11-2020

Effectiveness of Building Systems Strategies for Mitigation of Airborne Transmission of SARS-CoV-2

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Final Report to Carrier Corporation

by

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November 2020

Ref: SU Contract # CON04883
Internal Report No. BEESL-R11-17-2020-JZ
Distribution: Carrier Corporation, Syracuse University

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Abstract

Airborne transmission has been recognized as a major transmission pathway for the infectious disease COVID-19. This study investigated the effectiveness of several indoor air quality (IAQ) control strategies on the mitigation of airborne transmission of SARS-CoV-2, the virus that causes COVID-19. The well-known airborne disease infection risk model (Wells-Riley equation) was used to estimate the infection risk of the SARS-CoV-2 in seven (7) different types of spaces including conference center/ballrooms, hotel bistro//cafeteria, hotel lobby, classrooms (lecture), conference room/small classroom, hotel or cruise ship guest rooms and open plan offices. The IAQ control strategies included increased ventilation rate, improved air distribution system and filtration, semi-open space partition, in-room air purification and disinfection, and personal protective equipment. The effectiveness of each individual strategies and selected combined strategies were evaluated using the risk estimation model. Several integrated (layered) mitigation strategies were recommended and classified based on their relative cost and effort of implementation. In addition, the potential of several selected air cleaning/disinfection products was also evaluated.

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 54.6 million people infected and 1,321 thousand people dead globally and 11.1 million people infected and 246 thousand people dead in the U.S. by November 16th, 2020 [1,2]. There are typically three possible transmission routes of infectious respiratory viruses: (1) the fomite route through direct contact with pathogen sources or indirect contact with contaminated surfaces, (2) droplet-borne route transmitted by medium (5-100μm) or large droplets (>100μm), and (3) airborne route (short-range and long-range) through aerosols (<5μm) (**Fig. 1**). The transmission of SARS-CoV-2 through the fomite and droplet-borne routes have traditionally been considered as the main paths, but more and more recent studies have revealed the possibility of airborne transmission, particularly in buildings with poor ventilation [3]. Some studies have identified airborne transmission as a likely major route for asymptomatic person-to-person transmission of SARS-CoV-2 [4–6].

In order to reduce the infection risk in indoor environments, various indoor air quality control strategies have been suggested to mitigate the airborne transmission, including source control, ventilation, and air cleaning/filtration across multiple scales from a whole building to zones and rooms, and to cubical and personal microenvironments [7,8]. However, the effectiveness of these strategies for reducing the risk of COVID 19 infection has not been well evaluated for specific indoor spaces such as open-plan offices, classrooms, hospitality guest rooms, restaurants, and cruise line guest cabins, where airborne transmission are more likely to occur due to high occupancy densities.

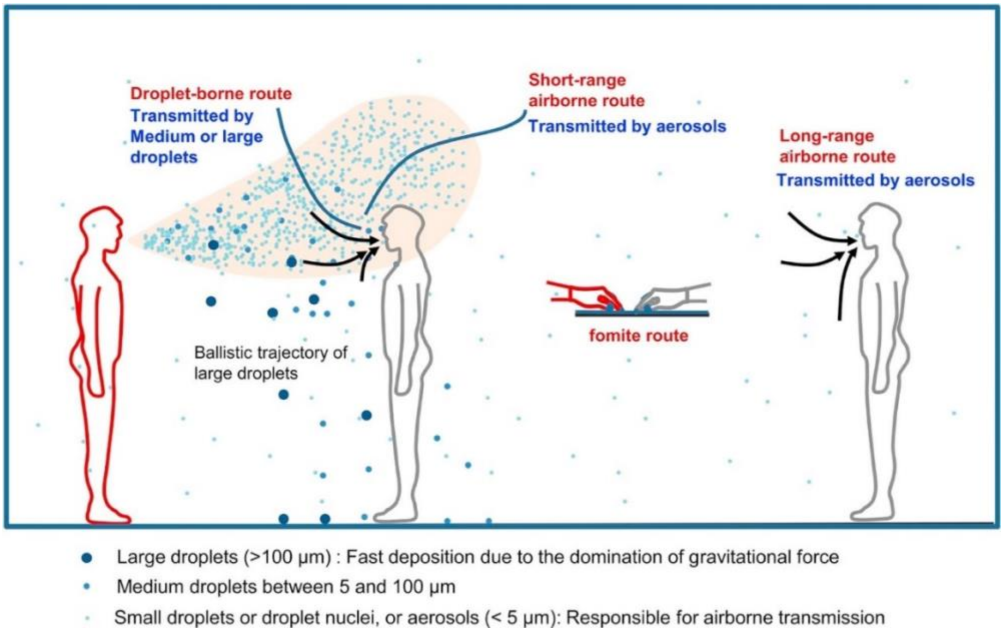


Fig. 1 Illustration of different transmission routes of infectious respiratory viruses, adapted from [9].

2. Goal and Objectives

This work was in direct response to Carrier's Research Opportunity on "Effectiveness of Building Systems Strategies for Mitigation of Airborne Transmission of SARS-COV-2". The goal was to identify evidence-based building systems strategies for mitigating airborne transmission and evaluate their relative effectiveness for specific indoor spaces, including open-plan offices, classrooms, hospitality guest rooms, and cruise line guest cabins. It was accomplished through the following specific objectives:

1) Develop a method and procedure to estimate the risk of COVID 19 infection associated with airborne transmission based on the estimation of the inhalation dose exposure to SARS-CoV-2;
2) Define baseline cases and estimate their infection risks for specific indoor spaces including open-plan offices, classrooms, hospitality guest rooms, and cruise line guest cabins under the current typical indoor configurations and HVAC system design and operation;
3) Identify mitigation strategies feasible for each of the specific spaces, including system retrofits and modifications to system operation and controls; and
4) Evaluate the effectiveness of the identified retrofit and control strategies in reducing the risk of infection relative to the baseline conditions and select the most effective ones and their combinations.

3. Methods

This study adopted a widely used empirical model with well-established baseline cases to evaluate the performance of different mitigation strategies.

3.1. Theoretical model

3.1.1. Wells-Riley model

One widely used approach for estimating the infection risk of airborne transmission in enclosed environments is the well-known Wells-Riley equation [10,11]. The model (Eqn. 1) is usually used to model the infection risk assuming a steady-state and well-mixed indoor environment. This model has also been extended by other researchers to include unsteady exposure [12] and imperfect mixing [13,14]. The modification of the original model for the unsteady-state and imperfect mixing condition will be discussed in more detail in the subsequent subsections. The infection possibility (P) is calculated as a function of the inhalation exposure dose [15], which depends on the number of virus carrier at the start of the exposure period (I), the infectious quantum generation rate per virus carrier (q), the fraction of infectious particle penetration through the mask (R), pulmonary ventilation rate (p), exposure time (t) and the equivalent fresh air changes in the room (Λ):

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

where N_C is the number of new cases, and N_S is the number of susceptible people. The fraction of infectious particle penetrated through the mask or respirator for susceptible (R_S) and infected (R_I) population can be calculated by Eqn. 2 and 3, respectively, in which both depend on the mask filtration efficiency (η_S or η_I). The penetration fraction (R) equals 1 when no mask or respirator is used during the exposure period. 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/respirator over the entire exposure period. It equals 1 when the mask is worn during the entire exposure period.

$$R_S = 1 - f_{R,S}\eta_S \quad (2)$$

$$R_I = 1 - f_{R,I}\eta_I \quad (3)$$

The equivalent air change rate (Λ) represents the equivalent total fresh/clean supply airflow rate for diluting the infectious virus concentration in the room air or the removal rate of the infectious viruses averaged over the room volume (i.e., total fresh/clean air delivery rate per unit of room air volume). It depends on the equivalent ventilation rate (λ_{vent}), pathogen inactivation rate by ultraviolet germicidal irradiation (UVGI) systems (k_{UV}) and infectious particle deposition rate ($k_{deposition}$), as shown in Eqn. 4. The equivalent ventilation rate includes the total equivalent fresh air supplied by the HVAC system (λ_{HVAC}) and infectious particle removal rate by portable air cleaners ($k_{AirCleaner}$). The fraction (f) of operation time over the entire exposure period is applied to each term in Eqn. 5 to determine the overall ventilation rate. The fresh/clean air change rate supplied by the HVAC system (λ_{HVAC}) includes the outdoor part and the recirculated part. The recirculated fresh/clean air change rate (Eqn. 6) depends on the recirculated air change rate ($\lambda_{recirculated}$) and the filtration efficiency of the filters in the HVAC system for the virus-containing particles (η_{filter}).

$$\Lambda = \lambda_{vent} + f_{UV}k_{UV} + k_{deposition} \quad (4)$$

$$\lambda_{vent} = f_{HVAC}\lambda_{HVAC} + f_{AirCleaner}k_{AirCleaner} \quad (5)$$

$$\lambda_{HVAC} = \lambda_{outdoor} + \lambda_{recirculated}\eta_{filter} \quad (6)$$

A portable air cleaner can supply additional fresh/clean air to the space. The infectious particle removal rate (or fresh air supply 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):

$$k_{AirCleaner} = \lambda_{AirCleaner}\eta_{AirCleaner} = \frac{CADR}{V} \tag{7}$$

The actual ventilation rate (λ_{vent}) is a spatial-variable that depends on the particular location in the space. Thus, an additional factor will be applied to the original equation in Eqn. 5 to adapt it to imperfect mixing scenarios. The infectious particle removal rates due to UVGI systems and deposition, and the fresh air supplied by air cleaners are assumed to be uniform in the whole space. Therefore, these terms do not have to be modified for imperfect mixing.

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 UV irradiation (k_{UV}). The infectious particle deposition rate ($k_{deposition}$) relies on an approximate estimate of gravitational settling (Eqn. 8) from Nicas et al. [16], which depends on the particle diameter (d_p) and room height (H). It is assumed that the deposited particles will not be resuspended into the air space again.

$$k_{deposition} = \frac{0.108{d_p}^2(1 + \frac{0.166}{d_p})}{H} \tag{8}$$

The pathogen natural inactivation rate is not considered in this study, in part because of the lack of existing data on the size-resolved natural inactivation rate of SARS-CoV-2 and in part because quanta generation rates (q), when back-calculated using Eqn. 1, will inherently account for any inactivation that occurred during the case study period [10].

3.1.2. Model modification for imperfect mixing

The original Wells-Riley model is based on the perfect-mixing assumption for room air. However, room air is typically not well-mixed in real scenarios. The indoor airflow pattern is highly dependent on room configurations (e.g., layout and furniture placement) and ventilation methods (e.g., displacement ventilation). In an imperfectly mixed space, the local ventilation rate (λ_{vent}) is a spatial-variable that depends on the particular location in the space. If the amount of exhaled breath generated by the infectors and inhaled by a susceptible person in a particular spatial location is known, the susceptible persons' infection risk can be estimated [11]. This can be done by conducting tracer gas measurements, which tracer gas is released from the locations of the infectors and the concentrations of the tracer gas at the locations of each susceptible person are then measured. It can also be obtained numerically by computational fluid dynamics (CFD) [17,18].

To incorporate this approach in our modified Wells-Riley model, a factor of ventilation efficiency ε_{vent} is applied to the ventilation rate in the model. The infectious particle removal rates due to UVGI systems and deposition, and the fresh air supplied by air cleaners are assumed to be uniform in the whole space, therefore, these terms do not have to be modified to adapt the imperfect mixing condition. Then Eqn. 5 can be rewritten as:

$$\lambda_{vent} = f_{HVAC}\lambda_{HVAC}\varepsilon_{vent} + f_{AirCleaner}k_{AirCleaner} \tag{9}$$

The ventilation efficiency (ε_{vent}) represents the dilution efficiency in a particular location compared to the perfect mixing ventilation, thus can be estimated by comparing the tracer gas (usually carbon dioxide) concentration in this location (C_i) and the concentration in the exhaust air ($C_{exhaust}$) by Eqn. 10. It equals 1 for the perfect-mixing scenario.

$$\varepsilon_{vent} = \frac{C_i}{C_{exhaust}} \tag{10}$$

The measurement or simulation data in literature or our previous studies will be used to estimate the empirical ventilation efficiencies of different ventilation or airflow patterns in this study. If the modified Wells-Riley model is applied to the population in the room, instead of each individual separately, then the ventilation efficiency (ε_{vent}) will also adopt the average level for the entire population in the space, more specifically, in the breathing zone. The combined effect of ventilation efficiency should be considered when applying multiple ventilation methods (i.e. HVAC system, natural ventilation, and air cleaner) together. Then a combined ventilation efficiency should be used obtain the combined ventilation rate, instead of being calculated separately as in Eqn. 9.

For different ventilation and airflow patterns, such as displacement ventilation (DV), personal ventilation (PV), or ventilation in semi-open space (e.g. workstation with partitions), the ventilation efficiency may vary greatly. According to a literature review by Zhang [8], the ventilation efficiencies of some HVAC ventilation approaches are shown in the table below.

Table 1. Ventilation efficiencies of different HVAC ventilation approaches in literature.

