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A systematic approach to estimating the effectiveness of multi-scale IAQ strategies for reducing the risk of airborne infection of SARS-CoV-2

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ABSTRACT

The unprecedented coronavirus disease 2019 (COVID-19) pandemic caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has made more than 125 million people infected and more than 2.7 million people dead globally. Airborne transmission has been recognized as one of the major transmission routes for SARS-CoV-2. This paper presents a systematic approach for evaluating the effectiveness of multi-scale IAQ control strategies in mitigating the infection risk in different scenarios. The IAQ control strategies across multiple scales from a whole building to rooms, and to cubical and personal microenvironments and breathing zone, are introduced, including elevated outdoor airflow rates, high-efficiency filters, advanced air distribution strategies, standalone air cleaning technologies, personal ventilation and face masks. The effectiveness of these strategies for reducing the risk of COVID-19 infection are evaluated for specific indoor spaces, including long-term care facility, school and college, meat plant, retail stores, hospital, office, correctional facility, hotel, restaurant, casino and transportation spaces like airplane, cruise ship, subway, bus and taxi, where airborne transmission are more likely to occur due to high occupancy densities. The baseline cases of these spaces are established according to the existing standards, guidelines or practices. Several integrated mitigation strategies are recommended and classified based on their relative cost and effort of implementation for each indoor space. They can be applied to help meet the current challenge of ongoing COVID-19, and provide better preparation for other possible epidemics and pandemics of airborne infectious diseases in the future.

1. Introduction

The unprecedented coronavirus disease 2019 (COVID-19) pandemic caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has made more than 125 million people infected and more than 2.7 million people dead globally with more than half million deaths in U. S. alone [1]. Although a few biopharmaceutical companies have developed vaccines against COVID-19 [2,3], the worldwide distribution and use still require more time [4]. The COVID-19 pandemic is likely to last for a long period [5]. Recently, some new SARS-CoV-2 variants have been identified in some countries, bringing the world more unknown challenges to fight against the pandemic [6–10]. Minimizing the virus transmission is still essential in reducing the risk of COVID-19 infection.

There are typically three transmission routes of infectious respiratory viruses, including fomite route through contacts, droplet-borne route transmitted by medium or large droplets, and airborne route through aerosols that can remain suspended over a longer time [11]. The transmission of SARS-CoV-2 through fomite and droplet-borne routes was used to be considered as the main pathways, but more and more recent studies have revealed that the airborne transmission could be considered as the most relevant transmission route [12–21], particularly in crowded and inadequately ventilated indoor spaces [22–24]. Fennelly [25] measured particle size distribution of infectious aerosols and observed that pathogens are more commonly found in small particles (<5 μm). Some studies have identified airborne transmission as a likely major pathway for asymptomatic transmission of SARS-CoV-2 [26,27] and the superspreading events [28]. Considering the substantial proportion of asymptomatic cases [29–31], airborne transmission is very important for analyzing the infection risk of COVID-19. Many public institutes, including WHO, U.S. CDC, PHAC and ASHRAE, have raised the concern on the airborne route of SARS-CoV-2 transmission [23,24,32,33].

People spend almost 90% of their time in indoor environments

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Nomenclature

A	Room area (m^2)
c_i	Conversion factor
c_v	Viral load in the sputum (RNA copies/mL)
$C_{exhaust}$	Tracer gas concentration in the exhaust air
C_i	Tracer gas concentration in the target location
d_p	Particle diameter (μm)
$f_{AirCleaner}$	Fraction of air cleaner operation time (%)
$f_{recirculated}$	Recirculated air fraction of the supply air for the HVAC system (%)
f_R	Fraction of time using a mask over the entire exposure period (%)
f_{UV}	Fraction of UVGI system operation time (%)
H	Room height (m)
I	Number of infectors
$k_{AirCleaner}$	Infectious particle removal rate by air cleaners (h^{-1})
$k_{deposition}$	Infectious particle deposition rate (h^{-1})
$k_{inactivation}$	Pathogen natural inactivation rate in the air (h^{-1})
k_{UV}	Pathogen inactivation rate by UVGI systems (h^{-1})
N	Total occupant number in the space
N_C	Number of new cases
N_d	Particle number concentration (#/cm^3)
N_S	Number of susceptible people
p	Pulmonary ventilation rate (m^3/h)
P	Infection possibility (%)
P_b	Overall infection probability for an occupant who visited multiple spaces (%)
P_i	Infection probability in the i-th space (%)
q	Infectious quantum generation rate per infector (h^{-1})
R_0	Basic reproduction numbers
R_a	Required ventilation rate per room area (L/s·m^2)
R_I	Fraction of infectious particle penetration through the infector's face mask (%)
R_p	Required ventilation rate per person (L/s·p)
R_S	Fraction of infectious particle penetration through the susceptible individual's face mask (%)
t	Exposure time (h)
V	Room volume (m^3)
V_d	Volume of a single particle (cm^3)
ε_{vent}	Ventilation factor
$\eta_{AirCleaner}$	Filter efficiency of air cleaner (%)
η_{filter}	Infectious particles filtration efficiency by the filters (%)
η_I	Filtration efficiency of the infector's mask (%)
η_S	Filtration efficiency of the susceptible individual's mask (%)
$\lambda_{AirCleaner}$	Airflow rate of air cleaner (m^3/h)
λ_{HVAC}	Fresh air supply rate by the HVAC system (h^{-1})
$\lambda_{outdoor}$	Outdoor airflow rate of the HVAC system (h^{-1})
$\lambda_{recirculated}$	Recirculated airflow rate of the HVAC system (h^{-1})
λ_{supply}	Total supply airflow rate of the HVAC system (h^{-1})
λ_{vent}	Equivalent ventilation rate (h^{-1})
Λ	Equivalent fresh air change rate (h^{-1})

[34–37]. Home-based outbreaks were found to be the dominant category (79.9%), followed by transportation-based outbreaks (34.0%) [38]. Nearly all superspreading events took place indoors [28]. Many indoor spaces have a high occupant density, but do not provide adequate fresh air [39], which increase the infection risk through airborne transmission. The transmission by airborne route was considered to greatly contribute to some reported outbreak events. For example, the SARS-CoV-2 spread among the members of the Skagit Valley Chorale during a weekly rehearsal eventually made 53 out of 61 members infected. Such a severe spread was highly suspected to be caused by the airborne transmission [14]. The outbreak event that happened in a Guangzhou restaurant was likely caused by the recirculated air, which carried infectious aerosols emitted by an index case [15,40]. A retrospective analysis for these two outbreak events also supported the airborne transmission of SARS-CoV-2 [41]. The outbreaks in a tour coach in Hunan province [16], a call center in Seoul [18] and a tour coach in Zhejiang province [17] also indicated the possibility of airborne transmission. It is increasingly clear and accepted that airborne transmission is an important contributor to the rapid and long-distance spreading of the SARS-CoV-2 [42].

Indoor air quality (IAQ) control strategies can be applied to reduce the infection risk of COVID-19 through airborne transmission [43,44]. Improving indoor ventilation systems, using air cleaning technologies and wearing masks can improve the IAQ and reduce the infection risk significantly. These strategies have been introduced and discussed in other published papers [43–45] and recommended by WHO [46], U.S. CDC [47–49] and ASHRAE [50].

A well-known mathematical model for estimating the infection risk through airborne transmission is the Wells-Riley model [51,52]. It assumes well-mixed air and a steady-state infectious particle concentration in a confined space. The estimation depends on the susceptible individual's inhalation exposure to the suspended pathogen generated by the infectors. The Wells-Riley model has been widely used to evaluate the airborne infection risk of respiratory diseases, such as influenza, tuberculosis, SARS-CoV-1, middle east respiratory syndrome (MERS), measles [53–57], and more recently, SARS-CoV-2. Dai and Zhao [45] used it to estimate the required ventilation rate in four scenarios ensuring a less than 1% infection probability. Harrichandra et al. [58] used it to estimate the airborne SARS-CoV-2 infection risk in nail salons. Multiple Wells-Riley model-based tools have been developed to help people evaluate the airborne transmission risk of COVID-19 [59–64]. Considering the steady-state and well-mixed assumption for the indoor air, the Wells-Riley model has also been extended by some researchers to include unsteady exposure [65] and imperfect mixing [66,67]. In addition, the computational fluid dynamics (CFD) approach has also been conducted for studying the infectious particle dispersion in indoor environments and evaluating the infectious risk in according with the exposure dose [15]. But the CFD approach requires comprehensive information for the room and ventilation configurations, and the simulation process is usually time-consuming. Another widely used mathematical approach to model the transmission of COVID-19 is the Susceptible-Exposed-Infectious-Recovered (SEIR) epidemic disease model, which is usually used to estimate the epidemic disease transmission through all possible routes among a considerable number of populations (typically in a community scale) over a longer period (at least a few days) [68,69]. However, the SEIR model does not link the exposure directly to the risk of infection, and hence is not suitable for evaluating the effectiveness of IAQ strategies on airborne transmission.

This study aims to develop a systematic approach for evaluating the effectiveness of multi-scale IAQ control strategies in mitigating the infection risk in different building and transportation spaces. The IAQ control strategies across multiple scales will be introduced, including elevated outdoor air, high-efficiency filters, advanced air distribution strategies, standalone air cleaning technologies, personal ventilation, and face masks. The effectiveness of these strategies will be evaluated for specific indoor spaces, including long-term care facility, school and college, meat plant, retail stores, hospital, office, correctional facility, hotel, restaurant, casino and transportation spaces. The results can be applied to help handle the current challenge of ongoing COVID-19, as well as provide better preparation for possible epidemics or pandemics of airborne infectious diseases in the future.

