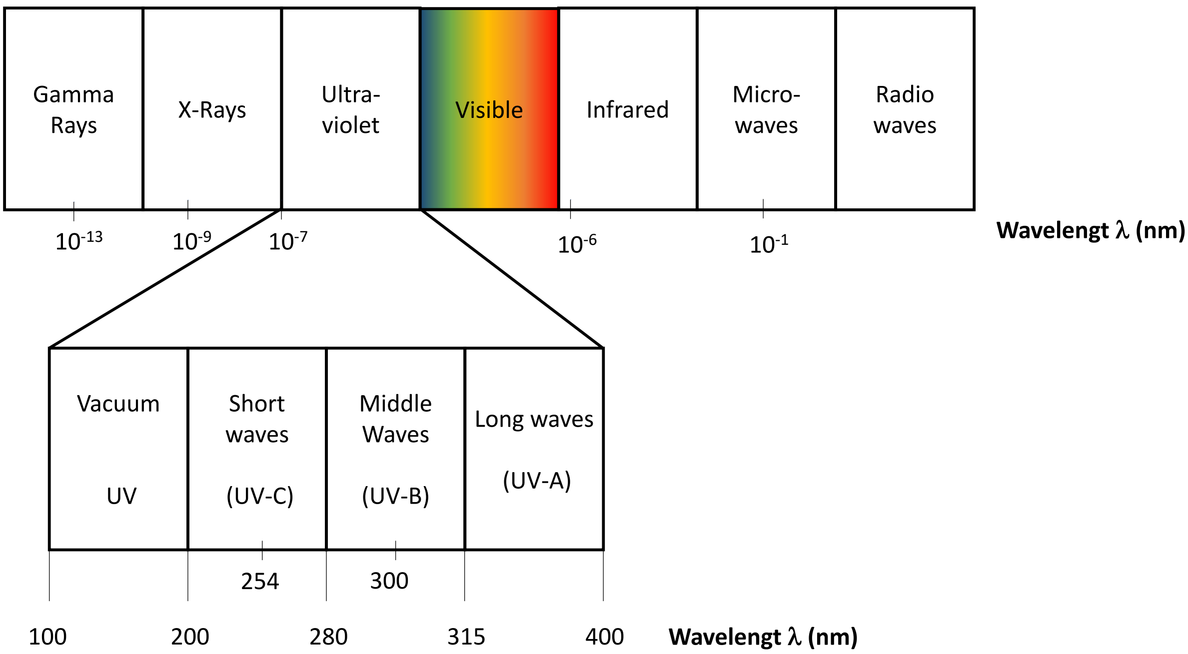

Figure 1. Solar radiation spectrum.

UVGI and Coronavirus

The UV-C photons are interacting with the genetic material (RNA) of the virus to destroy its structure. Harmed viruses can't be infectious. UVGI is more effective for ssRNA viruses compared to dsRNA viruses (Tseng & Li, 2007). SARS-CoV-2 is a ssRNA virus and belongs to *Coronaviridae*. To decode the sort: ss means single stranded, ds double stranded and RNA expresses the genetic material. In laboratory research from Tseng & Li relative humidity is affecting the efficacy in destroying the virus. For higher relative humidity's a higher dose of UVGI is required. The additional accumulated moist creates a better protection against UVGI.

Efficiency UVGI

The exposure of viruses towards UVGI (doses) is expressed in mJ/cm², the radiant energy per surface area. It is the product between irradiation intensity E per surface area (mW/cm²) and the exposure time t (s).

$$D = Et$$

The decay of virus concentration is a first order process with a constant value, called the k-value or susceptibility constant of pathogen k (cm²/mJ) (Noakes et al, 2015).

$$\varphi(t) = e^{-kD} = e^{-kEt}$$

For multiple viruses the dose to destroy 90% is studied (Tseng & Li, 2007; Malayeri et al, 2016), including the coronavirus.

The efficiency of UVC can be expressed in equivalent air changes per hour (ACH). Assuming a well-mixed ventilated room the equivalent is the log-reduction λ multiplied by the volume V of the room. The product λV can be used as sink to estimate the infection probability. An equivalent ACH of 6 to 8 is achievable. The sink terms used in infection probability models such as the Wells-Riley models are mechanism eliminating pathogens from the air, e.g. to ventilate indoor environments, deposition from pathogens as well as destroying pathogens by UVGI.

Far UVC (222 nm) versus traditional UVC (254 nm)

Novel lighting techniques are creating the potential to irradiate other wavelengths. Fluorescent lamps based on mercury is irradiating a wavelength of 254 nm. LED and fluorescent lamps based on excimer gases (Krypton Chloride), created opportunities to irradiate a wavelength of 222, called far UVC. Unfortunately, the supply of far UVC is limited yet.

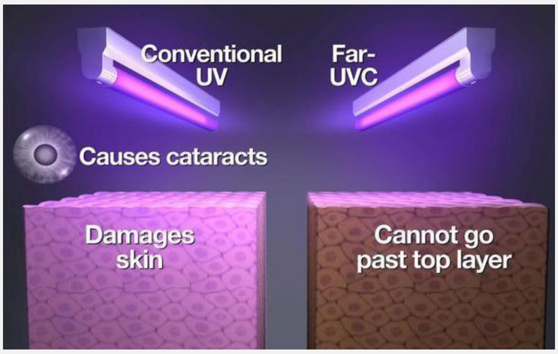

Figure source: CBS News

Table 1. Dose for log-reduction of UVGI wavelengths 254 nm and 222 nm. For UVC 254 nm the median was taken based on a review article (Heßling et al, 2020), for UVC 222 nm a laboratory study has been used (Welch et al, 2020).

	k-value [cm²/mJ]	Log 1-reduction D_{90} [mJ/cm²]	Log 2-reduction D_{99} [mJ/cm²]	Log 3-reduction $D_{99,9}$ [mJ/cm²]
UV-C (254 nm)	Not available	3,70	NA	NA
UV C (222 nm)				
HCoV-229E	4.1	0.56	1.10	1.70
HCoV-OC43	5.9	0.39	0.78	1.20

Positioning UVGI fixtures in rooms and environmental factors

For a high efficiency to destroy floating viruses a well-mixed ventilated room is required. Positioning depends on the wavelength of the used UVGI fixture. Especially UVC (254 nm) can harm humans if inappropriate positioned.

From a Health and Safety perspective UVC fixtures must be installed above 2,1 meters to avoid direct irradiation in the living zone (to protect eyes and skin of humans). This requirement is only needed for UVC with a wavelength of 254 nm. UVC with a wavelength of 222 nm can't harm eyes and skin due to the limited penetration of this irradiation on human tissues. Therefore, installing fixtures on ceiling is allowed for far UVC (222 nm).

Health and Safety and UVC

The current safety limit for UVC (254 nm) is set on 6 mJ/cm², the safe dose (ICNIRP, 2004). It prevents skin burning and consequently potential skin cancer as well is eye damage. Comparing UV irradiation caused by sun irradiation: at the safety limit of 6,0 mJ/cm² the dose is achieved after 10 minutes at a UV-index of 10 while it takes 8 hours indoors using UVC before the dose has been achieved.

The human exposure for upper room UVGI fixture has been set on 1/3 from the safety limit. By exchanging lamps, the UVGI should be switched off to avoid direct irradiation. For far UVC (222 nm) the limited penetration of UVC irradiation on human tissues seems very low and therefore it is thought no harmful (Welch et al, 2018). A dose of 24,0 mJ/cm² is the safety limit.

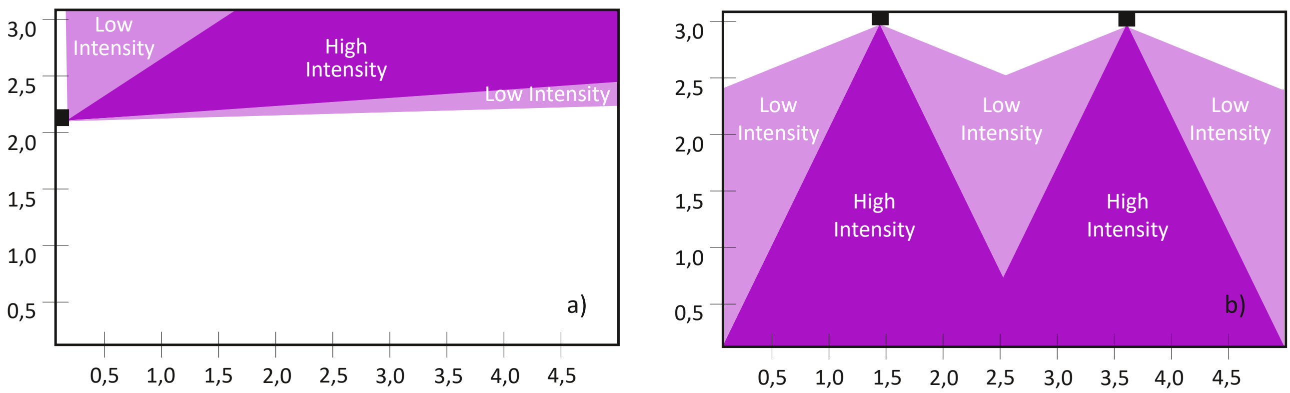

Figure 2. Positioning of UV-C fixtures. a) UV-C 254 nm, b) UV-C 222 nm

Figure 3. Example of application of UVC fixtures: Hospital ward room. [Source: Germicidal Lamps & Applications (GLA)]

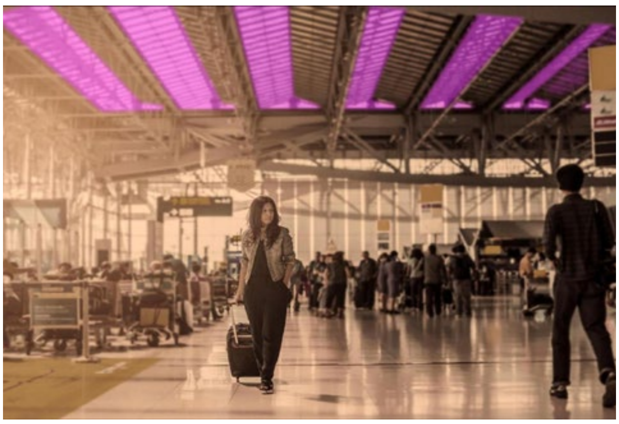

Figure 4. Example of application of UVC fixtures: Airport. [Source: Colombia University]

Based on the log 1, log 2 and log 3 -reductions due to far UVC (222 nm) no limitations on direct irradiations are required (ICNIRP, 2004).

Design and commissioning of UVGI fixtures

For design and commissioning this article is focused on the commercial wide available UVC lamps with a wavelength of 254 nm.

The reflection of ceiling should be considered to prevent excessing the safety limit of 6,0 mJ/cm² during 8 hours.

To compute the required irradiation intensity at different parts of the room based on the product specifications Computational Fluid Dynamics (CFD) simulations can be used. It shows intensity for every point in the room. This depends on the distance to the fixture and angle of the irradiation (Gilkeson & Noakes, 2012).

UVC irradiation can't cause harm when penetrating to glass. The wavelengths of UVC are filtered out.

To determine the required dose the irradiation intensity in order to destroy coronaviruses at different points in the room UVC radiometers can be used. This measurement also gain insight if the safety limits are not exceeded. A laboratorial calibrated radiometer complying the ISO/IEC 17025 is recommended. Consider if the radiometer is sensitive for far UVC (222 nm).

Conclusion

UVGI can be very effective to destroy coronaviruses. Especially in indoor environments with inappropriate ventilation, with a consequence to obtain an unacceptable infection probability. Good engineering practice and taking care of safety limits to protect eyes and skins is crucial for an effective and safe application of UVGI. ■

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"Air conditioning" – Virus spreaders or infection prevention?

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The COVID-19 superspreading events affecting the meat industry across most parts of the western world dominated the newspapers and unsettled many people. Concerns grew that room ventilation systems aid the spread of the Corona virus, or its reproduction inside the ventilation system. Overall, these worries are unjustified in most cases.

Keywords: COVID-19, aerosols, air condition, filter, UV-C, risk assessment

By means of dilution and separation of air pollutants, room ventilation systems can lower the infection risk indoors substantially. Proper planning and operation as intended, including maintenance, are important prerequisites. However, it is necessary that operators of certain room ventilation systems reassess the operation of their systems.

What is "air condition"?

In the everyday lingo, the term "air condition" is being used for all kinds of ventilation devices and systems. That is to no surprise: For non-specialists the split air conditioner available in DIY-stores is just as much an air condition as the ventilation system with an equipment room the size of a football field, supplying ventilation to e.g. 500 hotel rooms, its swimming pool, its kitchen and conferencing areas (**Figure 1**). It is this undifferentiated use of the term "air condition" which leaves users of air conditions currently in great concern.

In the meat processing industry, which was regarded as Corona "hot spot" during the summer, only a small amount of fresh air is being supplied to the processing

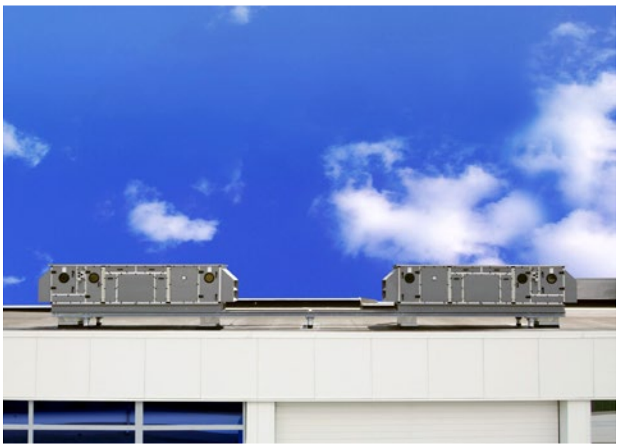

Figure 1. Room ventilation systems can help to lower infection risk. [Photo courtesy of Howatherm]

rooms. For cooling these rooms only recirculating coolers are being used. Such devices draw in the available indoor air, cool it down and blow it back into the room. A dilution of air pollutants is feasible only via the minimal required (i.e. legally specified) air change. Although the standard VDI 6022 Part 1 also requires filters for secondary air units and said recirculating air coolers, those measures are not being implemented here. Airborne pathogens and pollutants are not being separated from the indoor air in these cases. In contrast, modern ventilation systems in offices have multiple filtration stages and are being operated with a supply of 100% outdoor air. This allows for the separation of air pollutants as well as droplets carrying viruses. The overall concentration of contaminants is lowered by diluting the room air with fresh outdoor air. In fact, in order to afford the separation of viruses from indoor air HEPA filters are not always necessary. Airborne viruses are seldom "naked" but are usually attached to other, larger particles and droplets. This is in line with findings of higher infection rates in dust-carrying indoor air.

Some viruses can survive on surfaces for extended periods. However, neither will they reproduce on these surfaces nor inside room ventilation systems. Unlike bacteria, viruses themselves need a host organism in order to reproduce.

Is retrofitting filters feasible?

Retrofitting filters in existing devices is not impossible, but it also is not an all-round solution. And whether it is a practical approach is another question. Especially when using HEPA filters, the pressure loss is quite considerable. The ventilation concept therefore needs reassessment. The used air in meat-processing rooms brings a considerable humidity and particle load to the ventilation system. Thus, HEPA filters can be expected to clog quite quickly, and due to capillary action, the filter mesh will become soaked too. This increases the risk of microbial contamination and its growth on the filter. Certainly, this means increased filter inspections at the very least.

What is the role of air temperature and humidity when it comes to the spread of the corona virus?

Leclerc et al. (2020) compiled a database listing a variety of superspreading events worldwide, and many of these events started in the food processing industry. What are the driving forces behind these events?

In the food processing industry in general, but particularly in the meat processing industry low indoor air temperatures are necessary (5 – 10°C) since meat spoils rapidly at higher temperatures. Additionally, the air inside the slaughter room is being dehumidified. Even air with a relative humidity of 100% at 5°C only has 20% of humidity left when it is being warmed up to 25°C. This is what happens when the cooled air is being inhaled by the workers. The air takes humidity from the mucous membranes of the respiratory system which weakens the protective effect of these membranes (Lauc et al., 2020). The airways become more prone to infection; fewer germs (in this case viruses) suffice to trigger an infection.

In many production areas, where the processes require lower temperatures and a low relative humidity strict rules on breaks for the workers are in place: The workers are allowed to work under these conditions only for a limited interval. They must recover from these conditions in a room with comfortable temperature and humidity before they go back to work the next interval in this stressing environment.

A noisy work environment and physical labour also play an important role. Loud talking or even shouting as well as taxing levels of manual labour not only increase the amount of aerosols emitted but also the emission speed. In addition, the size spectrum of droplets is altered.

Keep 2 m of distance, and everything is fine?

Recent footage from inside some meat processing plants show distance between the individual workers is not kept. However, 2 m is not the gold standard when it comes to a safe distance. Qureshi et al. (2020) discussed this number in a meta study and concluded that 2 m indeed is recommendable since the larger droplets sink to the floor quickly, mostly within this radius. However, using high-speed cameras Bourouiba et al. (2014) showed that aerosols produced by coughing and sneezing emits aerosols of a large range: some droplets are visible to the naked eye and sink fast, but the finer fraction can cover distances of up to 8 m.

Dry air increases the evaporation of aerosols. The individual droplets shrink in size and therefore are suspended in the air for longer periods and can cover larger distances. Studies regarding the spread of droplets only consider gravity but ignore tail- and head wind as well as thermal factors. Currents and thermal updraught distort the spreading pattern significantly. A laminar flow from the ceiling towards the floor for example is being used in operation theatres for a long time now, in order to keep the operating table protected from airborne particles. In contrast a reverse flow, from the floor to the ceiling will keep airborne particles suspended for a longer time. Thus, a ventilation concept for rooms is important when taking measures for infection prophylaxis.

UV-Radiation as silver bullet?

UV-C radiation in room ventilation systems has been used successfully for many years where disinfection and prevention of biofilm formation is required, i.e. in heat exchangers. The efficacy of UV-C radiation and its killing-effect on viruses is well proven (**Figure 2**). Researchers at the University of Boston report a very high killing rate for the Corona virus on surfaces. That is not very surprising: For many viruses the required doses for a killing-effect are known and are achievable for a range within the UV-spectrum. The reduction of various airborne viruses in room ventilation systems was proven, for example, in a research project of the German "*Stiftung Industrieforschung*".

When using radiation to kill bacteria and viruses suspended in an airflow, the dwell time of the viruses within the effective range of the radiation source is critical. Additionally, the radiation intensity needs to be sufficiently high. Currently, room ventilation systems can be fitted with low-pressure or high-pressure lamps.

The wavelength of the radiation used is important. UV-C lamps emit radiation with wavelengths far below the 254 nm emission sufficient to kill viruses. The emission at 185 nm produces ozone. This gas kills viruses, but it must not seep into the room itself due to its irritating and harmful effect on humans. Ozone-free lamps filter out this wavelength and only use the emission at 254 nm for disinfection. Ozone can also be eliminated by using filters coated with activated charcoal.

A spin-off of UV-technology is a current hype where residential lighting is equipped with UV-C lamps, which are usually labelled as "sterilization lamps". In one case these lamps are advertised with a picture of a young family and their toddler relaxing under such lamps. But: UV-C radiation is cell toxic. Not only viruses are killed by what can be considered a sun burn, but the DNA of human cells is damaged as well. UV-C cannot kill viruses and be harmless at the same time. A disinfection of a room by means of "sterilization lamps" is not realistic, especially not in occupied rooms.

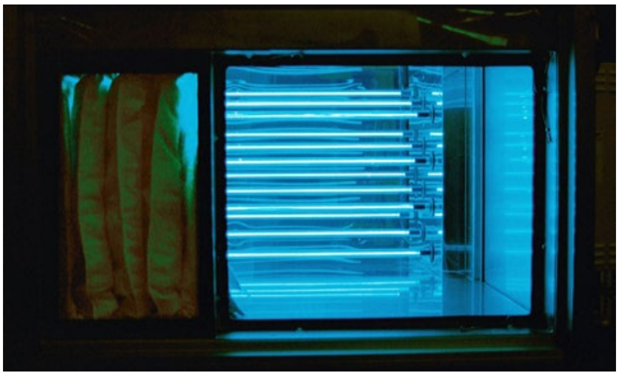

Figure 2. For many viruses the required doses for a killing-effect are known and are achievable for a range within the UV-spectrum. [Photo courtesy of Howatherm]

Masks, Shields and the like…

First and foremost, (textile) face masks hamper the spread of aerosols that are emitted during breathing, speaking and physical activity. They catch the larger droplets in particular. Since a lot of the respirated air moves through the gaps between mask and face instead of moving through the tissue, face masks are no replacement for the required distancing but are a supplementary measure. While they offer a small amount of protection for the wearer, the main purpose of textile face masks is the protection of others. Good protection for the wearer can be achieved by wearing professional personal protective equipment, certified masks, at least level FFP2. However, increased tightness comes with increased discomfort, especially when wearing masks for several hours. Ask the paramedics transporting Corona-infected persons at the height of the first wave, what wearing a tight-fitting rubber mask for hours on end does to your face!

When staff are required to wear masks in their work environment, a proper introduction to mask hygiene is highly recommended.

Plexiglass-shields are also useful physical barriers for the larger droplets and are helpful when two people are standing face-to-face at a small distance, such as reception areas and check-outs. Regular disinfection is vital, i.e. a wipe down of said shields with a disinfectant. Shields are not a solution when it comes to increase occupancy rates for rooms since they do not decrease the spread of fine aerosols. Those must be removed or reduced by ventilation.

How should owner-operators react to new findings?

Technical solutions

Ventilation: Currently, the focus lies on increasing the rate of fresh air. Fresh air dilutes the concentration of airborne viruses inside a room. Wherever feasible, room ventilation systems should be operated with a supply of 100% outdoor air. Depending on the outdoor conditions, air must be humidified to comfortable levels, i.e. 40% to 60% r. h..

In rooms without mechanical ventilation effective window ventilation is of high importance.

Filtration: When technical reasons only allow recirculation of air, indoor air should be decontaminated by air purifiers. Fine aerosols can be separated by fine filters. However, those filters tend to clog quickly and under conditions of high relative humidity they carry the risk of mould growth and growing through of microorganisms. Frequent inspections and, possibly, replacement of filters is required.

UV-Radiation: Ozone free UV-C radiation devices suitable for installation in room ventilation systems are available and promise a high killing-effect.

Curtailing maintenance intervals: room ventilation systems and all their components are to be maintained as per manufacturers specifications as well as according to the current acknowledged rules of technology, especially VDI 6022 and VDI 3810 Part 4. With respect to the currently increased infection risk, shortening maintenance intervals can be required.

Organizational measures, such as reducing the occupancy rate of rooms and social distancing, cohort rules or the introduction of regeneration breaks during work carried out in dry, cold air and personal protective equipment such as face masks also offer a potential for risk reduction.

Do not underestimate the effect of instruction

All measures that require cooperation of the person to be protected work the better, the more the person understands the mechanism. These mechanisms need to be understood and accepted as well as supported by stringent personal hygiene.

What must the owner-operator do?

The infection risks described in this article do not only occur in the meat processing industry but also in other branches. Whenever special and hitherto unknown risks occur, in this case the Corona pandemic, operators must make use of advanced technology and recent scientific findings in order to avoid an increased infection risk. When encountering new findings regarding risk potentials they must take anticipatory action. A currently valid risk assessment of each room ventilation system must be checked and updated accordingly when new findings arise. The operator cannot entirely delegate this responsibility to a third party or by means of a service contract. Operators are always obliged to at least perform suitable checks to make sure tasks delegated are indeed carried out effectively.

Conducting a risk assessment of room ventilation systems requires skilled knowledge, such as provided by VDI certified experts for indoor air quality. Even the selection of the personnel and experts carrying out risk assessment is the operator's responsibility. ■

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Calculating the risk of infection

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Keywords: Calculating the risk of infection: air quality, health, Wells-Riley, ventilation, infection risk, airborne transmission

Introduction

In the light of the COVID-19 pandemic, there is a natural need to know more about the SARS-CoV-2 virus and how it develops. Ideally, we would like to look into the future and anticipate on that basis in order to limit the consequences. Building performance simulation models have been used for decades to calculate the energy demand of a building design. This may also allow us to say something about thermal comfort, for example in the event of overheating. We also use Computational Fluid Dynamics (CFD) technology to analyse the air flow in rooms and around buildings, for example ventilation efficiency. However, when it comes to ventilation and health, so far we find much less information on the prediction options. Ventilation, the flow rate/air exchange rate normally are boundary conditions and not part of the analysis of a design solution, unless it concerns fully naturally ventilated buildings. In practice, however, these are rarely designed and built. But when it comes to infections where airborne transmission is important, ventilation is crucial and depends, for example, on the use of a room and the risk that one wishes to accept. In that case, building code requirements or requirements as set out in prepared program of requirements for specific type of buildings, e.g. through labelling schemes, may not necessarily be sufficient. How do we deal with this? In this article we want to give a brief description of the model that may be used in that case, the Wells-Riley model.