Ventilation mode	Ventilation efficiency (ε_{vent})	Ref.
Displacement ventilation (DV)	1.2 – 2	Per analysis of the data in [19]
Semi-open space	1.1 – 3.6 (typically 2 – 3)	Per analysis of the data in [20,21]
Semi-open space + DV	14 – 100	Per analysis of the data in [22]
Personal ventilation	1.4 – 10	Per analysis of the data in [23]

3.2. Key parameters

3.2.1. Infectious quantum generation rate per infector (q)

One quantum in the risk model represents an infectious dose that would infect 63% of the population with the exposure per the Wells-Riley Equation, i.e., the infection dose ID_{63} (Riley et al. 1978). The infectious quantum generation rate (q) has a unit of quanta per hour (h^{-1}), and is typically back-calculated from epidemiological studies. It describes the number of infectious particles/pathogens in a way that implicitly includes both the number of virus particles generated in time and the infectivity of particles (which also inherently captures particle size effects and probability of deposition in appropriate regions of the respiratory system) [10]. The magnitude of q depends on the specific disease type, the original epidemiological case study, the interventions, and the activity intensity of the infected [10,24]. Currently, there are limited data available for the quantum generation rate of different diseases, especially for SARS-CoV-2. Another parameter typically used to evaluate the infectious risk of a disease is the basic reproduction ratio (R_0). The basic reproduction ratio is the classical epidemiological measure associated with the reproductive power of the disease. R_0 provides a threshold for the stability of the disease-free equilibrium point. When $R_0 < 1$, the disease dies out; when $R_0 > 1$, an epidemic occurs [25]. **Table 2** lists the R_0 and q of some diseases from literature.

Table 2 R_0 and q of some diseases from literature.

Disease	q [h^{-1}]	R_0 [-]	Ref.
Influenza	15-500[a]	1.6-3.0	[10,26]
Tuberculosis	1-50[b]	2.2-5.5	[10,26]
SARS	10-300	2.0-5.0	[10,26]
MERS	6-140	0.5-1.2	[26]
Measles	570-5600	11.0-18.0	[10,26]

[a] 67 and 100h^{-1} are both commonly used.
[b] 13h^{-1} is commonly used.

For SARS-CoV-2, there are very limited available data regarding its q and R_0. The widely used R_0 of SARS-CoV-2 is between 2.0 and 2.5 [26–31], which is close to influenza, TB, and SARS. Therefore, the q of SARS-CoV-2 is supposed to be close to influenza, TB, and SARS as well. Dai and Zhao [26] analyzed the statistical relationship between R_0 and q of MERS, TB, influenza, and SARS, and estimated an approximate q between 14 and 48 h^{-1} using the curve-fitting approach. However, due to the limited available data, the fitted relationship between R_0 and q may not be accurate enough for estimating the q of SARS-CoV-2. Buonanno et al. [24] used a novel approach for predicting the viral load emitted by a contagious subject on the basis of the viral load in the mouth, the type of respiratory activity (e.g., breathing, speaking, whispering), respiratory physiological parameters (e.g., inhalation rate), and activity level (e.g., resting, standing, light exercise). It revealed that q could be lower than 1 h^{-1} in resting state, and greater than 100 in light activity and vocalization state. A typical q of 142 h^{-1} was estimated based on their results for a case who is speaking and doing light exercise. Miller et al. [32] reported a q as high as 1000 h^{-1} level for a super spreader.

3.2.1.1. Back-calculation for estimating q value of SARS-CoV-2

3.2.1.1.1. Guangzhou restaurant

In this study, we used several real outbreak events to back-calculate the quanta number of SARS-CoV-2. The first case is the outbreak event happened in a Guangzhou restaurant in January 2020 [33,34]. There were totally 18 tables and 89 people in the room, and nobody wore masks during the exposure event. The initial infectious patient (A1) was sitting in table A (**Fig. 2**). All other people were not infected before the instance. The room has a volume of 431 m^3 (height of 3.14 m, length of 17 m, and an average width of 8.1m). The exposure duration is assumed to be 1h (53 min and 73 min for table B and C, respectively, according to [33,34]). The tracer gas decay experiments showed that the equivalent outdoor air supply was 0.75-1.04 L/s·person [34]. Eventually, a total of 9 people were found to be infected (all sitting on table A, B, and C), of which 4 people on table A (same table with the infected), 3 people on table B, and 2 people on table C. Assuming that all 9 people were infected due to the airborne transmission, then q equals to 175-208h^{-1} (depends on the outdoor air supply) based on the proposed steady-state perfect-mixing risk model (Eq. 1). Due to the room and ventilation system configuration, the CFD simulation showed that the indoor air might not be ideally well mixed, and air circulation happened within the local zone (ABC zone). Then if only the ABC zone is used as the confined space for estimation, q will become 209-253 h^{-1}. The target ABC zone is 3.2 by 8.4 m with a height of 3.14 m, and totally 20 susceptible people were in this zone.

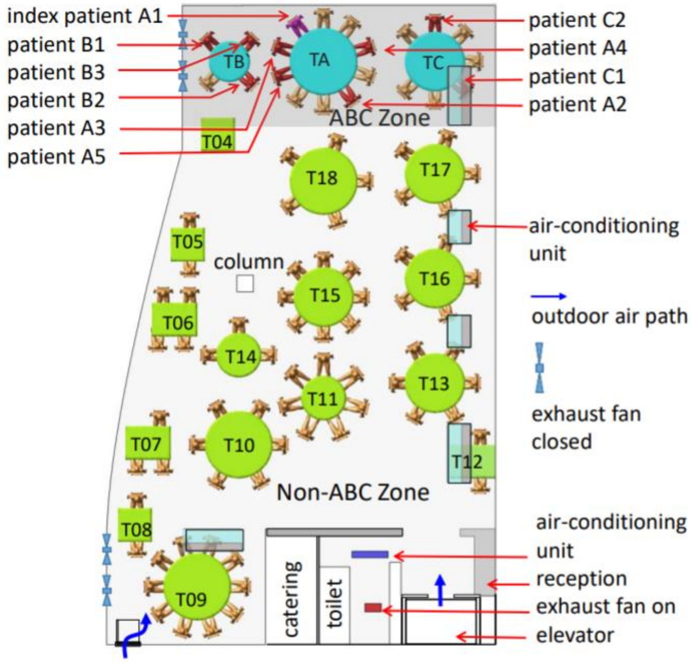


Fig. 2 Room configuration of the target case, from [34].

3.2.1.1.2. Hunan coach and bus [35–37]

Another case study we used was the COVID-19 outbreaks on a tour coach and a bus in Hunan in March 2020. Both outbreaks were caused by the same patient. For the outbreak on the coach (**Fig. 3**), there were totally 49 people (48 susceptible and 1 infectious) on the vehicle (11.3m long and 2.5m wide). The available height is assumed to be 2.5m as well. Most people on the vehicle did not wear masks during the travel, and all the infected patients did not wear masks. Thus, the number of people who wore masks is assumed to be zero in this study. The total travel time was 2 hours, and the vehicle was fully confined with all windows closed during the travel (no natural ventilation). The HVAC system was on, and Li presented an outdoor ventilation rate of 1.72L/s·person in the coach [38]. Eventually, 8 people were infected during this travel. According to the proposed model, the estimated q is 86 h^{-1}.

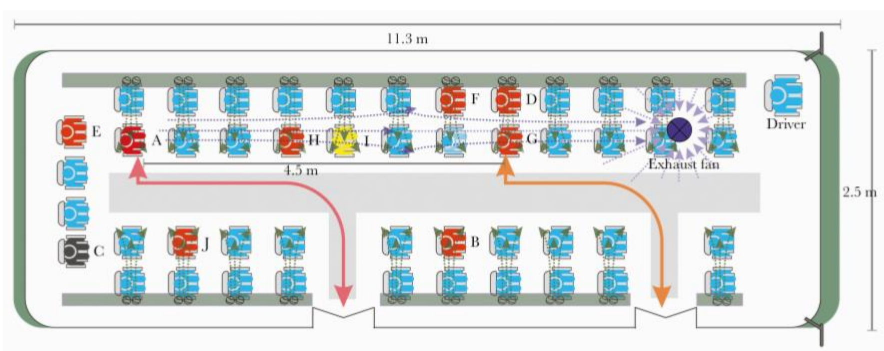


Fig. 3 COVID-19 outbreak in a Hunan tour coach [37].

For the outbreak on the bus (**Fig. 4**), there were totally 13 people (12 susceptible and 1 infectious) on the vehicle (5.5m long and 2.5m wide with 18 seats). The available height is assumed to be 2.5m. Only one out of 12 passengers on the vehicle wore the mask during the travel. The travel is 1 hour long, and the vehicle was fully confined with all windows closed during the travel (no natural ventilation). The HVAC system was on, and Li presented an outdoor ventilation rate of 3.22L/s·person in the bus [38]. Eventually, 2 people were found to be infected due to this travel. The passenger wore the mask did not get infected. According to the proposed model, among the passengers without masks, the estimated q is 47h^{-1}.

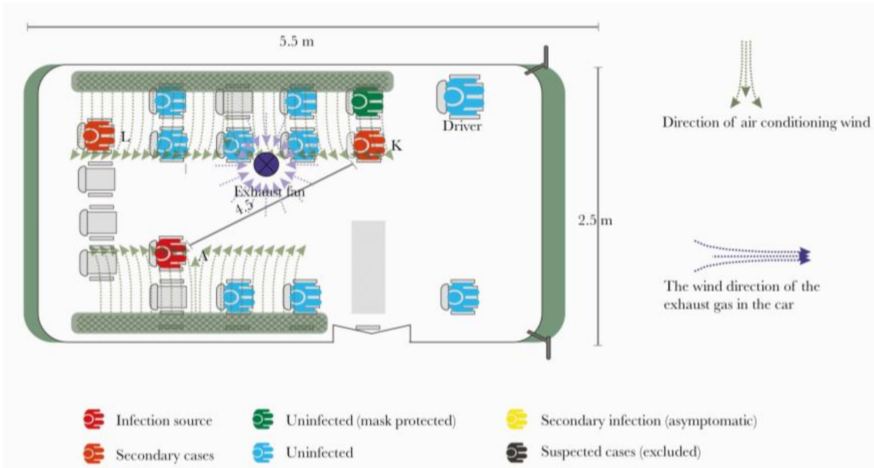


Fig. 4 COVID-19 outbreak in a Hunan bus [37].

3.2.1.1.3. Other outbreak cases

Other outbreak events we found did not provide detailed information regarding the building configuration or ventilation conditions, which may cause a big uncertainty on the estimated q values. One is the outbreak in a tour coach in Zhejiang [39]. A total of 23 people out of 67 people got infected after a 100 min travel with an index patient in a tour coach. The outdoor ventilation rate is not available for this case. Considering its similarity to the Hunan coach, the ventilation rate of the Hunan coach case (1.72L/s·person) is adopted for back calculation. According to the proposed model, the estimated q is 405h^{-1}.

The last case is the Seoul call center outbreak event [40]. A total of 78 people out of 136 people in the call center were confirmed to be infected after 9 working days (assuming 8-hour working time for each working day) since the first case got infected. The outdoor ventilation rate is not available for this case. Then, a ventilation rate required by ASHRAE 62.1 (5L/s·person) is adopted. Assuming all cases were infected by the index patient through airborne transmission, based on the proposed model, the estimated q is 113h^{-1}. However, the estimation of q for this case may have a large uncertainty since many assumptions were made during the estimation.

3.2.1.2. Estimated q in other studies

Table 3 summarized the estimated q from other studies about the SARS-CoV-2 published so far. The estimated value of q varied as low as 1 h^{-1} up to 970 h^{-1}. In this study, the q is assumed to be 100 h^{-1} to represent a mid-level generation rate.

Table 3 Estimated q of SARS-CoV-2 from different studies.

Activity	q [h^{-1}]	Note	Ref.
Estimated using the Wells-Riley model for real outbreak events			
Singing	970±390	Skagit Valley Chorale superspreading event	[32]
Light activity	0.225	For health care workers	[41]
Seated+eating/speaking	209-253	Guangzhou restaurant case in [33,34]	This study
Sedentary in a tour coach	86	Hunan coach case in [37,38]	This study
Sedentary in a minibus	47	Hunan minibus case in [37,38]	This study
Sedentary in a tour coach	405	Zhejiang coach case in [39]	This study
Seated+speaking	113	Seoul call center case in [40]	This study
Estimated using medical models			
Resting	<1		[24]
Intermediate	≤100	Estimated based on the viral load in the sputum	
Light activity+vocalization	>100		
Light exercise+speaking	142		[24]
Estimated using statistical methods			
Sedentary state	14-48	Estimated based on the fitting curve between q and R_0 from the data of other respiratory diseases (e.g. influenza and SARS)	[26]
Adopt the data estimated by other studies			
Light exercise+speaking	142	Use the data estimated by [24]	[42]
Light exercise+speaking	142	Use the data estimated by [24]	[43]
Speaking in classroom	2	In the original paper, the assumed q is 1h^{-1} with a 50% reduction due to the effort of wearing cloth masks.	[44]

3.2.2. Pulmonary ventilation rate (p)

Table 4 shows the short-term inhalation rates by activity level for people of different ages, which is from the Exposure Factors Handbook [45] released by USEPA. The activities in the office/classroom/guest room are usually at sedentary/passive or light-intensity level. Most related studies use 0.3 m^3/h as the pulmonary ventilation rate [10,26,44], which is the mean level for sedentary/passive activities. This value was also used in the present study.