2. Methodology

2.1. Risk estimation model

2.1.1. Wells-Riley model

The Wells-Riley model [70,71] is usually used to model the infection risk of airborne transmission in enclosed environments assuming a steady-state and well-mixed indoor environment. The infection possibility (P) is calculated as a function of the inhalation exposure dose [72], which depends on the number of pathogen carriers (i.e. infectors, I), the infectious quantum generation rate per infector (q), the fraction of infectious particle penetration through the face mask (R), pulmonary ventilation rate (p), exposure time (t) and the equivalent fresh air change rate in the room (Λ):

$$P = \frac{N_C}{N_S} = 1 - e^{-R_S R_I \frac{Iqpt}{V\Lambda}} \tag{1}$$

The fraction of infectious particle penetrated through the masks for susceptible (R_S) and infected (R_I) population depend on the mask filtration efficiency (η_S or η_I) and can be calculated by Eqs. (2) and (3), respectively. An additional fractional factor (f_R) is multiplied by the original filtration efficiency of the mask to represent the fraction of time using a mask over the entire exposure period.

$$R_S = 1 - f_{R,S}\eta_S \tag{2}$$

$$R_I = 1 - f_{R,I}\eta_I \tag{3}$$

The equivalent air change rate (Λ) represents the equivalent supply flow rate of fresh air per unit volume of the room space. It depends on the equivalent ventilation air change rate (λ_{vent}), pathogen inactivation rate by ultraviolet germicidal irradiation (UVGI) systems (k_{UV}), infectious particle deposition rate ($k_{deposition}$) and pathogen natural inactivation rate in the air ($k_{inactivation}$):

$$\Lambda = \lambda_{vent} + f_{UV}k_{UV} + k_{deposition} + k_{inactivation} \tag{4}$$

The equivalent ventilation rate (λ_{vent}) includes the fresh air supply rate by the heating, ventilation, and air conditioning (HVAC) system (λ_{HVAC}) and standalone portable air cleaners ($k_{AirCleaner}$). The original Wells-Riley model is based on the perfect-mixing assumption. However, indoor airflow patterns and mixing level are highly dependent on room configurations and air distributions. In order to evaluate the infection risk in imperfect-mixed scenarios, an additional ventilation factor (ε_{vent}) is multiplied by the ventilation rate in the model, representing the dilution efficiency in a particular location compared to the perfect mixing ventilation. It can be estimated by comparing the tracer gas concentration in the target location (C_i) and the concentration in the exhaust air ($C_{exhaust}$) through Eq. (5), which is similar to the zone air distribution effectiveness in ASHRAE 62.1 [22]. It equals one for the perfect mixing condition. Spaces with more efficient air distribution (such as displacement ventilation) have a ventilation factor greater than one. A similar ventilation factor was also applied incorporating with the Wells-Riley model by Sun and Zhai [73]. The equivalent ventilation rate (λ_{vent}) can be calculated by Eq. (6).

$$\varepsilon_{vent} = \frac{C_{exhaust}}{C_i} \tag{5}$$

$$\lambda_{vent} = f_{HVAC}\lambda_{HVAC}\varepsilon_{vent} + f_{AirCleaner}k_{AirCleaner} \tag{6}$$

The fresh air supplied by the HVAC system (λ_{HVAC}) includes the outdoor part and the recirculated part. The recirculated fresh air supply rate (Eq. (7)) depends on the recirculated airflow rate ($\lambda_{recirculated}$) and the infectious particles filtration efficiency by the filters (η_{filter}).

$$\lambda_{HVAC} = \lambda_{outdoor} + \lambda_{recirculated}\eta_{filter} \tag{7}$$

The total supply airflow rate of the ventilation system equals to the summary of outdoor airflow rate and the recirculated airflow rate, which can be calculated by

$$\lambda_{supply} = \lambda_{outdoor} + \lambda_{recirculated} = \frac{\lambda_{outdoor}}{1 - f_{recirculated}} \tag{8}$$

A portable air cleaner can supply additional fresh air. The infectious particle removal rate by air cleaners ($k_{AirCleaner}$) can be estimated by its airflow rate ($\lambda_{AirCleaner}$) and filter efficiency ($\eta_{AirCleaner}$), or based on its clean air delivery rate (CADR) and room volume (V):

$$k_{AirCleaner} = \lambda_{AirCleaner}\eta_{AirCleaner} = \frac{CADR}{V} \tag{9}$$

The pathogen removal rate by the UVGI system depends on the fraction of UVGI operation time (f_{UV}) and the pathogen inactivation rate due to ultrafine (UV) irradiation (k_{UV}). The infectious particle deposition rate ($k_{deposition}$) relies on an approximate estimate of gravitational settling (Eq. (10)) [74], which depends on the particle diameter (d_p) and room height (H). The possible impacts of environmental conditions on particle deposition [75] are not considered in this study.

$$k_{deposition} = \frac{0.108 d_p^2 \left(1 + \frac{0.166}{d_p}\right)}{H} \tag{10}$$

2.1.2. Key parameters in the model

2.1.2.1. Infectious quantum generation rate per infector (q). Quantum generation rate per infector (q) is a critical parameter in the Wells-Riley model. The magnitude of q depends on disease species, infector activities (e.g. breathing, coughing) and interventions (e.g. wearing masks), and may vary significantly case by case [70,76]. The value of q of a COVID-19 infector is currently not well established. It is believed to be close to the q of influenza and SARS-CoV-1 because their basic reproduction numbers (R_0) are close [45,77–82]. Dai and Zhao [45] analyzed the statistical relationship between R_0 and q of other respiratory diseases, and estimated an approximate q between 14 and 48 h^{-1} for SARS-CoV-2 using the curve-fitting approach. Buonanno et al. [76] used a novel approach (Eq. (11)) for predicting the viral load emitted by a contagious subject based on the viral load in the sputum. It revealed that q could be lower than 1 h^{-1} in resting state and greater than 100 h^{-1} in light activity state.

$$q = c_v \cdot c_i \cdot p \cdot \int_0^{10\mu m} N_d(d_p) \cdot dV_d(d_p) \tag{11}$$

The conversion factor c_i is typically between 0.01 and 0.1 with a reported average value of 0.02 [76]. A typical q of 142 h^{-1} was estimated for a case who is speaking and doing light exercise [76]. Li et al. [15] estimated a q of 79.3 h^{-1} for an COVID-19 outbreak in a Guangzhou restaurant. Miller et al. [14] reported a q as high as 970 h^{-1} level for a super spreader during a chorale rehearsal. Buonanno et al. [41] proposed a new approach to evaluate the airborne transmission and performed a retrospective analysis for the Guangzhou restaurant case and the Skagit Valley Chorale case and revealed quantum generations of 61 h^{-1} and 341 h^{-1}, respectively.

In this study, the infectious quantum generation rate is estimated based on the viral load model (Eq. (11)). Previous studies measured the viral load of COVID-19 patients and suggested that the viral load can typically reach 10^9 RNA copies/mL [76,83–88], which is used in this study. A reported average value of 0.02 is applied as the c_i in the model [76]. The highest droplet number concentration in Ref. [76] is adopted. The droplet volume calculation uses the geometric mean diameters for each particle size bin (i.e., 0.55 μm, 1.7 μm, and 5.5 μm for particles of 0.3–1 μm, 1–3 μm, and 3–10 μm, respectively [98]). Three different activity levels are considered: sedentary and light-intensity (breathing or whispering while seated or standing), moderate-intensity (speaking while seated or standing) and high-intensity (breathing or speaking while running or doing exercises). A Monte Carlo approach is applied to Eq. (11) to obtain the probability distribution of q for various age groups in various activities (Table 1), by adopting the probability density functions characteristic (normal distribution) of pulmonary rates in Table 3. The other parameters adopt constant values as presented above.

2.1.2.2. Size distribution of infectious particles. Considering the different aerodynamic features (e.g. deposition, filtration by filters) between the particles of different diameters, sufficient knowledge of droplet size is important for understanding virus transmission through the aerosol route. Researchers [57,89] have observed that most expelled droplets are in smaller size (typically below 2 μm). However, droplets in smaller diameters may contain less virus due to the smaller particle volume. When considering the droplet volume and droplet size distribution, larger droplets actually contain more pathogens [76,89].

Some studies have conducted measurements of virus size distribution in indoor environments, which accounts for a combination of all human respiratory activities that occur indoors. Stephens [57] reviewed such studies for influenza and estimated the size-resolved distribution of q using the data in literature [90]. It was observed that 15% of pathogens are in the 0.3–1 μm size range, 25% in the 1–3 μm size range and 60% in the 3–10 μm size range [57]. A report from CDPH [91] suggested the distribution of 20%, 30% and 50% for infectious particles in 0.3–1 μm, 1–3 μm and 3–10 μm, respectively. The published data [92,93] regarding the measured virus size distribution for SARS-CoV-2 in indoor environments are summarized in Table 2 (the original data were reclassified into bins of 0.3–1 μm, 1–3 μm and 3–10 μm in accordance with ASHRAE 52.2 [94]). Considering the virus size distribution in literature [57,91–93], the airborne infectious particle size distribution in this study is specified as probabilistic and assumed to follow the uniform distribution in each segment, i.e. 10-20% in 0.3–1 μm range, 20–30% in 1–3 μm, and 50–70% in 3–10 μm. It is generally consistent with the infectious particle size distribution defined in other modeling works [70,91]. The difference of size distribution between different age groups or activities is neglected [57].

2.1.2.3. Pulmonary ventilation rate (p). The pulmonary ventilation rate in the Wells-Riley model is associated with the infectious aerosol dose inhaled by each susceptible person (Eq. (1)), and also related to the q of infectors (Eq. (11)). The short-term inhalation rates by activity level for people in different ages is shown in Table 3. Three different activity levels are considered for each age group, including sedentary or light-intensity, moderate-intensity and high-intensity activities. The pulmonary rates are assumed to follow normal distributions.

2.1.2.4. Removal efficiency of filters for infectious particles (η_{filter}). The particle removal efficiency of filters used in the HVAC system is usually rated by minimum efficiency reporting values (MERVs). MERVs report a filter's ability to capture particles between 0.3 and 10 μm. The efficiency of MERV-rating filters for different particle size range is adapted from ASHRAE 52.2 [94]. The detailed information about the efficiency for each particle size is discussed in Supplemental Information. Considering the size distribution of infectious particles, the particle-size-weighted virus filtration efficiencies of different filters are presented in Table 4.

Table 1
Estimated infectious quantum generation rate.

Age group	Age [years]	Infectious quantum generation rate (Mean ± SD) [h^{-1}]		
		Sedentary or light activities	Moderate-intensity activities	High-intensity activities
Children	<16	58 ± 31	251 ± 134	492 ± 270
Adults	16–61	58 ± 31	318 ± 177	610 ± 347
Elders	>61	58 ± 31	305 ± 158	555 ± 307

2.1.2.5. Removal efficiency of different masks on infectious particles (η_S and η_I). Face masks provide air filtration at a personal level for wearers, which is a critical strategy for mitigating infection risk. Face masks can reduce the average emission rate by approximately 30%, 50% and 95% with cloth, surgical and N95 masks, respectively [96]. Konda et al. [97] measured the mask filtration efficiency for particles in different diameters (Table 5). The particle-size weighted removal efficiencies of different masks can be estimated based on the assumed infectious particle size distribution. The particle-size-weighted efficiency is around 32%, 44% and 95% for cloth, surgical and N95 masks, respectively.