Modelling of the infection risk

The process of transmission of infectious microbiological contamination (e.g. viruses, bacteria, fungi) is not straightforward. This includes the characteristics of the pathogen, how many particles are produced in a host that is potentially pathogenic, how well the pathogen survives or remains viable outside that host (human, animal) and how good the immune system of the person who 'receives' the pathogen is. Linked to this is also the amount of viruses, bacteria or fungal spores (dose) needed to actually become ill and how this dose is received (peak or over a longer period of time). Different pathogens behave differently. For some of them the necessary information is already known, for many others, including the SARS-CoV-2 virus, this is clearly not yet the case. Fortunately, more and more knowledge is becoming available, for example with regard to the chance of survival outside the host [1,2].

In terms of transmission routes, three main routes are assumed in the transmission of pathogens that can cause respiratory tract infections such as COVID-19: the direct route via droplets, the indirect route via contact surfaces and the airborne route via aerosols. The latter route also includes faecal-oral transmission. The distinction between droplets and aerosols is normally made at the level of the size of the particle containing the pathogen. This is based on the assumption that droplets fall out quickly (deposition) and aerosols remain in the air longer. A (rather arbitrary historical) cut-off measure for this is 5 microns. Although there is consensus from aerosol scientists about the size, it should be noted that particles larger than 5 microns (even up to ~50 microns) can stay airborne for a prolonged amount of time in the indoor environment [3]. The size also determines how far a particle can penetrate the human airway system. This is another parameter with respect to sensitivity. The place where a pathogen enters the body to cause the infection, the receptor, is different for different infectious diseases and can be present at several places, more in the upper respiratory tract and/or the lower respiratory tract.

The direct and contact routes are important to recognize in the transmission of COVID-19, but for the indoor environment the airborne transmission route is something that can be influenced by the air handling systems present in buildings. Ventilation and the air flow in a room can prevent pathogens from infecting someone or limit the risk of doing so. We would therefore like to have models for this in order to be able to say something about how a certain air handling solution contributes to reducing the risk of infection.

Wells-Riley

In [4] some examples of models that try to estimate the risk of infection are summarized. However, there is one model that has been mainly used for this purpose for several decades, the so-called Wells-Riley Equation (1) [4]:

$$N_C = S\left(1 - e^{-Iqpt/Q}\right) \qquad (1)$$

Here N_c [-] stands for the number of newly infected cases over exposure time t [h], S [-] the number of people that potentially can be infected in the room to be examined, I [-] the number of infected people in the room, q [quanta/h] the amount of so-called 'quanta' produced in the room by an infected person, p [m³/h] the breathing volume flow rate of a person that potentially can be infected and Q [m³/h] the ventilation flow rate in the room to be examined. The term between brackets indicates the risk of infection in a room. It assumes a constant concentration of quanta in the room due to the production of pathogens (source) and ventilation (sink). The exponent indicates the number of inhaled quanta.

In the Equation (1), the term 'quanta' is notable. This is not a common term but has been developed specifically for this equation. Wells assumed that not every droplet/aerosol that is inhaled will lead to an infection. He then defined a quantum as the number of infected droplets (nuclei) needed to infect 1-1/e of the susceptible population in a room [4], i.e. a 63% chance of becoming infected. This number depends on, for example, the type of virus. In practice, determining the number of quanta for a particular pathogen is not straightforward. In principle, this is done by assuming available information/data and then calculating what the number of quanta has been in an outbreak at a location (e.g. a church or restaurant). With that new cases for a virus outbreak can be assessed.

The use of the Wells-Riley equation is based on a number of assumptions. These are summarized by [4,5] and relate to, among other things: - the incubation time (time between infection and the first symptoms; this means that a person infected in the situation under investigation will not contribute to the infection risk for that situation; COVID-19 is somewhat more special in the sense that the incubation time is about 5-6 days, but that infectivity can already occur 1-3 days before symptoms present themselves [6]), - the fact that a (perfectly) mixed situation is assumed with respect to the concentration of germs in the room, - that the average concentration that is inhaled during the stay is taken into account, - that the course of the infection is not taken into account, i. e. a peak, or over a prolonged period with fluctuations in concentration. In [7], as an alternative to the average concentration, the average concentration is derived from a 'clean' situation without pathogens present. This is closer to a practical situation in which an infected person enters a room and is present for a period of time.

The Wells-Riley model is often used when estimating the risk of infection in buildings. In the model, as shown in Equation (1), only ventilation (Q [m^3/h] = $\lambda_{ven} \cdot V$; where λ_{ven} [h^{-1}] is the ventilation rate and V [m^3] is the volume) is given as an option to reduce the risk using building control measures. However, more so-called 'sink' terms (λ) can be added, such as inactivation of the virus (λ_{inact}), deposition (λ_{dep}) and filtration (λ_{fil}) or the application of UVGI. These, in combination with the volume of the room and similar to the ventilation flow rate, can be expressed as a first order loss. For the SARS-CoV-2 virus, for example, a value of 0 to 0.63 h^{-1} can be used for inactivation, or 0.3 – 1.5 h^{-1} for deposition [7].

Examples - Application of Wells-Riley provides insight into the risk of infection. It is generally assumed that there is one infected person in the room. For the situation of the choir in Skagit Valley (USA) the risk of infection was calculated to be more than 80%. However, the parameters are sensitive to uncertainties. In particular, the production of quanta is an important parameter that can only be derived indirectly from the information available for cases.

Table 1 presents some examples of the risk of infection in different situations. The first example concerns the case of the choir in Skagit Valley in the United States.

Table 1. *Examples of Wells-Riley application for different situations. Values used for production of quanta and respiration rate from [7,8].*

Room		**Koor Skagit Valley**	**Aircraft cabinet**	**Office room**
Volume	m^3	810	480	240
Exposure time	h	2.5	2.5	8
Number of infected persons	–	1	1	1
Number of susceptible persons	–	60	299	19
Breathing flow rate	m^3/h	1.1 (1.0)	0.5	0.5
Production quanta	quanta/h	970 (450)	10	10
Mask efficiency*	–	0	0 (0.5)	0 (0.5)
Air exchange rate	h^{-1}	0.7	20**	2
Other 'sinks'	h^{-1}	0.62	–	–
Infection risk	%	83 (53)	0.1 (0.03)	7.5 (1.9)
Number of persons	–	49.7 (31.5)	0.4 (0.1)	1.4 (0.4)

* Applies to both infected and susceptible persons.

** including recirculated and filtered air

This is a well-known example, in which a large part of the people present was infected [7]. The other two examples concern an aircraft cabin and an office situation. For the aircraft situation it is assumed that the recirculation part is 100% filtered by means of a HEPA filter. This assumes that the recirculated air is free of virus particles. For the aircraft and office situation, for comparison, the effect of the use of masks is also taken into account.

The results show that the chance of infection for the choir was indeed very high. Note, however, that the production of the number of quanta was derived from the available data of this case. This was determined by [7] at 970 quanta/h. Nevertheless, final values for the quanta production are still under discussion. At the moment slightly lower values are assumed [8]: 450 quanta/h for singing, 70 quanta/h for quiet talking and 5 quanta/h for breathing only. Assuming 450 quanta/h and also a slightly lower value for the breathing flow rate (1 m^3/h) for the Skagit Valley case, this significantly reduces the risk to 53%. In the example we assume singing during the whole period. In practice, this will not be the case and you could be averaging over a period of time, as assumed for the aircraft and office situation (10% talking, 90% quiet; upwards rounded value). For the example of the aircraft, full (ideal) mixing is assumed. In practice, there is a form of compartmentalization of the ventilation. If we assume ten compartments, then the risk in the compartment where an infected person is sitting increases by a factor of 10.

To get an impression of the sensitivity of some parameters we refer to **Figure 1** in which the effect of the quanta production, exposure time and the sum of the 'sink' terms (including the ventilation rate) on the risk of infection is visualized. Among other things, it is clear that exposure time is an important parameter in the risk of infection. For a long residence time, for example, a high ventilation rate is necessary to minimize the risk.

Restrictions - Using the Wells-Riley equation is a good way to get a better understanding of the risk of infection in a given situation and how sensitive a building or system related measure is for reducing the risk. However, there are important comments to be made when using Wells-Riley. First of all, Wells-Riley only deals with the airborne transmission route (long-range [9]). This means, more or less, that only the aerosols are looked at and not the effect of larger droplets. The risk of the direct route is therefore not treated with the Wells-Riley model. This may lead to an overestimation of the quanta for a certain outbreak if other routes are not excluded. For the corona virus, the direct route is still seen as an important route. Although aerosols also play a role in this (short-range) route [3,9], the role of ventilation in this route, without specific measures, is clearly more limited. Nevertheless, the Wells-Riley model can at least analyse and minimize the risk via airborne transmission. In addition, the assumption of perfect mixing is an important starting point. For (relatively) small rooms, or rooms with a limited height and reasonable ventilation (ventilation rate at

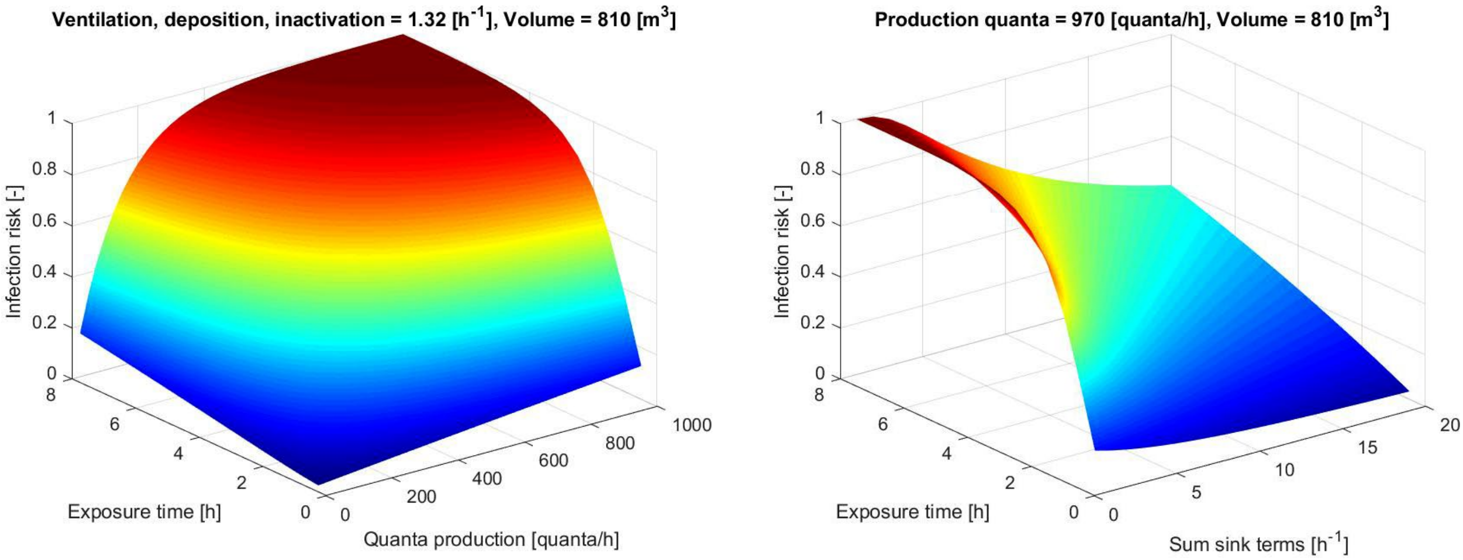

Figure 1. Sensitivity to infection risk as a function of quanta production and exposure time [left] and the sum of sink terms (especially ventilation rate) and exposure time [right]; model [7].

least 1 h^{-1} order of magnitude), this premise will be a reasonably good approximation. For larger spaces such as monumental churches this is not necessarily the case. Here, a trade-off will have to be made, for example, by including part of the volume in the analysis or by assuming a certain ventilation effectiveness.

Alternatives – In order to be able to say something about the spread of virus particles in a room, the airflow in the room will have to be modelled. This can be done using Computational Fluid Dynamics (CFD). Although this technique provides insight into how particles move in a room, and in theory the exposure to quanta could be determined, it is much more complex than the Wells-Riley model. The latter therefore is preferred for determining the risk of infection. However, in order to investigate the effect of a ventilation solution and variants thereof, or of a so-called cough screen, CFD could be used. For the purpose of validation, these simulations should be combined with measurements.

Tools

Because every situation is different and therefore the risk of infection, a webtool has been developed that allows to assess the risk yourself. An example of that is presented in eerstehulpbijventilatie.nl (in Dutch: 'first aid for ventilation'). The webtool is just one example of the several tools that have been developed over the last months. The other tools generally reside as an Excel-tool, though webtools are appearing in parallel as well. Most are based on the Wells-Riley equation, several assuming the transient approach as presented by [7].

The Dutch webtool initially was developed for application in a church building, with a focus on singing during a service. Further development towards a more generic tool is planned and is expected to be online in October.

The current Dutch webtool allows to calculate the risk of infection based on the specified number of people. It also calculates the R0 value, i.e. how many people are potentially infected by one infected person in a given situation. In principle, you want to keep that value < 1. The user can compare this with the displayed infection risk/contamination risk.

This webtool is based on the model described by [7]. It assumes a starting situation where there is no contamination in the room and is a more extended version of Equation (1). It describes the build-up of the concentration over time, just like the well-known models that describe the CO_2 concentration in a room (see **Figure 2** on the left). **Figure 2** (right) shows the parallel build-up of the quanta concentration. The original equation (Equation (1), by definition, will show higher risks.

In the model choices have been made for the production of quanta and for the breathing volume. As far as quanta is concerned, the following values are used: 450 q/h for singing, 10 q/h for listening during the church service. For the breathing flow rate: 1.0 m^3/h is assumed for singing and 0.5 m^3/h for listening. The 'sinks' are not included. For the user a 'traffic light' has also been added, to indicate the risk of infection. Up to and including 1%: green; from 1% up to and including 5%: orange; above 5%: red. This is of course

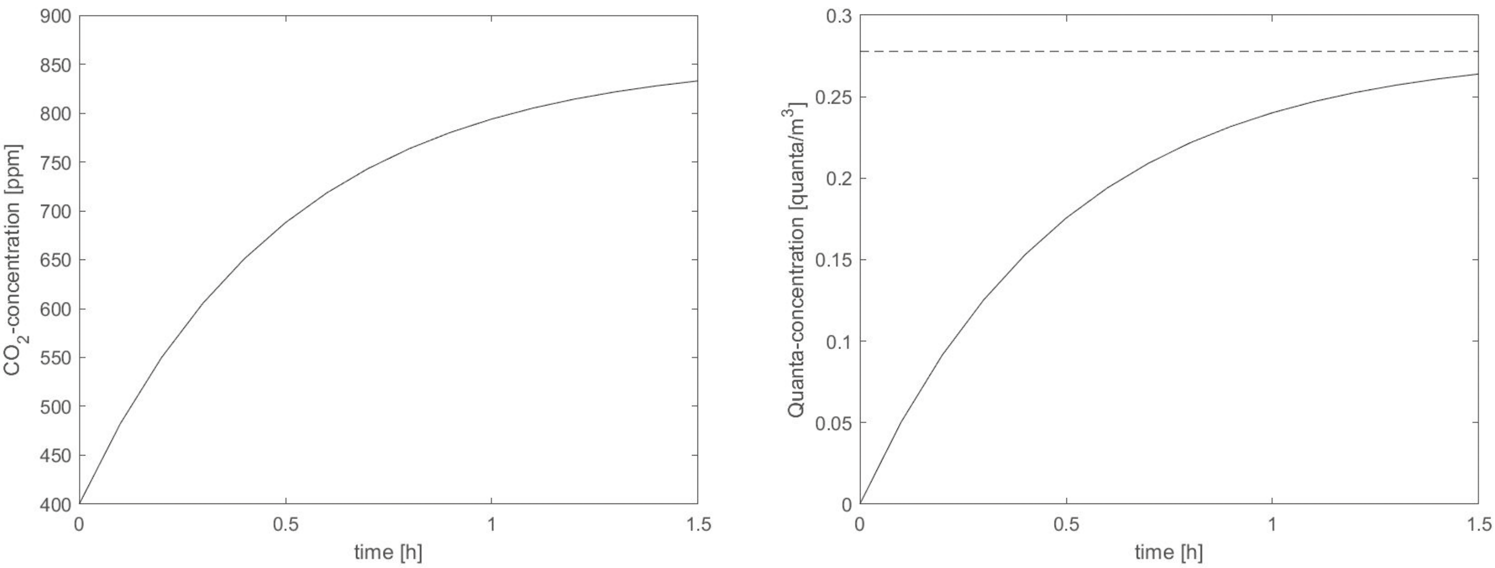

Figure 2. Build-up of the CO_2 concentration [left] and the comparable build-up of the quanta concentration [right]. Equation (1) uses the limit value (black dotted line - right).

a choice and does not mean that if the risk is less than 1% no one can get sick. The webtool also calculates the maximum number of people that may be present so that a maximum CO_2-concentration of 800 ppm is not exceeded ('class A'). Also, with this number of persons an R0 value is provided. In this way the user can compare the outcome to the number of people that originally was entered. The maximum number of people that can use a room is related to the 1.5 m distance protocol. Finally, to repeat, knowledge about the virus is still developing. This concern, for example, the amount of quanta and the contribution of the airborne transmission route to the infection risk. The information presented here should be seen in that light, and as a supplement to the current measures to reduce the risk of infection.

In conclusion

The modelling of the airborne infection risk has a sudden renewed focus. Until now, outside the care and cure environment, this risk has not yet been included (consciously) a lot in the design of buildings and its air handling systems. Current experiences once again remind us that air quality and ventilation is more than perception and a not too high CO_2 level as a proxy for the concentration of all other, in general, chemical substances that may be present in the air. Recognizing the biological component offers the opportunity to put ventilation in buildings in a broader perspective. The use of the Wells-Riley model makes it possible to do so in a more quantified way. Despite the limitations of the model, at least the effect of variants can be compared. With that, the application of other techniques for reducing the risk also gets a better comparison. ■

Acknowledgement

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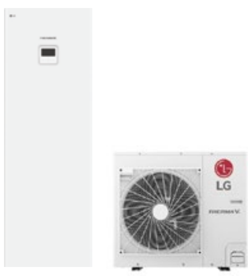

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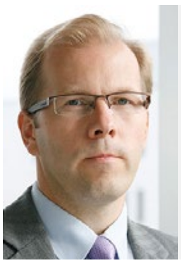
Articles

Ventilation rate and room size effects on infection risk of COVID-19



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Available information on COVID-19 shows that transmission of this disease has been associated with close proximity (for which general ventilation isn't the solution) and with spaces that are simply inadequately ventilated. From superspreading events it is known that outdoor air ventilation has been as low as 1–2 L/s per person. In the following it is analysed that is the infection probability in common spaces when ventilation corresponds to about 10 L/s per person recommended in existing standards.

The effect of outdoor air ventilation on virus concentration in the air is illustrated in **Figure 1**. Mixing ventilation reduces very high concentration near the source to a roughly constant level in the room from about 1.5 m distance of the source. Reduction of the virus concentration with effective ventilation allows to control the exposure, i.e. the dose that is closely linked to the infection probability and depends on the breathing rate, concentration and time.

In principle there are two major ways to reduce the dose and infection risk: to increase the ventilation and to reduce the occupancy time. In existing ventilation systems, it is typically not possible to increase the fan speed significantly, so the system can deliver the performance it is sized to do. Sometimes it may be possible to increase total airflow rates by 10–20% overall and by balancing possibly more significantly in specific rooms. In epidemic conditions, obviously demand control has to be overruled and systems should run on nominal or maximum speed. From a legal point of view, the outdoor air ventilation rate must fulfil at least national minimum requirements set in the local building code or other regulatory documents (which may also include specific regulation for COVID-19). If a national ventilation regulation does not exist then typically local building laws will always contain a provision for "good building practice", referring to the use of national, European or international standards and guidelines. Typical sizing according to ISO 17772-1:2017 and EN 16798-1:2019 results in default Indoor Climate Category II to 1.5–2 L/s per floor m² (10–15 L/s per person) outdoor airflow rates in offices and to about 4 L/s per floor m² (8–10 L/s per person) in meeting rooms and classrooms.

Ventilation improvement in existing or new buildings brings a question, are the ventilation rates of Category II enough, or is more outdoor air ventilation needed to reduce the risk of cross-infection? Infection risk is currently not addressed in these standards as design criterion. On the other hand, cross-infection risk is well known and applied in the design of hospital buildings where it leads to ventilation with a 6-12 air change per hour (ACH) rate. Hospital ventilation systems have worked well in COVID-19 conditions as cross-infections have been under control, illustrating that high capacity ventilation is capable to keep aerosol concentration at low level. In non-hospital buildings, there are evidently lower emission rates and smaller numbers of infected persons per floor area. So, a lower ventilation rate than in hospitals, for instance Category I ventilation rate, could be considered as a starting point for the risk reduction. It is also worth noting that 4 L/s per floor m² in meeting rooms and classrooms corresponds to 5 ACH and is not much below the air change rate of patient rooms with precautions against airborne risks.

Probability of infection

Infection risk can be calculated for different activities and rooms using a standard airborne disease transmission Wells-Riley model, calibrated to COVID-19 with correct source strength, i.e., quanta emission rates. In this model, the viral load emitted is expressed in terms of quanta emission rate (E, quanta/h). A quantum is defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons. With the Wells-Riley model [1], the probability of infection (p) is related to the number of quanta inhaled (n) according to Equation (1):

$$p = 1 - e^{-n} \quad (1)$$

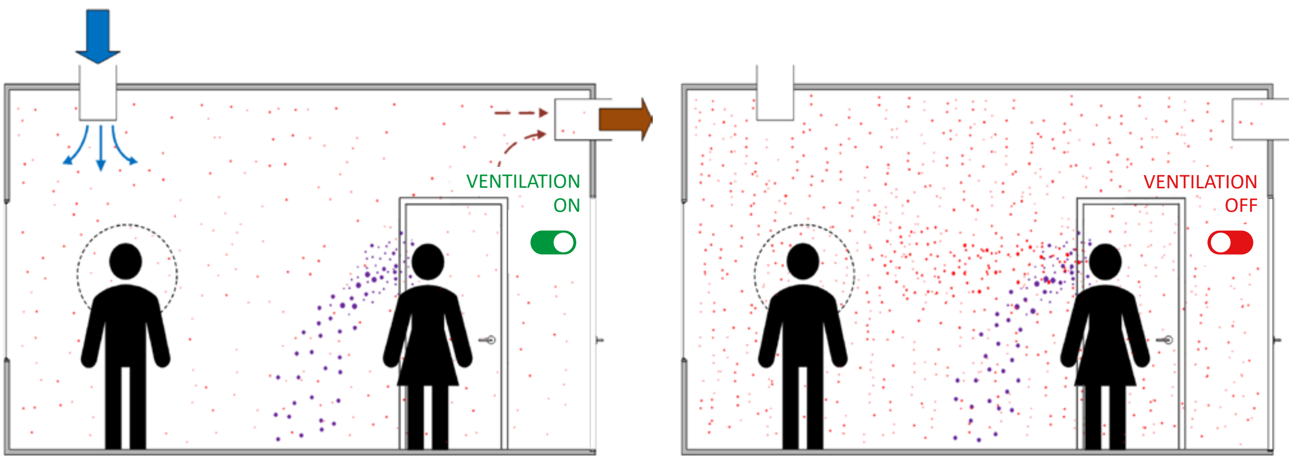

Figure 1. Illustration of how an infected person (speaking woman on the right) leads to aerosol exposure (red spikes) in the breathing zone of another person (man on the left in this case). Large droplet exhalation is marked with purple spikes. When the room is ventilated, the amount of virus-laden particles in the breathing zone is much lower than when the ventilation system is off. Left figure: ventilation system on, right figure: ventilation system off. [Figure courtesy of REHVA]

The quanta inhaled (n, quanta) depends on the time-average quanta concentration (C_{avg}, quanta/m^3), the volumetric breathing rate of an occupant (Q_b, m^3/h) and the duration of the occupancy (D, h):

$$n = C_{avg} Q_b D \tag{2}$$

The airborne quanta concentration increases with time from an initial value of zero following a "one minus exponential" form, which is the standard dynamic response of a fully mixed indoor volume to a constant input source. A fully mixed material balance model for the room can be applied to calculate the concentration:

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \tag{3}$$

where

- E quanta emission rate (quanta/h);
- V volume of the room (m^3);
- λ first-order loss rate coefficient [2] for quanta/h due to the summed effects of ventilation (λ_v, 1/h), deposition onto surfaces (λ_{dep}, 1/h) and virus decay (k, 1/h);
- C time-dependent airborne concentration of infectious quanta (quanta/m^3).

The surface deposition loss rate of 0.3 1/h may be estimated based on data from [3, 4]. For virus decay Fears [5] shows no decay in virus-containing aerosol for 16 hours at 53% RH, whereas van Doremalen [6] estimated the half-life of airborne SARS-CoV-2 as 1.1 h, which equates to a decay rate of 0.63 1/h. An average value of these two studies is 0.32 1/h.