Table 4 Short-term inhalation rates, by activity level (adapted from [45]).

Age [years]	Short-term inhalation rates [m³/h]									
	Sleep or nap		Sedentary/passive		Light intensity		Moderate intensity		High intensity	
	Mean	95th	Mean	95th	Mean	95th	Mean	95th	Mean	95th
0-1	0.2	0.3	0.2	0.3	0.5	0.7	0.8	1.3	1.6	2.5
1-2	0.3	0.4	0.3	0.4	0.7	1.0	1.3	1.7	2.3	3.1
2-3	0.3	0.4	0.3	0.4	0.7	1.0	1.3	1.7	2.3	3.2
3-6	0.3	0.3	0.3	0.3	0.7	0.8	1.3	1.6	2.2	2.9
6-11	0.3	0.4	0.3	0.4	0.7	0.9	1.3	1.7	2.5	3.5
11-16	0.3	0.4	0.3	0.5	0.8	1.0	1.5	2.0	2.9	4.2
16-21	0.3	0.4	0.3	0.4	0.7	1.0	1.6	2.2	2.9	4.4
21-31	0.3	0.4	0.3	0.4	0.7	1.0	1.6	2.3	3.0	4.6
31-41	0.3	0.4	0.3	0.4	0.7	1.0	1.6	2.2	2.9	4.3
41-51	0.3	0.4	0.3	0.4	0.8	1.0	1.7	2.3	3.1	4.6
51-61	0.3	0.5	0.3	0.4	0.8	1.0	1.7	2.4	3.2	4.7
61-71	0.3	0.4	0.3	0.4	0.7	1.0	1.6	2.0	2.8	4.0
71-81	0.3	0.4	0.3	0.4	0.7	0.9	1.5	1.9	2.8	3.9
≥81	0.3	0.4	0.3	0.4	0.7	0.9	1.5	1.9	2.9	4.1

3.2.3. 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 10μm. **Table 5** lists the efficiency of MERV-rating filters for different particle size range, which is available in ASHRAE 52.2 [46].

Table 5 Minimum Efficiency Reporting Value (MERV) ratings in ASHRAE 52.2 [46].

MERV	Particle removal efficiency [%]		
	0.3-1μm	1-3μm	3-10μm
1			<20
2			<20
3			<20
4			<20
5			≥20
6			≥35
7			≥50
8		≥20	≥70
9		≥35	≥85
10		≥50	≥85
11	≥20	≥65	≥85
12	≥35	≥80	≥90
13	≥50	≥85	≥90
14	≥75	≥90	≥90
15	≥85	≥90	≥90
16	≥95	≥95	≥95
HEPA	≥99.9	≥99.9	≥99.9

As a conservative approach, the lower bound of removal efficiency for each particle size range in ASHRAE 52.2 [46] (i.e. MERV 11-16 filters for 0.3-1μm particles, MERV 8-16 filters for 1-3μm particles, and MERV 5-16 filters for 3-10μm particles) is used to estimate the particle-size-weighted average filter efficiency. For values not specified in ASHRAE 52.2 (i.e., MERV 1-10 filters for 0.3-1μm, MERV 1-7 filters for 1-3μm, and MERV 1-4 filters for 3-10μm), the average value of 1st percentile of the filtration efficiency distributions ($P_{1\%}$) from Dillon and Sextro [47] is calculated for each particle size range. If $P_{1\%}$ was not given for a specific MERV rating filter (i.e., MERV 1-4, 6, 9, and 10), the efficiency of the closest lower MERV-rating filter is adopted, which is the same approach as used in [44]. Filtration efficiency of 10% is assumed for MERV 1-4 filters for 3-10 μm since it's not specified by ASHRAE 52.2 or Dillon and Sextro [47].

Virus can be contained in particles of different sizes. Data from existing literature show that in non-hospital environment, approximately 20%, 30% and 50% of the viruses are contained in 0.3-1μm, 1-3μm and 3-10μm, respectively [44]. This assumption was also adopted to determine the particle-size-weighted virus filtration efficiency (**Table 6**).

Table 6 Assumed particle removal efficiency of different filters for 0.3-1μm, 1-3μm, 3-10μm, and total particle-size-weighted average.

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

[a] The average efficiency of MERV 7 for 1-3μm is 33% based on the values specified in [47]. However, the lower bound of MERV 8 for 1-3μm in ASHRAE 52.2 is 20% [46]. Since the efficiency for the same particle size range of the higher MERV-rating filter is usually equal or greater than the lower MERV-rating filters, the efficiency of the closest lower MERV-rating filter (i.e. MERV 6) is adopted as the efficiency of MERV 7 filter in this study.

[b] Assuming 20% of infectious particles are in 0.3-1μm size, 30% are 1-3μm, and 50% are 3-10μm [44].

3.2.4. CADR of portable air cleaners

Clean Air Delivery Rate (CADR) is the "equivalent" volumetric airflow rate (CFM or m^3/h) that has had all the particles of a given size distribution removed. Many studies reported the CADRs of different air cleaners. There are also numerous air cleaner products available on the market. Liu et al. [48] reviewed the efficiency and cost of some commonly-used air cleaners around the world (**Table 7**). The CADRs vary greatly depending on their specific air purifying technologies. Generally, the CADRs are roughly between 300 and 800 m^3/h (or between 180 and 480 CFM) for different air cleaner products.

Another approach to estimating the infectious particle removal is based on the multiplication of airflow rate and the single-pass filtration efficiency, which is the same method of calculation of recirculated clean air in an HVAC system with a filter in the recirculation or mixed-air duct. The efficiency of different filters can be found in **Table 6**.

Table 7 CADR of different air cleaners from the literature [48].

Origin	Brand	CADR [m^3/h]	CADR [CFM]
Europe	Philips	301-910	177-536
	Blueair	105-800+	62-471
	Electrolux	193.5-439	114-258
Japan	Sharp	312-800	184-471
	Panasonic	322-700	190-412
	Daikin	200-500	118-294
US	Honeywell	243-700	143-412
China	Yadu	360-588	212-346
	Broad	240-2000	141-1177
	Lexy	100-840	59-494
	TCL	220-403	129-237
South Korea	Samsung	179-719	105-423

3.2.5. Removal efficiency of different masks on infectious particles (η_S and η_I)

Face masks provide air filtration at a personal level for wearers. It is a critical means for reducing the risk of SARS-CoV-2 infection. Therefore, it is highly recommended by WHO. According to the existing studies, face masks can reduce the average emission rate by around 30%, 50% and 95% with cloth, surgical and N95 masks, respectively. Mueller et al. [49] conducted a quantitative analysis to compare the particle removal efficiency of different types of masks, which is shown in **Table 8**. Konda et al. [50] measured the mask filtration efficiency for particles in different sizes in **Table 9**. Considering the infectious particle size distribution assumption in this study, the particle-size-weighted efficiency is 32%, 44% and 95% for cloth, surgical and N95 masks, respectively, which is close to our assumption.

Table 8 Particle removal efficiency of different masks.

Masks	Particle removal efficiency η_S and η_I [%]
Charcoal filter-1	75
Surgical-1	75
Surgical-2	62
Surgical-3	53
N95-1	>99
N95-2	91
Cloth	<30 to 91

Table 9 Mask filtration efficiency for 0.3-1μm, 1-3μm, 3-10μm and total particle-size-weighted average.

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

[a] Calculated average value of the data measured in [50].
[b] Assuming 95% for all size ranges. The measured efficiency in [50] is larger than 95%.
[c] Assuming 20% of infectious particles are in 0.3-1μm size, 30% are 1-3μm, and 50% are 3-10μm [44].

3.2.6. Particle deposition

The same particle size bins as those used for HVAC filter MERV ratings are considered here to simplify the calculation; values are calculated using the geometric mean diameters for each particle size bin (i.e., 0.55μm, 1.7μm, and 5.5μm for particles of 0.3-1μm, 1-3μm, and 3-10μm, respectively [44]). The particle deposition rate can be calculated by Eqn. 8.

3.3. Baseline case development

Four typical types of buildings or indoor spaces were studied in this research, i.e., office buildings, educational buildings, hotels, and cruise line. First of all, the typical configurations of the four types of space were defined in terms of the space layout, HVAC system, occupancy density and schedule, and system control strategy. Then specific spaces based on the input from Carrier were defined.

3.3.1. Space layout

3.3.1.1. Floor plan

The four types of buildings are all complex indoor spaces which contains rooms of different functions. The medium-sized office model, primary school model, and large hotel model from the DOE prototype building models are selected as the baseline case in this study [51]. The floor plan of the medium-sized office model has an area of 17,875 ft^2 (1,660 m^2), which includes spaces for open-plan offices, enclosed offices, corridors, storage rooms, and conference rooms (**Fig. 5**a) [52]. In this study, the floor plan for the middle and top floor will be selected. The floor plan of the primary school model has an area of 73,960 ft^2 (6,871 m^2), which includes classrooms, library, mechanical room, lobby, cafeteria, kitchen, and gym (**Fig. 5**b). The floor plan of the large hotel has an area of 20,355 ft^2 (1,891 m^2). In this study, in order to represent the case with the guest rooms, the floor plan of the second to the fifth floor will be selected and include primarily guest rooms (**Fig. 5**c) [53]. The Diamond Princess cruise line flor plan (952 × 205 ft) was adopted from an online search. The deck plan for the guest rooms was used here [54].

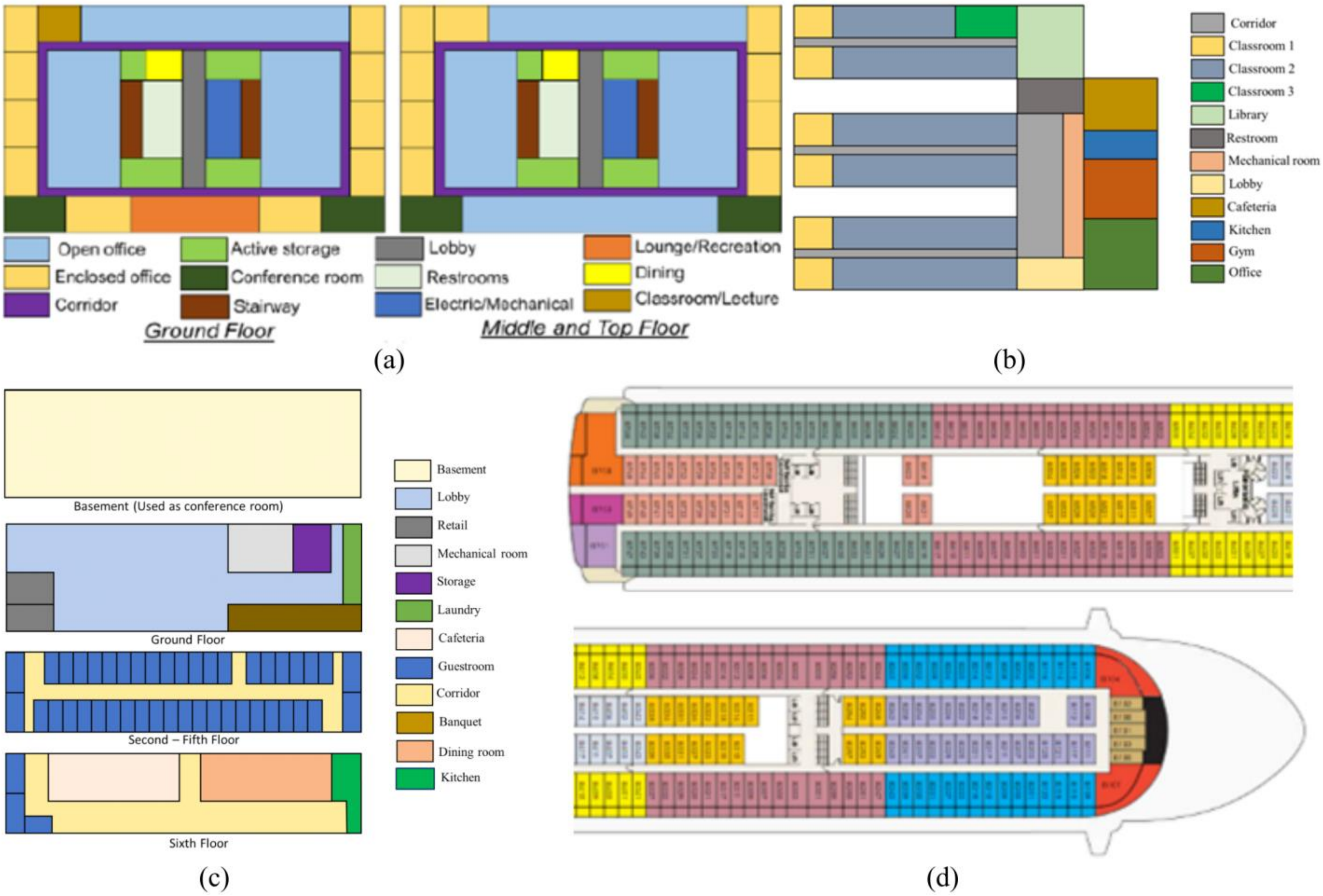


Fig. 5 Floor plan of four space types: (a) mid-size office building [52], (b) school [53], (c) hotel [53], and (d) cruise ship [54].