2.1.2.6. Particle deposition. For the calculation of particle deposition, the same particle size bins as those used for HVAC filter MERV ratings are considered here to simplify the calculation, and values are calculated using the geometric mean diameters for each particle size bin (i.e., 0.55 μm, 1.7 μm, and 5.5 μm for particles of 0.3–1 μm, 1–3 μm, and 3–10 μm, respectively [98]) by Eq (10). Although it has been revealed that environmental conditions such as air temperature, humidity and airflow velocity may affect the travelling and deposition of exhaled aerosols, the conditions in most indoor environments are within a relatively narrower range. Therefore, typical indoor environments (23 °C, 50%RH and low airflow velocity) are assumed in this study. The possible impacts of environmental conditions on particle deposition are not considered.

2.1.2.7. Inactivation rate. van Doremalen et al. [99] observed an inactivation rate of 0.63 h^{-1} for SARS-CoV-2. Fears et al. [100] measured a nearly zero decay rate. Schuit et al. [101] revealed a mean decay rate of 0.48 h^{-1} without sunlight. Smither et al. [102] suggested a decay rate of 0.95 h^{-1} in aerosols at medium humidity condition and 0.24 h^{-1} at high humidity condition. Dabisch et al. [103] observed decay rates of 0.36 h^{-1} and 1.02 h^{-1} in the environment with room temperature and no sunlight. Therefore, the typical inactivation rate of SARS-CoV-2 aerosols at typical indoor temperature and humidity is generally between 0 and 1 h^{-1}. Sunlight can possibly contribute greatly to the inactivation of SARS-CoV-2 [101,103], but is not considered in this study. A uniform distribution of inactivation rate between 0 and 1 h^{-1} is assumed in the model.

2.2. Definition of baseline cases

Significant percent of outbreaks have been reported in long-term care facility, manufacturing facility, correctional facility, school and college, healthcare facility and hospital, retail, restaurant and office facility, indicating these scenarios as hotspots for COVID-19 outbreaks [104–106]. The space layouts, occupant status and ventilation configurations of various spaces vary greatly. The researchers at the U.S. DOE and PNNL created prototypes of typical commercial buildings in accordance with ASHRAE 90.1 and IECC standards [107–109], which are used to define the baseline cases in this study. Design guidelines or real practices are adopted to define the baseline of other cases that were not defined by DOE and PNNL. The outbreaks tied to transportation spaces, such as airplanes, cruise ships and buses, have been widely reported [16,17,110–116], which will also be discussed.

The occupant number in the space is determined by the default occupant density in ASHRAE 62.1 [22] or the available data from literature or practices. Three different age groups are considered, including children, adults and elders. The occupant activities in different spaces are presented in ASHRAE 62.1 [22]. The occupant exposure duration is assigned based on the most typical practices in real scenarios. The required outdoor ventilation rate can be calculated based on the data in ASHRAE 62.1 [22], which depends on the space area and occupant number (Eq. (12)). For other cases, the data from literature or typical practices are used to define the baseline ventilation rate. The baseline definitions for all studied spaces are listed in Table 6, while more detailed information can be found in Supplemental Information.

Table 2
Distribution of airborne SARS-CoV-2 across particle diameters (adapted from Refs. [92,93]).

Particle aerodynamic diameter [μm]	Distribution of airborne SARS-CoV-2 across particle diameters [%]					
	Protective-apparel removal room A [92]	Protective-apparel removal room B [92]	Medical staff's office [92]	Patient room B [93]	Patient room C [93]	Average
0.3–1	96	58	24	0	0	36
1–3	2	5	18	41	50	23
3–10	2	37	59	59	50	41

Table 3
Short-term pulmonary rates, by activity levels (adapted from Ref. [95]).

Age group	Age [years]	Short-term pulmonary rates (Mean ± SD) [m^3/h]		
		Sedentary or light activities	Moderate-intensity activities	High-intensity activities
Children	<16	0.3 ± 0.2	1.3 ± 0.85	2.5 ± 1.75
Adults	16–61	0.3 ± 0.2	1.6 ± 1.15	3.0 ± 2.3
Elders	>61	0.3 ± 0.2	1.6 ± 1.0	2.8 ± 2.0

Table 4
Particle removal efficiency of different filters.

MERV	Particle removal efficiency η_{filter} [%]			
	0.3–1 μm	1–3 μm	3–10 μm	Particle-size-weighted[a]
1	0	0	10	5–7
2	0	0	10	5–7
3	0	0	10	5–7
4	0	0	10	5–7
5	3	17	20	16–18
6	3	17	35	23–28
7	9	17	50	32–39
8	9	20	70	43–54
9	9	35	85	55–67
10	9	50	85	59–70
11	20	65	85	66–74
12	35	80	90	76–82
13	50	90	90	82–86
14	75	90	90	87–88
15	85	90	90	89
16	95	95	95	95
HEPA[b]	99.9	99.9	99.9	99.9

[a] Monte Carlo approach is implemented that adopts uniform probability distribution of particle sizes, i.e. 10-20% in 0.3–1 μm, 20–30% in 1–3 μm, and remaining 50–70% in 3–10 μm.
[b] High-efficiency particulate air (HEPA) filters.

Table 5
Mask filtration efficiency for 0.3–1 μm, 1–3 μm, 3–10 μm and total particle-size-weighted average.

Mask	Particle removal efficiency η_{filter} [%]			
	0.3–1 μm	1–3 μm	3–10 μm	Particle-size-weighted[c]
Cloth (cotton/silk, with gap)[a]	27	33	34	32–33
Surgical (with gap)[a]	41	44	45	44
N95[b]	95	95	95	95

[a] Average value of the data measured in Ref. [97].
[b] Assuming 95% for all size ranges.
[c] Monte Carlo approach is implemented that adopts uniform probability distribution of particle sizes, i.e. 10-20% in 0.3–1 μm, 20–30% in 1–3 μm, and remaining 50–70% in 3–10 μm.

$$\lambda_{outdoor} = R_p \times N + R_a \times A \tag{12}$$

2.3. Multi-scale IAQ strategies for mitigating airborne transmission

The U.S. CDC [47–49] and WHO [46] have provided guidance for infection risk mitigation strategies in different spaces. Some of the strategies mainly focus on mitigating the airborne transmission, including improving ventilation rate, upgrading filters, using air cleaners or upper-room UVGI systems and wearing masks. ASHRAE [50] introduced some air cleaning technologies to mitigate the disease transmission through aerosols. Zhang [43] and Morawska et al. [44] introduced similar control strategies for mitigating infection risks in spaces like office and classroom.

The current IAQ control strategies can be roughly divided into three categories, i.e. source control, ventilation and air cleaning [43]. For the control of SARS-CoV-2 generation sources, it can be achieved through isolating infectors or preventing the virus emission from them. Therefore, limiting the occupant number or applying intermittent occupancy [135], and removing the expelled aerosols locally by wearing masks or applying local air exhaust [136–138], are the strategies that possibly could control the virus source [43,139]. For the room ventilation, it aims to supplying sufficient clean air and delivering it to occupants. The ventilation can be improved by increasing the airflow or outdoor air fraction of the ventilation system, optimizing the room air distribution to avoid cross-infection [43]. The air cleaning strategies involve applying air filtration or purification in the ventilation duct, locally in the room, and for the breathing zone. For the ventilation system, high-efficiency filters can be installed in the duct. Standalone air cleaners and upper-room UVGI systems can provide additional clean air. Properly wearing masks is another air cleaning approach for the susceptible individuals since the infectious particles can be filtered by masks before being inhaled [139].

These IAQ control strategies can be implemented in different scales, from a whole building, to a room or space, to personal microenvironments and the breathing zone, which could result in different performance. Generally, the strategies implemented in building scale can mitigate infection for a considerable number of occupants but are not able to control the airborne transmission locally in a room or the breathing zone. Besides, these control strategies may cause more penalties on building energy consumption. The strategies in room, personal and breathing zone scales are more likely to mitigate the infection effectively since they are closely associated with the quantity of inhaled infectious particles. The possible IAQ control strategies in different scales are presented in Table 7 and illustrated in Fig. 1.

The performance of each IAQ control strategy is analyzed in this study based on the Wells-Riley model. For a baseline case (see Table 8), the mixing ventilation with reference ventilation rate defined in Table 6 is applied. Persily and Gorfain [140] suggested that the average outdoor air fraction for building ventilation system to be around 25%, which is used as the baseline outdoor air fraction. It is consistent with the configurations in other studies [57]. A MERV 8 filter is used for the recirculated air of the ventilation system for the baseline case, in accordance with ASHRAE 62.1 [22], except for the hospital operating room and the airplane cabin where the ventilation system typically use HEPA filters [141]. Standalone air cleaners and upper-room devices are not used in the baseline case. People in the baseline scenario do not wear any mask.

Table 6
Configurations of baseline cases.