Assuming the quanta concentration is 0 at the beginning of the occupancy, equation (3) is solved and the average concentration determined as follows:

$$C(t) = \frac{E}{\lambda V}\left(1 - e^{-\lambda t}\right) \tag{4}$$

$$C_{avg} = \frac{1}{D}\int_0^D C(t)\,dt = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right] \tag{5}$$

where

- t time (h)

Calculation examples can be found from papers analysing the Skagit Valley Chorale event [7] and quanta generation rates for SARS-CoV-2 [8]. Quanta emission rates vary over a large range of 3–300 quanta/h depending strongly on activities so that higher values apply for loud speaking, shouting and singing and also for higher metabolism rates, as shown in **Table 1**. Volumetric breathing rates depend on the activity being undertaken as shown in **Table 2**.

Although SARS-CoV-2 quanta/h emission values include some uncertainties, it is already possible to calculate infection risk estimates and conduct comparisons on the effect of ventilation and room parameters. Results from such calculations are shown in **Figure 2** for commonly used ventilation rates and rooms. It is assumed that in all calculated rooms, there is one infected person. The following time-averaged quanta emission rates calculated from activities shown in **Table 1** were used: 5 quanta/h for office work and classroom occupancy, 15 quanta/h for a restaurant, 10 quanta/h for shopping, 21 quanta/h for sports and 19 quanta/h for meeting rooms. While typical COVID-19 infection rates in the general population have been in the magnitude of 1:1000 or 1:10 000, the assumption that only one infected person is in a room that is used by, e.g., 10 (office), 25 (school) or 100 persons (restaurant) is highly valid.

A risk assessment as shown in **Figure 2** helps to build a more comprehensive understanding of how virus laden aerosols may be removed by ventilation. The results show that with Category II ventilation rates according to existing standards, the probability of infection is reasonably low (below 5%) for open-plan offices, classrooms, well-ventilated restaurants, and for short, no more than 1.5-hour shopping trips or meetings in a large meeting room. Small office rooms occupied by 2-3 persons and small meeting rooms show a greater probability of infection, because even in well ventilated small rooms the airflow per infected person is much smaller than that in

Table 1. *90th percentile SARS-CoV-2 quanta emission rates for different activities [9].*

Activity	Quanta emission rate, quanta/h
Resting, oral breathing	3.1
Heavy activity, oral breathing	21
Light activity, speaking	42
Light activity, singing (or loud speaking)	270

Table 2. *Volumetric breathing rates [10, 11].*

Activity	Breathing rate, m^3/h
Standing (office, classroom)	0.54
Talking (meeting room, restaurant)	1.1
Light exercise (shopping)	1.38
Heavy exercise (sports)	3.3

large rooms. Therefore, in an epidemic situation small rooms could be safely occupied by one person only. In normally ventilated rooms occupied by one person there is no infection risk at all because of no emission source. There is also a very visible difference between 1 L/s m² and 2 L/s m² ventilation rate in an open plan office (note that 1 L/s m² is below the standard). Speaking and singing activities are associated with high quanta generation, but also physical exercises increase quanta generation and breathing rate that directly affects the dose. Thus, many of indoor sports facilities (excluding swimming pools and large halls) are spaces with higher probability of infection if not specially designed for high outdoor ventilation rates.

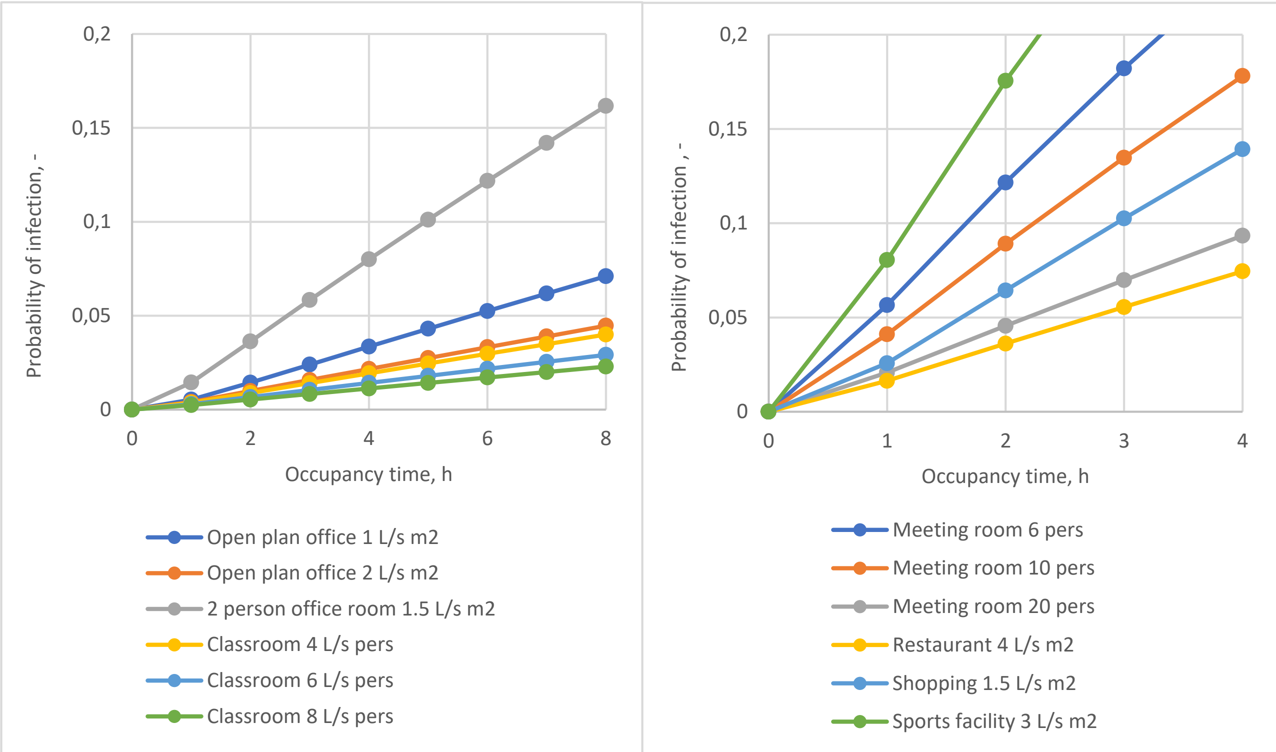

Figure 2. Infection risk assessment for some common non-residential rooms and ventilation rates. 1.5 L/s per m² ventilation rate is used in 2-person office room of 16 m², and 4 L/s per m² in meeting rooms. Detailed input data is reported in Table 3.

Table 3. *Infection risk probability calculation workflow for the cases reported in Figure 2.*

Case Specific Input Parameters	Floor area A (m²)	Height h (m)	Ventilation rate per floor area L/(s m²)	Quanta emission rate quanta/h	Breathing rate m³/h	Occupancy time Δt (h)	Air change rate k_{ven} (h^{-1})	Total first order loss rate k_{tot} (h^{-1})	Room volume V (m³)	x steady state concen-tration [ ]	Average concen-tration quanta/m³	Quanta inhaled (dose) quanta	Probability of infection –
Open plan office 1 L/s m²	50	3	1	5	0,54	8	1,2	1,82	150	0,93	0,02	0,07	0,071
Open plan office 2 L/s m²	50	3	2	5	0,54	8	2,4	3,02	150	0,96	0,01	0,05	0,045
2 person office room 1.5 L/s m²	16	3	1,5	5	0,54	8	1,8	2,42	48	0,95	0,04	0,18	0,162
Meeting room 6 pers	18	3	4	19	1,1	8	4,8	5,42	54	0,98	0,06	0,56	0,428
Meeting room 10 pers	25	3	4	19	1,1	8	4,8	5,42	75	0,98	0,05	0,40	0,331
Meeting room 20 pers	50	3	4	19	1,1	8	4,8	5,42	150	0,98	0,02	0,20	0,182
Classroom 4 L/s pers	56	3	2	5	0,54	8	2,4	3,02	168	0,96	0,01	0,04	0,040
Classroom 6 L/s pers	56	3	3	5	0,54	8	3,6	4,22	168	0,97	0,01	0,03	0,029
Classroom 8 L/s pers	56	3	4	5	0,54	8	4,8	5,42	168	0,98	0,01	0,02	0,023
Restaurant 4 L/s m²	50	3	4	15	1,1	8	4,8	5,42	150	0,98	0,02	0,16	0,147
Shopping 1.5 L/s m²	50	3	1,5	11	1,38	8	1,8	2,42	150	0,95	0,03	0,32	0,272
Sports facility 3 L/s m²	50	3	3	21	3,3	8	3,6	4,22	150	0,97	0,03	0,85	0,573

Infection risk probability calculation workflow is illustrated in **Table 3**. The total airflow rate is calculated as a product of L/s per floor area ventilation rate value and the floor area, therefore the larger the room the larger the total airflow rate per infected person (1 infected person is assumed in all rooms). It should be noted that the number of occupants has no effect because the calculation is per infected person. The room height (volume) matters on the concentration development so that the source E is switched on at time t = 0 and the concentration starts to build up. In the calculation, 8-hour occupancy was considered and the average concentration is quite close to the steady state as the value in the parentheses is higher than 0.9 in all cases (1.0 will correspond to the steady state).

It is important to understand the limitations of the probability calculation:

- Results are sensitive to quanta emission rates which can vary over a large range, as shown in **Table 1**. The uncertainty of these values is high. Also, there are likely to be superspreaders that are less frequent but may have higher emission rates (as in the choir case [7]). This makes absolute probabilities of infection uncertain, and it is better to look at the order-of-magnitude (i.e. is the risk of the order of 0.1% or 1% or 10% or approaching 100%). The relative effect of control measures may be better understood from this calculation, given the current state of knowledge;
- Calculated probability of infection is a statistical value that applies for a large group of persons, but differences in individual risk may be significant depending upon the individual's personal health situation and susceptibility;
- Assuming full mixing creates another uncertainty because, in large and high rooms, the virus concentration is not necessarily equal all over the room volume. In the calculation, a 50 m² floor area is used for an open-plan office. Generally, up to 4 m high rooms with a maximum volume of 300 m³ could be reasonably well mixed; however, it is more accurate to simulate concentrations with CFD analyses. Sometimes thermal plume effects from occupants may provide some additional mixing in high spaces such as theatres or churches.

These limitations and uncertainties mean that rather than predicting an absolute infection risk, the calculation is capable of comparing the relative effectiveness of solutions and ventilation strategies to support the most appropriate choice. Calculation results are easy to convert to the form of relative risk. In **Figure 3**, this is done for an open plan office where 2 L/s per person ventilation rate (0.2 L/s per m²) with occupant density of 10 m² per person is considered as 100% relative risk level. This ventilation rate that is a half of an absolute minimum of 4 L/s per person can be used to describe superspreading events. Results in **Figure 3** show that a common ventilation rate of 2 L/s per m² will reduce the relative risk to 34% and doubling that value to 4 L/s per m² will provide relatively smaller further reduction to 19%.

Finally, **Figure 3** allows to estimate what is the difference between Category II and I ventilation rates. With 10 m² per person occupant density, the airflow rates become 1.4 and 2.0 L/s per m² in Category II and I respectively when low polluting materials are considered. Thus, Category II ventilation results in 43% relative risk and Category I in 34% that shows significant improvement as the curve has quite deep slope at that range.

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Conclusions

While there are many possibilities to improve ventilation solutions in future, it is important to recognise that current good practice and knowledge allows the use of many rooms in buildings during a COVID-19 type of outbreak as long as ventilation rates correspond to or ideally exceed existing standards and a cross-infection risk assessment is conducted. Regarding the airflow rates, more ventilation is always better, but to dilute the aerosol concentration the total outdoor airflow rate in L/s per infected person matters. This makes large spaces ventilated according to current standards reasonably safe, but smaller rooms occupied by fewer people and with relatively low airflow rates pose a higher risk even if well ventilated. Limiting the number of occupants in small rooms to one person, reducing occupancy time and applying physical distancing will in most cases keep the probability of cross-infection to a reasonable level. For future buildings and ventilation improvement, Category I ventilation rates can be recommended as these provide significant risk reduction compared to common Category II airflow rates. ■

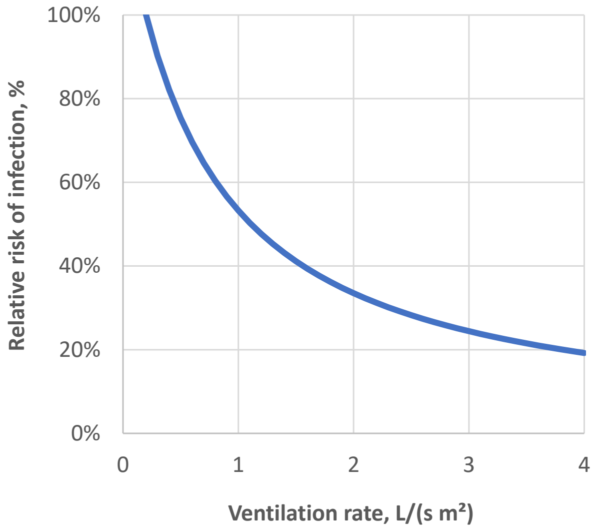

Figure 3. Relative risk in open plan office of 50 m^2 where 2 L/s per person (0.2 L/s per m^2) ventilation rate is considered as a reference level for a superspreading event with 100% relative risk.

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A tool for HVAC systems operational strategy assessment for reducing infection risk in existing and newly designed buildings

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Introduction

COVID-19 pandemic is today an unresolved medical problem and any possible measure that may lower SARS-CoV2 virus propagation has to be applied. While the medical research area is still learning about how the virus spreads and the severity of illness it causes, and there is no unanimous consensus on the airborne infection route, starting from this today even more recognised possibility, the engineering research area is working to produce guidelines focusing on how to reopen and safely use buildings after the lockdown, providing advice on specific components, buildings/space types, and suggesting mitigation measures [1].

If airborne viral emission and diffusion are assumed to be important, there are several design and operational measures that can be undertaken for reducing the airborne infection risk in closed spaces as buildings:

- ventilation rates should be increased as much as compatible with comfort and energy issue;
- indoor air and extracted air should not be recirculated;
- individuals should avoid staying directly in the flow of air from another person;
- the number of people sharing the same indoor environment should be minimized, and last resort;
- people working/studying/etc. in a common space should correctly wear protective facial masks.

Effects on virus spread of all these measures are not easily quantifiable, but for some of them some simple modelling can help to understand their relative effectiveness. For this reason, a simplified tool has been developed to assess comparatively effectiveness and potential application of such of actions on both existing and new building and HVAC systems.

Tool background

The tool is based on the standard airborne disease transmission Wells-Riley model, i.e. quanta based and full mix hypothesis behind, described in [2] and [3]. It extends the single room model to a Multi-rooms Model with possible air recirculation among rooms, through centralised HVAC system and via air transfer to common service area (corridor, toilettes and staircases) where air extraction to outside is performed via dedicated exhaust air ductwork. The model is a dynamic model, i.e. the time dependent problem is solved.

It is possible to partially remove the full-mix hypothesis using the ventilation Contaminant Removal Effectiveness, ϵ_r, which depends on the chosen air distribution system. In the tool it is possible to modify the recirculation ratio from 1 to 0 and eventually to add an HEPA filter or equivalent virus removal/inactivation equipment (UV-C, etc.) on the return air lo lower as much as possible the virus spread via air recirculation. The model also accounts for "virus losses" in the HVAC system (deposition in ducts, in AHU and natural decay when contaminated air moves through such components), using the same approached used for rooms but in steady state approximation, i.e. using virus removal coefficients as done for general spaces.

Splitting the ductwork in supply and return branches, which can have significant different virus concentrations, and using a volume weighting factor to account for the different pathways different virus concentrations have to go through before to reach the AHU or to reach each served spaces, under Quasi Steady State Hypothesis the **concentration balance equation on the return ductwork** can be rewritten for each branch ***i*** as:

$$C_{ETA,i}(t) = C_i(t) - \lambda_{Rd,d,i} \cdot \frac{V_{V;Rd,i}}{q_{V;ETA,i}} \cdot C_{avg;i}(t) \quad (1)$$

where

$C_{ETA,i}$ is virus concentration in extracted air at the end of specific ductwork branch from Room *i* to AHU, in [quanta/m^3];

$C_{avg;i}$ is average virus concentration in this ductwork branch air volume, [quanta/m^3];

$\lambda_{Rd,d,i}$ duct virus removal coefficient for ductwork serving Room *i*, [h^{-1}];

$V_{Rd,i}$ volume of return ductwork serving Room *i*, in [m^3];

$q_{V;ETA,i}$ extracted volume air flow from Room *i*, in [m^3/h].

with

$$\lambda_{Rd,d,i} = \lambda_{R,d,i} + \kappa_{R,i} + \lambda_{R,ad,i} \quad (2)$$

where

$\lambda_{R,d,i}$ virus removal coefficient by deposition on surfaces of ductwork serving Room *i*, [h^{-1}];

$\kappa_{R,i}$ virus decay coefficient of ductwork serving Room *i*, [h^{-1}];

$\lambda_{R,ad,i}$ virus removal coefficient by additional measurements of ductwork serving Room *i*, [h^{-1}];

Assuming linear approximation

$$C_{avg;i}(t) \cong \frac{C_{ETA,i}(t) + C_i(t)}{2} \;;\; \alpha_{R,i} = \frac{V_{Rd,i}}{q_{V;ETA,i}} \quad (3)$$

it is

$$C_{ETA,i}(t) = \left(\frac{1 - 0.5\,\lambda_{Rd,d,i} \cdot \alpha_{R,i}}{1 + 0.5\,\lambda_{Rd,d,i} \cdot \alpha_{R,i}}\right) \cdot C_i(t) = \beta_{R,i} \cdot C_i(t) \quad (4)$$

where

$\alpha_{R,i}$ dimensional removal factor for return branch *i*, in [h];

$\beta_{R,i}$ dimensionless removal factor for return branch *i*, [–] defined as $\beta_{R,i} = \frac{1-0.5\,\lambda_{Rd,d,i} \cdot \alpha_{R,i}}{1+0.5\,\lambda_{Rd,d,i} \cdot \alpha_{R,i}}$.

Air Handling Unit is modeled using same approach after mass conservation balance is applied to the system described by **Figure 1**, where an air dumper is controlling the recirculation ratio (RF).

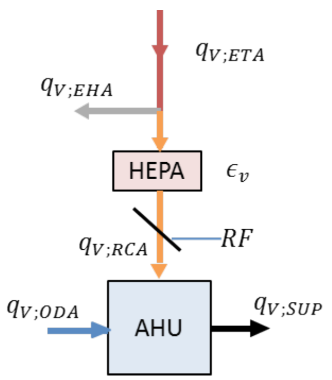

Figure 1. Recirculation managed by AHU with removal/deactivation device on the return duct after exhaust air expulsion.

The input to the removal/deactivation device, identified as HEPA filter in **Figure 1**, is the weighted virus concentration in the extracted ait from each room as

$$C_{ETA}(t) = \sum_{i=1}^{N} C_{ETA,i}(t) \cdot \frac{q_{V;ETA,i}}{q_{V;ETA}} = \sum_{i=1}^{N} \beta_{R,i} \cdot C_i(t) \cdot \frac{q_{V;ETA,i}}{q_{V;ETA}} \quad (5)$$

Thus, the recirculated air virus concentration before mixing with outdoor ventilation air is

$$C_{RCA}(t) = (1-\epsilon_v)\cdot C_{ETA}(t) \tag{6}$$

where ϵ_v is the removal/deactivation device efficiency, [–], and the supply air virus concentration is given by:

$$C_{UTA-in}(t) = C_{ODA}(t)\cdot(1-RF) + C_{RCA}(t)\cdot RF \tag{7}$$

where

$C_{ODA}(t)$ virus concentration in outdoor air, in [q/m³], usually null;

RF UTA recirculation factor, in [–]; defined as $RF = q_{V;RCA}/q_{V;SUP}$

Thus, under Quasi Steady State Hypothesis, the virus concentration balance over the AHU as black box is written as for the ductworks as:

$$C_{SUP}(t) = \left(\frac{1-0.5\,\lambda_{UTA}\cdot\alpha_{UTA}}{1+0.5\,\lambda_{UTA}\cdot\alpha_{UTA}}\right)C_{UTA-in}(t) = \beta_{UTA}\cdot C_{UTA-in}(t) \tag{8}$$

where coefficients λ_{UTA}, α_{UTA} and β_{UTA} have the same meaning as expressed before for the return ducts.
Under Quasi Steady State Hypothesis, the concentration delivered by each supply ductwork branch *i* can be written as for the return ductwork as:

$$C_{SUP,i}(t) = \left(\frac{1-0.5\,\lambda_{Sd,d,i}\cdot\alpha_{S,i}}{1+0.5\,\lambda_{Sd,d,i}\cdot\alpha_{S,i}}\right)\cdot C_{SUP}(t) = \beta_{S,i}\cdot C_{SUP}(t) \tag{9}$$

where $\lambda_{Sd,d,i}$ is the duct virus removal coefficient for ductwork supplying Room *i*, [h⁻¹]

Combining equations from (1) to (8), assuming null the virus concentration in the outdoor air, the virus concentration in the supply air to each room can be written as function of the virus concentration in each room:

$$C_{SUP,i}(t) = \beta_{S,i}\cdot\beta_{UTA}\cdot RF\cdot(1-\epsilon_v)\cdot\sum_{k=1}^{N}\beta_{R,k}\cdot C_k(t)\cdot\frac{q_{V;ETA,k}}{q_{V;ETA}} \tag{10}$$

where the dimensionless virus removal factors $\beta_{S,i}$, β_{UTA} and $\beta_{R,k}$ account for virus removal due to deposition and decay in the ductworks and AHU, while ϵ_v is the efficiency of the virus removal/inactivation unit.

For the **generic Room *i*, the concentration balance in full mix hypothesis** is

$$\frac{dC_i(t)}{dt} = \dot{C}_{s,i}(t) + \gamma_i C_{SUP,i}(t) - \lambda_i\, C_i(t) \tag{11}$$

where

$\dot{C}_{s,i}$ virus concentration source in Room *i*, in [q/(h m³)],

γ_i virus supply coefficient in Room *i* due to recirculation, [h⁻¹].

λ_i virus total removal coefficient in Room *i*, [h⁻¹].

To account for specific flow pattern due to air distribution system typology and thus partially remove the full mix hypothesis, the virus supply coefficient γ_i is defined as:

$$\gamma_i = q_{V;SUP,i}\cdot\epsilon_{r,i}/V_i \tag{12}$$

where

$q_{V;SUP,i}$ supply air volume flow rate to Room *i*, in [m³/h];

$\epsilon_{r,i}$ ventilation Contaminant Removal Effectiveness Room *i*, (=1 for full mix), [–];

V_i volume of Room *i*, in [m³].

To account for facial mask effect on virus spread by the infected person, the virus concentration source is defined as

$$\dot{C}_{s,i} = \left(1-\epsilon_{IPFM,i}\right)\cdot IP_i\cdot e_i/V_i \tag{13}$$

where

e_i virus emission rate per person in Room *i*, in [q/(h pers)];

IP_i number of infected people in Room *i*, in [pers]

$\epsilon_{IPFM,i}$ facial mask efficiency for infected person in Room *i*, [–].

Instead, the effect of facial masks worn by susceptible people is taken into account when calculating the infection risk probability using the Wells-Riley model, i.e.

$$R\%_i = \left(1 - e^{-(1-\epsilon_{SPFM,i})\cdot IR_i \cdot t_{ex,i} \cdot C_{avg,i}}\right) \cdot 100 \quad (14)$$

where

$\epsilon_{SPFM,i}$ facial mask efficiency for susceptible people in Room i, [–].

IR_i present people breathing rate in Room, in [m^3/h];

$t_{ex,i}$ exposure time (given space occupancy time interval) in Room, in [h]

$C_{avg,i}$ average virus concentration in the given space over the occupancy time interval, in [q/m^3].

The average number of potentially infected people is then given in each room by

$$NIP_i = \frac{R\%_i}{100}(NP_i - IP_i) \quad (15)$$

where

NP_i number of people in Room i, [pers];

IP_i number of infected people in Room i, in [pers].

Combining equation (10) with equation (11) it is possible to write for each room i an ordinary differential equation like

$$\frac{dC_i(t)}{dt} = \sum_{j=1}^{N-1} a_{i,j} \cdot C_j(t) + a_{i,i} \cdot C_i(t) + s_i(t) \quad (16)$$

which can be approximated by an algebraic equation substituting the time derivative with a forward finite difference obtaining

$$C_i^{\tau+1} = \left(1 + \Delta t \cdot a_{i,i}\right) \cdot C_i^{\tau} + \sum_{j=1}^{N-1} \Delta t \cdot a_{i,j} \cdot C_j^{\tau} + \Delta t \cdot s_i^{\tau} \quad (17)$$

where

Δt is the discretization time interval, in [h];

$a_{i,j}$ coupling coefficients, in [h^{-1}];

s_i^{τ} virus source term, in [q/(h m^3)];

τ integer time index ($t = \tau \cdot \Delta t$), [–].