3.3.1.2. Typical Room layout

A literature review was conducted to investigate what typical configurations were used before for similar studies. The open-plan office is the most commonly studied space. Several studies have reported the general information of the open-plan offices. PNNL developed the detailed space types and their area based on the data from National Commercial Construction Characteristic (NC3) [55]. National Air Filtration Association (NAFA) Foundation defined a typical office space layout in their own study [10]. Carter and Zhang [56] analyzed 31 commercial office buildings and defined the area of typical open-plan offices. The data is shown in **Table 10**. Three types of work stations were found in the open-plan office, including partitioned cubicles (**Fig. 6**a) [56], polygon workstations (**Fig. 6**b) [57], and individual table (**Fig. 6**c) [58]. In this study, we will focus on the open-plan office with the partitioned cubicles.

Table 10 Typical room layout and occupancy density from the literature

Reference	Area [m^2]	Height [m]	Occupancy Density [p/m^2]
Open-Plan Office			
PNNL Medium	162	2.74	0.05
PNNL Large	537	2.74	0.05
NAFA Report	500	3	0.05
ASHRAE	N/A	N/A	0.05
BIFMA	N/A	N/A	0.17
Classrooms			
PNNL	266	3.96	0.25
NAFA Report	100	3	0.35
ASHRAE	N/A	N/A	0.35
Hotel Guest Rooms			
PNNL	39	3.96[a], 3.05	0.05
ASHRAE	N/A	N/A	0.1
Cruise Line Guest Rooms			
Interior	11-17	2.13[b]	0.12-0.27
Ocean View	14	2.13[b]	0.14-0.21
Balcony	14	2.13[b]	0.21
Suite	78	2.13[b]	0.06

[a] First floor
[b] https://boards.cruisecritic.com/topic/697943-our-friend-is-7-feet-2-inches-tall-can-he-cruise/

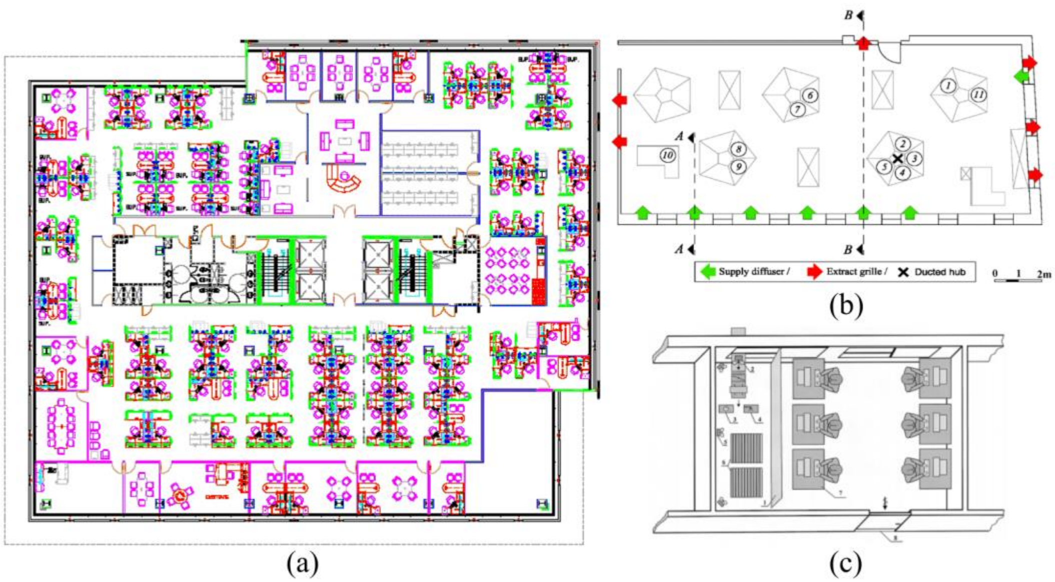
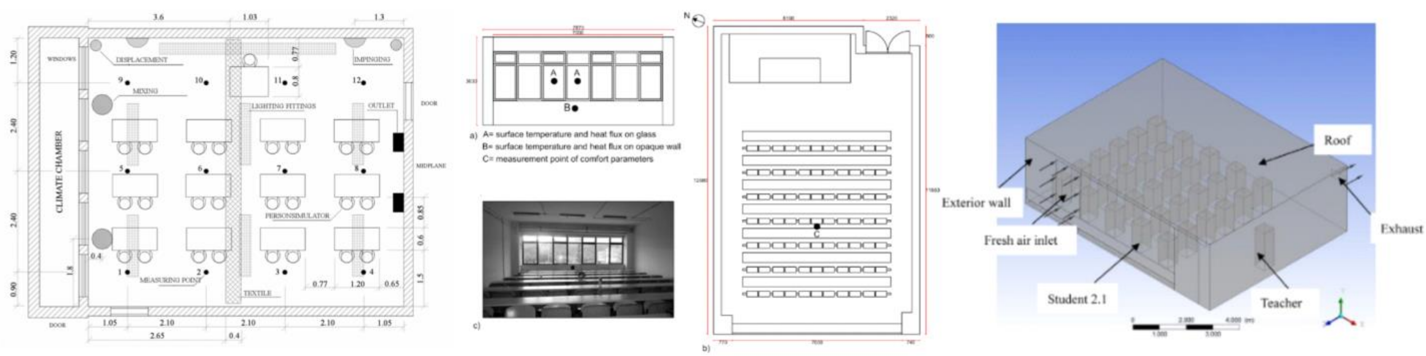


Fig. 6 Typical open-plan office layout: (a) partitioned cubicles [56]; (b) polygon workstations [57]; (c) individual table [58]

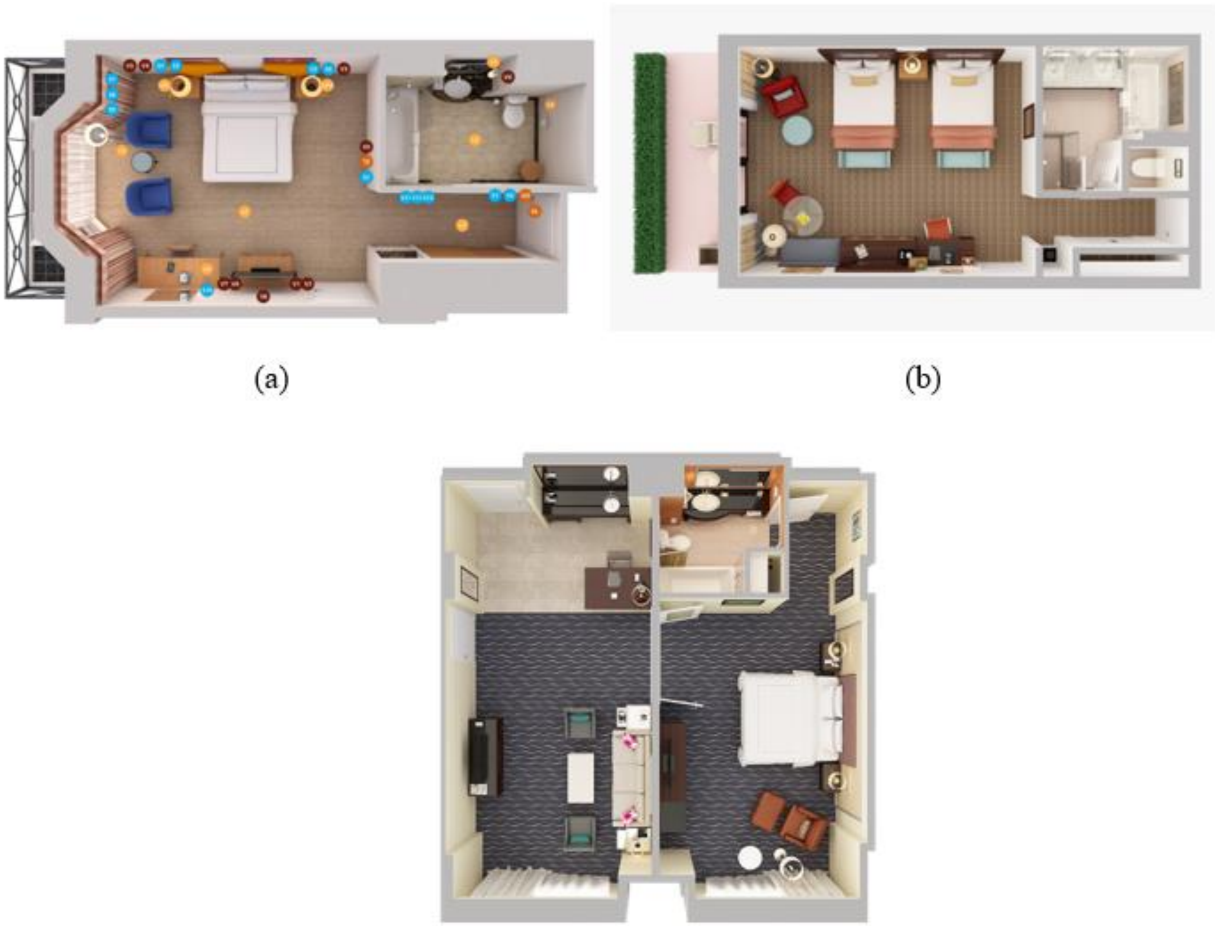
The classroom is a space that has large occupancy density and, therefore, higher infection risks. The typical layout used in PNNL and NAFA's study has been included in **Table 10**. Three types of configurations were also found in the literature, including classrooms with shared tables (**Fig. 7**a) [59], auditoriums (**Fig. 7**b) [60], and regular classrooms with individual chairs (**Fig. 7**c) [61].



(a) (b) (c)

Fig. 7 Typical classroom layout: (a) classroom with shared tables [59]; (b) auditoriums [60]; (c) classroom with individual chairs [61]

Usually, there are different types of guest rooms in hotels, including standard rooms with a king bed (**Fig. 8**a), standard rooms with two queen beds (**Fig. 8**b), and suites (**Fig. 8**c). The study by PNNL developed the hotel model with a uniform typical room area 39 m^2, which represents a standard room. And also, because the standard rooms with two queen-sized beds are the most common room type, this study will focus on this type of layout.



(a) (b)

(c)

Fig. 8 Typical hotel guest room layout: (a) king-bed room [62]; (b) standard rooms with two queen beds[63]; (c) suites

Because there is very limited data published for the cruise line guest rooms, an online search was done to investigate the typical layout of the cruise line guest rooms. Usually, four types of rooms are available on the cruise: interior rooms (**Fig. 9**a), ocean view rooms (**Fig. 9**b), balcony rooms (**Fig. 9**c), and suites (**Fig. 9**d). Since the interior room is the one which has the smallest area, the largest occupancy density, and possibly the worst ventilation, this study will focus on evaluating the infection risk in the interior room.

(a) (b) (c) (d)

Fig. 9 Typical cruise line guest room layout [64]

3.3.1.3. Carrier room layout

Carrier also provides space layouts for their own interested spaces, including conference center/ballroom, bistro/cafeteria, and lobby in the hotel, class and conference room in school, guest rooms in the hotel or cruise line, and open-plan office in the office building (**Table 11**).

Table 11 Information for Carrier interested spaces

Space Type	Area [m^2]	Height [m]	Exposure [h]
Hotel			
Conference Center/Ballroom	1,600	7	2
Bistro/Cafeteria	350	4	0.5
Lobby	350	4	0.5
Educational Building			
Classroom	125	4	8
Conference Room/Small Classroom	40	3	2
Cruise Line or Hotel			
Guest Room	14	2.5	10
Office Buildings			
Open-Plan Office	350	3	8

3.3.2. Occupancy density

The occupancy density of each space defines the required outdoor airflow rate as well as the number of susceptible. The occupancy density used in previous studies for four types of buildings is based on typical room area and default occupant density in **Table 13** from ASHRAE 62.1 [22] summarized in **Table 10**, while occupant numbers in the hospitality guest room and cruise line guest room are assumed to be two.

Other than that, Carrier also provided occupancy data for their interested spaces. All these data were summarized in **Table 12**.