Scenario[a]		Space type	Space layout		Occupant status				Ventilation configuration		
			Area [m^2]	Height [m]	Density [#/100m^2]	Number [person]	Duration [h]	Activity level[c] [−]	R_p [L/s·p]	R_a [L/s·m^2]	Ventilation rate[d] [L/s]
Long-term care facility		Bedroom (double resident)	36.8	3.0	/	2	11	Elder Sed.	2.5	0.3	16.0
		Dining room	70.0	3.0	/	20	2	Elder Mod.	3.8	0.9	139.0
		Living room	50.0	3.0	10	5	2	Elder Sed.	2.5	0.3	27.5
		Physical therapy room[b]	23.2	3.0	20	5	2	Elder Mod.	5	0.3	32.0
Educational	K-12	Classroom	99.0	4.0	35	35	4[e]	Child Sed.[e]	5	0.6	234.4
		Library	840.1	4.0	10	84	1	Child Sed.	2.5	0.6	714.1
		Cafeteria/dining room	624.0	4.0	100	624	1	Child Mod.	3.8	0.9	2932.8
		Gym	1976.2	8.0	7	138	1	Child High	10	0.9	3158.6
	College	Classroom (small)	51.5	3.0	/	25	2	Adult Sed.	5	0.6	155.9
		Classroom (large)	150.0	4.0	/	96	2	Adult Sed.	5	0.6	570.0
		Library (public study area)	338.6	6.0	/	96	2	Adult Sed.	2.5	0.6	443.2
		Auditorium	1134.0	14.6	/	1500	2	Adult Sed.	3.8	0.3	6040.2
		Computer lab	84.3	4.0	/	38	2	Adult Sed.	5	0.6	240.6
		Dining hall	573.5	4.0	100	574	1	Adult Mod.	3.8	0.9	2697.4
		Study lounge	84.3	4.0	/	21	2	Adult Sed.	2.5	0.6	103.1
		Gym (fitness area)	256.0	8.0	/	60	2	Adult High	10	0.9	830.4
		Resident hall (bedroom)	21.5	3.0	/	2	8	Adult Sed.	2.5	0.3	11.5
		Greek house (social gathering)	50.0	3.0	/	20	4	Adult Mod.	2.5	0.3	65.0
Manufacturing facility	Meat plant	Processing room (dense)	434.0	4.0	/	108	8	Adult Mod.	5.0	0.9	930.6
		Processing room (sparse)	434.0	4.0	/	27	8	Adult Mod.	5.0	0.9	525.6
Retail	Standalone	Core shopping space	1600.4	6.0	15	240	1	Adult Mod.	3.8	0.6	1872.2
	Strip mall	Store (large)	348.4	5.2	8	28	1	Adult Mod.	3.8	0.3	210.9
		Store (small)	174.2	5.2	8	14	1	Adult Mod.	3.8	0.3	105.5
Healthcare facility	Hospital	Operating room	55.7	4.3	/	3	4	Adult Sed.	/	/	198.2
		Patient room (patient + doctor)	20.9	4.3	/	2	1	Adult Sed.	/	/	49.6
		Physical therapy room	487.6	4.3	/	26	2	Adult Mod.	/	/	186.0
		Dining room	696.5	4.3	/	75	1	Adult Mod.	/	/	902.4
		Lobby	1474.3	4.3	/	21	1	Adult Mod.	/	/	499.3
Office	Medium	Open plan office	191.9	2.7	5	10	8	Adult Sed.	2.5	0.3	82.6
		Enclosed office	42.3	2.7	5	2	8	Adult Sed.	2.5	0.3	17.7
		Conference room	43.2	2.7	50	22	2	Adult Sed.	2.5	0.3	68.0
		Lounge	89.6	2.7	50	45	1	Adult Sed.	2.5	0.6	166.3
Correctional facility	Prison	Housing (double resident cell)	10.0	3.0	/	2	8	Adult Sed.	2.5	0.6	11.0
		Housing (dormitory)	160.0	3.0	25	40	8	Adult Sed.	2.5	0.6	196.0
		Dayroom	160.0	6.0	30	48	12	Adult Sed.	2.5	0.3	168.0
Lodging	Hotel	Guest room/bedroom	39.0	3.0	/	2	8	Adult Sed.	2.5	0.3	16.7
		Banquet/dining room	331.7	3.0	70	232	2	Adult Mod.	3.8	0.9	1180.1
		Lobby	1308.2	4.0	30	392	1	Adult Mod.	3.8	0.3	1882.1
Other public facilities	Restaurant	Dining room (ordinary)	371.7	3.0	70	260	1	Adult Mod.	3.8	0.9	1322.5
		Dining room (fast-food)	116.1	3.0	70	81	0.5	Adult Mod.	3.8	0.9	412.3
	Religious	Worship hall	204.0	4.0	/	200	2	Adult Sed.	2.5	0.3	561.2
	Casino	Poker room	253.1	4.0	120	304	4	Adult Mod.	3.8	0.9	1383.0
Transportation spaces	Airplane	Cabin	101.8	2.2	/	160	4	Adult Sed.	3.5	/	560
	Cruise ship	Guest room (double resident)	17.0	3.0	/	2	8	Adult Sed.	2.5	0.3	10.1
		Casino	635.5	3.0	120	763	4	Adult Mod.	3.8	0.9	3471.4
		Cafeteria/Bistro	80.0	3.0	100	80	2	Adult Mod.	3.8	0.9	376.0

(continued on next page)

Table 6 (*continued*)

Scenario[a]		Space type	Space layout		Occupant status				Ventilation configuration		
			Area [m^2]	Height [m]	Density [#/100m^2]	Number [person]	Duration [h]	Activity level[c] [−]	R_p [L/s·p]	R_a [L/s·m^2]	Ventilation rate[d] [L/s]
	Subway	Cabin	40.7	2.5	/	176	0.5	Adult Sed.	/	/	480.5
	Bus	Transit bus	30	2.5	/	60	0.5	Adult Sed.	/	/	210
		Tour coach	30	2.5	/	50	2	Adult Sed.	/	/	175
		School/shuttle bus	15.4	2.2	/	16	0.5	Child Sed.	/	/	56
	Taxi	Cabin	3	1.3	/	4	0.5	Adult Sed.	/	/	41.2

[a] References for baseline definition of various scenarios: Long-term care facility [117,118]; K-12 school [108]; College [119–122]; Meat plant [123]; Retail facility [108]; Hospital [108]; Office [124,125]; Correctional facility from typical practices; Hotel [108]; Restaurant [108]; Religious facility [126]; Casino [127]; Airplane [128,129]; Cruise ship [130,131]; Subway [132]; Transit bus [133]; Tour coach [133]; School bus [133,134]; Taxi from typical practices.
[b] Physical therapy rooms existed in buildings where residents require medical cares, such as nursing homes.
[c] Sed.: sedentary; Mod.: moderate-intensity activities; High: high-intensity activities.
[d] Outdoor air ventilation rate (calculated by Eq. (12)).
[e] When a teacher is infector, the exposure duration is 1 h and the activity level for the infector is adult moderate-intensity level.

Table 7
Possible IAQ control strategies in different scales.

Strategies	Scales			
	Building	Room	Personal	Breathing zone
Source control	• Reducing occupants	• Reducing occupants • Intermittent occupancy	• Local air exhaust	• Face masking
Ventilation	• Increased ventilation supply airflow • Elevated outdoor air fraction for ventilation system	• Semi-open partition • Displacement ventilation	• Personal ventilation	
Air cleaning	• High-efficiency filters for ventilation system	• Portable air cleaners • Upper-room UVGI		• Face masking

The proposed cases are simulated by applying different control strategies to the baseline cases. Elevated ventilation rates are analyzed, including 50%, 75% and 100% outdoor air based on the baseline total supply airflow rate. Increased total supply airflow rate are also tested, including 50% and 100% more supply flow rate within the limitation of system capacity. Advanced air distribution methods are tested. The ventilation factor (ε_{vent}) of displacement ventilation may vary greatly, depending on exact air distribution patterns. It generally has the potential to reduce the pollutant concentration in the occupied zone by a factor of 1.2–2, which is close to the zone air distribution effectiveness for displacement ventilation in ASHRAE 62.1 [22]. In this study, the ventilation factor (ε_{vent}) of displacement ventilation is assumed to be as a uniform distribution between 1.2 and 2. Installing partitions in the room to form semi-open spaces can provide a ventilation factor between 2 and 3 [142]. A more effective approach is to integrate the displacement ventilation and partitions, with a uniform distributed ε_{vent} between 14 and 100 [143]. Personal ventilation has the potential to improve the air quality by a factor of 1.4–10 [144], which is close to the air distribution effectiveness in ASHRAE 62.1 [22]. However, personal ventilation and combined displacement ventilation and partitions strategy likely require professional design before being used. Higher-efficiency filters are also considered, including MERV 13 and HEPA filters as recommended by ASHRAE [50,145].

Portable air cleaners are widely used nowadays. Zhao et al. [146] reviewed the most popular air cleaners and suggested a median CADR level of 361 m^3/h. Liu et al. [147] observed similar results. The use of air cleaners usually depends on the room scale or occupant number. Liu et al. [147] reviewed the CADR and typical applying area of air cleaners. The CADR per square meter is roughly between 6 and 16 m^3/h. The Association of Home Appliance Manufacturers (AHAM) recommended a minimum CADR of 12 m^3/h per square meter when selecting an air cleaner for home use [148], which is in accordance with the U.S. EPA's guide [149]. Therefore, the CADR of the air cleaners in this study is determined by the room area with a reference of 12 m^3/h per square meter.

Upper-room UVGI systems are considered a supplement to other control strategies. The effectiveness of UVGI system on respiratory diseases has been studied [150–153]. Appropriate use of upper-room UVGI system can inactivate airborne virus significantly. A well-designed upper-room UVGI system can typically provide equivalent 12 to 16 air changes per hour to the room [150,151]. In this study, the efficacy of an upper-room UVGI system is assumed to be 12 h^{-1}. The performance of virus inactivation by the upper-room UVGI system also depends on the room air distribution. Displacement ventilation may reduce the efficiency as the residence time of the virus in the irradiated zone decreases. The UVGI system is assumed to provide 9.6 air changes per hour (80%) when integrated with a displacement ventilation system [154].

Face masks, including cloth, surgical and N95 masks, can filter droplets significantly and protect the susceptible individuals [155]. People in the U.S. are more likely to wear cloth masks than surgical and N95 masks [156]. But surgical and N95 masks can provide better protection. Germany recently requires all individuals in the country to wear medical-grade face masks [157]. In this study, cloth masks will be considered as the most typical personal protective equipment (PPE), but surgical and N95 masks will be discussed as well. However, it may not be possible for people to wear masks in some scenarios, e.g. dining, sleeping or performing high-intensity activities [158].

2.4. Model setting and simulations

A stochastic Monte Carlo approach is applied to consider for the possible variation of the input data and increase the representativeness of the estimation since the unknown parameters in the model can vary greatly. The simulation trials for each case are 100,000. The probability distribution of each unknown parameter has been introduced in above sections. The Monte Carlo approach is performed for estimating the probability distributions of quantum generation rates and infection probabilities. This study focuses on airborne transmission due to asymptomatic infectors. The estimated proportion of active asymptomatic patients (around 1% based on current data [159–162]) is used to assign the number of index patients in the target space with a minimum of one infector. The number of new infection cases can be estimated based on the infection probability and the susceptible occupant number.