Equation (16) represents a set of N equations that can be easily solved using matrix notation as

$$\{C_i\}^{\tau+1} = \left[b_{i,j}\right] \cdot \{C_i\}^{\tau} + \{\Delta t\ s_i\}^{\tau} \quad (18)$$

where

$$b_{i,i} = 1 + \Delta t \cdot a_{i,i}$$
$$b_{i,j} = \Delta t \cdot a_{i,j}\ \forall\ i \neq j \quad (19)$$

NOTE: to have a fast-to-solve problem fixed air flow rates over the whole calculation day are assumed; this assumption implicates constant coefficient for the matrix equation (18), but does not change the model structure, which can account for variable flows calculation (if air flow time schedule are provided as input) just updating the matrix coefficient each time step.

System layout and limitations

To have a relatively easy and fast to use tool some limitations have been applied as

- constant ventilation air flow rate during the whole day;
- fixed building plan layout typology to allow fast data input and calculations (see **Figure 2**);
- rooms number is unlimited (memory space is just sized to manage 100 rooms, but can be expanded according to the available computer memory), while there is only one corridor, one toilet and one staircase compartment;
- extraction-only systems are possible in toilets and staircase only;
- transferred air through the corridor is automatically calculated, if any exists due to extraction in toilets and/or in staircase compartments;
- virus source (infected person) can be placed in any place and can be more than one, each with its specific virus strength.

The basic assumption to use the tool is that all supply and extracted air flow rate to/from each room are known and the extracted flow rate is provided as a fraction of the supply one. These parameters are usually provided in the system design masterplan.

To avoid to solve an air flow network, a simplified approach is then used to calculate transferred air flows, which are allowed only between rooms and corridor, and corridor to toilets and/or staircase if any exhaust air extraction is in place there. The basic assumption is that any room is always in pressurized state, i.e. only exfiltration and transferred air flows are allowed (**Figure 3**). An air mass balance on the whole system is then performed to calculate transferred air flows assuring air mass conservation consistency.

Input checks are employed as well as mass balance check to avoid that some inconsistent input is producing inconsistent result.

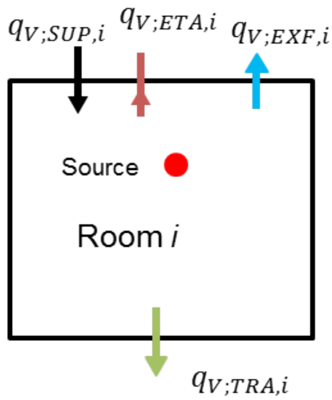

Figure 3. Air mass balance in Room *i*.

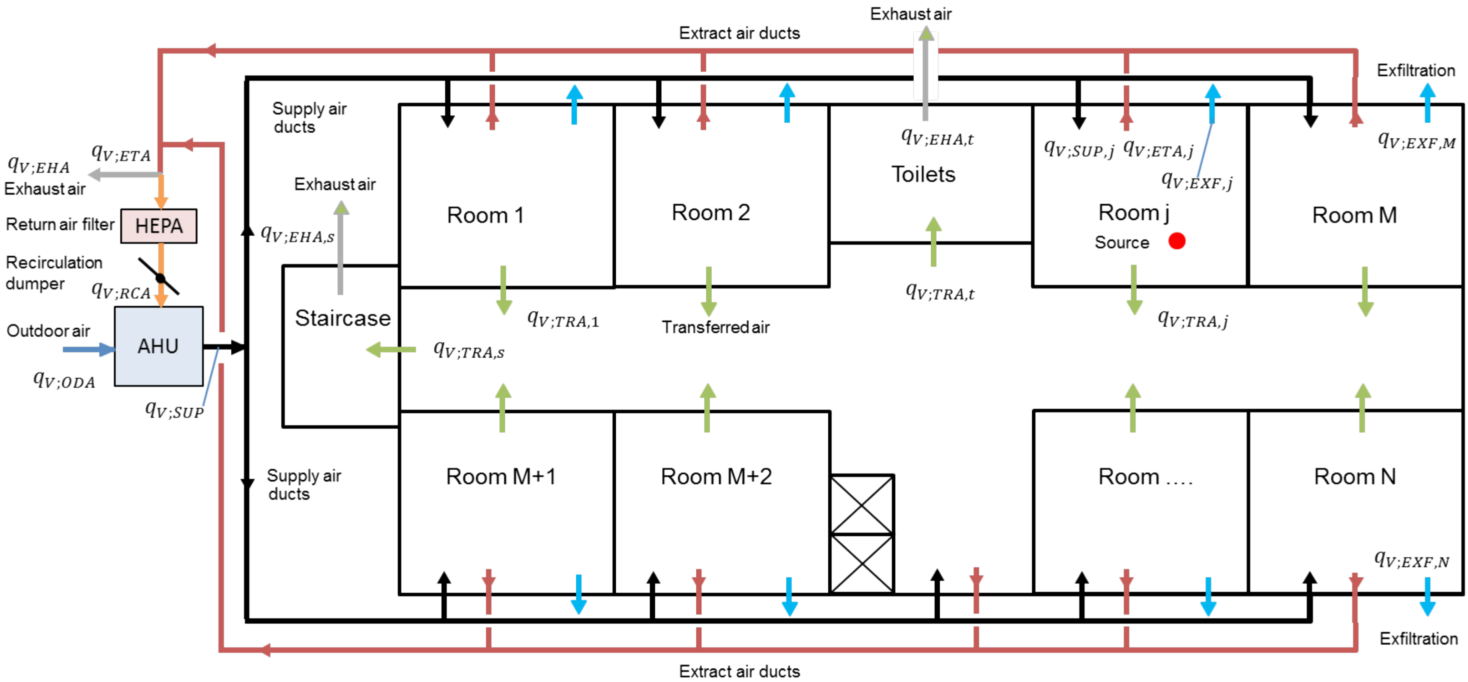

Figure 2. System layout.

An occupancy schedule can be specified only with to time slots inside the building operational time in a day (the tool calculates for one day only), but it can be different in any room.

Tool output

As result of the tool calculation the following data are available in the main sheet of the Excel workbook (Multi-cal):

- average virus concentration in each room, corridor, toilettes and staircase, over the working day, in quanta/m³;
- individual infection risk over the day in each of those spaces calculated with the Wells-Riley model, in [%];
- average number of potentially infected people in each room, corridor, toilettes and staircase, over the working day;
- virus air to surface deposition over the day in each space, on AHU surfaces, on HEPA or equivalent virus removal/inactivation equipment (V-C, etc.), on supply and return ductworks, in quanta.

The virus concentration time evolution in each space is reported (using a printout time interval, which can be greater than the integration time interval) in a second sheet called "Concentrations", while air to surface virus deposition time history is available in a third sheet called "Depositions".

In the main sheet diagrams, see **Figure 4**, are available for:

- virus concentration time history in each space;
- virus air to surface deposition time history in each space;
- individual infection risk in each space histogram;
- average number of potentially infected people in each room histogram.

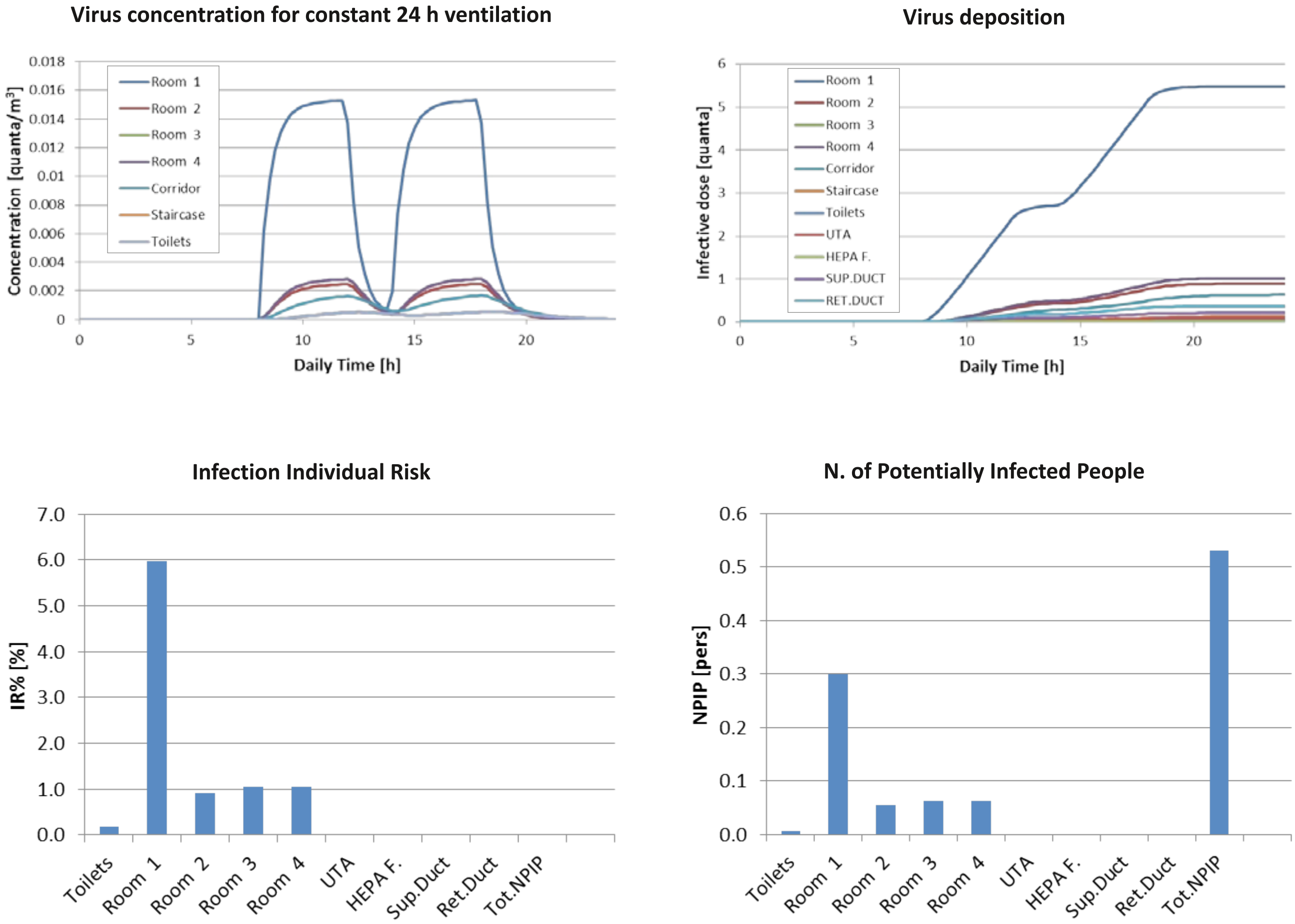

Figure 4. Tool graphic output.

How to use it

The developed tool, with some limitations, allows comparing possible improvements on both ventilation solutions for new buildings/systems and retrofit and operational strategies for existing buildings/systems under pandemic condition. It is using today the infection risk probability function from Wells-Riley model to assess the infection risk, but is physically based (i.e. mass balance based) and can easily updated with different infection risk probability functions or just using virus particles concentration instead of quanta to give a RELATIVE picture of different proposed actions.

The current tool, developed under Excel using VBA programming language, is enough simple to use and fast to execute for a **COMPARATIVE COVID-19 infection risk analysis** for a standard building floor and the most common air distribution layout, which makes it not the most flexible tool useful for any kind of application.

This tool is intended to be used by expert only, who know the meaning of each input and their implication on the results, for the large uncertainties on several of its parameters.

Some very sensible and specific COVID-19 input parameters are provided in drop-down lists, as virus emission rate per person, susceptible people breathing rates, etc., the selection of which is under the responsibility of the tool user nevertheless they are taken from the most updated scientific sources (as reported in the disclaimer).

Tool availability

This tool has been produced with the intention to give to any socially responsible HVAC engineer a simple and fast to use engineering "weapon" in fighting against COVID-19 pandemic. For this reason, this tool will be freely available after the COVID-19 REHVA Task Force has evaluated its consistency and decided how practically to make it available. Look constantly at REHVA website to get informed on its release. ■

Acknowledgement

This work has been carried out during my mandate as AiCARR expert in the COVID-19 REHVA Task Force, the work of which was stimulus for developing the model. For this reason, I would like to acknowledge all Task Force participants and AiCARR for this opportunity.

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Simplified estimation of the risk of infection by aerosol-bound viruses in ventilated rooms




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Introduction

The continuing risk of infection with COVID-19 (Coronavirus SARS-CoV-2) has led to intensive discussions in many countries about how different rooms can be used in the future. It should be noted that there will always be a risk of infection in rooms with several people, as transmission of the virus cannot be ruled out without the use of an unreasonable amount of protective clothing that goes beyond mouth-nose protection in everyday life. Viruses can be transmitted between people via three different ways without direct physical contact:

- Contact surfaces
- Droplets
- Aerosols

The transmission of viruses via contact surfaces can be significantly reduced by regularly cleaning all relevant surfaces and disinfecting the hands. Transmission by droplets is also significantly reduced by wearing a mouth-nose protector. Neither transmission path is directly influenced by the use of ventilation systems. At temperatures below typical room temperatures, viruses may remain active on surfaces for a longer period of time (Chan et al. 2011) which is not taken into the following considerations, just like the influence of relative humidity.

The present contribution focuses on the transmission of viruses by aerosols, since this transmission path cannot be prevented by simple measures and is responsible for the critical spread of viruses in closed rooms. Aerosols are very small particles, which can be produced by human respiration, for example. Ventilation of the room can directly influence the concentration of aerosols contaminated with viruses. Therefore, this transmission path is of particular importance for safety assessments of rooms and events in ventilated rooms.

A simplified analysis of the complex transportation processes by aerosols in ventilated rooms is described, which allows an estimation of the risk of infection in different rooms and usage situations. This analysis explicitly does not deal with medical or individual-related factors, since the focus is on the technically adjustable parameters of different rooms or ventilation systems. With the introduced calculation model, it can be estimated, which risk of infection exists, standardized to a reference state, and in which rooms special precautions for infection protection should be taken.

Based on this approach it can be shown that the air exchange rate, the room volume, the length of stay and the occupancy of the rooms significantly influence the relative risk of infection. Especially in rooms with relatively high room occupancy and long durations of stay, high air exchange rates generated by mechanical ventilation are necessary to reduce the relative risk of infection by aerosol-bound transmission of viruses.

Known routes of virus propagation

In the transmission of respiratory diseases, the World Health Organization distinguishes significantly between the three mechanisms (World Health Organization 2014):

In **direct contact transmission,** a virus is transmitted through direct skin and mucous membrane contact without the virus using another medium for its transport route.

Indirect contact transmission is the transmission of a virus to one or more non-infected persons by a process known as droplet transmission. In droplet transmission, viruses are transmitted by spraying infectious droplets from the airways of an infected person onto the mucous membranes or conjunctiva of non-infected persons in the near field of the infected person.

The larger droplets relevant for droplet infection have a significant sink rate, so that they settle on the ground or other surfaces within a few seconds (Wells 1934). During this flight phase, they cover a distance of about 1.5 m.

Since the droplets settle quickly on surfaces, transmission can also occur through contact with contaminated surfaces if, after surface contact, the person subsequently transports the viruses into the area of their own conjunctiva or mucous membranes, for example, via their hands (WHO 2014).

In the case of **aerosol transmission,** viruses can be transmitted from an infected person to a larger number of uninfected persons by means of very small droplets or particles. Droplets below a critical particle size can evaporate during the flight phase to form so-called droplet nuclei. These droplet nuclei consist partly only of solid residues and have the potential to be transported as aerosol in the ambient air for several hours due to their low mass and the resulting low sinking speed. WHO classifies airborne particles with a particle diameter of at least 5 µm as droplets. Particles that consist only of solid residues as well as droplets below a particle diameter of 5 µm are summarized as droplet nuclei (World Health Organization 2014). In the following, airborne droplet nuclei are referred to as aerosols according to this classification.

If aerosols are formed from the sputum of people with respiratory diseases, there is a risk of infection through inhalation of these aerosols, as the small particles may be contaminated with viruses. A critical factor in this transmission path is that the usual measures such as hand hygiene, keeping minimum distances and wearing simple mouth-nose covers are only partially or almost not effective (World Health Organization 2014). The formation of droplets and aerosols is clearly shown in **Figure 1**.

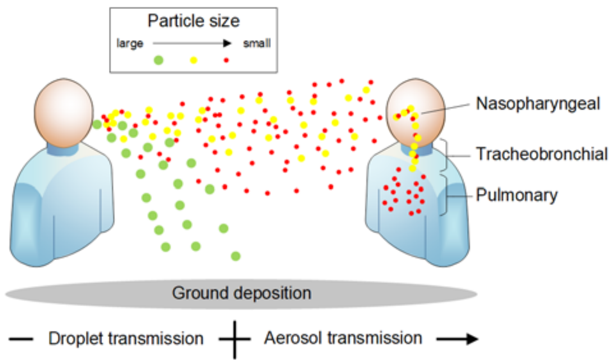

Figure 1. Schematic representation of propagation mechanisms according to (Pan et al. 2019).

In view of the current SARS-CoV-2 pandemic, the role of aerosols in the transmission of the virus is intensively discussed in science and studied worldwide.

Recent studies have shown that aerosol transmission in combination with unfavorable ventilation conditions can lead to transmission of SARS-CoV-2 (Guenther et al. 2020; Li et al. 2020). In view of the data available to date, scientists expressly warn of the danger posed by aerosol transmissions with SARS-CoV-2 (Fineberg 2020). Possible measures for the containment of aerosol transmissions indoors are ventilation measures that result in a high outdoor air exchange rate, low air circulation and a rapid removal of breathable air, in particular (Morawska and Cao 2020; Somsen et al. 2020). In order to quantify the effectiveness of these measures more precisely, the effects of ventilation or air purification on the contamination of indoor air with viruses must be investigated in more detail.

In the following, this paper will focus on the spread of viruses through aerosols. This transmission path cannot be effectively suppressed by classical measures such as regular disinfection of a surface or wearing a mouth-nose cover.

Spread of viruses in rooms through aerosols

The type of airflow in a room plays a central role in the spread of viruses indoors. The majority of all mechanically ventilated rooms have mixed ventilation. With **ideal** mixed ventilation, all impurities and particles are distributed evenly throughout the entire room volume, so that there are no local concentration differences. The theory of ideal mixed ventilation assumes that the air movements caused by ventilation, thermal forces and diffusion are sufficient to distribute all local emissions evenly throughout the room volume.

In practice, higher concentrations of pollution can occur locally in **real** mixed ventilation systems.

In addition to mixed ventilation, displacement ventilation/layer flow and displacement flow are also used in practice. While displacement flows are limited to special areas such as a clean room and are therefore not considered further in the following, displacement flows are often used in particular for rooms with higher ceilings.

The propagation of pollutants in the room and the main parameters of ventilation efficiency are described in the REHVA Guidebook on Ventilation Effectiveness (Mundt 2004). The air exchange efficiency is a measure for the flushing of a room. The ventilation efficiency considers the removal of local emissions.

In this paper, all investigations will refer to the approach of an *ideal* mixed ventilation. An evaluation of a source air flow is planned for a later date.

It should be noted that even if a room is freely ventilated by open or tilted windows, a mixed or displacement air flow can be generated. In the case of free ventilation, however, it is difficult to give an exact value for the air exchange. The exchange of air with the environment depends on the type of window opening and frame geometry as well as wind and temperature conditions. A transfer of the results to the case of free ventilation is only possible with the restrictions mentioned above.

Effect of ideal mixed ventilation in case of virus transmission by aerosols

If there is at least one infected person in a room, viral aerosols are potentially released into the room air. In the case of ideal mixed ventilation, the polluted aerosols are distributed throughout the entire room volume and the concentration of the aerosols polluted with viruses can be calculated from the emission rate of the virus-carrying particles and the outdoor air volume flow. The room air volume only has an effect if the dispersion processes are considered transiently. In a stationary state, only the fresh air volume flow rate is decisive as a room air technical parameter.

For the evaluation of transient effects in room air flows, the nominal time constant τ_n can be used, which indicates the fastest possible time for an air change:

$$\tau_n = \frac{V_R}{\dot{V}_R} \qquad (1)$$

As trace gas investigations show, stationary states in the room air are reached after about five space-time constants.

Risk of infection by aerosol-bound viruses in a room

Transmission of infection in a room via aerosols cannot be ruled out under the protective measures in use today. Although this transmission route is very complex and many medical details are only partially known, the following section will derive a model in which rooms of different sizes and uses can be compared with regard to the existing risk of infection. This simplified model is subject to restrictions, which will also be discussed in the following sections. It should be noted that the decay curves of functional SARS-CoV-2 viruses on aerosols under different room air conditions are not known. Therefore, for all subsequent calculations it is assumed that there are no significant differences between SARS-CoV-2 viruses in different indoor air conditions. This assumption may, however, be inadmissible, especially in rooms with very different relative humidity, since humidity has been shown to have an influence on the decay rate of functional viruses in aerosols (Smither et al. 2020). Since the current state of research does not allow an exact quantification of this effect, this effect is neglected in this paper.

In the literature, approaches can be found that describe the risk of infection as a function of the quantity or number of inhaled viruses. A well-known approach is the Wells-Riley model (Riley et al. 1978). This approach was originally developed to model infection chains of a measles outbreak in an elementary school. The risk of infection is determined here based on a so-called "quanta concentration" in the indoor air. A quantum describes the amount of virus that must be ingested by a person to become infected with a given probability. The risk of infection AR_{Inf} after Wells-Riley is described by equation (2).

$$AR_{Inf} = 1 - e^{-\frac{I \cdot q \cdot p \cdot \tau}{LW}} \quad (2)$$

Here, I corresponds to the number of infected persons in a room, q stands for the "quanta emission rate", i.e. the rate of quanta that an infected person emits into the indoor air. The pulmonary ventilation rate of a person is denoted by p, with τ indicating the time that a non-infected person stays in the aerosol-loaded environment. The air exchange rate of the room is described with the abbreviation LW. The equation is based on the assumption that the infected and infectious persons are in the room at the same time and that the "quanta concentration" in the ideally mixed room air corresponds to the equilibrium concentration for the entire period (Riley et al. 1978).

In this approach, the "quanta emission rate" is a hypothetical quantity and not a directly measurable quantity, since it can usually only be determined empirically from the reproduction number in transmission chains in epidemic studies. Reproduction rate is an epidemiological variable and describes the average number of persons infected by an infected person (Robert Koch Institute 2020a). The calculation of this quantity is therefore subject to a high degree of uncertainty, especially since in these studies the transmission mechanism cannot always be clearly attributed to aerosol transfer (Azimi and Stephens 2013). Despite this uncertainty, in the current SARS-CoV-2 pandemic, this approach has been used in several studies to assess the risk of indoor infection from aerosol transmission (Dai and Zhao 2020; Sun and Zhai 2020; Buonanno et al. 2020).

Simplified evaluation of ventilated rooms

For a simplified approach to assessing the risk of infection in a room contaminated with virus-carrying aerosols, the following simplified assumption states that the risk of infection increases linearly with the number of inhaled viruses. The risk of infection in this model is thus proportional to the number of inhaled viruses. This consideration corresponds to a linearization of the Wells-Riley model, where here the virus quantity is not considered in the form of quantum, but as the number of viruses. The validity of this linearization could not be checked so far. However, the linearization is an important assumption in this paper in order to avoid quantifying the medical effects that are relevant for aerosol transmission. The use of the Wells-Riley model would not allow this circumvention. Therefore, the risk of infection AR_{Inf} can be defined according to equation (3) as the product of the number of inhaled viruses n_V and an infection parameter κ_{Inf}. The infection parameter κ_{Inf} includes all processes that are decisive for triggering an infection, apart from the inhaled virus quantity. At this point, no medical or personal effects during the transmission process of the virus are considered for modeling purposes. Neither will it be considered what other medical circumstances must be taken into account for a person to become ill. For comparing rooms of different designs and uses, all complex factors are compared using the infection parameter κ_{Inf} for an average person as given.

$$AR_{Inf} = n_V \cdot \kappa_{Inf} \quad (3)$$

The number of inhaled viruses n_V can generally be calculated from equation (4) using the temporal integral of the virus concentration $\zeta(t)$ in a room at the time t as well as the respiratory volume flow $\dot{V}_A$ where under stationary boundary conditions during the entire duration of the stay τ a mean virus concentration $\bar{\zeta}$ can be accepted.

$$n_V = \int_{t=0}^{\tau} \zeta(t) \cdot \dot{V}_A \cdot dt = \bar{\zeta} \cdot \dot{V}_A \cdot \tau \quad (4)$$

In this model approach, the mean virus concentration $\bar{\zeta}$ in a room can be determined according to equation (5) from the exhaled aerosol volume flow contaminated with viruses $\dot{n}_{Aerosol}$ of a person, the volume flow rate decisive for the air exchange of the room $\dot{V}_R$, and a probability value for the presence of at least one infected person P_{KRP}. Concentration effects that occur when an infected person enters the room are neglected here. However, the effect of concentration has a greater influence especially in the case of short residence times compared to the respective nominal time constant. In this balance, the number of viruses inhaled by the persons in the room is also neglected.

$$\bar{\zeta} = \frac{\dot{n}_{Aerosol}}{\dot{V}_R} \cdot P_{KPR} \qquad (5)$$

The probability P_{KPR} at n_{inf} infected persons in a total population n_p meeting at least one infected person in a group with n_R people in a room is approximated by equation (6) (Consileon Business Consultancy GmbH 2020; Tabarrok 2020).

$$P_{KPR} = 1 - \left(1 - \frac{n_{Inf}}{n_p}\right)^{n_R} \qquad (6)$$

This leads to the absolute risk of infection AR_{inf} according to equation (7):

$$AR_{Inf} = \frac{\dot{n}_{Aerosol}}{\dot{V}_R} \cdot \left(1 - \left(1 - \frac{n_{Inf}}{n_p}\right)^{n_R}\right) \cdot \dot{V}_A \cdot \tau \cdot \kappa_{Inf} \qquad (7)$$

With this equation, the absolute risk of infection in any room can be calculated based on the simplifications described. However, an evaluation and interpretation of the results remains difficult, since some parameters of this equation cannot be given with sufficient certainty. Therefore, in the next section the relative risk of infection in a room is dealt with.