Table 12 Occupancy information

Typical Room Layout		Carrier Room Layout	
Space Type	**Occupancy [person]**	**Space Type**	**Occupancy [person]**
Hotel		**Hotel**	
Guest Room	2	Conference Center/Ballroom	750
		Bistro/Cafeteria	230
		Lobby	115
Educational Building		**Educational Building**	
Classroom	35	Classroom	70
		Conference Room/Small Classroom	20
Cruise Line or Hotel		**Cruise Line or Hotel**	
Guest Room	2	Guest Room	2
Office Buildings		**Office Buildings**	
Open-Plan Office	25	Open-Plan Office	18

3.3.3. Outdoor airflow rate

The outdoor airflow rate required in the breathing zone ($\lambda_{outdoor}$ or V_{bz}) of the occupiable space or spaces in a ventilation zone shall be not less than the value determined in accordance with ASHRAE 62.1 [65] per Eqn. 11.

$$\lambda_{outdoor} = V_{bz} = R_p \times P_z + R_a \times A_z \tag{11}$$

where R_p is the outdoor airflow rate required per person, R_a is outdoor airflow rate required per unit floor area, P_z is zone population, the number of people in the ventilated space/zone during use and A_z is zone floor area, the net occupiable floor area of the ventilated space/zone. The minimum average ventilation rates in the breathing zone can be determined based on the data in **Table 13**, which is adapted from ASHRAE 62.1 [65]. Mixing ventilation is used in all scenarios, and the indoor room air is assumed to be well-mixed.

Table 13 Minimum ventilation rates in the breathing zone [65].

Occupant category	People outdoor air rate R_p		Area outdoor air rate R_a		Default occupant density
	CFM/person	L/s·person	CFM/ft^2	L/s·m^2	#/1000ft^2 or #/100m^2
Office buildings					
Office space	5	2.5	0.06	0.3	5
Educational facilities					
Classrooms (age 9+)	10	5	0.12	0.6	35
Hotels, motels, resorts, dormitories					
Bedroom/living room	5	2.5	0.06	0.3	10

3.3.4. Total supply airflow rate

The total supply airflow rate (outdoor + recirculated air) is determined based on the total cooling and heating load and the temperature difference between the zone supply and return air. The recirculated air can be filtered to help further dilute the virus concentration in the ventilated space in addition to the dilution by outdoor air supply. With the same outdoor airflow rate, the performance of the filtration system increases with the total supply airflow rate. Persily and Gorfain [66] studied more than 100 randomly selected U.S. office buildings and calculated the outdoor air fraction for each building (**Fig. 10**). The study found that for buildings with economizers, the outdoor air fraction is very scattered, ranging from 0 to 100%. But for buildings without economizers, the outdoor air fraction is around 25%. Therefore, a 25% outdoor air fraction (75% recirculation fraction) is suggested by Stephens [67]. The total supply airflow rate can be calculated as

$$\lambda_{supply} = \frac{\lambda_{outdoor}}{1 - f_{circulated}} \tag{12}$$

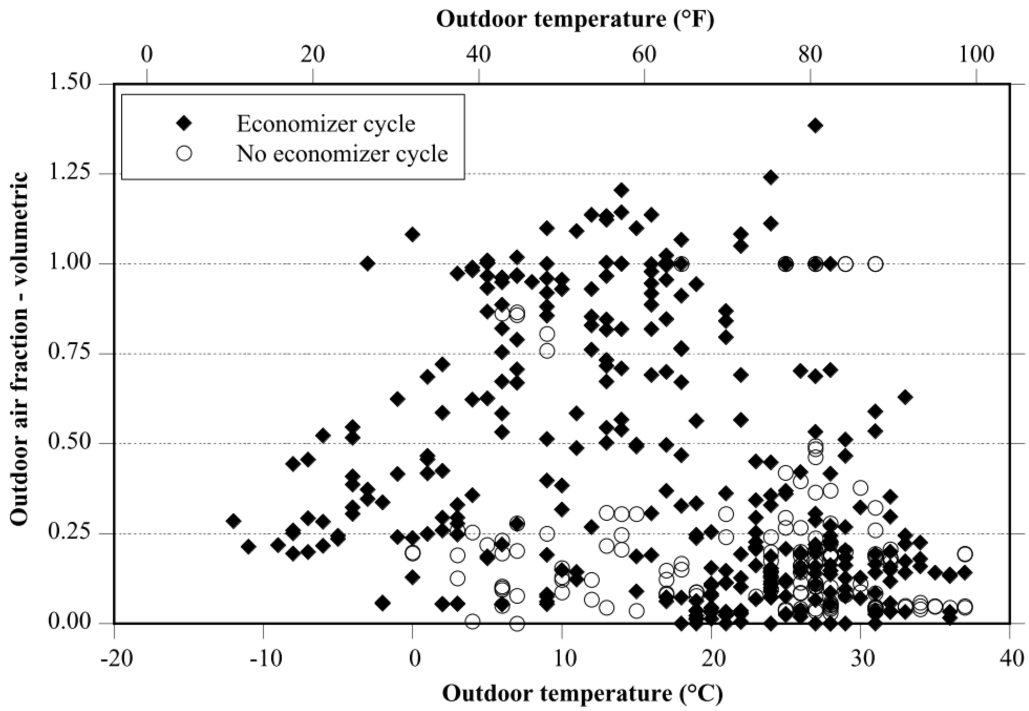


Fig. 10 Volumetric outdoor air fraction versus outdoor temperature [66]

Carrier also suggested ranges of total air flow rate for each type of space based on their experience and interest. Ranges of total airflow rates were given in **Table 14**. These values were used for Carrier room layouts for risk estimation.

Table 14 Total supply flow rate for Carrier room layout

Space Type	Total Supply Flow Rate [cfm/ft^2 (ACH)]
Hotel	
Conference Center/Ballroom	1.5 – 4.0 (3.9 – 10.5)
Bistro/Cafeteria	1.0 – 3.0 (4.6 – 13.7)
Lobby	1.0 – 3.0 (4.6 – 13.7)
Educational Building	
Classroom	1.0 – 3.0 (4.6 – 13.7)
Conference Room/Small Classroom	1.0 – 2.0 (6.1 – 12.2)
Cruise Line or Hotel	
Guest Room	0.75 – 1.5 (5.5 – 11.0)
Office Buildings	
Open-Plan Office	1.0 – 3.0 (6.1 – 18.3)

3.3.5. Filter

ASHRAE Standard 62.1 [68] requires 'Particulate matter filters or air cleaners having either 1) a MERV of not less than 8 where rated in accordance with ASHRAE Standard 52.2 or 2) the minimum efficiency within ISO ePM10 where rated in accordance with ISO 16890 shall be provided upstream of all cooling coils or other devices with wetted surfaces through which air is supplied to an occupied space. Therefore, in this study, a MERV 8 filter were used in the baseline cases.

4. Results

4.1. Risk estimation of the typical baseline case

Table 15 summarized the typical configurations of each type of room. The detailed layout of the four spaces is shown in **Fig. 11**. The breathing rate is assumed to be 0.3 m^3/h for all scenarios, which is determined based on the sedentary activity. The supply airflow rate is estimated by the required outdoor airflow rate and a recirculated fraction (75% in this study). MERV 8 filters are used for the recirculated air in the HVAC system, which is assumed to be an All Air System with constant outdoor and total airflow rates. It is assumed that only one person is infected in the target room, and masks are not used in all scenarios. The infection risk for SARS-CoV-2 is estimated based on the proposed model. The estimated risks (probabilities of infection) are shown in **Table 15**. The probability of infection in the hospitality room and cruise line are significantly higher than office and classroom, which is mainly due to the much higher percent of infected person (1 out of 2 occupants in the room or 50%), lower ventilation rate and longer exposure time assumed in the baseline case.

Table 15 Typical configurations and risk probability in each type of room.

Space	Space info		Occupant				HVAC settings						Risk
	Area	Height	Number[b]	Age	Breathing rate	Exposure time	Vent. mode	Vent. rate	Total vent. rate	Supply air flow rate[c]	Outdoor air fraction	Filter	Infection possibility
	m^2	m	#	year	m^3/h	h	/	$m^3/(h\cdot person)$	m^3/h	m^3/h	%	MERV	%
Office	500	3	25	Adults	0.3	8	Mixing	30.6	765	3060	25	8[d]	8.662
Classroom	100	3	35	10-11	0.3	8	Mixing	24.2	846	3384	25	8	10.719
Hotel GR[a]	25	3	2	Adults	0.3	10	Mixing	23	45	180	25	8	76.420
Cruise line GR	15	3	2	Adults	0.3	10	Mixing	17.1	34	137	25	8	94.221

[a] GR: guest room;

[b] Occupant numbers in office and classroom are estimated based on typical room area and default occupant density from ASHRAE 62.1 [65], while occupant numbers in hospitality guest room and cruise line guest room are assumed to be two.

[c] Supply air flow rate is estimated by the required outdoor air flow rate and recirculated fraction (75% in this study). The outdoor air flow rate is estimated according to the requirements in AHSRAE 62.1 [65] .

[d] From ASHRAE 62.1 [65].

[e] The cluster of the guest rooms is assumed to be guest rooms in one floor, which include 39 standard rooms (24.5 m^2/ea.) and 4 suits (39 m^2/ea.) [53].

Fig. 11 Detailed layout of the four spaces

4.2. Performance evaluation of the individual control strategy on typical baseline case

Necessary strategies are required to be applied in the study scenarios to reduce the infection risk. The possible risk control strategies include reduced occupancy density, improved HVAC systems with increased outdoor air supply, enhanced filtration and operation control, in-room filtration, and disinfection devices [69], improved room configurations, and personal protective equipment (PPE, typically masks). The common approach to improve the efficiency of HVAC systems is using higher-efficiency in-duct filters (e.g., MERV14 or HEPA) as well as increasing the fresh air supply rate (e.g., double ventilation rate or 100% outdoor air). Different ventilation modes besides mixing ventilation (MV), such as displacement ventilation (DV) and personal ventilation (PV), can be used to improve ventilation efficiency, although it may be more expensive and time-consuming to retrofit the existing ventilation system.

In-room devices can also be used for removing pathogens, including using UVGI systems (e.g., upper-room UVGI) or portable air cleaners. However, the secondary pollutant emission (such as ozone) and potential adverse effects on occupant health due to UV irradiation should be considered when using UVGI systems indoors. Room configurations, such as the room layout or furniture placement, will affect the indoor airflow pattern and ventilation efficiency. A strategy commonly used in office buildings is the semi-open space configuration, e.g., workstations with partitions. However, this approach cannot be applied in smaller spaces like hospitality guest rooms. Personal protective equipment (e.g., masks) is very useful for reducing the infection risk by directly reducing the exhaled pathogens from infectors and the inhaled pathogens by the susceptible people. **Table 16** shows the possible control strategies which are available to be used in different scenarios.

Table 16 Proposed control strategies for different scenarios.

Scenario	Ventilation			In-room device	Room configuration	Mask
	Airflow rate	Mode	Filter			
Office						
Baseline	ASHRAE 62.1	MV	MERV8	None	None	None
Control	Double, 100% outdoor air	MV, DV, PV	MERV8, MERV14, HEPA,	UVGI, Air cleaner	Semi-open partitions	Cloth, Surgical, N95
Classroom						
Baseline	ASHRAE 62.1	MV	MERV8	None	None	None
Control	Double, 100% outdoor air	MV, DV, PV	MERV8, MERV14, HEPA	UVGI, Air cleaner	Semi-open partitions	Cloth, Surgical, N95
Hospitality guest room and bistro						
Baseline	ASHRAE 62.1	MV	MERV8	None	None	None
Control	Double, 100% outdoor air	MV, DV	MERV8, MERV14, HEPA	UVGI, Air cleaner	None	None
Hospitality lobby and ballroom						
Baseline	ASHRAE 62.1	MV	MERV8	None	None	None
Control	Double, 100% outdoor air	MV, DV	MERV8, MERV14, HEPA	UVGI, Air cleaner	None	Cloth, Surgical, N95
Cruiser line guest room						
Reference	ASHRAE 62.1	MV	MERV8	None	None	None
Control	Double, 100% outdoor air	MV, DV	MERV8, MERV14, HEPA	UVGI, Air cleaner	None	None

The performance of each strategy can then be evaluated using the modified Wells-Riley model. The infection risk of applying each possible strategy in the baseline office scenario is estimated in **Table 17**. It can be observed that using masks is the most effective strategy for reducing infection risk. A surgical or N95 mask can reduce the infection risk by more than 90%. For HVAC systems, using personal ventilation may be the best approach for reducing risk when ε_{vent} = 5. The displacement ventilation only reduces the infection possibility by 23.9% based on the adopted empirical ventilation efficiency (ε_{vent} = 1.5). The result greatly depends on the value of ventilation efficiency. Elevating supply airflow rate (double airflow rate in this study) or using 100% outdoor air can reduce more risk and reach an equivalent level as using HEPA filters in HVAC systems. For in-room filtration and disinfection devices, the upper-room UVGI system (0.2W/m^2 irradiation with around equivalent 4h^{-1} air changes) can reduce considerable risk compared to the portable air cleaner (CADR=400m^3/h). The portable air cleaner used in this study has the lowest improvement in reducing infection risk, which can be increased if an air cleaner with a larger CADR is used. Semi-open space configuration in the office can reduce the risk by half when ε_{vent} = 2.5.