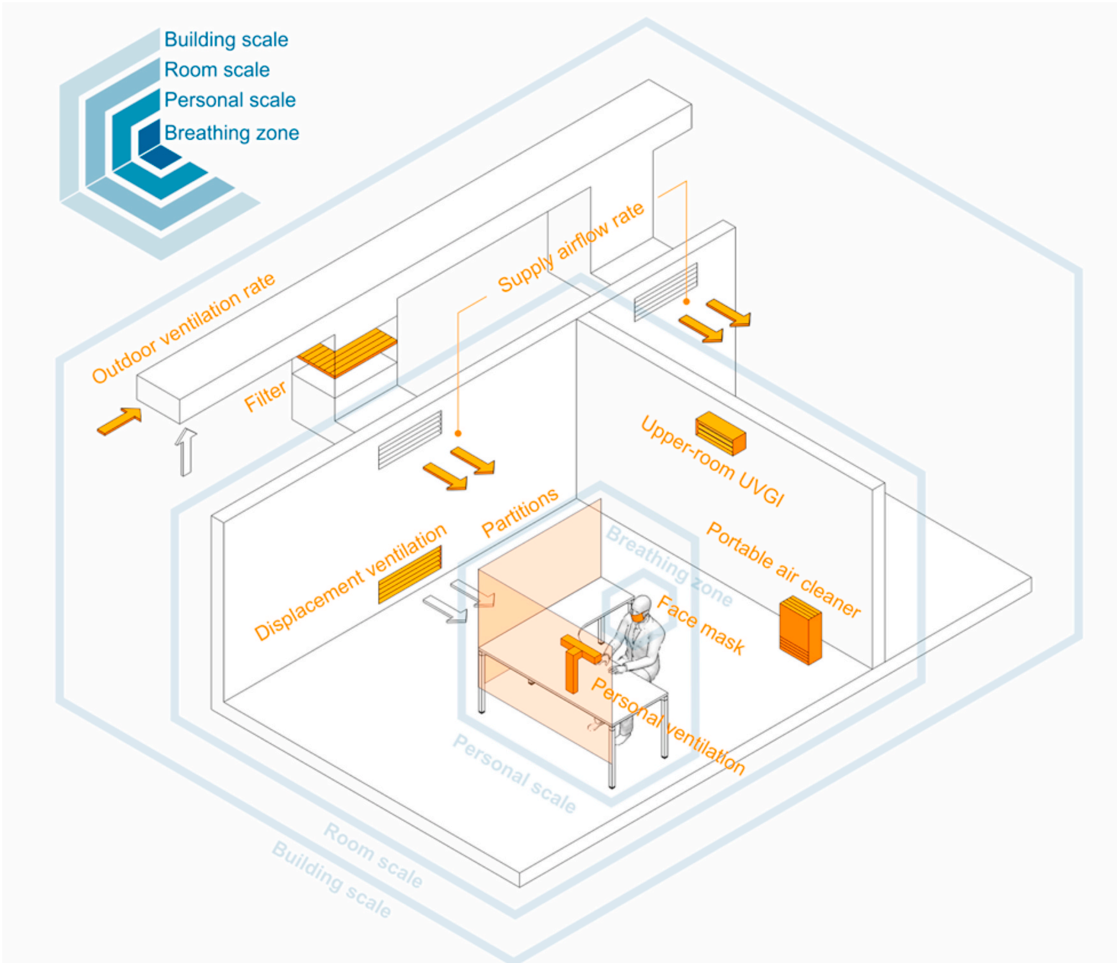

Fig. 1. Possible control strategies in different scales.

The basic reproduction number (R_0) of COVID-19 due to airborne transmission [163] can be simply represented as

$$R_0 = \frac{N_C}{I} \tag{13}$$

R_0 indicates the disease spreading in population. When $R_0 < 1$, the disease dies out; when $R_0 > 1$, an epidemic occurs in the population [68]. In order to control the COVID-19 spreading through airborne transmission, both infection probability and R_0 should be minimized in the target space.

The infection probabilities are estimated space by space. The infection probability of an occupant in the building depends on the risks of the spaces he/she visited, which indicates the importance of the occupant's behavior and scheduling. Assuming that the infection risks in different spaces are independent from each other, the overall infection probability for an occupant in the building (P_b) can be simply estimated based on the infection probabilities in all spaces he/she visited (P_i) by

$$P_b = 1 - (1 - P_1)(1 - P_2)\dots(1 - P_i) \tag{14}$$

3. Results and discussion

3.1. Baseline infection risk in different spaces

The estimated infection probability and R_0 of SARS-CoV-2 for the baseline spaces are shown in Table 9. It is observed that the standard deviations (SD) of infection probability and R_0 are relatively high, indicating a wide variation for both parameters. The infection probabilities over 10% and the R_0 over 5 are marked in the table, indicating the spaces with high infection risks. Generally, under the baseline conditions (without any control strategy), almost all the studied scenarios are facing very high infection risks.

Spaces in long-term care facilities, colleges, meat plants, hotels, restaurants, casinos and cruise ships are facing considerably higher infection probabilities (over 30%) and have a higher potential to result in a serious outbreak or even superspreading event ($R_0 > 10$). It is generally consistent with the reported cases [104–106]. For each scenario, the risks in different spaces can vary greatly. The spaces in the long-term care facility generally have high infection probabilities, particularly physical therapy room, dining room and bedroom. Considering the dense occupancy and high infection probability in the dining room, the disease is more likely to spread out in the dining room ($R_0 = 9.2$). The occupant living in the same bedroom with the index patient, is exposed to a considerable infection probability (50%). But the disease is unlikely to spread out across bedrooms ($R_0 < 1$), unless more people get infected during the gathering in other public spaces like dining room or therapy room.

The infection probabilities in K-12 school spaces are not as high as the probabilities in the long-term care facility. The dining space, gym and classroom have higher infection probabilities. However, considering the occupant number in K-12 schools, the disease has more potential to spread out among the students, particularly in the dining space. The infection risk in the library is low, probably due to the low occupancy and relatively better ventilation. For the virus spreading in classrooms, it can be observed that a teacher (13.2%) is much more likely to spread the

Table 8
Configurations of baseline and proposed cases.

Strategies		Baseline	Proposed
Ventilation system	Ventilation rate (outdoor air)	• Reference values in Table 6 (25% outdoor air)	• Baseline supply air, 50% outdoor air • Baseline supply air, 75% outdoor air • Baseline supply air, 100% outdoor air
	Total supply airflow rate	• Estimated based on ventilation rate and reference outdoor air fraction (25%)	• 50% more supply air, 25% outdoor air • Double supply air, 25% outdoor air
	Air distribution[a]	• Mixing	• Displacement ventilation • Partitions (semi-open space) • Displacement ventilation + Partitions • Personal ventilation
	Filter	• MERV 8[b]	• MERV 13 • HEPA
Standalone devices	Portable air cleaners	• None	• CADR = 12m^3/(h·m^2) × room area
	Upper-room UVGI system	• None	• Equivalent ACH[c] = 12h^{-1} or 9.6h^{-1}
PPE	Mask	• None	• Cloth mask • Surgical mask • N95 mask

[a] Mixing ventilation: $\varepsilon_{vent} = 1$; Displacement ventilation: $\varepsilon_{vent} = 1.2$ to 2; Semi-open space with partitions installed: $\varepsilon_{vent} = 2$ to 3; Displacement ventilation with partitions installed: $\varepsilon_{vent} = 14$ to 100; Personal ventilation: $\varepsilon_{vent} = 1.4$ to 10; all assuming uniform distribution.
[b] HEPA filter is used in the baseline cases of hospital operating room and airplane cabin. All other spaces use MERV 8 filter as the baseline setup.
[c] Equivalent ACH = 12 h^{-1} for mixing ventilation and equivalent ACH = 9.6 h^{-1} for displacement ventilation.

disease to the class members, than a student patient (3.8%) because of the teacher's higher q. The prediction is in agreement with the results from the other studies [164,165].

The infection risks in the college spaces vary significantly. Studying spaces, such as classrooms, library and computer labs, are generally less hazardous than the non-studying spaces. It is highly consistent with the reported outbreaks in colleges [166–171]. Gym, dining hall and Greek house in a social gathering are exposed to very high infection risks and can result in superspreading events (high R_0). Considering that people are less likely to wear masks in these spaces, reopening is not recommended for these spaces unless high-efficiency infection mitigation strategies are applied. Based on Eq. (14), for a student who only visited studying spaces, the overall infection probability is around 10%, which is much lower than the probability for a student who also visited dining hall, gym, and Greek house (89%). The infection probability in bedrooms of the resident hall is extremely high when living with an infector (52.5%). However, the disease is unlikely to spread across the bedrooms in the resident hall, unless infection happened in other public spaces.

The employees in the processing room of meat plant meet great challenges of COVID-19 infection. Superspreading event is likely to happen in the processing room with dense employees (R_0 over 28). It is consistent with the frequently reported superspreading events in meat plants [123,172–180]. The retails also have high infection risks. The infection probability in smaller store is much higher than the probability in larger store and mall. But the mall and large store usually have more customers, thus have more potential to spread out the disease to more

Table 9
Infection probability and basic reproduction number (R_0) for baseline cases.

Scenario		Space type	Infection probability [%]		R_0 [-]	
			Mean	SD	Mean	SD
Long-term care facility		Bedroom (double)	**50.0**	29.9	0.5	0.3
		Dining room	**48.2**	28.7	**9.2**	5.5
		Living room	**10.6**	9.4	0.4	0.4
		Physical therapy room	**78.3**	29.0	3.1	1.2
Educational	K-12	Classroom (*between students*)	3.8	3.6	1.3	1.2
		Classroom (*teacher is the infector*)	**13.2**	12.0	4.5	4.1
		Library	0.3	0.2	0.2	0.2
		Cafeteria/ dining room	**10.1**	8.9	**8.9**	7.9
		Gym	8.3	7.7	**5.6**	5.2
	College	Classroom (small)	3.1	2.9	0.7	0.7
		Classroom (large)	0.9	0.8	0.8	0.8
		Library (public study area)	0.9	0.8	0.8	0.8
		Auditorium	1.1	1.1	1.1	1.1
		Computer lab	2.0	1.9	0.7	0.7
		Dining hall	**14.6**	12.8	**13.8**	12.1
		Study lounge	3.8	3.6	0.8	0.7
		Gym (fitness area)	**38.0**	27.0	**22.4**	15.9
		Resident hall (bedroom)	**52.5**	30.4	0.5	0.3
		Greek house (social gathering)	**77.5**	30.2	**14.7**	5.7
Manufacturing facility	Meat plant	Processing room (dense)	**53.7**	31.2	**28.5**	16.5
		Processing room (sparse)	**47.8**	29.9	**12.4**	7.8
Retail	Standalone	Core shopping space	8.4	7.8	**6.6**	6.2
	Strip mall	Store (large)	**17.8**	15.4	4.8	4.1
		Store (small)	**30.1**	23.0	3.9	3.0
Healthcare facility	Hospital	Operating room[a]	1.0	0.9	0.0	0.0
		Patient room (patient + doctor)	4.5	4.2	0.0	0.0
		Physical therapy room	**29.0**	22.4	**7.2**	5.6
		Dining room	6.4	6.1	4.8	4.5
		Lobby	6.7	6.5	1.3	1.3
Office	Medium	Open plan office	**12.6**	11.0	1.1	1.0
		Enclosed office	**39.8**	26.7	0.4	0.3
		Conference room	6.2	5.7	1.3	1.2
		Lounge	1.4	1.3	0.6	0.6
Correctional facility	Prison	Housing (double resident cell)	**59.5**	31.4	0.6	0.3
		Housing (dormitory)	7.9	7.2	3.1	2.8
		Dayroom	**11.6**	10.2	**5.4**	4.8
Lodging	Hotel	Guest room/ bedroom	**41.0**	27.2	0.4	0.3
		Banquet/ dining room	**27.8**	21.5	**21.2**	16.4
		Lobby	**12.0**	10.8	**11.6**	10.5