Relative risk of infection by aerosols in different rooms

Under normal living conditions, it must be assumed that even if recommended precautions and rules of conduct are strictly adhered to, an infection with COVID-19 in rooms can never be completely ruled out. The **absolute** risk of infection is never zero if there are at least two people in a room. For a simplified risk assessment, a reference case should therefore be defined where all other cases can be evaluated. By means of this reference case and assuming that all unknown or undetailed medical phenomena are the same in all rooms considered, a **relative** risk of infection can be determined instead of the absolute risk of infection, which cannot be quantified exactly.

In the following, the average living situation is considered as the reference environment in this context, whereby each inhabitant of a household can be infected like the population of all persons in Germany. Thus, the transmission of a virus through aerosols in a room can be compared with the probability of infection in an average apartment. In principle, any reference can be selected at this point. The values of the relative risk always refer to the selected reference case.

For a typical apartment, the relevant volume flow rate can be calculated by equation (8) as the product of the floor area A_{ref}, the clear room height h_{ref} and the air exchange rate LW_{ref}.

$$\dot{V}_{R,ref} = A_{ref} \cdot h_{ref} \cdot LW_{ref} \qquad (8)$$

This results in the air exchange rate *LW* generally as the quotient of air volume flow and room volume:

$$LW = \frac{\dot{V}_R}{V_R} = \frac{1}{\tau_n} \qquad (9)$$

The floor space assumed in **Table 1** for the reference apartment corresponds to the average living space for households in Germany according to the supplementary program "Living in Germany" of the 2018 Microcensus, whereby two persons present can be assumed with approximately 46 m² per capita (Statistical Offices of the Federal Government and the States 2019). For living spaces, it is assumed that the entire room air is exchanged every two hours. Together with a stay of 8 h, which was chosen analogous to a typical working day, the reference scenario can thus be regarded as a day at the weekend or a working day in the home office. To calculate the probability of encountering a person who is infected, 83 million inhabitants and, at the beginning of August 2020, about 10,000 currently infected persons are assumed for Germany, which is calculated from the number of all registered cases minus those already recovered and deceased (Robert Koch Institute 2020b). The number of people actually infected is often estimated to be many times higher.

Table 1. *Assumptions for the reference environment of a typical apartment.*

	Parameter	Value
Floor space in m²	A_{ref}	93
Room height in m	h_{ref}	2.4
Air exchange in 1/h	LW_{ref}	0.5
Number of persons present	$n_{R,ref}$	2
Length of stay in h	τ_{ref}	8
Likelihood of encountering at least one infected person	$P_{KPR,ref}$	0.00024

If equation (7) is now used for any scenario to be evaluated AR_{Inf} and for the reference scenario of a typical apartment $AR_{Inf,ref}$, the relative risk of infection RR_{Inf} can be calculated according to equation (10).

$$RR_{Inf} = \frac{AR_{Inf}}{AR_{Inf,ref}} \tag{10}$$

Used as follows:

$$RR_{Inf} = \frac{\frac{\dot{n}_{Aerosol}}{\dot{V}_R} \cdot \left(1-\left(1-\frac{n_{Inf}}{n_p}\right)^{n_R}\right) \cdot \dot{V}_A \cdot \tau \cdot \kappa_{Inf}}{\frac{\dot{n}_{Aerosol}}{\dot{V}_{R,ref}} \cdot \left(1-\left(1-\frac{n_{Inf}}{n_p}\right)^{n_{R,ref}}\right) \cdot \dot{V}_A \cdot \tau_{ref} \cdot \kappa_{Inf}}$$

$$= \frac{\dot{V}_{R,ref}}{\dot{V}_R} \cdot \frac{\left(1-\left(1-\frac{n_{Inf}}{n_p}\right)^{n_R}\right)}{\left(1-\left(1-\frac{n_{Inf}}{n_p}\right)^{n_{R,ref}}\right)} \cdot \frac{\tau}{\tau_{ref}} \tag{11}$$

$$= \frac{A_{ref} \cdot h_{ref} \cdot LW_{ref}}{V \cdot LW} \cdot \frac{\left(1-\left(1-\frac{n_{Inf}}{n_p}\right)^{n_R}\right)}{\left(1-\left(1-\frac{n_{Inf}}{n_p}\right)^{n_{R,ref}}\right)} \cdot \frac{\tau}{\tau_{ref}}$$

This relative risk assessment allows the general infection parameter κ_{Inf}, which cannot be quantified according to the current state of knowledge, to be removed from the equation, assuming for simplicity that it is the same in all considered environments and for all persons. Furthermore, assuming that persons with the same physiological characteristics are present in both environments, both the exhaled aerosol quantity $\dot{n}_{Aerosol}$ as well as the respiratory volume flow $\dot{V}_A$ can be shortened. Remaining variables in the equation are exclusively technical parameters of the room, the room occupancy, and the statistical variables describing the current course of infection.

Different room parameters and uses

In order to evaluate the relative risk of infection compared to a stay in one's own living environment, boundary conditions for different ventilated comparison environments are defined below. Unless otherwise stated, the volume of air in the room refers to the clear internal dimensions without taking into account furniture or other fixtures.

No breaks or interruptions are taken into account in the times of stay. At this point it should be noted that the design values for air exchange rates given in standards and guidelines often do not correspond to the actual conditions. All values for air exchange rates, retention times, and occupancy rates given here are not to be understood as generally valid for the respective room types, but rather as examples for the assumed example.

The assumptions for the comparative measurements in the **Table 2** are as follows: A **single-family house** with a similar room height, hygienic air exchange, and length of stay as the reference apartment is assumed as a further residential building. Together with a floor space of 140 m², this results in a volume of approximately 336 m³, which is assumed here for simplicity as an air compound. In order to be able to consider situations with several house guests, occupancy rates of up to 20 persons are considered in the following.

The reference values for a **classroom** for an exemplary school day are based on a field study on air quality and acoustics in schools carried out by *Heinz Trox Wissenschafts gGmbH* in the spring and summer of 2019. The evaluation of the recorded room geometries results in an average floor area of 64 m² with an average clear height of 3.27 m, a room volume of about 210 m³, and an average of 27 seats. The mechanical ventilation units recorded within the scope of the field study had nominal volume flows of up to 850 m³/h, which, however, could not be operated with the highest fan speed due to the increased flow noise during lessons. Accordingly, air exchange rates below 4/h can be assumed to be realistic.

Table 2. *Assumptions and typical boundary conditions for comparison environments.*

		Single family house	Classroom	Multi-person office	Open-plan office	Lecture Hall (large)	Exhibition hall (large)
V	m³	390	210	65	1200	10.000	138.000
LW	1/h	0,5	to 4	to 4	to 4	up to 3,5	2 ... 5
$n_{R,max}$	–	20	35	4	33	1000	4000
τ	h	8	5	8	8	1,5	2.5

An office environment with an average 40-hour week is considered as representative of a typical workplace. Based on the Technical Rules for Workplaces ASR A1.2, which concretize the workplace guidelines, 8 m² floor space per workstation is assumed. For a **multi-person office** with four workstations, a conservative estimate results in a floor space of 26 m² and a room volume of 65 m³, while maintaining the minimum permissible clear room height of 2.75 m for this floor space. **Open-plan offices** with a floor space of 400 m² or more and a clear height of at least 3 m are still considered open-plan offices, resulting in a minimum room volume of 1,200 m³. Together with a minimum space requirement of 12 m² per workstation, this results in a maximum occupation of 33 persons. (Federal Institute for Occupational Safety and Health (BAuA) 2013).

A lecture hall and an exhibition hall will be used as additional non-residential buildings. For an exemplary large **lecture hall** with seating for about 1,000 people, a floor space of 935 m² and a volume of about 10,000 m³ is assumed. For lecture halls at RWTH Aachen University, typically 3 to 3.5 air changes per hour are set.

With an **exhibition hall,** an environment with a very large spatial volume is still considered. The assumed comparative environment is based on a large hall of the Frankfurt Fair. With side lengths of around 75 and 160 m and an average clear height of around 13 m, the result is a gross floor area of 12,000 m² and an air volume of around 156,000 m³. The specified air exchanges were taken from the current "Protection and Hygiene Concept for the Organization of Trade Fairs and Congresses on the Exhibition Grounds of Messe Frankfurt (Status 18.05.2020)". With the floor space of 3 m² per person or ticket sold, as provided for by current regulations, the maximum occupancy of the hall is 4,000 persons.

Comparison of the relative risk of infection in different environments

In the following, the infection risk is graphically represented for the different rooms under variable boundary conditions relative to the apartment assumed as the reference environment. In the diagrams below, the number of persons is plotted above the air exchange rate, with the relative risk of infection shown in color according to a traffic light extended by the color orange. To allow comparison of different scenarios by color, the same air exchange and risk axes were chosen for all immobile environments in **Figure 2**. Yellow corresponds to a double, and red to at least six times the relative risk of infection. The lines superimposed on the color gradients indicate the limits of half, equal and double the risk of infection compared to the reference environment for easier orientation. It is to be pointed out again that the visualizations, which represent calculated values based on all simplifications mentioned through equation (11), apply in each case only to the exemplarily accepted space volumes and durations of stay. The influence of latter-mentioned sizes is not dealt with further here.

In the case of a **single-family house,** a family of four persons is assumed at first, whereby the relative risk of infection is already indicated from two persons upwards, analogous to the assumed occupation of the reference apartment. With an assumed air exchange rate of 0.5/h, the risk of infection is already one third higher for four persons than in the case of the reference apartment: While both persons have about 46 m² floor space and 110 m³ air volume each in the first-mentioned environment, 35 m² and 84 m³ per capita remain in the considered single-family house. If 20 persons are present for a family celebration or on a comparable occasion, the relative risk of infection is about 6.6 with unchanged ventilation habits. 3.3 air changes per hour would be necessary for a relative risk of 1. It should be pointed out that the assumption made here of an air network in the entire building is not unrestricted in reality, so that locally higher infection risks can occur within the building.

Classrooms are particularly critical because of their sometimes high-occupancy rates and long operation times. If half an air exchange per hour is also assumed, which is quite realistic under unfavorable outside conditions and insufficiently used window ventilation, the assumed maximum occupation with 35 persons present would result in an almost 12-fold higher risk of infection than in the reference environment. Even with a very low occupancy of 18 persons, a relative risk of 1 would still require about three times the air exchange rate per hour and thus a volume flow of 630 m³/h. A volume flow of this magnitude can only be provided all year round by a ventilation system. The flow noise caused must be so low that the learning environment is not negatively affected. Pure window ventilation will not be able to provide sufficient air exchange, especially in winter and in noisy outdoor environments.

When comparing the office spaces, the significantly more spacious traffic areas for open-plan offices in the ASR A1.2 become apparent. Whereas in a **multi-person office** with four full occupants, a relative risk of 1 requires about 2.5 air changes per hour, in an **open-plan office** about 1.5 air changes per hour would be

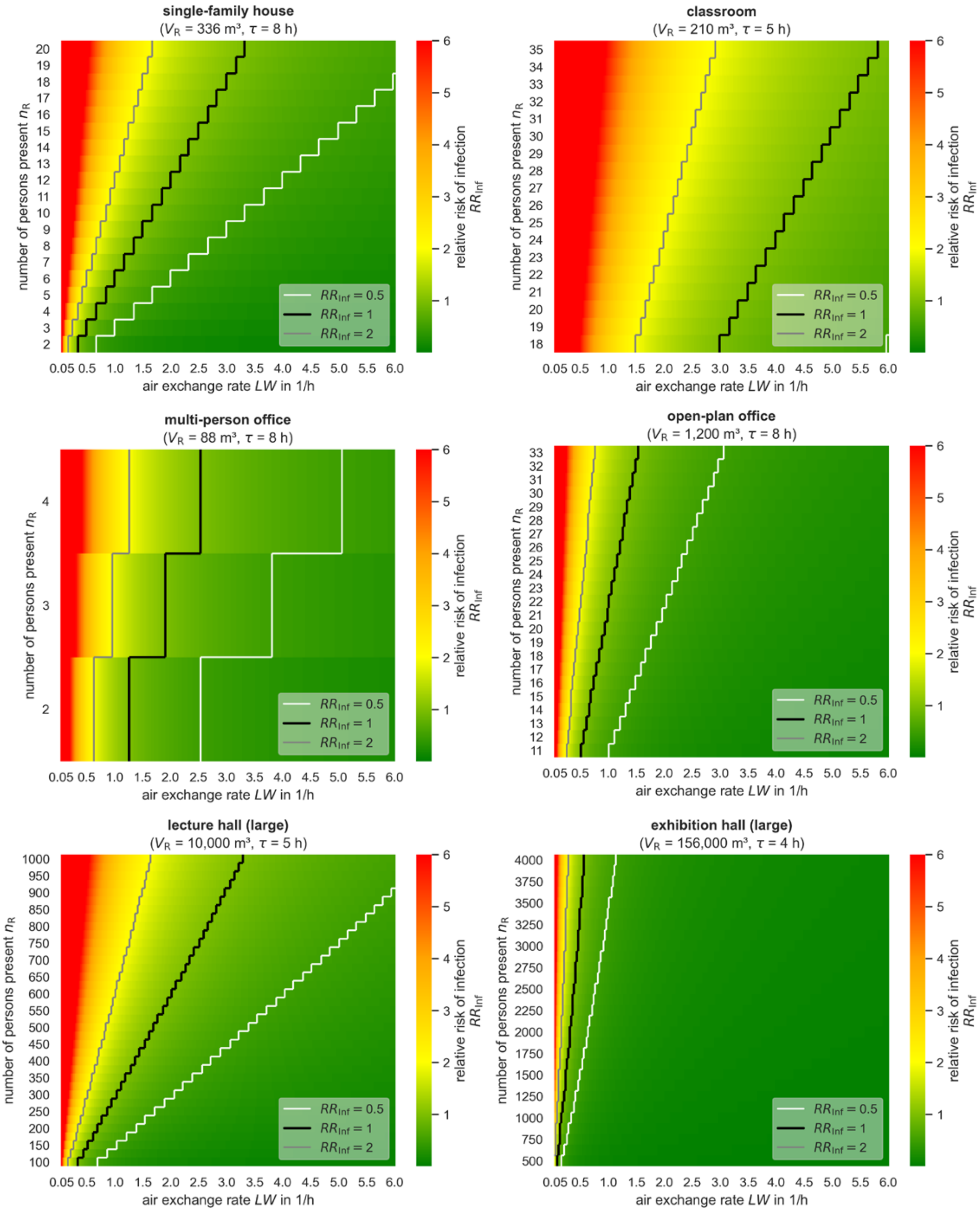

Figure 2. Relative risk of infection by aerosols in different immobile comparison environments compared to the reference apartment.

sufficient even with the assumed full occupancy of 33 people. The minimum number of persons considered in the diagram is 11 persons, which is one third of the maximum number of persons.

In the case of the large **lecture hall**, a 3.3-fold air exchange per hour is sufficient to achieve a relative risk of infection of 1 when fully occupied. Also, lower occupancy densities with one tenth of the maximum occupancy are shown in order to be able to consider a typical examination situation or less numerously attended events. In the case of the **exhibition hall**, the risk of infection at typical air exchange rates - even at maximum occupancy - is significantly lower than the risk in the domestic reference environment. In contrast to the room types presented so far, these event rooms require much larger room volumes anyway in order to ensure a sufficiently large smoke-free layer in case of fire, for example. Although the area-related person density is not dissimilar to that of a classroom, each person has a significantly larger vertical column of air at his or her disposal. It should be noted here that stand structures can significantly reduce the traffic area compared to the gross floor area.

Particularly in large rooms, it must be taken into account that the assumption made here of ideal mixed ventilation must be critically questioned. A complete dilution of the polluted aerosols is not always to be expected, so that locally higher concentrations of aerosols can occur. However, in this first analysis the storage capacity of the room volume is also neglected, although for an air exchange rate of 3/h, which can be assumed to be realistic in case of a trade fair, the space-time constant is 20 minutes. Consequently, the stationary values assumed here would only be reached after one hour and forty minutes (corresponding to $5{\cdot}\tau_n$). In order to clarify the concentration distribution in larger rooms, measurements are planned by the Heinz Trox Foundation in the autumn of this year.

Summary

In this paper, an approach was developed to calculate a relative risk of infection by virus transport via aerosols in different rooms and uses compared to an apartment as a reference environment. Based on the current ratio of COVID-19 infected persons and the total population in Germany, the probability of an infected person being present in the room was modelled for the respective room occupancy. With this probability and based on room-specific parameters and a hypothetical rate of infectious aerosol particles released into the room air by an infected person, a model for the equilibrium concentration of infectious aerosol particles in the room air was established.

The results show that with sufficiently high air exchange rates in all comparison environments, a relative risk of infection by aerosols smaller than 1 can be achieved. The risk of infection from contaminated aerosols is lower in this case than in the reference environment of a typical apartment. Even if this value does not indicate absolute safety, this reference allows a consideration of further protective measures. However, it is also clear that without adequate ventilation of the rooms, the risk of infection is very high.

In classrooms, this analysis shows that, given the high occupancy rates and length of stay, high air exchange rates are required to maintain relative risk of infection in the area at 1. In the short term, at least one CO_2 traffic light should be used in practice as an indicator of the amount of outside air for each person. For all new schools and renovation measures, the installation of a sufficiently dimensioned ventilation system is urgently recommended. In rooms with a larger room volume such as open-plan offices, lecture halls and exhibition halls, there is a relative risk of infection of less than 1 even for comparatively low air exchange rates, since the person-related air volumes are very high due to the large room air volumes. Additional storage or buffering effects, which become more significant with increasing room heights, were not considered in this analysis.

In conclusion, it should be emphasized that the method presented in this paper allows for the analysis of **relative** risks and thus provides a comparative perspective to the public discourse, which often focuses on absolute risk and collateral.

Outlook

For more detailed considerations the calculation model has to be modified accordingly in a next step. The following aspects could be included in future considerations, which extend the scope of the presented model.

Consideration of different infection events

In the previous considerations, it was assumed that the persons in the reference household and the comparison environment to be considered came from the same population. In order to take local hotspots or sources of infection into account, different numbers of infected persons and different sizes of populations can be assumed for the reference and comparison environment.

Consideration of different activity levels

In the context of this paper, it was assumed for simplicity's sake that the respiratory volume flows in the reference and comparison environments did not differ from each other, which meant that they cancelled each other out and did not have to be further considered. Thus, by considering different respiratory flow rates, different activity levels and workloads could be approximated. Furthermore, new findings on the production rate of aerosols contaminated with viruses can be included in this analysis, taking into account different metabolic rates.

Consideration of different speech components and volumes

Furthermore, different speech fractions and volumes should be considered by differentiating the exhaled aerosol volumes between the reference and comparison environments, since significant differences in the respective aerosol exposure are to be expected between still and quiet work in a library, a visit to the cinema or work in a call center. The increased release of aerosols as a result of certain respiratory activities could already be demonstrated in the context of a choir rehearsal (Hamner et al. 2020). In this context, investigations by Asadi et al. could be used (Asadi et al. 2019).

Influence of ventilation efficiency

Depending on the airflow and temperature conditions used, there can be considerable differences in the aerosol concentration in a room. Thereby local effects in real mixed ventilation systems like stagnation and short-circuit flows have to be addressed and evaluated. Additionally, the effect of a source air flow on the aerosol dispersion can be considered. The natural uplift flow of the supply air introduced near the ground with low temperature and low momentum transports the contaminated breathing air from the occupied zone directly upwards and towards the ceiling near extraction. This enables a better air quality near the floor. In addition, the influence of air filtering and the effectiveness of additional cleaning methods such as the use of UVC sources should be investigated in connection with mechanical ventilation.

Transient effects in indoor air flows

Finally, the transient effects of indoor air flows, especially in large rooms, can be discussed. Here, the storage capacity of the available room volume can be considered, which especially influences the evaluation of rooms with temporary use. In addition, the investigation of natural ventilation scenarios with cross-ventilation and impulse ventilation is of great importance, since most buildings in Germany do not have a mechanical ventilation system. ■

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Practical guidance for ventilation of healthcare facilities

- Ventilation is important but certainly not the holy grail

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The Expert Panel Corona healthcare in the Netherlands, a collaboration between The Netherlands Organisation for Applied Scientific Research (TNO), Eindhoven University of Technology (EUT), Association Contamination Control Netherlands (VCCN) and Royal HaskoningDHV (RHDHV), was started in March 2020 to help healthcare facilities deal with urgent questions about technical infrastructure and HVAC systems arising because of the sudden COVID-19 pandemic. Many healthcare facilities were supported by setting up quick video calls and knowledge was shared through "FAQ & Guidance" and webinars. This article gives an overview of lessons learned, guidance, recommendations and considerations for healthcare facilities to continue safe functioning during the pandemic, with special focus on aerogenic transmission routes and the role of ventilation in risk management for SARS-CoV-2. Further information on the expert panel and its recommendations can be found in the FAQ [1].

Regular ICU and isolation room capacity cannot deal with large volumes of patients requiring specialist care for COVID-19. Accordingly, as the pandemic gathered pace, regular patient rooms had to be called into service to accommodate COVID-19 patients. These rooms had mostly not been designed to provide safe environments for care of highly infectious patients. Functional, technical and installations adjustments were called for. However, it quickly became apparent that available evidence offered no consensus either on the specific risks associated with different transmission routes, nor on which measures were likely to be effective to mitigate these risks. Around the world, healthcare organizations wrestled with the urgent question of how to prevent transmission of COVID-19 within their facilities.

Principles and approach

To help Dutch healthcare organisations take sensible and proportionate action, the Expert Panel on Corona healthcare has developed a practical guide that offers advice on short-term measures. This guidance has been based on key findings from current scientific evidence and/or literature, and has been developed around a set of pragmatic action principles.

The **key findings** from the current evidence base can be summarized as follows.

- SARS-CoV-2 is a respiratory virus in which the primary infection occurs via drip contact "coughing", [2, 3, 4]
- Secondary contamination can occur by air via aerosols, [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]
- On a surface, the virus can remain infectious for 2-3 days, [17, 18, 19]
- In the air, a virus can remain infectious for several hours, [17, 18]
- Infection may be caused by faecal-oral transmission, [20, 21]

Action principles shaping the practical guide developed for areas where COVID-19 suspect or COVID-19 confirmed patients reside by the Expert Panel are:

- Prevention of airflows from contaminated to non-contaminated areas. It should not be possible for air from spaces where COVID-19 (suspected) individuals are present to spread to other areas and/or parts of the facility. Organisational operational, installations-based and functional design-based measures can contribute to this goal.
- Adequate ventilation, e.g. by making sure outdoor air supply complies with applicable building codes*.
- Prevent recirculation of air in centralized systems. This helps prevent aerogenic spread and contributes to protection of vulnerable patients.
- Precautionary approach. The current evidence base has many unknowns regarding the dispersion routes of the virus and associated risk levels. Absence of evidence

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* This is based on the Dutch situation. In other countries the building codes may not be sufficient.

is not evidence of the absence of risk. A reasonable suspicion is sufficient basis to take action.
- Proportionality. The cost and side-effects of measures recommended should be proportionate to the (probable) degree of reduction of the risk of infection.

A particular objective of the guidance is to help healthcare facilities make sense of the heated scientific and media debate around the possible aerosol spread of SARS-CoV-2 and the efficacy (or not) of ventilation.

Research has found detectable amounts of virus on particles smaller than 5 µm in size. Particles of this size can remain airborne for a long time and hence cover greater distances than those generally prescribed in social distancing measures (1.5 m in the Netherlands). At the same time, media reports have suggested that ventilation measures could entirely eliminate infection risks from airborne transmission, effectively making buildings completely *corona-proof*. As a result, healthcare facilities have experienced pressure to implement rigorous and costly ventilation measures.