The various strategies can be combined and integrated to achieve desired risk reduction [7]. The ten scenarios suggested by Zhang [8] are estimated for all four types of spaces as in **Table 18**. The same approach and procedure established can be applied to evaluate the effectiveness of additional specific risk reduction strategies in further studies. The results demonstrate that with proper integration of the control strategies, it is possible to reduce the risk by a factor of 74.6% to 100% from the baseline scenarios, but one should note that all these cases require masks on.

Table 17 Infection risk estimation of each possible strategy in the baseline office scenario.

Strategy		**Feature**	**Risk [%]**	**Improvement [%]**
Reference		Baseline settings in **Table 12**	8.662	N/A
Ventilation system	Double ventilation rate	$3060 \times 2 m^3/h$	5.318	38.6
	100% outdoor air	$f_{circulated} = 0\%$	5.885	32.1
	DV	$\varepsilon_{vent} = 1.5$	6.595	23.9
	PV	$\varepsilon_{vent} = 5$	2.461	71.6
	MERV14	$\eta_{filter} = 87\%$	6.349	26.7
	HEPA	$\eta_{filter} = 99.9\%$	5.888	32.0
In-room devices	UVGI	$k_{UV} = 4h^{-1}$ [a]	2.738	69.4
	Air cleaner	CADR = $400 m^3/h$; $\varepsilon_{vent} = 1$	7.581	12.5
Room configuration	Semi-open space	$\varepsilon_{vent} = 2.5$	4.456	48.6
Mask	Cloth	$\eta_S = \eta_I = 50\%$	2.243	74.1
	Surgical	$\eta_S = \eta_I = 75\%$	0.566	93.6
	N95	$\eta_S = \eta_I = 95\%$	0.023	99.7

[a] Estimated from [70,71] for $0.2 W/m^2$ irradiation.

Table 18 Infection risk of different strategies.

Scenario	**Ventilation**			**Room configuration**	**Mask**	**Risk Probability [%]**	**Improvement [%]**
	Rate	**Mode**	**Filter**				
Office							
Reference[a]	Reference	MV	MERV8	None	None	8.662	
1	Double	MV	MERV14	None	Cloth	0.930	89.2
2	Double	MV	MERV14	None	Surgical	0.233	97.3
3	Double	MV	MERV14	Semi-open space	Surgical	0.102	98.8
4	Double	DV	MERV14	Semi-open space	Surgical	0.005	99.9
5	Double	MV	HEPA	None	Surgical	0.214	97.5
6	Double	MV	HEPA	Semi-open space	Surgical	0.093	98.9
7	Double	DV	HEPA	Semi-open space	Surgical	0.005	99.9
8	Double	MV	MERV14	None	N95	0.009	99.9
9	Double	MV	MERV14	Semi-open space	N95	0.004	99.9
10	Double	DV	MERV14	Semi-open space	N95	0	100
Classroom							
Reference	Reference	MV	MERV8	None	None	10.719	
1	Double	MV	MERV14	None	Cloth	0.950	91.1
2	Double	MV	MERV14	None	Surgical	0.238	97.8
3	Double	MV	MERV14	Semi-open space	Surgical	0.097	99.1
4	Double	DV	MERV14	Semi-open space	Surgical	0.005	100.0
5	Double	MV	HEPA	None	Surgical	0.216	98.0
6	Double	MV	HEPA	Semi-open space	Surgical	0.088	99.2
7	Double	DV	HEPA	Semi-open space	Surgical	0.004	100.0
8	Double	MV	MERV14	None	N95	0.010	99.9
9	Double	MV	MERV14	Semi-open space	N95	0.004	100.0
10	Double	DV	MERV14	Semi-open space	N95	0	100.0
Hospitality guest room							

Reference	Reference	MV	MERV8	None	None	76.420	
1	Double	MV	MERV14	None	Cloth	13.826	81.9
2	Double	MV	MERV14	None	Surgical	3.652	95.2
3	Double	MV	MERV14	Semi-open space	Surgical	1.610	97.9
4	Double	DV	MERV14	Semi-open space	Surgical	0.086	99.9
5	Double	MV	HEPA	None	Surgical	3.348	95.6
6	Double	MV	HEPA	Semi-open space	Surgical	1.464	98.1
7	Double	DV	HEPA	Semi-open space	Surgical	0.078	99.9
8	Double	MV	MERV14	None	N95	0.149	99.8
9	Double	MV	MERV14	Semi-open space	N95	0.065	99.9
10	Double	DV	MERV14	Semi-open space	N95	0.003	100.0
Cruise line guest room							
Reference	Reference	MV	MERV8	None	None	94.221	
1	Double	MV	MERV14	None	Cloth	23.958	74.6
2	Double	MV	MERV14	None	Surgical	6.618	93.0
3	Double	MV	MERV14	Semi-open space	Surgical	2.869	97.0
4	Double	DV	MERV14	Semi-open space	Surgical	0.151	99.8
5	Double	MV	HEPA	None	Surgical	6.053	93.6
6	Double	MV	HEPA	Semi-open space	Surgical	2.605	97.2
7	Double	DV	HEPA	Semi-open space	Surgical	0.137	99.9
8	Double	MV	MERV14	None	N95	0.274	99.7
9	Double	MV	MERV14	Semi-open space	N95	0.116	99.9
10	Double	DV	MERV14	Semi-open space	N95	0.006	100.0

[a] Use the baseline settings in **Table 12**.

4.3. Risk estimation for the Carrier baseline case

Carrier also provided the configurations and system parameters for more specific spaces of their interests (**Table 19**). To determine the baseline case for Carrier interested spaces, cases with different total supply flow rates within the specified range were created and their infection risks were estimated using the proposed model. Same as the forementioned typical baseline case, the breathing rate was assumed to be 0.3 m^3/h for all scenarios assuming sedentary activity. MERV 8 filters were used for the recirculated air in the HVAC system. It was assumed that only one person was infected in the target room, and masks were not used in all scenarios. The estimated risks (probabilities of infection) are shown in **Fig. 12**. The hotel/cruise line guest room has the highest infection risk (~90%) due to high fraction of initial virus carrier among the occupants (1 out of 2), while the hotel lobby, bistro, and ballroom have the lowest infection risk (0.1-0.2%) due to high total ventilation rate specified for the large number of occupants. The conference room, classroom and open-plan office have the medium risk of infection (~10%). For all 7 spaces, the infection risk decreased with the total supply airflow rate due to the impact of the MERV 8 filter in the recirculation air duct). Therefore, the worst cases (with the lowest total supply airflow rate) were used as the reference for estimating the potential of different risk reduction strategies.

Table 19 Space information of Carrier interested cases

Space Type	Area [m^2]	Height [m]	Occupancy [person]	Exposure [h]	Ventilation (fresh air) cfm/person (ACH)	Total Supply cfm/ft^2 (ACH)
Conference Center/Ballroom	1,600	7	750	2	BL=6.7 cfm/p (0.8 ACH)	1.5 cfm/ft^2 (3.9 ACH)
					130% BL (1.0 ACH)	2.0 cfm/ft^2 (5.2 ACH)
					200% BL (1.5 ACH)	2.5 cfm/ft^2 (6.5 ACH)
					100% OA (3.9 ACH)	3.0 cfm/ft^2 (7.8 ACH)
						3.5 cfm/ft^2 (9.1 ACH)
						4.0 cfm/ft^2 (10.5 ACH)
Hotel Bistro/Cafeteria	350	4	230	0.5	BL=9.0 cfm/p (2.5 ACH)	1.0 cfm/ft^2 (4.6 ACH)
					130% BL (3.3 ACH)	1.5 cfm/ft^2 (6.9 ACH)
						2.0 cfm/ft^2 (9.1 ACH)
					100% OA (4.6 ACH)	2.5 cfm/ft^2 (11.4 ACH)
						3.0 cfm/ft^2 (13.7 ACH)
Hotel lobby	350	4	115	0.5	BL=10.0 cfm/p (1.4 ACH)	1.0 cfm/ft^2 (4.6 ACH)
					130% BL (1.8 ACH)	1.5 cfm/ft^2 (6.9 ACH)
					200% BL (2.8 ACH)	2.0 cfm/ft^2 (9.1 ACH)
					100% OA (4.6 ACH)	2.5 cfm/ft^2 (11.4 ACH)
						3.0 cfm/ft^2 (13.7 ACH)
Classroom (Lecture)	125	4	70	8	BL=9.2 cfm/p (2.2 ACH)	1.0 cfm/ft^2 (4.6 ACH)
					130% BL (2.8 ACH)	1.5 cfm/ft^2 (6.9 ACH)
					200% BL (4.4 ACH)	2.0 cfm/ft^2 (9.1 ACH)
					100% OA (4.6 ACH)	2.5 cfm/ft^2 (11.4 ACH)
						3.0 cfm/ft^2 (13.7 ACH)
Conference room/Small Classroom	40	3	20	2	BL=6.6 cfm/p (1.9 ACH)	1.0 cfm/ft^2 (6.1 ACH)
					130% BL (2.4 ACH)	1.25 cfm/ft^2 (7.6 ACH)
					200% BL (3.7 ACH)	1.5 cfm/ft^2 (9.1 ACH)
					100% OA (6.1 ACH)	1.75 cfm/ft^2 (10.7 ACH)
						2.0 cfm/ft^2 (12.2 ACH)
Guest Room	14	2.5	2	10	BL=9.7 cfm/p (0.9 ACH)	0.75 cfm/ft^2 (5.5 ACH)
					130% BL (1.2 ACH)	1.0 cfm/ft^2 (7.3 ACH)
					200% BL (1.9 ACH)	1.25 cfm/ft^2 (9.1 ACH)
					100% OA (5.5 ACH)	1.5 cfm/ft^2 (11.0 ACH)
Open-Plan Office	350	3	18	8	BL=17.7 cfm/p (0.5 ACH)	1.0 cfm/ft^2 (6.1 ACH)
					130% BL (0.7 ACH)	1.5 cfm/ft^2 (9.1 ACH)
					200% BL (1.0 ACH)	2.0 cfm/ft^2 (12.2 ACH)
					100% OA (6.1 ACH)	2.5 cfm/ft^2 (15.2 ACH)
						3.0 cfm/ft^2 (18.3 ACH)

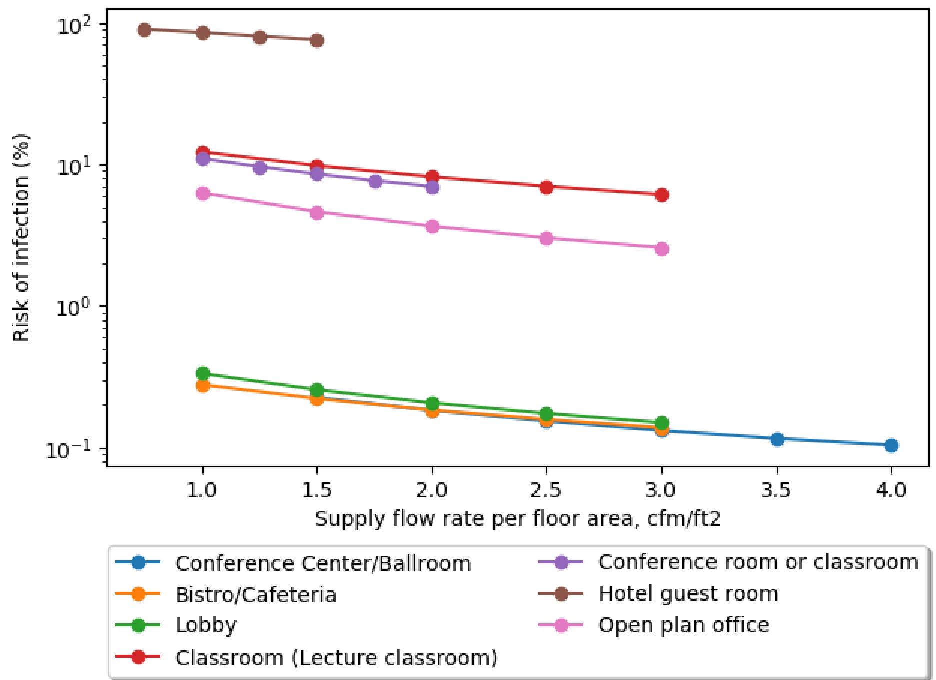


Fig. 12 Risk of infection vs. total supply airflow rate

4.4. Performance evaluation of the individual control strategy on Carrier baseline case

A series of control strategies have been identified for mitigating the spread of the SARS-CoV-2 as discussed in Sec. 4.2. Similar control strategies were tested for Carrier interested spaces. These strategies can be classified into four categories: 1) ventilation system, including better air distribution system such as displacement ventilation, increased total supply air flow rate, increased ventilation rate (baseline level per ASHRAE 62.1, 130% baseline level per ASHRAE 189.1 [72], 200% baseline level per COGfx study [73], and 100% outdoor air), and improved filtration system (MERV 8 to MERV 13); 2) in-room air cleaning, including UVGI and portable air cleaner (with 5 cfm/p, 10 cfm/p, and 15 cfm/p CADR); 3) room configuration, e.g. semi-open space; and 4) masks, including cloth mask, surgical mask and N95 masks. Each control strategy is tested individually first for each type of spaces to evaluate their effectiveness.