(*continued on next page*)

Table 9 (*continued*)

Scenario		Space type	Infection probability [%]		R_0 [-]	
			Mean	SD	Mean	SD
Other public facilities	Restaurant	Dining room (ordinary)	**14.7**	12.8	**12.6**	11.0
		Dining room (fast-food)	8.4	7.8	**6.7**	6.2
	Religious	Worship hall	1.7	1.6	1.7	1.6
	Casino	Poker room	**47.0**	29.6	**35.2**	22.2
Transportation spaces	Airplane	Cabin	2.3	2.2	1.8	1.7
	Cruise ship	Guest room (double resident)	**56.7**	31.1	0.6	0.3
		Casino	**41.7**	27.9	**39.4**	26.4
		Cafeteria/ Bistro	**20.3**	16.3	**16.0**	12.9
	Subway	Cabin	0.6	0.5	0.5	0.5
	Bus	Transit bus	0.6	0.6	0.4	0.4
		Tour coach	2.9	2.7	1.4	1.3
		School/ shuttle bus	2.2	2.1	0.3	0.3
	Taxi	Cabin	3.2	3.0	0.1	0.1

[a] Surgical masks are used.

people. Physical therapy room, dining room and lobby are the spaces with higher risks in the hospital. The infection probabilities in patient room are relatively low, because of the high ventilation rate per occupant. The infection probability in the operating room is very low (1%) due to the use of surgical masks. The office spaces generally have high infection probabilities, particularly the enclosed office (39.8%). But the disease is more likely to spread out to more people in other public spaces with more occupants, such as open plan offices and conference rooms (higher R_0).

The susceptible individual who lives together with an infector in the same double-residence cell in the prison is highly possible to get infected (nearly 60% infection probability). Then the COVID-19 can spread to more people during the gathering activities in the dayroom ($R_0 = 5.4$). Another type of housing unit, i.e. dormitory, are more likely to spread the disease than the housing cell, likely due to its high occupancy. Considering that the actual living environment in the prison may be even worse, e.g. more crowded dormitory or cell, longer gathering time and inadequate ventilation, the infection risks in real prison scenarios could be much higher. It can partially explain the frequent outbreaks in the prison [181–186], as well as the severe superspreading phenomenon [28].

For a hotel, the susceptible individual faces extremely high infection probability in the bedroom where an infector occupied, but the disease is more likely to spread to other people during the contacts in a public space (e.g. dining room or cafeteria). Banquet room has the highest potential to spread out the disease, due to the high-intensity activities and dense occupancy. Restaurants have high infection risks and can spread out the disease significantly, as encountered in the reported actual cases [187]. The infection probability in the worship hall of a religious building is not as high as the probability in other public spaces. But the disease can still spread out among the people in the worship hall ($R_0 = 1.7$). The infection risk in the casino is almost the highest among all the scenarios. Considering the high-intensity activities and crowded occupancy, the casino has a very high potential for superspreading outbreak ($R_0 = 35.2$).

For the transportation spaces, cruise ship basically has the highest infection risk since it typically contains casinos and dining spaces, where the disease can spread out readily. The infection probability in airplanes is similar to the probability in tour coaches and school buses, around 2–3%. Due to the considerable passengers presented in the airplane and tour coach, the disease can spread out in these two scenarios ($R_0 = 1.8$ for airplane and $R_0 = 1.4$ for tour coach). The infection risks during shorter transits are typically lower than the risks during longer transits.

3.2. Effectiveness of multi-scale control strategies

The infection risks, including infection probability and R_0, in different spaces using various control strategies are calculated. The reductions of the infection probability and R_0 for the same case should be same since the susceptible number is the same. The infection risk and R_0 reduction of each individual control strategy are determined relative to the baseline case by the model simulation (Fig. 2). The ventilation system with more outdoor air can reduce more infection risk. An average risk reduction of 27% can be achieved when using 100% outdoor air (OA). Increasing the total supply airflow rate can reduce considerable infection risk as well. Doubling the total supply airflow rate can reduce around 37% risk in average. A higher-efficiency filter in the ventilation system can supply more cleaned air. A HEPA filter can reduce equivalent infection risk to the strategy applying 100% outdoor air. Room air distributions can greatly impact the infection risk. Displacement ventilation (DV) can reduce average 26% infection risk, while installing partitions can reduce around 46% risk. Personal ventilation (PV) can reduce more infection risk, average 67%. Integrating displacement ventilation and partitions can maximize the ventilation factor with an average 96% of infection risk reduction. The impacts of the standalone air cleaning technologies vary greatly in various spaces, from below 10% risk reduction to over 85%. The average risk reduction for air cleaners is around 31%, and the reduction for the upper-room UVGI system is around 59%. Wearing cloth masks can generally reduce considerable infection risk (average 48%), while surgical and N95 masks can reduce more risks, i.e. average 63% and 99%, respectively.

In addition to the infection risk reduction potential, the functional scale and cost should also be considered. Some control strategies, such as high-efficiency filters for the ventilation system, may not be able to provide as high as infection risk reduction as strategies like applying personal ventilation or wearing masks. But it can improve the IAQ for the whole building, indicating that it is functional for a larger scale of susceptible individuals. Besides, some control strategies may have a higher cost, e.g. personal ventilation or displacement ventilation, which makes these strategies difficult to implement in many buildings. There have been many investigations regarding the effectiveness of possible control strategies for mitigating the infection risk of COVID-19. However, most of these studies conducted qualitative analyses or did not consider the costs and functional scales of the strategies [43–45]. The mean infection risk reduction potentials and approximate costs of

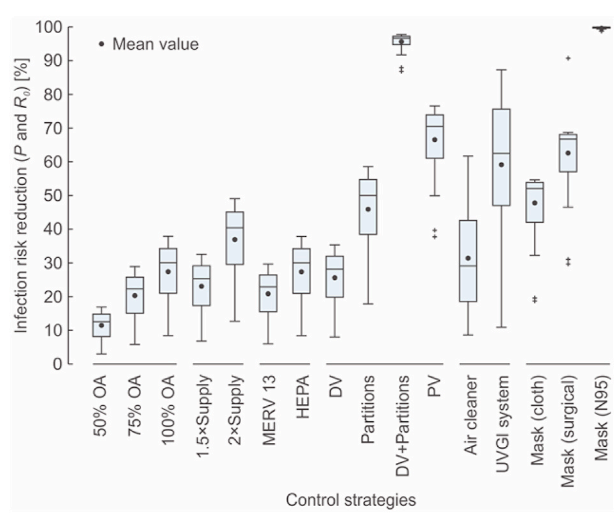

Fig. 2. Risk reduction distribution of the mean infection probabilities and R_0 in different spaces.

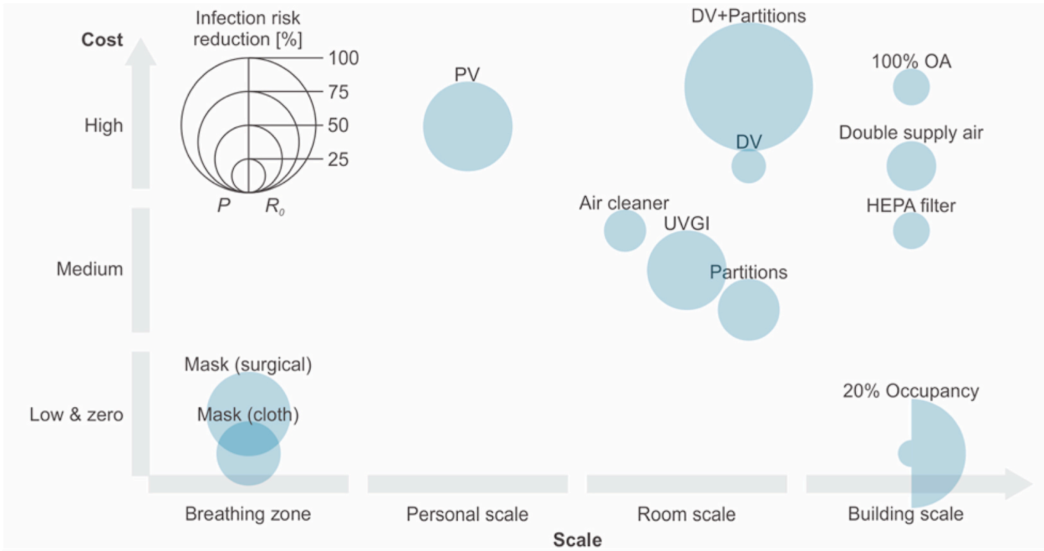

Fig. 3. Infection risk reduction potentials and costs of control strategies in different scales.

control strategies in different scales are shown in Fig. 3. Air cleaners, UVGI systems, partition installation and HEPA filters are considered as medium-cost strategies because they usually require the purchase of a few devices or materials. Personal and displacement ventilations are considered as high-cost strategies because they require an upgrade for the entire ventilation system or some parts of it. The ventilation systems using 100% outdoor air or doubling total also considered high-cost strategies, considering the additional energy consumption for heating or cooling the elevated outdoor air.