A closer look at the evidence, however, reveals that the evidence base for aerosol transmission through small particles is far from unequivocal. The guide accordingly tries to provide healthcare facilities with a nuanced account of sensible ventilation measures to take which reduce risks without breaking the bank on far-reaching but possibly ineffective measures.

The practical guide offers general advice and directions. Successful implementation requires that healthcare facilities contextualize this general guidance based on their own specific situation. The guide offers recommendations on how to go about this. Guidance focuses on areas in healthcare facilities where high-performance air treatment systems are not normally in place: general inpatient and treatment areas and public areas.

Ventilation is important but certainly not the holy grail

To tackle contamination risk in specific departments where COVID-19 (suspect) patients or residents are present, measures on various fronts need to be taken: wearing of PPE by staff, and possibly visitors; increased supply of outside air and/or more thorough air treatment; changes to routing of air to avoid recirculation of air from potentially contaminated areas to other spaces. This is especially important for areas where activities associated with heightened aerosol emission levels take place, such as intubation/extubation, exercise tests, dental surgery, and physical examinations. Additional measures also need to be considered in spaces where care processes and/or spatial characteristics require people to be in close mutual proximity – defined as closer than the minimum required for social distancing (1.5 meter in the Netherlands).

The Corona Expert Panel advises health service providers to take only measures that are proportionate both to the known or estimated infection risk level, and to the level of risk reduction that can be achieved. Tackling ventilation issues is an important strategy for addressing COVID-19 related risks, but it is not a panacea: according to the Corona Expert Panel, good ventilation helps to reduce the risk of contamination, but will not reduce the risk of contamination to zero. This advice is based on established guidelines, recent insights from the scientific literature and its own research. [22, 23, 24]

Airborne contamination

Various studies have demonstrated that SARS-CoV-2 virus particles can move through aerosols. They have also established that the viral load of particles travelling distances of more than about 2 metres is sufficient to theoretically cause infections. [15] But the crucial questions to be answered in order to draw up are practical: what is the actual contribution of this transmission route to total risk and total number of infections; and what role do ventilation systems play in allowing or hindering dispersal of virus particles by this route? [4, 5, 14, 16, 6-13] Current research does not provide a clear answer to either of these questions.

Regardless of particle size, the concentration of virus particles will be highest close to the source, especially within the exhalation cloud. [25] However, the scientific literature offers no consensus on which sizes of particles are emitted in which numbers during various activities such as breathing, talking, singing, sneezing and coughing. This is true for the whole range of particles from small (< 5 µm) to very large (> 100 µm). What does seem clear is that the number of particles emitted depends on the noise level produced by the source. [23]

Ambient humidity strongly affects particles < 40 µm. At low relative humidity (RH), these particles will quickly decrease in size and weight, allowing them to be carried much further by air flows. On the other hand, lower RH leads to faster dispersion, dilution and dissipation of particles. There is no clear evidence of a net effect of RH on infection risk. Dilution of concentrations of smaller particles (aerosols) to reduce the risk of contamination through airborne transmission can also be achieved through providing clean outdoor air (ventilation). Overall, ventilation appears to be more effective in reducing airborne particle concentration than lowering of RH. As particle size increases, the effect of RH becomes less marked, with effects apparently negligible for particles > 80 µm. [24] Particles > 100 µm will quickly precipitate under the influence of gravity, travelling no further than about 1.3 meters.

Multi-factorial and unclear contamination causation mechanisms

Multiple factors co-determine the risk and severity of indoor air contamination. The number of (infected) persons in a room, source strength of the emittor(s), the size of the room, the susceptibility to infection of receivers (based on age, physical condition, predisposition) and the length of stay in the room are all important.

There is no consensus in the literature on what constitutes a safe threshold value for concentration of airborne virus particles. Nor is it clear what level of infection risk could be considered acceptable under different circumstances, for instance when set off against the risks of delayed diagnosis and/or treatment of other conditions. And while there is a growing body of indirect evidence, direct evidence of airborne SARS-CoV-2 transmission over greater distances has not yet been found.

In summary, neither causation mechanisms nor requisite ventilation performance levels are clear, but there is a reasonable suspicion that improving ventilation may reduce infections risks, although not to zero. Calculations done using the Wells-Riley model bear this out. The Wells-Riley model [23] estimates the probability of an individual infection occurring, taking into consideration variables such as concentration of infectious particles in the exhaled air, exposure time, and the minimum viral load required to achieve infection. Calculations using the model show that ventilation providing outdoor air change rates compliant with the Dutch building code already leads to a considerable reduction in individual infection risk compared to a baseline assuming no ventilation. The calculations also show that further improvements in ventilation lead to diminishing returns. Doubling the amount of ventilation further reduces the risk, but by less than half. Reducing risk to a level approaching zero requires unrealistically high ventilation quantities, which would essentially create an outdoor environment indoors. Even then, absolute zero risk could not be guaranteed. Creating a *corona-proof* environment through ventilation is impossible.

Given these considerations, the Expert Panel advises to at least ensure compliance of ventilation systems with requirements set out in the national building codes* and in specific guidelines and professional standards for care facilities. It should be verified under operational conditions that all ventilation systems function properly and achieve their design specification ventilation capacities.

Triage and behavioural compliance

Where no infected persons are present, no infections occur. The risk of infected persons being present in indoor healthcare environments can be very substantially reduced through thorough advance and on-site triage. Advance triage consists of behavioural protocols prescribing self-isolation and testing in the case of symptoms consistent with COVID-19. On-site triage involves encouraging or coercing individuals exhibiting behaviours that might indicate infection, such as coughing or sneezing, to leave the premises. If these measures are implemented systematically, the likelihood of infected persons being present and hence the risk of infection by air will be very low. Residual risk remains: not all individuals who are carriers of SARS-CoV-2 exhibit symptoms, so they won't be found through triage. However, the risk of such asymptomatic or presymptomatic individuals infecting others is limited, as they do not exhibit the behaviour (coughing) most associated with spread of the virus. The risk of airborne contamination through asymptomatic or presymptomatic carriers is especially low. For all eventualities, adherence to physical distancing guidelines and prevention of strong person-to-person airflows are sensible and proportional precautions. [22, 26]

Applying recirculation units

Several questions to the panel have expressed concern about the possible risks posed by recirculation units. Spreading of virus particles through indoor environments always occurs. Recirculation units accelerate this spread, potentially increasing contamination risks. On the other hand, recirculation will lead to more rapid reduction of the concentration of contaminants in the vicinity of the source, thereby reducing risks.

* This is based on the Dutch situation. In other countries the building codes may not be sufficient.

Recirculation as such does not lead to dilution and discharge: this is affected by admixture of outdoor air.

Within individual rooms, application of recirculating units, for (additional) cooling and/or heating, is not a problem, provided the available ventilation provides a sufficient admixture of outdoor air to be fed into the room. Care should, however, be taken to prevent the occurrence of very powerful air flows in the room. These can cause the exhalation cloud to travel much further than normal, a so-called “extended plume”. Such an extended plume could potentially infect persons over distances of more than one-and-a-half meters.

Recirculation of air across multiple rooms may be problematic if insufficient outdoor air is added. In buildings where the likelihood of infected persons being presented is high, and in facilities housing at risk populations, the safest option is to set the recirculation units to “outdoor air only” mode. In the Netherlands, systems recirculating air across multiple rooms are generally found only, and infrequently, in older buildings.

Proportional measures

The Corona Expert Panel recommends health service providers to take only measures that are proportionate to the risk of infection and the degree of risk reduction that can be achieved. This avoids expenditure on less urgent and less effective adjustments. It should be borne in mind that there is a reasonable suspicion of contamination by air, but that this transmission route has not been proven. Except under very high-risk circumstances, adherence to physical distancing and ventilation compliant with the national building code and the specific guidelines and professional standards for care building ventilation will be sufficient to reduce risks to acceptable levels. Minimalization of risks through ventilation measures is technically challenging and very costly, and elimination of risks through ventilation alone is impossible. Ventilation has a valuable contribution in reducing the risk of infections, but is not a panacea to reduce all COVID-19 infection risks. ■

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Considerations on pandemic resilient healthcare facilities

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Summary

The healthcare response to the current COVID-19 pandemic has required marshalling nearly all available capacity in the system. The peak months of the pandemic have seen an almost complete cessation of all but the most urgent regular care. Healthcare systems and facilities must be made more resilient to future outbreaks to avoid large and damaging social, economic and health impacts from missed care. Since it was established in March 2020 in the Netherlands, the Corona Expert Panel has collected evidence, drawn up guidance and provided practical advice to help care institutions cope with unprecedented and very challenging circumstances. Through its work, the Expert Panel has identified a number of intervention areas and strategies in design and management of facilities that healthcare providers can pursue to achieve a higher level of resilience in dealing with future pandemics. This paper zooms in on these areas and strategies and issues a call to action.

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The Corona Expert Panel

In March of 2020, The Netherlands Organisation for Applied Scientific Research TNO, Eindhoven University of Technology (TU/e), the Association Contamination Control Netherlands VCCN and Royal HaskoningDHV (RHDHV) jointly established the Expert Panel on corona care. The objective of the expert panel was to collect evidence, issue guidance and provide practical advice to help healthcare organisations to minimize the risk of airborne contamination in their care facilities. While efforts have understandably been focused on short-term issues and operational responses, over the course of its activities the expert panel has identified a number of design and organisational strategies that healthcare organisations can pursue to be better able to cope with demand from future outbreaks or other large-scale acute events without unnecessary disruption to regular care processes. Since COVID-19 is the first large-scale global pandemic in modern times but very probably not the last, it is advisable to start preparations now in order to avoid negative impacts in the future.

Problems in short-term response

The expert panel found that three main issues contributed to problems in coping with COVID-19 demand and exacerbated the negative impacts of the pandemic.

A lack of scale-up or "surge" capacity meant that crucial facilities for dealing with patients – intensive care units and isolation rooms – quickly became overloaded. Alternative arrangements had to be made, pulling into temporary service regular inpatient wards or even non-patient care areas such as convention centres and concert halls. Since intensive care and isolation capacity are crucial to all complex acute care, responding to COVID-19 meant a very substantial reduction in capacity for regular hospital care. Such capacity for non-COVID-19 care as remained was underused: patients were very reluctant to come to hospital facilities, out of fear of contracting the virus there. Essential diagnoses were missed and crucial treatments postponed, resulting in avoidable adverse health effects.

Although yet unproven, airborne transmission is a suspected route by which Sars-Cov-2 spreads. As a precautionary measure it is advisable to provide care to infected or suspected infected patients in environments with controlled airflow and air treatment. However, most HVAC systems have not been designed to allow continuation of regular care while providing this type of care environment for large numbers of patients. For instance, in most hospitals HVAC systems do not employ zoning or segmentation with the appropriate air flow direction which would allow separation of COVID-19 and non-COVID-19 logistical streams. Climatization issues were also apparent: cooling capacity was often insufficient to prevent overheating in staff wearing airtight protective clothing.

Where conditions in hospitals were and are very challenging, the situation has proven substantially worse in long-term and elderly care facilities and rehabilitation centres. While many of these turned into infection hot spots and consequently needed to provide care to large numbers of very vulnerable patients, HVAC systems in these facilities are generally very limited and do little to protect residents and staff from airborne infection. Logistical lay-outs are generally very basic and do not allow for separation of care for infected and non-infected residents.

How can we do better?

It seems clear that improvements in technical and functional design are required if we are to deal with future pandemics without incurring the level of adverse social, economic and health-related impacts we have seen in the current crisis. On the basis of the evidence and practical experience that the expert panel has collected, several avenues for improvement have been identified. These centre on the functional lay-out of care facilities, on design and operation of installations, and on organisational measures.

In this paper, measures are discussed for hospitals. Most of them are also applicable to long-term care and rehabilitation facilities. Getting it right in these latter facilities is especially important, to combine protecting vulnerable people from infection with safeguarding quality of care and quality of life.

Lay out of health care facilities

Lay-out related options for improving outbreak preparedness while leaving normal operational capacity and efficiency relatively untouched, focus on: lay-outs for inpatients wards; design for physical distancing in indoor areas; logistics, specifically the presence and positioning of staff and visitor changing areas; and on segmentation and redundancy of critical facilities such as ICUs.

Inpatient wards

Inpatient wards in hospitals typically contain a mixture of single rooms, 2-person rooms and 4-person rooms, with variants such as 3-person rooms occasionally encountered. This type of lay-out is suboptimal in terms of conditions required for effective COVID-19 response, or indeed for responses to any major outbreak of communicable disease with airborne transmission. Multi-patient rooms increase the risk of patient-patient and patient-staff transmission, while not offering a working environment where scarce staff can be deployed with maximum efficiency. To reduce contamination risks, spatial concepts employing single rooms exclusively or predominantly are known to be effective. If fitted with appropriate ventilation systems, single rooms can be repurposed as emergency isolation rooms. Lay-outs where all single rooms are fitted with airlocks – which could be activated to provide full-scale isolation when needed –are possible, though such lay-outs would come with substantial consequences in terms of spatial requirements (and, accordingly, costs), and might not perform too well from the viewpoint of patient experience and patient-staff interaction requirements in normal circumstances.

The increased level of demand associated with pandemic conditions puts particular strain on available staff capacity. Open plan wards, traditionally known as "Nightingale wards", potentially allow more efficient deployment of nursing staff, through reducing transfer distances and transfer times between patients. Open plan wards are generally not considered acceptable under normal circumstances, for reasons including infection prevention, privacy and personal dignity. However, research findings collected during the present pandemic suggest that their collective space characteristics may actually help to mitigate traumatic psychological effects of hospitalization for COVID-19. Patients report experiencing feelings of isolation, neglect and anxiety when hospitalized for COVID-19 in single rooms. These adverse effects would logically be much less pronounced if patients receive care in a communal setting.

However, advanced the adaptability features included in the functional design of the care facility, transforming single room wards into open plan wards and back again would be unfeasible both in terms of technical complexity and cost. In existing hospitals, this would require major renovation; for new hospitals it would mean designing all interior walls as movable partitions or to incorporate in new to build hospitals having flexible walls. A sensible strategy could be to include buffer inpatient capacity in the form of open plan wards. This type of capacity is not deployed under normal conditions, but is pulled into service during scale-up. This way, in a pandemic, each patient could be cared for in an environment most suited to their individual needs.

Design for physical distancing in indoor areas

Where people are in intensive contact, defined as physical proximity during a short time (e.g. exceeding 10 minutes), personal protective equipment (PPE) is the preferred method to reduce the risk of infection. However, there are areas in healthcare facilities where this type of contact occurs, but where PPE measures cannot be assumed to be in place: waiting areas and public and commercial spaces such as main halls and food courts. In these areas physical distancing is a necessary precautionary measure to reduce the risk of infection through airborne transmission. Waiting areas in most hospitals are currently too cramped relative to patient turnover to allow the relevant departments to function at anything like full capacity. To counter this, functional briefs for hospitals should adopt both a higher overall ratio for waiting area space relative to total floor space, and increased baseline and production-related dimensions for individual waiting areas. Additionally, centralized waiting zones, and ICT-enabled "just in time" planning could reduce crowding in individual waiting areas. Also alternating physical consults and digital consults gives relief on the occupation of the waiting rooms.

Though there is no firm evidence base in the literature, in practice physical distancing requirements are often also imposed for areas that see a high volume of shorter interactions: entrances, circulation areas such as corridors, and vertical transport points. To allow physical distancing in these areas, more spacious dimensioning is required and/or control measures must be put in place to limit throughput.

Logistics

When providing patient care in a pandemic, strict adherence to PPE and other safety protocols is crucially important. To stimulate compliance and support staff and patient safety, hospital floor plans should include changing areas where staff can change clothing and put on PPE. These areas should be positioned in such a way as to allow separation of clean and contaminated logistical streams. For emotional and psychological well-being, it must be possible for patients and visitors to be in close physical contact for longer periods of time. Ideally, patients and visitors should be free to choose timing and duration of contacts. Effecting this without unacceptable compromises to safety, presupposes that visitors wear special-purpose clothing and use PPE. Accordingly, hospital floor plans should include changing areas and


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storage facilities for visitors. These spaces, too, must allow separation of clean and contaminated materials, with a proper separation between clean and contaminated, should be incorporated in the floor plan.

Segmentation and redundancy

During the severe early phases of the COVID-19 pandemic, regular patient care came to an almost complete standstill. Critical departments such as the intensive care wards and imaging diagnostics were entirely turned over to care for COVID-19 sufferers. Except at the peak of the pandemic, this was not primarily due to operational capacity as such. Rather, the fact that COVID-19 care took place in these departments meant that the whole department had to be considered a high-risk, potentially infected area and hence could no longer be considered safe areas for regular care. Even where such safety risks were not objectively present, subjective risk perception on the part of patients and staff meant they were reluctant to come in for treatment or for work in these departments.

Segmentation of critical departments into independent smaller units can reduce this problem. It opens up the possibility of dedicating part of the capacity to handling COVID-care (or care related to other outbreaks), while keeping the rest available for regular care. This presupposes that these smaller units are functionally and technically independent of each other and have distinct access and egress routes for patients, staff and goods.

Installations

Installations-based options for outbreak preparedness cover ventilation, air locks, and redundancy and over-dimensioning of fixed and mounted technical equipment.

Ventilation

Current technical hospital designs favour centralized air handling systems. Diversification of systems at building block, floor or even room level is perfectly feasible technically, and would offer much greater flexibility in tailoring ventilation levels to changing needs for smaller areas or individual rooms. This could even take the form of room-specific ventilation systems taking in air from outside directly through the façade. Such systems could also reduce the risk of interference between ventilation systems operating in different zones. Additionally, recirculation of air must be considered a risk factor for transmission of airborne viruses in centralized air systems, but is not an issue at room level, provided sufficient outdoor air is added to the mixture to reduce the concentration of harmful viruses.

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Care delivery in outbreak situations creates peak demands for ventilation and cooling capacity. Designing and dimensioning installations so they provide this peak level on a structural basis would create an increased level of energy demand and run contrary to the directive to move towards more sustainable HVAC systems, where reducing demand is one of the pillars supporting the transition, along with improving efficiency of systems performing and a switch towards renewable energy sources. Control systems that only produce peak level airflows and cooling when these are specifically needed are available on the market and could contribute to tackling this issue. Another option worth considering is maximising the potential for natural ventilation, by the simple expedient of making sure that windows can be opened. Care is needed though to avoid introduction of unwanted airflows from outside.

Air locks

Depending on the transmission route of the outbreak, department-level aerogenic air locks may be a useful means to prevent the spread of contaminants from one area to another. Aerogenic air locks aim to prevent airborne spread as much as possible and separate the contaminated area from the rest of the hospital. When properly designed and positioned, changing rooms for staff and visitors, and logistic locks can double as aerogenic air locks and can also be applied on department or building block level. To prevent spreading of contaminated air through apertures between rooms above false ceilings, realizing all interior walls as airtight floor-to-structural ceiling partitions could be considered. This is most likely only feasible in new built care facilities and would only be proportionate in areas to be assigned as containment areas.

Redundancy and over-dimensioning

It is sensible to equip all patient rooms with a level of fixed and mounted technical supplies that allows scaling-up of these rooms for more complex treatment. This includes oxygen and other medical gases, wall sockets, water, drainage and disposal facilities (especially for medical and hazardous waste), as well as data hook-up points for ventilator equipment, monitoring, and CVVH dialysis.

Organisational measures

Opportunities to improve organisational preparedness focus on use of online and remote care; rostering of staff to support segmentation of critical departments; adequate supplies of protective equipment and protocol adherence; and regional scale-up and care distribution contingency planning.


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Online and remote care

An unforeseen, but largely positive outcome of the current crisis has been the acceleration in adoption and upscaling of online consultation and diagnostics, as well as remote support of care givers in primary care and long-term care. Technically, this has been possible for some time, but implementation has lagged, due in large part to issues around acceptance and trust. As traditional alternatives became unavailable in the crisis, care providers and patients were forced to switch to online alternatives, and found the transition surprisingly unproblematic. Structural implementation of the change would bring obvious advantages in "normal" times: it would obviate the need for patients to travel to and from hospitals for routine appointments, reduce spatial requirements for outpatient care, and allow medical professionals to use their sparse time more efficiently. Increased familiarity with and use of online modes would also allow a smoother shift towards the sort of online-first paradigm that is required to keep regular outpatient care going under pandemic conditions. Even where patients still come to the hospital for appointments, it makes sense to handle part of their patient journey online. For instance, checking in digitally, with a digital card, e-ticket or any other smartphone-based method would avoid possible contamination through touch screens and would reduce waiting lines and crowding. Special opening hours for persons vulnerable to the virus could also be an option.

Rostering of staff to support segmentation of crucial departments

Above, we have argued for hospital designs that allow segmentation of crucial departments such as intensive care and radiology into independently functioning smaller units. To have an effect in practice, this physical segmentation must be supported by rostering of staff. Dedicated teams working only in one of the units must be established and maintained. Crucially, this also includes support and logistics staff to avoid cross-contamination through e.g. goods delivery and cleaning activity. Additionally, each unit should have its own distinct routing for supplies and waste. In summary, each unit should be physically, logistically and organisationally self-contained.

Adequate supplies of protective equipment and protocol adherence

Capacity problems during the current pandemic have been compounded by the frequent unavailability of sufficient supplies of protective equipment. As a result, staff members became infected and operational capacity of healthcare providers was reduced. Infections among staff also occurred because no adequate protocols for self-protection were in place (at least in the early phases of the pandemic). Even where these were available, unfamiliarity in combination with peak levels of pressure meant they often were not adhered to. Lessons learned during the current pandemic should be used by healthcare organisations to ensure a higher level of organisational preparedness for future outbreaks.

Task differentiation at regional level

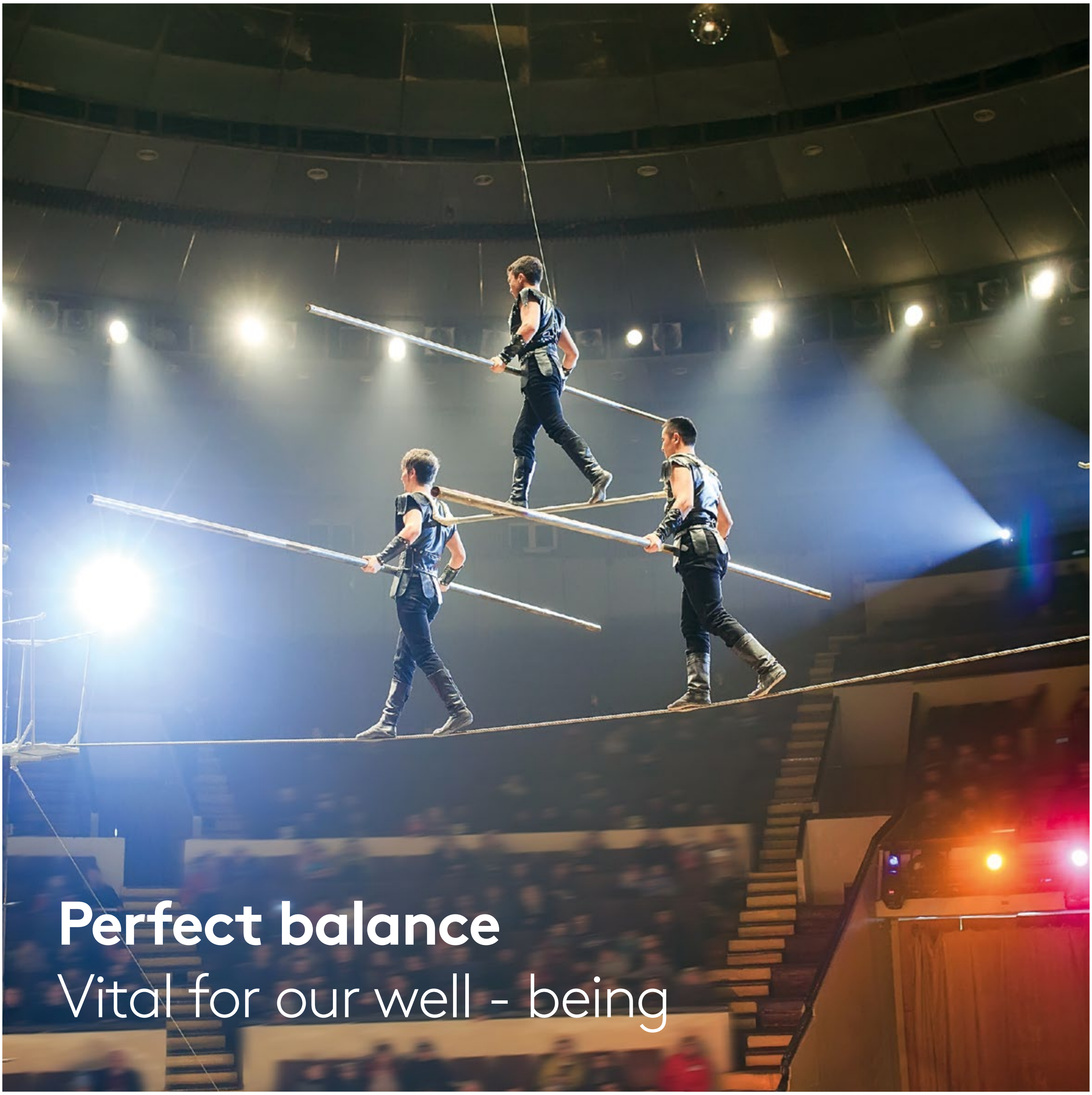
Although design, technical and organisational measures can be taken to better allow continuation of regular care under pandemic conditions, providing the two types of care on a single hospital site remains inherently challenging and is likely to affect quality and efficiency of care. Better results might be obtained if regional contingency and distribution plans could be drawn. In these regional configurations, during large-scale outbreaks some hospitals would switch entirely to care for infected patients, while other sites in the region would be dedicated to keeping regular care going. This presupposes triage and allocation of patients through a pooled regional system.