4.4.1. Conference center/ballroom

The performance of each control strategy in the conference center/ballroom is summarized in **Fig. 13**. Because of the large floor area, high occupancy, and large amount of outdoor air and total supply air, the infection risk of the baseline case is only 0.23%. The most effective strategy is wearing N95 mask, which can reduce the risk to almost 0%. Even with a cloth mask, the risk of infection can be reduced to 0.11%. As discussed before, the risk of infection reduces with the total supply airflow rate. With 100% outdoor air, the risk of infection can be reduced from 0.23% to 0.13%. Usually MERV 8 filter can be replaced with up to MERV 13 filter without significant system modification. Therefore, MERV 8-13 filters are tested and results show that MERV 13 filter can reduce the risk to 0.15% by filtering the recirculated air. The performance of the portable air cleaners is tested based on four levels of CADR per person. It was shown that increasing the CADR with the air cleaners by 15 cfm/p can reduce the risk to 0.13%. However, the benefit of increasing total supply flow rate and clean air delivered by the air cleaner and upgrading the filtration system decreases with further upgrading. For example, increasing the total supply flow rate from 1.5 to 2.0 cfm/ft^2 reduces more risk than increasing the total supply flowrate from 2.0 to 2.5 cfm/ft^2. The potential of each risk reduction strategy is summarized in **Fig. 14**. Since the cloth mask is the more readily available and more frequently used in daily life, it is used for evaluating the potential of the mask. It was shown that increasing the total supply airflow rate, using the UVGI and semi-open space can all achieve more risk reduction than the cloth mask. The best environmental control strategy is the UVGI system which can reduce the infection risk by 65% while the cloth mask can only provide 52% reduction in risk. The other four strategies, displacement ventilation, 100% outdoor air, MERV 13, and air cleaner, can reduce the infection risk by 30%, 43%, 35%, and 43% from the baseline condition, respectively.

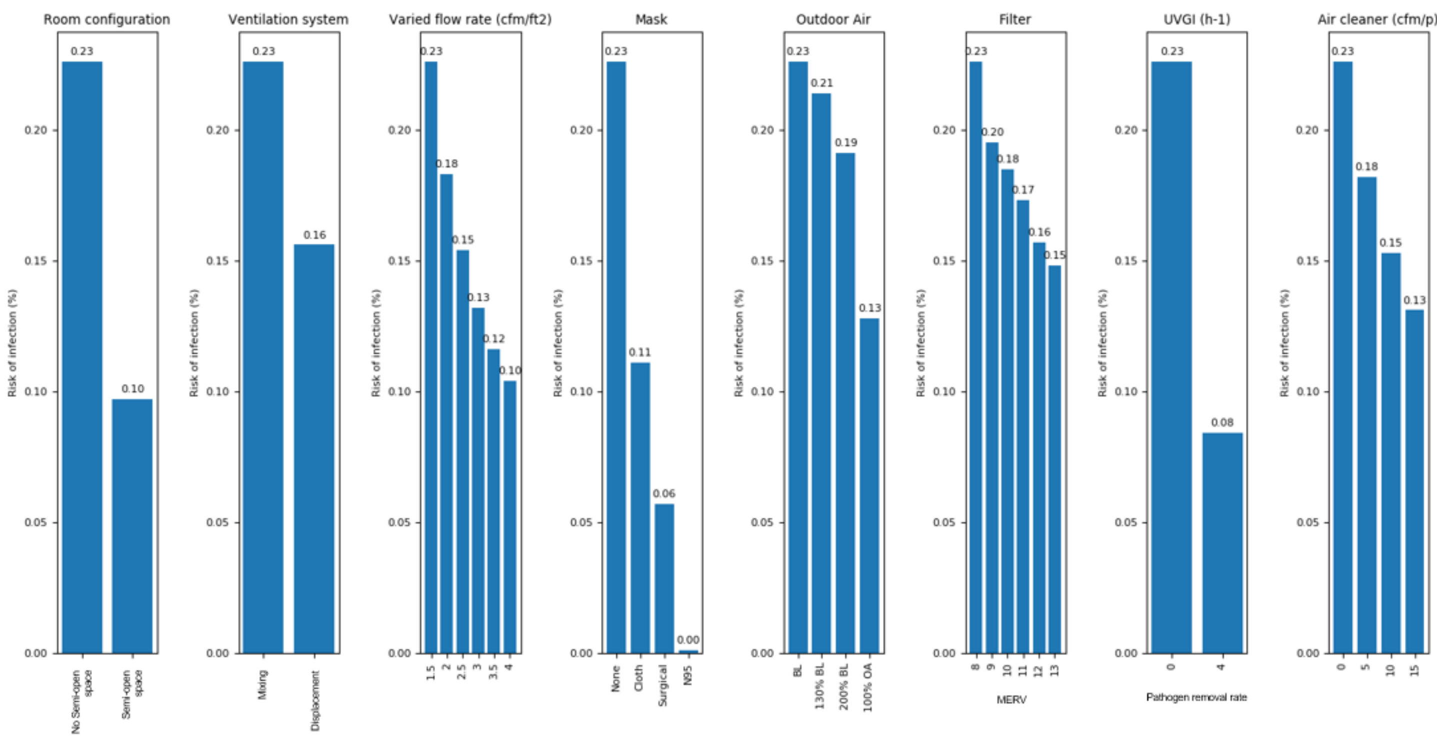


Fig. 13 Effects of individual risk reduction strategies for conference center/ballroom

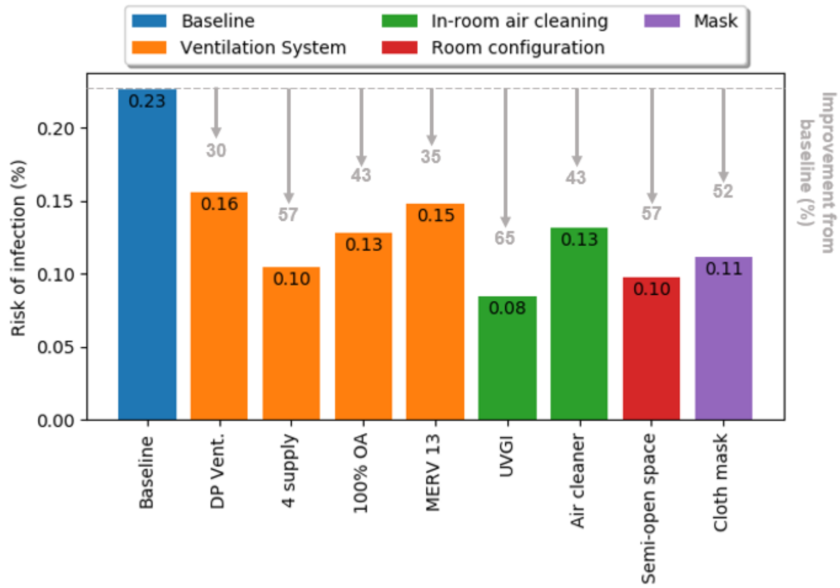


Fig. 14 Potential of individual risk reduction strategy for conference center/ballroom

4.4.2. Hotel bistro/cafeteria

The performance of each control strategy in the bistro/cafeteria is summarized in **Fig. 15**. Similar to the conference center/ballroom, the infection risk of the baseline case is only 0.28% due to the high ventilation rate and total supply airflow rate as well as the shorter exposure (0.5h). The most effective strategy is still wearing N95 mask, which can reduce the risk to almost 0%. A cloth mask can reduce the risk to 0.11%. Increasing the total supply airflow rate, ventilation rate and clean air by air cleaners and upgrading the filter can all help reduce the infection risk. One should note that since in the baseline case the ventilation rate is more than 50% of the total air flow rate, 200% baseline outdoor air is not included in this analysis. The potential of each risk reduction strategy is summarized in **Fig. 16**. It was shown that increasing the clean air delivered by the air cleaners and semi-open space can all achieve more risk reduction than the cloth mask while increasing the total supply airflow rate and UVGI reduce the risk by similar amount to the cloth mask. The best environmental control strategy is the semi-open space which can reduce the infection risk by 57% while the cloth mask can provide 50% reduction in risk. The other three strategies, displacement ventilation, 100% outdoor air, and MERV 13 filter, can reduce the infection risk by 32%, 25%, and 18%, respectively.

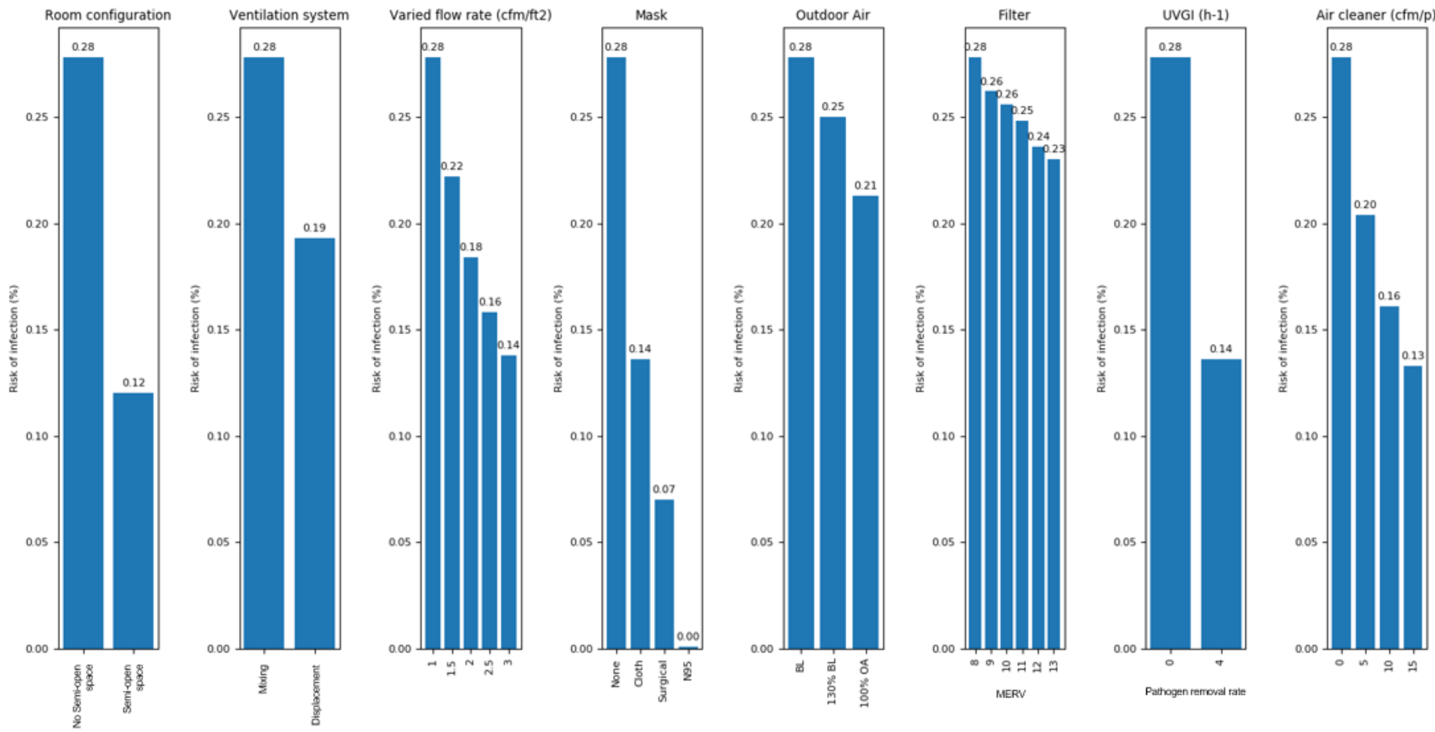


Fig. 15 Effects of individual risk reduction strategies for bistro/cafeteria

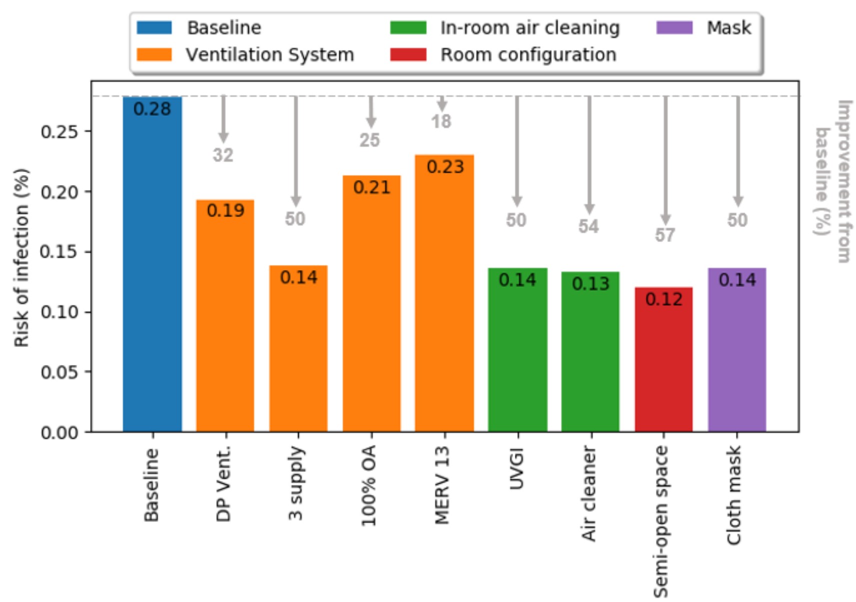


Fig. 16 Potential of individual risk reduction strategy for bistro/cafeteria

4.4.3. Hotel lobby

The performance of each control strategy in the lobby area is summarized in **Fig. 17**. Compared with the bistro/cafeteria, the lobby area has only half occupancy, and therefore, the infection risk of the baseline case is a little higher than the previous case. The N95 mask can still reduce the risk of infection to 0% and a cloth mask can reduce the risk to 0.16%. The potential of each risk reduction strategy is summarized in

Fig. 18. It was shown that increasing the total supply airflow rate, UVGI and semi-open space can reduce the risk of infection by 55% which is better than the cloth mask (52%). The other four strategies, displacement ventilation, 100% outdoor air, MERV 13 filter, and portable air cleaners, can reduce the infection risk by 30%, 36%, 27%, and 39%, respectively.