It can be observed from Fig. 3 that integrating the displacement ventilation and partitions can reduce more infection risk in the room scale but can be costly as well, while using displacement ventilation alone has a much lower reduction in infection risk. Personal ventilation can considerably reduce the infection risk at the personal scale but has a high cost. Personal ventilation can only be used in scenarios where occupants are more stationary. Using air cleaners has a medium cost and a moderate potential for infection risk reduction. Higher CADR for air cleaners is encouraged. Installing partitions and using the UVGI systems can have higher risk reduction potentials. Wearing mask has a moderate infection risk reduction potential and a low cost but can only work for the breathing zone. The effectiveness of the occupancy restriction strategy is illustrated in Fig. 3 as well. The 20% occupancy restriction does not change the infection probability greatly (average 20%) since at least one infector is assumed to exist in the space. But the R_0 can be reduced significantly (average 81%) as less susceptible people will be infected. Therefore, occupancy restriction is a strategy that can significantly contribute to the control of disease spreading in the population. Another potentially effective and low-cost room-scale strategy on source control is the intermittent occupancy strategy, which implements intermittent breaks in room occupancy [135]. It requires all occupants to leave the room periodically and the room occupancy time should be reduced as much as possible. It was reported that asking students to leave the room during the 15min break after a 35min class can reduce 35% inhaled pathogen compared to when the students stayed in the room during the break [135]. However, this study adopts the steady-state model, which does not consider the variation of indoor infectious particle concentration over time. The intermittent occupancy strategy is therefore not discussed in this study.

Although some control strategies in building and room scales may have higher costs and relatively smaller risk reduction potential, it does not mean that the infection risk mitigation should primarily rely on the strategies in smaller scales. Control strategies in building and room scales can reduce the “background” infection risk in the confined space, while strategies in personal scale and breathing zone can provide additional local protection to occupants. Considering that personal ventilation and mask wearing are unlikely to be implemented in some scenarios, enhanced ventilation is therefore essential. Besides, the high risk reduction potential of personal ventilation and mask wearing depends on the proper use of them. For example, improper use of face masks or any violation of mask wearing guidelines can put the susceptible occupants at risk. Therefore, when designing risk mitigating strategies, the risk reduction, cost, and scale of the control strategy should be considered comprehensively, rather than just focusing on one aspect.

3.3. Integrated effects of multiple control strategies

A single control strategy usually cannot provide adequate protection for occupants. It is necessary to integrate multiple strategies. Engineering control strategies at the building scale, i.e. elevated outdoor air, increased total supply air and higher-efficiency filters, should be applied as the primary mitigation strategy because they protect a large number of occupants and can be more reliably applied. Room-scale control strategies, including air distribution strategies and standalone air cleaning devices, should be applied to supplement the building level strategies. Personal ventilation system can be adopted to further reduce the risk of infection at the personal scale. Administrative strategies, such as restricting occupancy, must be implemented when the engineering controls cannot provide a safe environment. Face masks are essential because they reduce virus emission and protect individuals at the personal level.

For the control strategies at the building scale, applying HEPA filters is equivalent to the effectiveness of adopting 100% outdoor air. When HEPA filters are adopted in the ventilation system, elevating the outdoor air does not improve the air quality significantly. Doubling the total supply air within the system capacity can further increase the clean air supply. Fig. 4 demonstrates the mean infection probabilities for three enhanced ventilation strategies in hotel banquet room and open plan office. The case applying double supply airflow rate, 25% outdoor air and HEPA filter has the same level of infection risk as the case using 100% outdoor air. Considering the substantial costs due to energy consumption penalty, the strategy of applying 100% outdoor air is not favored, unless HEPA filters cannot be used in the system. Therefore, the favored strategy for the ventilation system is the integration of double supply air and HEPA filter.

The integrated effectiveness of room-scale air distribution strategies and standalone air cleaning technologies in the hotel banquet room is

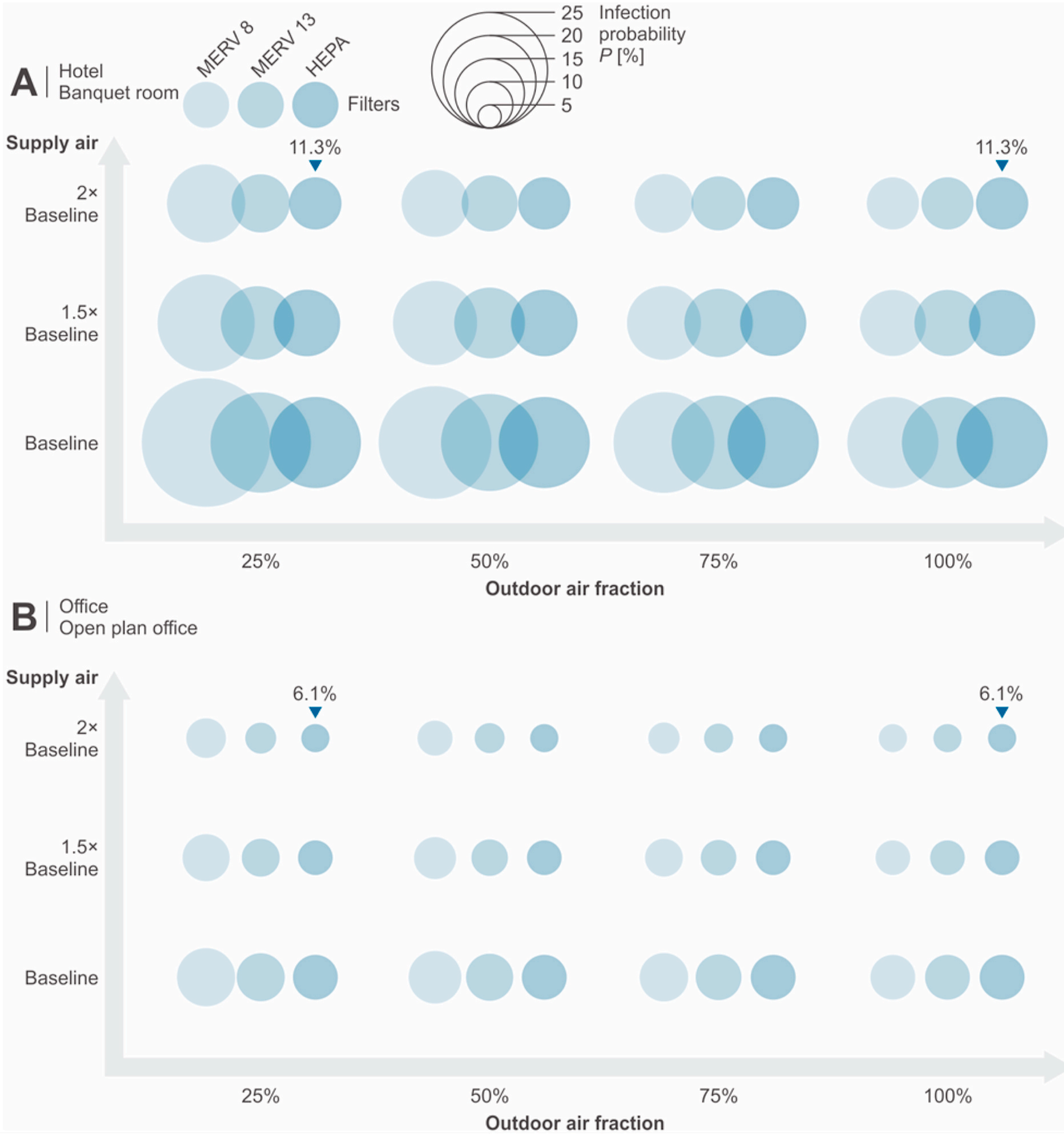

Fig. 4. Infection probability of integrating multiple ventilation system strategies in (A) hotel banquet room and (B) open plan office.

illustrated in Fig. 5 as an example. Partitions are favored than the displacement ventilation system due to the higher risk reduction potential, especially considering the higher cost of a displacement system. Combining displacement ventilation and partitions strategy can significantly reduce the infection probability. But professional design has to be done to better organize the air distribution for maximizing its effectiveness. Installing partitions is likely a more practical strategy. Portable air cleaners (AC) and upper-room UVGI systems can provide additional clean air but may not be so effective when the indoor infection probability is already at a lower level. However, for those spaces that cannot install partitions or apply displacement ventilations, air cleaners and UVGI system can mitigate more risks. When room-scale strategies still cannot maintain a safe indoor environment, personal ventilation system should be considered whenever possible. Further, administrative restriction on indoor occupancy needs to be conducted to reduce the disease spreading among people for those cases with high R_0. Face masks are considered as the final protection where hazards are not well controlled.

The proposed approach has also been applied to the studied building and transportation spaces to find the best practice for risk mitigation. The acceptable level of the COVID-19 infection probability is not clear. In this study, the mean infection probability should be reduced to a level below 0.1%, which is also a risk reference accepted by Buonanno et al. [41]. The mean value of R_0 should be lower than one. The possible practices for mitigating the infection risks to the target level for each space are shown in Table 10. The technology marked by a black dot is a technology that is applied in the target space. Otherwise, it means the technology is not implemented. The slash sign in the table indicates the technologies which are not practical to be applied in the target space. It is observed from the results that most spaces require double supply air, HEPA filter, displacement ventilation, partitions, air cleaners and UVGI systems. Dining spaces and open plan offices may need personal ventilation to provide additional clean air. Some other spaces, such as meat plant processing room and casino spaces, must request the occupants to

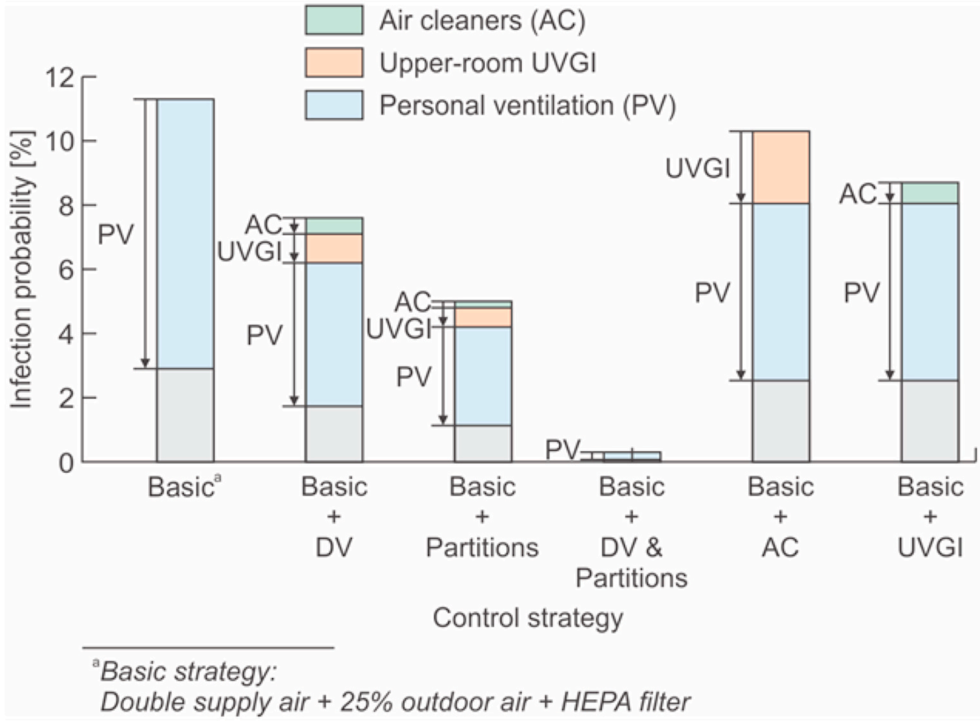

Fig. 5. Infection probabilities of integrating different air distribution strategies and standalone air cleaning technologies in the hotel banquet room.

wear masks. The housing spaces (e.g. bedroom, resident hall and resident cell) in various scenarios generally have a high infection probability since some strategies cannot be applied in bedrooms. The social gathering of college students in Greek houses has the highest risk even though all possible control strategies are applied. Therefore, social gathering in Greek houses should not be performed at the current stage. For most spaces, the infection risk can be reduced to be less than 0.1% using the integrated engineering control strategies according to the modeling. Wearing face masks can further reduce the risk, especially in public spaces where close contact with an infector can result in a higher risk.