The complexity of implementation regional contingency plans must not be underestimated. For instance, they also involve temporary allocation of staff to other hospitals and/or hospital sites. Also, sites not slated to deal with infected patients cannot allow themselves to drop their guard. It has been shown that COVID-19 patients can be infectious while still asymptomatic or presymptomatic. Systematic testing of patients, visitors and staff will be essential. Even then, centres dealing with regular care must be prepared for occasional occurrence of infections and must have emergency protocols in place to respond.

Regional distribution works best if hospital sites in the region are of similar scale and versatile enough to adapt to provision of different types of care.

Conclusions and call to action

It is obvious that functional, technical and organisational options are available to minimise adverse social, economic and secondary health impacts during future outbreaks. But all of these need advance planning. We cannot wait until the next epidemic is upon us. We must act now to plan, design and develop healthcare facilities that are resilient to future adversity. This calls for concerted and coordinated action by public authorities, healthcare providers and contractors, as well as architects, engineers and builders.■



Perfect balance

Vital for our well - being

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GOLD

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Rotary heat exchangers

save energy and prevent a need for recirculation which contributes to the decrease the risk of COVID-19 transfer

WILLIAM LAWRANCE
Product Manager for Air Handling Units at Swegon;
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TIMO SCHRECK
System Business Development Director at Swegon

The benefits of good ventilation and indoor air quality for comfort, health and productivity in both places of work and homes is undisputed.

According to WHO "poorly ventilated buildings affect air quality and can contribute to the spread of disease".

Other studies show that increasing the outdoor ventilation rate and minimising recirculation has a significant effect on reducing the spread of disease. By increasing the flow of well treated outdoor air we can dilute pollution in the room air. The room air distribution system needs to be effective in ensuring a proper ventilation of the whole space which also means effectively removing contaminants. This is influenced by the design of the room air devices and their positioning in the room. It is important to avoid short circuiting from supply air diffusers to extract valves.

It is also recommended that rooms can be additionally ventilated by opening windows but this, of course, depends on the weather, level of pollution and level of noise outside. Full fresh air ventilation systems with energy recovery provide a more reliable and comfortable solution.

Recirculation of air is to be avoided and this means we need to also avoid leakage of the extract air to the supply air in the ventilation unit.

The mechanism of transfer of the COVID-19 in air is still not clear although testing is being carried out now. It is then, possible that the virus can travel on aerosols with the ventilation air through the duct systems but to date, there is no evidence that virus can be transferred through a full fresh air ventilation system. A portion of that aerosol leaving the room will likely be caught by the surfaces of the ducts and duct components. Furthermore, ePM-filters will also catch a portion of the aerosol so by the time the extract air enters the ventilation unit the virus load will have been diluted.

Leakage of air in ventilation systems is, of course, wasteful but it can also affect the indoor air quality so we need to minimise leakage to both optimise the energy consumption and ensure the best possible air quality.

We differentiate between internal and external leakage. External leakage is the leakage through the unit casing between the inside and outside of the unit while internal leakage occurs between the dividing walls of the internal sections.

All types of air handling unit have a potential leakage of air past the filters which will have a negative impact on the air quality as well as dirty ducting with increased cleaning costs as a result.

Filter bypass leakage is classified according to the filter grade with the intention that the design of the filter frame and sealing is appropriate for the filtration required. Testing should be carried out in accordance with EN 1886. Eurovent certified air handling units are independently tested by third party laboratories and the results are published on the Eurovent home page.

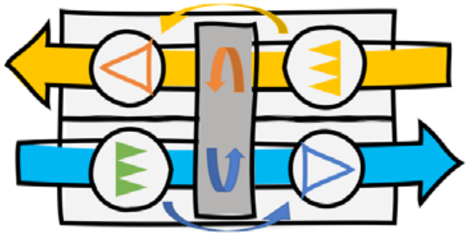
Heat exchangers for energy recovery are also potential sources for leakage. Plate heat exchangers should have small levels of leakage in themselves but a poor installation in the air handling unit can give rise to considerable leakage with energy losses and degraded air quality as a result. Well installed plate heat exchangers will have very low leakage but depending on the position of the fans and the construction of the unit there is a potential for leakage of extract air to supply air.

Rotary heat exchangers offer the advantage of a high efficiency with small space requirement and very little need for defrosting. But because they rotate, they are more difficult to seal effectively.

With rotary heat exchangers there are essentially four modes of leakage

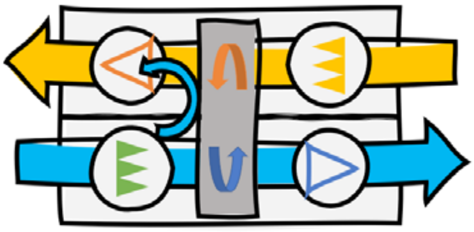
1. Peripheral leakage

Leakage around the periphery of the rotor will have a direct effect on the overall heating power of the rotor. The reduction in temperature efficiency can be quite significant and Leakage past the periphery seals will also contribute significantly to the leakage between airflows so it is important that the periphery seal is effective.

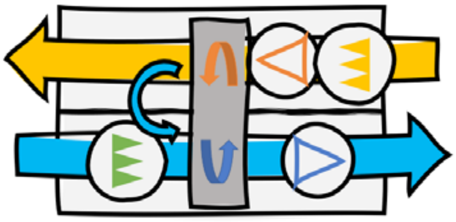


2. Leakage from the outdoor air side to the exhaust air side

Normally there will be a large pressure difference between the outdoor air side of the rotor and the exhaust side. This pressure drop drives a leakage from the supply to exhaust air side. Leakage in that direction will not affect the air quality but it will have an effect on the energy consumption. When we have the correct airflow at the supply air fan, we will have a higher airflow the fresh air filter and that means we will have a higher pressure drop there. We must also compensate on the exhaust side to ensure that we get the correct extract airflow. This is quite a complex calculation to make requiring an iteration to arrive at the correct result but without it, the power consumption of the fans will not be correct and that means any annual energy calculation will also be wrong.



If the extract fan is placed on the extract side of the rotor then the leakage will be in the other direction:

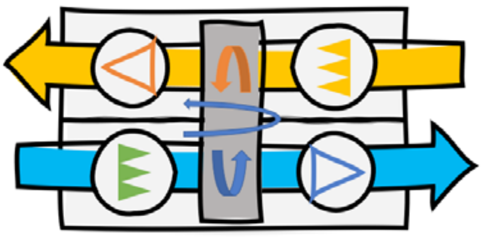


This will have a serious effect on the air quality and is not recommended at all.

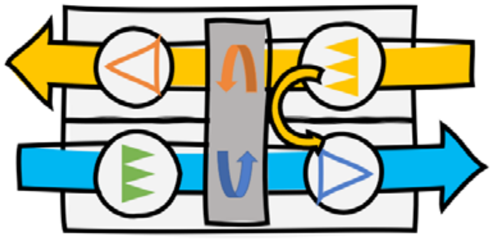
To be able to minimise the leakage of air between the airflows, the recommended arrangement of the fans is upstream of the rotor on both sides.

3. *Carry over leakage*

Rotary heat exchangers can carry extract air over to the supply air. This carry over leakage can be effectively eliminated by means of a purging sector. A small sector of the rotor is shielded off so that extract air cannot enter the rotor there and outdoor air is bled through the rotor in both directions to purge it of extract air. This purging function cleans the rotor of impurities and ensures a high quality of supply air. To drive this purging flow, we need a pressure difference; which must be created by the extract fan. The purging flow must also be added to the flow rate of the extract fan.



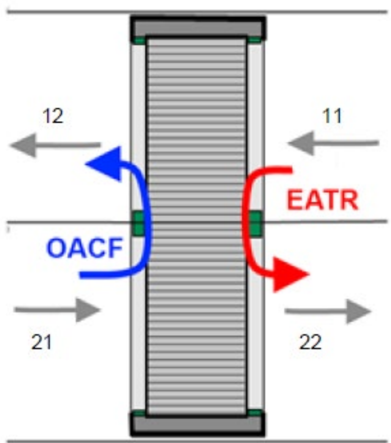
4. *Leakage from extract to supply on the room side of the rotor*



This leakage will depend on the pressure difference between the extract and the supply and if the fans are correctly positioned as shown, can be eliminated by throttling the extract air so that the pressure difference is in the right direction. This extra pressure drop must be included in the exhaust fan.

The leakages described in modes two to four above are defined in EN 16798-3:2018 [1] by two ratios: OACF and EATR.

Outdoor Air Correction Factor (OACF) and Exhaust Air Transfer Ratio (EATR)



OACF is the ratio of the outdoor air inlet and the supply air outlet flow:

From an air quality point of view, the OACF should be greater than 1 because that means the leakage is from supply to exhaust. If it is less than 1 then there is leakage from exhaust to supply and we want to avoid that.

EATR is the percentage of exhaust air recirculating to the supply air:

EATR is the leakage by the seal at the rotor on the room together with the carry-over leakage.

We need to consider these two leakage measures together. Both of them need to be kept within limits.

These definitions will also be found in the next version of EN 308 (heat exchangers - test procedures) but these standards do not give any limits. A new document to be published by Eurovent titled Eurovent REC 6/15-2020 effectively limits EATR to 1% and OACF to a range between 0.9 and 1.1

A proposal has been made for the inclusion of these leakages in the calculation of SFPint to the review study on the Ecodesign and Energy Regulations on ventilation units.

- **Note** that these definitions also apply to units with plate heat exchangers.
- **Note** also that it is not just the heat exchanger component that leak but take a holistic approach for the ventilation system.

Unfortunately, these internal leakages are today not part of Eurovent Certification programs so building ventilation designers need to understand them and request them of the ventilation unit manufacturers at design stage. In many cases, achieving an acceptable EATR requires that the extract air is throttled to achieve the correct pressure balance inside the unit. The pressure in the extract air upstream of the heat exchanger needs to be lower than that of the supply air downstream of the rotor.

Remember that to be able to calculate the EATR and OACF the manufacturer needs to know the actual pressure inside the unit and that means they need the pressure drop in all four of the ducts connected to the unit so it is important that information is provided.

What more can be done?

High efficiency filters placed after the supply air fans can provide additional security but they will also add cost to both the installation and operation so their use needs to be carefully evaluated in relation to use of the building.

Recommendations for the operation of existing ventilation systems during the COVID-19 epidemic are available (see https://www.rehva.eu/activities/covid-19-guidance/rehva-covid-19-guidance) and now we should consider how to build in the future. Well designed, installed, and maintained full fresh air ventilation systems with energy recovery provide a healthy and comfortable indoor air climate that will provide a reasonable level of protection and promote productivity. They can also be very energy efficient. ■

Reference

[1] EN 16798-3:2018 (Energy performance of buildings - Ventilation for buildings - Part 3: For non-residential buildings - Performance requirements for ventilation and room-conditioning systems

State of knowledge in Sweden during the Corona pandemic

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During the ongoing Corona pandemic, a survey of Swedish authorities, industry associations, and consultancy and real estate companies summarize the need to increase competence on HVAC and indoor environment. The knowledge improvement span the entire area: from the choice of technical components to the design, operation and maintenance. A topic emphasized is the requirement of an interdisciplinary perspective related to establishing knowledge.

Keywords: Ventilation; Indoor environment; HVAC; Interview survey; Corona pandemic, COVID-19; Interdisciplinary; Guidelines; Design; Maintenance

Background

At the beginning of the year 2020, the Corona Pandemic swept over the world like a Tsunami. Among other things, the use of the built environment and the operation have changed in many ways. There is a common understanding of the linkage between workplace use, in terms of, e.g. occupancy density, and spread of the virus. As an example, for buildings with constant airflow (CAV), reduced occupancy (because of the pandemic), could imply that the supplied airflow per person can be higher than the designed rate, or vice versa. When the supplied ventilation change, energy use in the built environment are affected.

The success to reduce the infection rate in the built environment can depend on the knowledge of the maintenance staff. Since the pandemic situation is new, the staff has to act outside customary conditions. The knowledge (or lack of knowledge) may affect the operational decisions made and not made during the now ongoing corona-pandemic. In order to prepare for future similar pandemics, it is useful to understand how these organizations have responded or not to Corona pandemic. Have they acted on knowledge, to which extent, and using what knowledge?

About the survey

The study included two parallel activates: a literature study to collect information about the Corona pandemic and its consequences regarding buildings' operation, especially for hospitals and care facilities, and interviews with experts and practicing professionals in the indoor environment and HVAC, in Sweden. Additionally, a reference group supported the processes of identification of interviews.

The study included twenty-one interviews, carried out during May-June 2020. The interviewees were personnel from public authorities, associations, consultants, suppliers, and real estate companies, see **Table 1**. The opinions expressed by the interviewees, should not be construed as the formal opinions of their organizations, but rather as individual opinion based on their experience.

Table 1. *List of organizations and number of interviewees.*

Swedish Authorities	*6*	
Industry Associations	*3*	
Consultancy Companies	*Design and Construction: 2*	*Distributors: 2*
Real Estate Companies	*Private Enterprises: 5*	*Public Enterprises: 3*

The precautionary principle

When it comes to reducing the spread of COVID-19 in indoor air, it is necessary to consider the evidence of airborne transmitted SARS-CoV-2 infection of humans. Currently, there is no conclusive evidence of human infection of SARS-CoV-2 by infectious aerosols through the ventilation systems in the built environment. Nevertheless, there is also a lack of evidence of that humans cannot be infected that way. As per the precautionary principle, due to the lack of such evidence the worst-case scenario, wherein humans could be affected with SARS-CoV-2 via indoor ventilation, cannot be rejected either.

The hierarchy for controlling the spread of infection

There are various measures to reduce the risk of airborne transmission of COVID-19 in buildings. The European organization REHVA has introduced an infection control pyramid [REHVA, 2020] that hierarchically places measures to reduce airborne risk in four levels, developed from a theory proposed by the US Centers for Disease Control, see **Figure 1**.

The most effective approach to reduce the risk of airborne infections is to remove the pathogen physically. The second most effective approach is to apply technical control, which in this context may involve technical ventilation measures. Then follows administrative measures, such as instructions and guidance. The relatively least effective measure, in REHVA's hierarchical infection control pyramid, is to provide personal protective equipment, such as facemasks and gloves.

Guidelines and Regulations

Several international organizations have revised their guidelines to deal with risks for airborne infection. In Sweden, there has been no revision of the building regulation. The interviewees of the authorities and one company expressed the opinion that it is too early to assess whether there is a need to revise the regulations. However, some interviewees argue for revisions. As per the interviewees, some specific future revisions of Swedish regulations could include increase possibilities for system flexibility, improved ventilation operation and control in hospital buildings, and increased possibilities for zoning of buildings.

According to the study, interviewees from the industry organizations expressed trust in the revision of REHVA's guidelines to reduce the risks for airborne

Figure 1. Hierarchical infection control pyramid, adopted from REHVA (2020), with four levels, for reducing the relative risk of airborne infection, where the top level is most effective and the bottom least effective.

infection. However, in this study, we have not valued the impact of revised guidelines. It can be a subject for future studies.

Real Estate Management

According to the interviews, the tenants express relatively little concern about virus infection from ventilation in their apartments. However, they expressed concern about the visits in the apartment from maintenance staff for HVAC-inspection and service, such as filter changes. During the pandemic conditions, the tenants have the option to deny entry for mandatory inspection and service. It may be worth investigating whether and how the lack of inspection and/replacement of filters harms the indoor environment.

As per the interviews, there are no cases when maintenance staff have adjusted airflows due to COVID-19. However, some systems automatically adjust the airflow (VAV-systems) based on demand, e.g. occupants in the room. The use of VAV-control and human infection during such pandemic may be worth to investigate further.

In hospitals and care facilities, there are cases wherein implemented measures where airflows and pressure were adjusted to reduce the possible spread of COVID-19. These measures were in accordance to already established guidelines from the period before COVID-19. Future studies could include the applicability of these guidelines.

Technical systems in the buildings

There are examples from the literature review of UV-radiation used in healthcare, with evidence of inactivating certain viruses and bacteria. However, there is currently no evidence of how effectively UV-radiation can eliminate SARS-CoV-19.

As per the interviewed experts working on filters, effective filtering of viruses requires HEPA filters. When used in air cleaners, it enables efficient purification. However, for good efficiency, high airflows are required, and conversion of the entire air volume in the room.

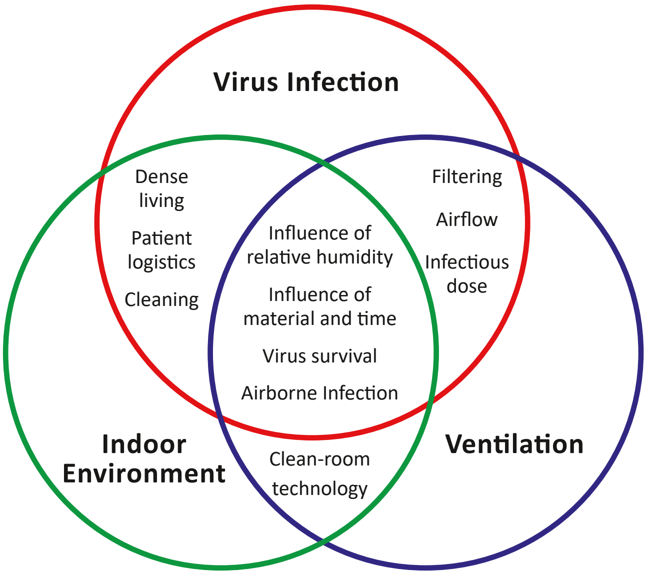

Figure 2. Illustration of interdisciplinary approach on addressing the spread of infection in the indoor environment as emerged from the interviews.

Knowledge gap

The survey results suggest needs to increase knowledge in the field of ventilation and indoor environment, including improving the general competence and expert competence on the topic. The knowledge improvement span the entire area of ventilation technology, such as design, operation, and maintenance.

Many interviewees emphasized the interdisciplinary of the issue. This perspective is essential to take into account when formulating strategies for strengthening knowledge. For the future, the study suggests the industry and the authorities to consider joint efforts to coordinate interdisciplinary expertise and finding budget. Several areas of knowledge gap emerged from the interviews. The study calls for continued interdisciplinary research and development work within the ventilation, indoor environment and virus infection. **Figure 2** provides an illustration of the identified knowledge gaps and disciplinary intersections.

Suggestions for future efforts

During the interviews, a few proposals on measures to reduce the risk of indoor airborne infection in the future emerged, for example:

- Establish a national expert service to support building maintenance professional to help their decisions to reduce risks for airborne virus infections in the indoor environment
- Develop appropriate information materials for the public to act in a manner to reduce risks for virus infections
- Facilitate broader interdisciplinary expert competence for developing future HVAC guidelines and regulations
- Initiate interdisciplinary educational efforts on basic and expert competence levels
- Coordinate expert competence for future training initiatives on ventilation, indoor environment and risks of indoor airborne infection for professionals
- Funding programs for interdisciplinary research and development on ventilation, indoor environment and airborne virus infection ■

Acknowledgement

The authors acknowledge the Swedish Energy Agency for funding the study.

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REHVA 3E

Safe operation of buildings and HVAC systems during the COVID-19 pandemic

ABOUT THE COURSE

This 6-hours online course covers key topics on how to resume activities, safely operate buildings and use densely occupied indoor spaces during and after the COVID-19 pandemic.

The course is based on the REHVA COVID-19 guidance documents, the modules providing basic theoretical knowledge with hands-on information thought by REHVA experts.

Participants get access to the latest REHVA guidebooks on air filtration and the hygiene requirements of ventilation systems.

Participants who successfully complete the online exams obtain a certification.

THIS COURSE IS SUITABLE FOR

- Facilities and Building Managers
- Occupational health and safety specialists
- Building Service Contractors
- Mechanical & HVAC Engineers
- Ventilation and air conditioning system inspectors
- Public authorities' technical representatives (regulators)
- Other building professionals involved in the management of indoor environment quality, building operation and system maintenance

SUCCESS STORY HOCHZIRL - NATTERS REGIONAL HOSPITAL (AT)

Energy efficiency in hospitals.

Targeted energy data monitoring shows where and in what quantity the energy is going.

Tirol Kliniken GmbH is the largest and most versatile health company in western Austria. The company operates seven locations with more than seventy buildings of various ages and technical structures. The Klimabündnis Österreich partner company is determined to contribute to achieving the international climate goals in the best possible manner, thereby ensuring the quality of life of present and future generations.

In order to keep energy consumption and the resulting costs under control and to be able to initiate any necessary measures in good time, Tirol Kliniken GmbH places great importance on targeted energy-data monitoring and continuous meter reading. Knowing where and in what quantity the energy is going is essential for energy-efficient operation.

TYPE OF BUILDING
Hospital

PROJECT
Renovation

FACILITIES
Heating

PRODUCTS
Belimo Energy Valve™

BELIMO®

Energy management with changing building technology.

At Hochzirl - Natters Regional Hospital, located in Natters, a 35-year-old gas boiler was replaced with newly dimensioned condensing technology. The aim here was to improve plant efficiency to over 88%. Alternative energy sources for this location can only be made available to a limited extent.

Potential for optimisation.

Modern condensing boilers require a low heating water return temperature for maximum efficiency. As hydronic systems have developed over the decades, continuous hydronic balancing now offers great potential for optimisation. In such complex system structures, the "low delta T" syndrome (i.e. insufficient temperature spread between the supply and return) usually occurs, which impairs the performance of the entire system and leads to additional energy demand on the pumps and the generator.

For this reason, a decision was made to carry out the renovation in several steps. First, pumps, hydronic circuits and regulating devices were replaced, followed by state-of-the-art hydronic balancing as a second step. The boiler was replaced after optimisation of the heating water circulation rate and the delta T adaptation between the supply and return.

Transparency with the Belimo Energy Valve™.

For this application in the heating network, only the multifunctional Belimo Energy Valves™ are used. The Belimo Energy Valve™ is an all-in-one product consisting of a modern control valve and a web server with internal memory. Thanks to various monitoring functions, data from a period of up to 13 months can be recorded.

Heating distributor in the heating station.

'Modulating hydronic balancing ensures greater efficiency in heating systems and increased user satisfaction. As a public enterprise, we want to support the state climate strategy "Tirol 2050" and the federal government's "Mission 2030" with concrete measures and set an example for the country'.

Ing. Mag. (FH) Martin Lackner, Energy Controller, Tirol Kliniken GmbH

The pre-installed software in the Belimo Energy Valve™ makes energy optimisation quick and easy. By determining the maximum value of the valve position, the associated booster pump can be optimally operated at any time under any load condition. Recording actual data allows for optimum adjustment of water quantities and/or power capacities after only one heating period. This means that the greatest savings potential can be expected for thermal energy.

Know where the energy is going.

Tirol Kliniken GmbH use continuous data monitoring at all locations supported by energy management. At the Natters location, significant improvements have already been achieved in the low delta T range. After a running time of only about 10 months, an improvement in the temperature spread of the entire system from 10°C to over 20°C has been recorded. The aim is to achieve a delta T of at least 25°C in winter (maximum 35°C) and not below 20°C in summer, depending on the water heating systems.

Savings in heating energy.

Based on the data collected to date, there have been noticeable savings of around 330,000 kWh compared with the previous year – from the heating distributor conversions alone. This represents a 16% saving in heating energy, without considering the additional benefit of the new condensing boiler. Since data was only recorded by the Belimo Energy Valve™ during the first heating period, the maximum water quantities were able to be adjusted after the heating phase based on actual user behaviour at the Belimo Energy Valve™. Further savings without loss of comfort are expected over the next heating period.

The Belimo Energy Valve™ was deliberately chosen for this project because continuous data recording in accordance with ISO50001 and evaluation in accordance with ISO50006 are sought after. Moreover, the expected synergy effects from combining the meter and control valve were a decisive reason for the cooperation with Belimo. This expectation was fully confirmed in operation.

Evaluation of the recorded data to optimise delta T and the V_{max} value in the roof ventilation centre.

THE MULTIFUNCTIONAL BELIMO ENERGY VALVE™

enables pressure-independent flow control as well as transparent monitoring of the heating or cooling system, ensuring that it is not operated with too low a temperature spread (delta T). By measuring, calculating and visualising important system data and with the performance reports provided by Belimo, energy-efficient system operation is guaranteed for the entire service life. The Belimo Energy Valve™ can be connected to the Belimo Cloud, providing easy access to data and reports – anytime, anywhere.

Product news

All inclusive.

As a global market leader, Belimo develops innovative solutions for the regulation and control of heating, ventilation and air-conditioning systems.

In doing so, actuators, valves, and sensors make up the core business. With a consistent focus on customer value, we deliver more than just products. We offer you the complete product range of actuator and sensor solutions for the regulation and control of HVAC systems from a single source. At the same time, we rely on tested Swiss quality with a 5-year guarantee. Our worldwide representatives in over 80 countries guarantee short delivery times and extensive support through the entire product life. Belimo does indeed include everything.

"Small" Belimo products have a major impact on comfort, energy efficiency, safety, installation, and maintenance. In short: small devices, big impact.

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- On site around the globe
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Combating COVID-19 with vaporized hydrogen peroxide bio-decontamination

JANICE BENNETT-LIVINGSTON
Marketing Manager, Vaisala Oyj

In January of 2020, the International Health Regulations Emergency Committee of the World Health Organization announced the outbreak of coronavirus disease 2019 (COVID-19). Clinical presentations of active cases of COVID-19 range from no symptoms to life threatening illness. The scientific and medical communities are learning more every day, but currently it is believed that COVID-19 is transmitted through sneezing and coughing or through contact with contaminated surfaces.

According to the US CDC, decontaminating for COVID-19 through standard procedures is appropriate. The World Health Organization's interim guidance on laboratory biosafety, disinfection procedures for COVID-19 recommends: "Appropriate disinfectants with proven activity against enveloped viruses … (e.g. hypochlorite (bleach), alcohol, hydrogen peroxide, quaternary ammonium compounds and phenolic compounds)."

Recent bio-decontamination work performed by Cleamix Oy at Korea's Centers for Disease Control has validated this approach, and the company performed hydrogen peroxide vapor bio-decontaminations in early 2020 during the coronavirus outbreak.

The Cleamix bio-decontamination units are portable, highly efficient hydrogen peroxide vapor generators. The generators use Vaisala's HPP270 series probes to automatically control vapor output during bio-decontamination. The probes also provide stable, accurate monitoring data that allows operators to observe process conditions in real-time.

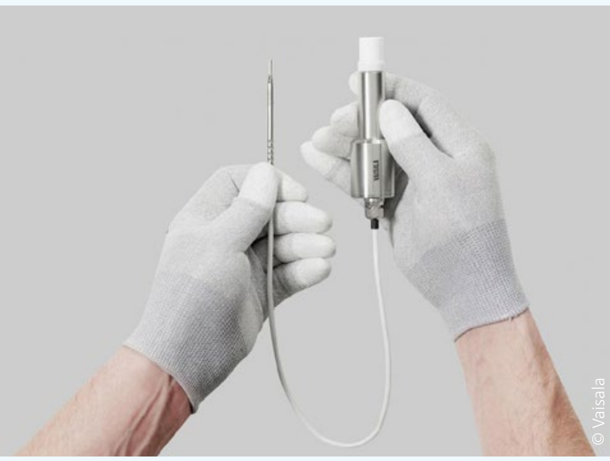
Bio-decontamination of Biosafety Labs

We recently spoke with Cleamix CEO **Panu Wilska** about the company's work with Korea's Centers for Disease Control (KCDC) in the wake of the corona-virus outbreak.

"The KCDC has Biosafety level 2 and 3 laboratories with a total volume 2,500 m^3," says Wilska. "Our bio-decontamination contract with our local partner BioAll included both laboratories. The labs were about equal in size, with multiple separate rooms, airlocks and corridors. To decontaminate the spaces, we used four portable networked Cleamix vapor generators."

Biosafety laboratories are used to study contagious materials safely; with protective measures for personnel and to prevent contamination. Biosafety labs are designed and operated in compliance with laws, policies, regulations, and guidelines for research into infectious agents. This research is needed to understand pathogens in order to produce vaccines and other treatments.

There are four levels of biosafety that define the type of research that can be performed and the safety measures that must be employed. These levels are based on the practices, processes and systems that provide protection from the pathogens being researched. From BSL-1 to BSL- 4, the protective barriers and processes increase. Biosafety level 1 covers work with microorganisms that present a minimal threat. Biosafety level 2 laboratories research agents with a moderate risk. Extra cautions and protections are used, with added constraints on access and processes. BSL-2 labs use biosafety cabinets and other containment systems.



Biosafety level 3 laboratories handle potentially lethal pathogens, are strictly controlled, must be registered with governing agencies, and have strict bio-decontamination procedures. BSL-3 labs require specialized facility design features, including airflow/ventilation controls, automatic and locking double doors. Biosafety level 4 laboratories encompass research on extremely high-risk pathogens or any agent with an uncertain level of pathogenicity. These labs employ the strictest safeguards, constraints, regulations, facility design and equipment requirements.

Inline H_2O_2 Concentration Measurement: Effective, Efficient

"During the bio-decontamination process, the HPP270 probes showed that the H_2O_2 concentration was rising quite rapidly," says Wilska. "The average treatment time per segmented area was seventy-five minutes, plus aeration time. Aeration was very fast as we could have the air conditioning system turned on after each treatment. The process was validated by biological indicators to have achieved a 6-log kill."

In bio-decontamination, a 6-log kill refers to the relative number of live microbes destroyed during disinfection. A 1-log kill has destroyed the total number of microbes by a factor of 10; a 6-log kill has destroyed the number of microbes by a factor of 1,000,000. A 6-log reduction is a common goal of bio-decontamination, whereas the goal of sterilization is to kill all microorganisms, viruses, and spores. Bio-decontamination is used due to its relative safety for operators, equipment and materials.

In summarizing Cleamix's work at the KCDC, Wilska says: "Our bio-decontamination took two working days; however, now that we know the layout and decontamination performance of these areas, the same work could be completed in one day. According to KCDC, the earlier procedure with a different vendor took four days to complete. After seven days of incubation, the results of our bio-decontamination were confirmed without any doubt – the process was 100% successful." ■

Daikin Europe on EU Green Deal: "Heat pumps are the answer to achieve climate targets"

Brussels, 24 September 2020 – Daikin, a global HVAC leader, today expresses its support for Europe's Green Deal. According to Daikin Europe, the decarbonization of Europe's heating sector will be key to making the continent a climate-neutral economy by 2050. The company also believes continuous innovations in heat pump technology will help to decarbonize Europe and to combine decarbonization with sustainable economic growth, the core principles of the Green Deal.

Europe wants to become the world's first climate-neutral continent by 2050, and the EU Commission aims to reduce emissions by at least 55% by 2030. At Daikin, we support this aim, striving to become a climate-neutral company globally by 2050.

Decarbonizing Europe and recovering from the COVID-19 pandemic are massive challenges. When presenting the Green Deal, the European Commission's President even called it Europe's "man-on-the-moon moment". In implementing the Green Deal, we look forward to seeing the EU and its Member States promoting low carbon technologies, like heat pumps.

Summary:

1. Europe wants to become the world's first climate-neutral continent by 2050. Heat pumps are a key part of making Europe climate-neutral by 2050.
2. Following the EU Green Deal initiative, policy makers in the EU Member States can act on two levels to achieve decarbonization: The most polluting heating systems must be phased out and renewable technologies need a level playing field.
3. Every euro invested in heat pump technology is a euro invested in local job creation.

Why heat pumps?

Today, the European building stock is responsible for approximately 36 % of all CO_2 emissions in the EU. Taking into account that almost 50 % of European Union's final energy consumption is used for heating and cooling, of which 80% is used in buildings, the potential for decarbonizing this sector is massive.

1. Heat pumps are a proven solution, and Europe has the technology, the expertise and the investments to expand further. From single family to multi-family homes, from renovation to new housing, from small to large commercial buildings and industrial plants, heat pumps today are ready and fit for the EU Green Deal.
2. Heat pumps are a low carbon heating technology. For each kWh of required heat, the carbon impact of a heat pump today is about half of a high efficiency gas boiler, with an even lower carbon footprint potential due to the further decarbonization of the EU electricity production.
3. Heat pumps make use of renewable energies such as thermal energy from the air, the water or the ground. These renewable energy sources are abundantly available in Europe; so do not need to be imported.
4. Heat pumps will increasingly use renewable electricity and are on the way to being a fully climate-neutral solution.
5. In addition, heat pumps are essential to enable balancing of the power grid, thus supporting the further deployment of a renewable energy production.

Investing in heat pumps also boosts EU economic growth as these products are widely developed and manufactured in Europe. Daikin, for example, has a European R&D center and 5 factories in Europe related to heat pump technology.

Every euro invested in heat pump technology is a euro invested in local job creation. The heat pump industry as a whole currently employs 225,000 people in Europe. New and further investments in renewable heating will pay dividends for the European economy as well as for our environment.

End carbon-based incentives

Following the EU Green Deal initiative, policy makers in the EU Member States can act on two levels to achieve decarbonization.

First, EU Member States could commit to ending the use of fossil fuels. The most polluting heating systems must be phased out. Austria no longer allows oil-based boilers to be installed in new homes as of January 2020. This is an excellent initiative. Policy makers could avoid incentives for fossil fuels. Even today, direct or indirect incentives benefit oil or gas-based boilers, due to different taxation of heat pumps compared with boilers for instance.

Secondly, renewable technologies also need a level playing field. The gap between electricity and gas prices in many Member States is too high to make a heat pump an economically attractive investment for EU citizens. Incentives can bridge that gap for a certain period, but in the long run, the cost of energy should reflect the carbon intensity more. Carbon pricing can contribute to further emissions reduction by extending the EU Emission Trading System (ETS) to all emissions of fossil fuel combustion in buildings and revising the Energy Taxation directive.

Motivating European consumers

The industry innovates relentlessly to make heat pumps attractive through a mix of product features, pricing, design, and installer- and end user friendliness. The industry can put more effort in explaining the benefits of heat pumps so that end users become more aware of them.

Patrick Crombez (General Manager Daikin Europe Heating and Renewables) states: "Governments can draw consumers' attention to heat pumps through

incentives for residential renovations, but also other means could make opting for heat pumps beneficial, such as reflecting the use of renewable energy in the building's total energy score. This sends a strong signal and invites consumers to do a detailed calculation of total cost of ownership and ecological advantages. At this point, the benefits of heat pumps will become evident to consumers."

"In the short term, government incentives can help accelerate the transition to carbon-neutral heating and make heat pumps accessible to all Europeans, but in the long-term accurate energy prices and a correct indication of the energy and carbon performance of a building need to be the end user motivations to invest in heat pump technology," adds Patrick Crombez.

The examples from other European countries show us this strategy works. For instance, France and Germany have set up extensive and widely popular oil boiler replacement schemes. In addition, Italy launched its 'Superbonus' to promote heat pumps thanks to a 110% payback credit.

What's next?

"Daikin has set itself the ambition to become a carbon-neutral company on a global scale by 2050. Decarbonizing the heating sector in Europe and achieving the Green Deal's bold target are the drivers of that vision. Daikin is convinced that all stakeholders – policy makers, industry leaders and consumers – have the same goal, to lay the foundations of a zero-emission future," concludes Patrick Crombez. ■

Zero Carbon Buildings 2050 Summary Report *

The Paris Agreement commits countries around the world to limiting global warming to well below 2°C above pre-industrial levels, with an aspiration target of limiting the temperature increase to 1.5°C. The cost of failing to reach these targets would be catastrophic, and considerably higher than the investment needed to deliver them. The EU must fully decarbonise its economy by 2050 in order to fulfil its commitment to the Paris Agreement objectives. This requires bold action across all sectors, and in none more than buildings.

Energy use in buildings currently accounts for 36% of greenhouse gas (GHG) emissions in the EU (European Commission, 2019) making buildings one of the largest contributors to EU GHG emissions. In its long-term strategy for 2050 (2018), the European Commission recognises the need for a near-complete decarbonisation of the EU's building sector to meet its climate goals. At the same time, European citizens have a lot to gain from the decarbonisation of buildings, including employment, health, lower household energy bills and system cost savings (Element Energy & Cambridge Econometrics, 2019). Despite the necessity, benefits and urgency of decarbonising buildings, it is one of the sectors that has arguably seen the least progress to date. With over 513.5 million stakeholders, whose lives and behaviour are directly impacted by changes related to buildings, it is notoriously difficult to implement policies to decarbonise the sector. The momentum and opportunities for rapid emissions reduction are there. Europe is setting out to implement the European Green Deal, starting up its Renovation Wave, revising key Directives as well as seeking to recover from the largest health and economic crisis of the last century. To help policy-makers at different levels in Europe capture this momentum, this report recommends a first-ever long-term roadmap of policies to deliver essential carbon reductions in the residential building sector. The report finds that there are three key areas to target in order to set the sector on a trajectory to zero emissions. These are: reducing energy demand through renovation of the building stock, shifting to zero-carbon energy carriers, and applying the principles of circularity to the building supply chain. Each of these areas will require policy-makers to introduce a combination of new regulatory and pricing policies. The need for these policies is urgent to put Europe on the right track, as there are very limited renovation windows left before 2050. The **figure** on the next page provides an outline for a policy package that will put the building sector on a trajectory to zero emissions.

Main policy messages

Current policies focusing on incentives and information are not enough to achieve full decarbonisation of the residential building sector. Additional regulatory and pricing policies as well as instruments that support the deployment of innovation are needed to reach the full emission reduction potential.

The areas that have the largest GHG emission reduction potential are:

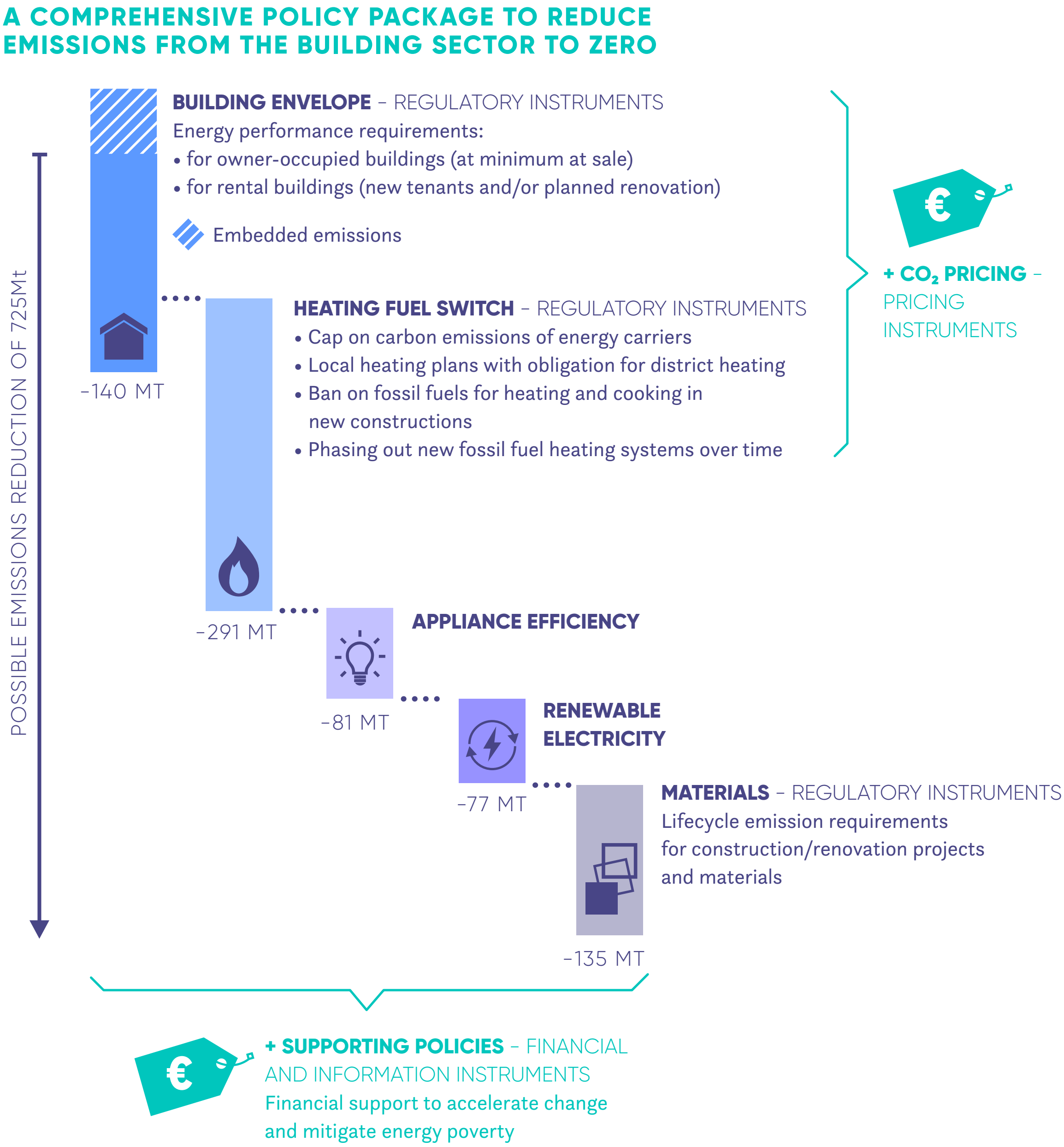
- Reducing energy demand by improving the energy performance of the existing building envelope
- Switching to zero-carbon fuels for heating, including a switch in heating systems
- Reducing embedded carbon in construction and renovation materials

These are also the areas that lack effective policy measures the most, both at EU and national levels.

A comprehensive policy package, built on the existing regulations, needs to be developed and implemented by the EU and individual Member States. It should at the least contain the following components:

- Minimum energy performance standards for existing buildings that apply at key moments in the building's lifetime, such as sale and change of tenants, or are set at a certain moment in time and subsequently tightened over time
- Regulatory policies to promote heating fuels and appliances switching, such as:

* Source: CE Delft, the Netherlands
https://www.cedelft.eu/en/publications/2474/zero-carbon-buildings-2050



- A cap on the CO_2 emissions of energy carriers for retail energy suppliers
- Local or regional heating plans to implement direct electrification of heating and district heating
- A rapid and equitable transition out of fossil fuel heating systems
- A ban on the use of fossil fuels for heating and cooking in new constructions
- CO_2-based taxation/pricing of energy carriers for heating (via revision of the Energy Taxation Directive), in combination with a scheme that uses the revenues to support low-carbon measures such as deep renovation, especially targeting low-income households
- Emissions requirements over the life cycle of construction and renovation projects, products and materials
- Supporting policies to facilitate the transition, including financial support to alleviate energy poverty

Full decarbonisation will require a concerted innovation effort. This calls for targeted tools to incentivise and deploy innovation, increasing innovation capacity in some areas of the building sector while addressing the fragmentation of the market and creating a demand for innovative solutions.

There is no time to waste in introducing these policies. Because the lifetime of most investments in the building sector is very long, delaying action means passing up key investment moments. Missing this window creates the threat of higher overall costs for society. ■

Send information of your event to Ms Nicoll Marucciova nm@rehva.eu

Exhibitions, Conferences and Seminars in 2020 & 2021

Conferences and seminars 2020

From 1 november 2020	Indoor Air 2020	Online	www.indoorair2020.org
5 November 2020	Brussels Summit	Online	https://www.rehva.eu/events/details/rehva-brussels-summit-2020
2-4 December	The 51st International Congress and Exhibition	Online	http://kgh-kongres.rs/index.php/en/

Conferences and seminars 2021

10-12 January 2021	Climamed	Lisbon, Portugal	http://www.climamed.org/en/
9-11 February 2021	2021 ASHRAE Winter Virtual Conference	Online	https://www.ashrae.org/conferences/2021-virtual-winter-conference
From 15 February 2021	Roomvent 2020	Online	http://roomvent2020.org/
22-26 March 2021	ISH 2021	Online	https://ish.messefrankfurt.com/frankfurt/en.html
24-26 February 2021	World Sustainable Energy Days 2021	Wels, Austria	https://www.wsed.at/en/world-sustainable-energy-days.html
14-16 April 2021	SBE21 Sustainable Built Heritage Conference	Bolzano, Italy	https://sbe21heritage.eurac.edu/
17-21 April 2021	Cold Climate	Tallin, Estonia	https://www.scanvac.eu/events.html
26-29 April 2021	13th IEA Heat Pump Conference	Jeju, Korea	http://hpc2020.org/
3-5 May 2021	40th Euroheat & Power Congress	Online & Vilnius, Lithuania	https://www.ehpcongress.org/
21-23 June	Healthy Buildings 2021 Europe	Oslo, Norway	http://www.hb2021-europe.org/index.html
15-18 August 2021	13th International Industrial Ventilation Conference for Contaminant Control	Toronto, Canada	https://www.ashrae.org/conferences/topical-conferences/ventilation-2021
13–15 September 2021	41st AIVC – ASHRAE IAQ joint conference	Athens, Greece	https://www.aivc.org/event/13-15-september-2021-conference-athens-41st-aivc-ashrae-iaq-joint-conference
22-24 September 2021	Aquatherm Tashkent	Tashkent, Uzbekistan	https://www.aquatherm-tashkent.uz/en/
29 Sept - 2 Oct 2021	ISK Sodex 2021	Istanbul, Turkey	http://www.sodex.com.tr/

! **Due to the COVID19 circumstances, the dates of events might change. Please follow the event's official website.** !

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Federation of
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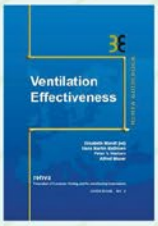
EUROPEAN GUIDEBOOKS

No.01: DISPLACEMENT VENTILATION IN NON-INDUSTRIAL PREMISES



No.02: VENTILATION EFFECTIVENESS

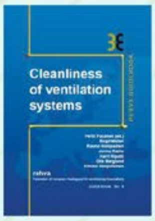
No.03: ELECTROSTATIC PRECIPITATORS FOR INDUSTRIAL APPLICATIONS

No.04: VENTILATION AND SMOKING

No.05: CHILLED BEAM APPLICATION GUIDEBOOK

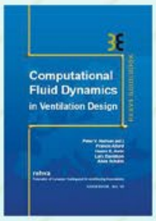
No.06: INDOOR CLIMATE AND PRODUCTIVITY IN OFFICES

No.07: LOW TEMPERATURE HEATING AND HIGH TEMPERATURE COOLING

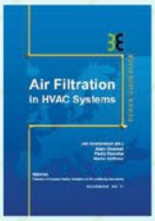


No.08: CLEANLINESS OF VENTILATION SYSTEM

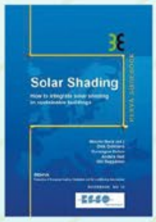
No.09: HYGIENE REQUIREMENTS FOR VENTILATION AND AIR-CONDITIONING SYSTEMS



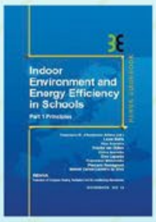
No.10: COMPUTATIONAL FLUID DYNAMICS IN VENTILATION DESIGN



No.11: AIR FILTRATION IN HVAC SYSTEMS

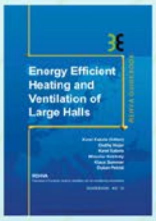


No.12: SOLAR SHADING



No.13: INDOOR ENVIRONMENT AND ENERGY EFFICIENCY IN SCHOOLS - PART 1

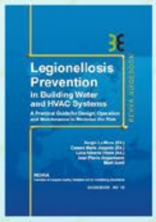
No.14: INDOOR CLIMATE QUALITY ASSESSMENT



No.15: ENERGY EFFICIENT HEATING AND VENTILATION OF LARGE HALLS

No.16: HVAC IN SUSTAINABLE OFFICE BUILDINGS

No.17: DESIGN OF ENERGY EFFICIENT VENTILATION AND AIR-CONDITIONING SYSTEMS



No.18: LEGIONELLOSIS PREVENTION IN BUILDING WATER AND HVAC SYSTEMS

No.19: MIXING VENTILATION

No.20: ADVANCED SYSTEM DESIGN AND OPERATION OF GEOTABS BUILDINGS

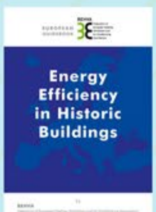
No.21: ACTIVE AND PASSIVE BEAM APPLICATION DESIGN GUIDE

No.22: INTRODUCTION TO BUILDING AUTOMATION, CONTROLS AND TECHNICAL BUILDING MANAGEMENT

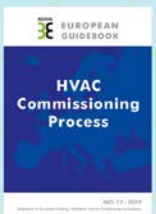
No.23: DISPLACEMENT VENTILATION

No.24: FIRE SAFETY IN BUILDINGS

No.25: RESIDENTIAL HEAT RECOVERY VENTILATION



No.26: ENERGY EFFICIENCY IN HISTORIC BUILDINGS



No.27: HVAC COMMISSIONING PROCESS (REHVA-ISHRAE)

No.28: NZEB DESIGN STRATEGIES FOR RESIDENTIAL BUILDINGS IN MEDITERRANEAN REGIONS

No.29: QUALITY MANAGEMENT FOR BUILDINGS