4. Summary and conclusions

A modified SARS-CoV-2 airborne transmission model has been applied to systematically evaluate multi-scale IAQ control strategies in mitigating the indoor infection risk in buildings and vehicles. Probability functions of essential model parameters were determined based on a comprehensive review of available literature to provide inputs for the stochastic simulation by the Mont Carlo method. Control strategies at building, room, personal and breathing-zone scales, including elevated outdoor air, high-efficiency filters, advanced room air distribution, standalone room air cleaning, personal ventilation and face masks, were analyzed. It was observed that under the established baseline conditions, the spaces in long-term care facilities, colleges, meat plants, hotels, restaurants, casinos and cruise ships would face considerable infection probabilities (over 30%) and have a higher potential to spread out among people ($R_0 > 10$).

The effectiveness of the control strategies has been analyzed for each space type in terms of risk reduction relative to the baseline conditions. More outdoor ventilation air can reduce more infection risk as expected. An average of 27% reduction of infection risk can be achieved with 100% outdoor air (OA) for the ventilation system. A HEPA filter for recirculated air can have the equivalent reduction. Doubling total supply airflow rate can reduce the infection risk by approximately 37% in average. Room air distributions can significantly impact the infection risk. Displacement ventilation can reduce the infection risk by 26%, while installing partitions can reduce more risk, around 46%. An average of 96% infection risk reduction can be achieved by integrating displacement ventilation and partitions. Personal ventilation can reduce the infection risk by 67%. The average risk reduction by air cleaners is around 31%, and the average reduction for the upper-room UVGI system is 59%. Wearing cloth masks can generally reduce considerable infection risk (average 48%), while surgical and N95 masks can reduce even more infection risk (63% and 99%, respectively).

When designing the risk mitigation strategies, the effectiveness, cost, and scale of the control strategy should be considered comprehensively. Enhanced ventilation at the building scale generally has higher costs due to increase in energy consumption for air heating or cooling but can mitigate risk for a large number of occupants and can be more reliably applied. Standalone room air cleaning is effective with moderate cost. Combining advanced air distribution (such as displacement and personal ventilation) with semi-open partition has high risk reduction potential, but with relatively high costs. Control strategies at building and room scales can reduce the "background" infection risk indoors, while strategies at personal scale and breathing zone (face masks) can provide additional needed local and personal protections.

To mitigate the infection risk to the target level ($P < 0.1\%$, $R_0 < 1$), most spaces require doubling supply air, HEPA filter, displacement ventilation, partitions, air cleaners and UVGI systems. Dining spaces and open plan offices may need personal ventilation to provide additional clean air. Some other spaces, such as meat plant processing room and casino spaces, need to require occupants to wear masks. The housing spaces generally have a high infection probability since many strategies cannot be applied in bedrooms. The social gathering of college students in Greek houses has the highest risk. Face masks are always recommended to further reduce the risk, especially due to possible close contact with an infector.

The well-mixing assumption of the model does not consider the detailed local airflow pattern in the room, which can impact the local infection risk for each individual in the room. Further studies considering the detailed indoor air distribution are needed for better understanding the local infection risk within a space. The definitions of the baseline cases in this study represent the most typical configurations.

Table 10
Possible practice for mitigating the infection risk to the target level.

Scenario		Space type	Control strategy[a]										Infection risk[f]	
			Double supply	100% OA[b]	HEPA filter	DV[c]	Part.[d]	AC	UVGI	PV	20% Occup.[e]	Mask	P [%]	R_0 [-]
Long-term care facility		Bedroom (double)	●		●	●	/	●	●	/	/	/	**10.3**	0.1
		Dining room	●		●	●	●	●	●	●		/	**0.17**	<0.1
		Living room	●		●	●	●	●	●	●	/		<0.1	<0.1
		Physical therapy room	●		●	●	●	●	●	/	/	●	**1.4**	<0.1
Educational	K-12	Classroom (*between students*)	●		●	●	●	●	●				<0.1	<0.1
		Classroom (*teacher is the infector*)	●		●	●	●	●	●	●			<0.1	<0.1
		Library	●		●		●						<0.1	<0.1
		Cafeteria/dining room	●		●	●	●	●	●				<0.1	<0.1
		Gym	●		●	●	●	●	●	/		/	<0.1	<0.1
	College	Classroom (small)	●		●	●	●	●	●				<0.1	<0.1
		Classroom (large)	●		●		●	●	●				<0.1	<0.1
		Library (public study area)	●		●		●	●	●				<0.1	<0.1
		Auditorium	●		●	●	●	●	●				<0.1	<0.1
		Computer lab	●		●	●	●	●	●				<0.1	<0.1
		Dining hall	●		●	●	●	●	●	●		/	<0.1	<0.1
		Study lounge	●		●	●	●	●	●				<0.1	<0.1
		Gym (fitness area)	●		●	●	●	●	●	/		/	**0.5**	0.3
		Resident hall (bedroom)	●		●	●	/	●	●	/	/	/	**11.8**	0.1
		Greek house (social gathering)	●		●	●	/	●	●	/		/	**36.3**	**6.9**
Manufacturing facility	Meat plant	Processing room (dense)	●		●	●	●	●	●	●		●	**0.1**	<0.1
		Processing room (sparse)	●		●	●	●	●	●	●		●	<0.1	<0.1
Retail	Standalone	Core shopping space	●		●	●	/	●	●	/		●	**0.5**	0.4
	Strip mall	Store (large)	●		●	●	/	●	●	/		●	**1.0**	0.3
		Store (small)	●		●	●	/	●	●	/		●	**2.0**	0.3
Healthcare facility	Hospital	Operating room	●		●	●	/	●	●	/	/	●[g]	**0.3**	<0.1
		Patient room (patient + doctor)	●		●	●	●	●	●		/		<0.1	<0.1
		Physical therapy room	●		●	●	●	●	●	/		●	**0.2**	<0.1
		Dining room	●		●	●	●	●	●			/	<0.1	<0.1
		Lobby	●		●	●	/	●	●	/		●	**0.3**	<0.1
Office	Medium	Open plan office	●		●	●	●	●	●	●			<0.1	<0.1
		Enclosed office	●		●	●	●	●	●	●	/	●	<0.1	<0.1
		Conference room	●		●	●	●	●	●				<0.1	<0.1
		Lounge	●		●	●	●	●	●				<0.1	<0.1
Correctional facility	Prison	Housing (double resident cell)	●		●	●	/	●	●	/	/	/	**17.3**	0.2
		Housing (dormitory)	●		●	●	/	●	●	/		/	**1.2**	0.5
		Dayroom	●		●	●	●	●	●	●			<0.1	<0.1
Lodging	Hotel	Guest room/bedroom	●		●	●	/	●	●	/	/	/	**7.3**	<0.1
		Banquet/dining room	●		●	●	●	●	●	●		/	<0.1	<0.1
		Lobby	●		●	●	/	●	●	/		●	**0.9**	0.8
Other public facilities	Restaurant	Dining room (ordinary)	●		●	●	●	●	●	●		/	<0.1	<0.1
		Dining room (fast-food)	●		●	●	●	●	●			/	<0.1	<0.1
	Religious	Worship hall	●		●	●	●	●	●				<0.1	<0.1
	Casino	Poker room	●		●	●	●	●	●	●		●	<0.1	<0.1
Transportation spaces	Airplane	Cabin	●		●	●	●	/	/				<0.1	<0.1
	Cruise ship	Guest room (double resident)	●		●	●	/	●	●	/	/	/	**14.0**	0.1
		Casino	●		●	●	●	●	●	●		●	<0.1	<0.1
		Cafeteria/Bistro	●		●	●	●	●	●	●			<0.1	<0.1
	Subway	Cabin	●		●		/	/	/	/	/	●	<0.1	<0.1
	Bus	Transit bus	●		●		/	/	/	/	/	●	<0.1	<0.1
		Tour coach	●		●	●	●	/	/				<0.1	<0.1
		School/shuttle bus	●		●	●	●	/	/				<0.1	<0.1
	Taxi	Cabin	●		●	/	●	/	/	●	/		<0.1	<0.1

[a] Black dot (●) means the technology is used; Slash sign (/) indicates the technologies which are not practical to be applied in the target space.
[b] 100% outdoor air (OA) strategy can be an alternative for HEPA filter, whenever HEPA filter cannot be used in the system.

[c] Displacement ventilation (DV) is less favored compared to the use of partitions, air cleaners or UVGI systems, since it requires professional design for maximizing its effectiveness.
[d] Part.: using partitions.
[e] 20% Occup.: restricting the room occupancy to 20% of its capacity for cases with high R_0.
[f] Infection probability P should be lower than 0.1% and R_0 should be lower than 1. Those cases that cannot achieve the target risk level are marked.
[g] Surgical masks are used.

But the actual risk in a specific space highly depends on its specific configurations, considering that the building spaces/rooms may vary greatly case by case. The present work only provides a reference evaluation for each scenario. Besides, a more quantitative analysis of the cost and energy consumption of different control strategies is also needed in further studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.107926.

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