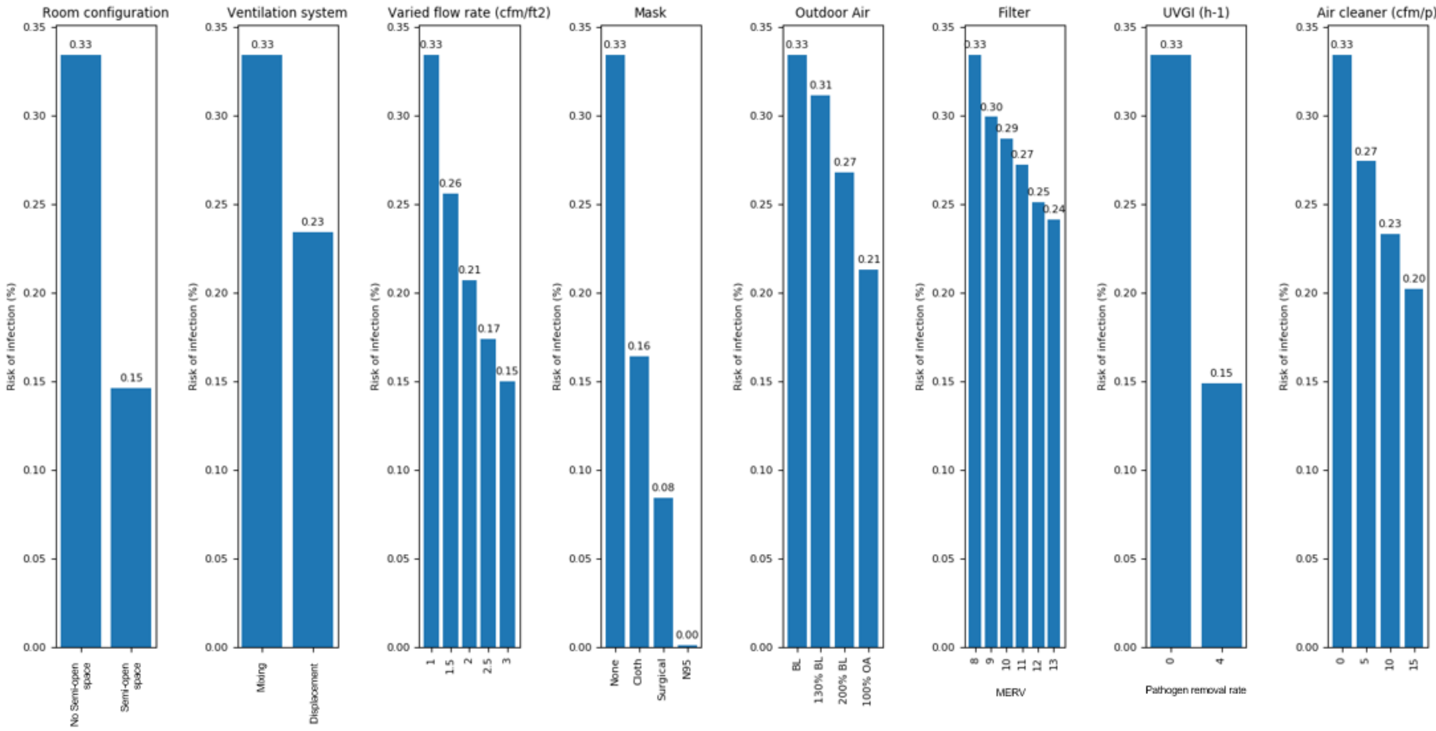


Fig. 17 Effects of individual risk reduction strategies for lobby area

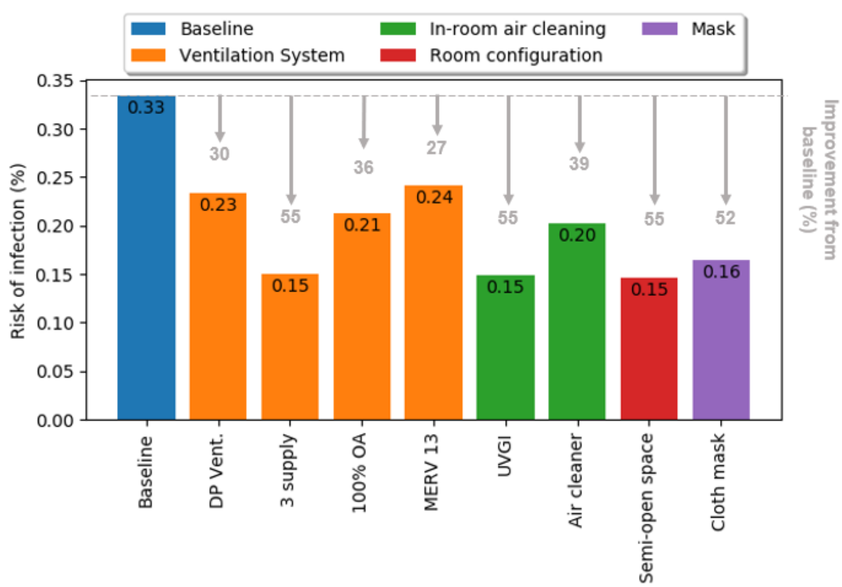


Fig. 18 Potential of individual risk reduction strategy for hotel lobby

4.4.4. Classroom (lecture)

The performance of each control strategy in the classroom is summarized in **Fig. 19**. Due to the smaller ventilation and total supply flow rate and longer exposure time (8h) compared with the first three cases, the infection risk of the baseline case is 12.31%. The most effective strategy is still wearing N95 mask, but the risk of infection while wearing N95 mask is 0.03%. The cloth mask can also reduce the risk by around 50% to 6.23%. The potential of each risk reduction strategy is summarized in **Fig. 20**. It was shown that increasing the total supply airflow rate, using the UVGI and semi-open space can reduce the risk of infection by 50%, 51%, and 55%, respectively, which are all higher than the cloth mask can do. The best environmental control strategy is using the semi-open space which can reduce the infection risk by 55% while the cloth mask can only provide 49% reduction in risk. The other four strategies, displacement ventilation, 100% outdoor air, MERV 13 filter, and air cleaner, can reduce the infection risk by 29%, 26%, 19%, and 48%, respectively.

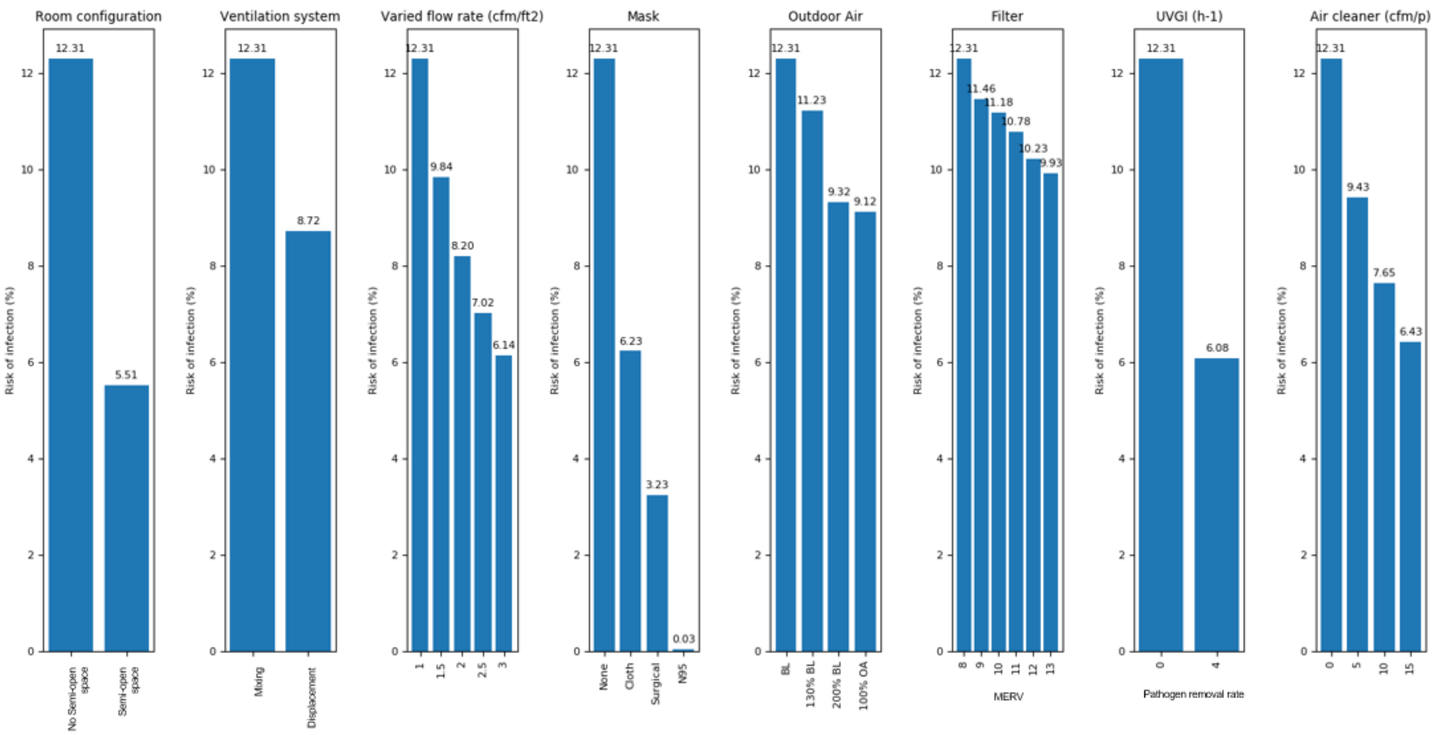


Fig. 19 Effects of individual risk reduction strategies for classroom (lecture)

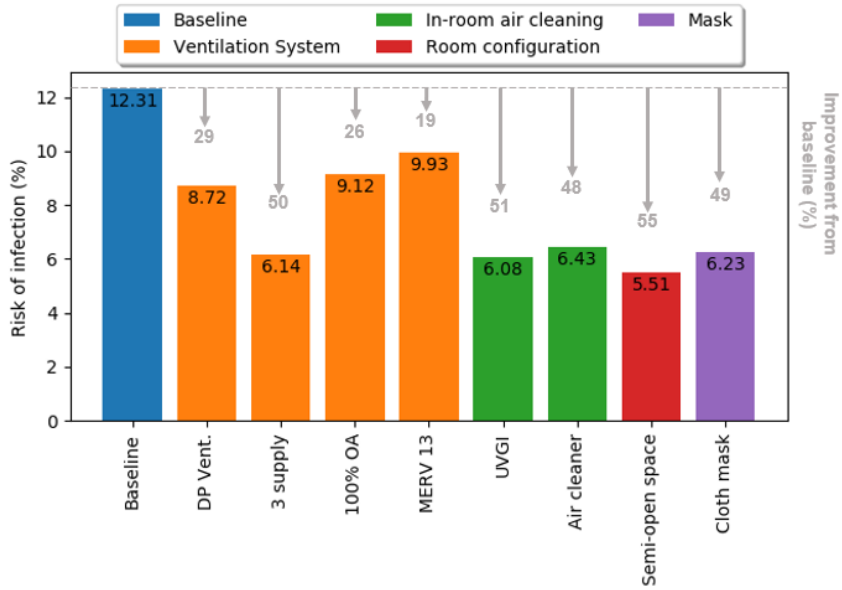


Fig. 20 Potential of individual risk reduction strategy for classroom (lecture)

4.4.5. Conference room/small classroom

The performance of each control strategy in the conference room/small classroom is summarized in **Fig. 21**. The infection risk of the baseline case is 11.05%. Wearing N95 mask reduces the risk of infection the most to 0.03%. The cloth mask can also reduce the risk to 5.58%. The potential of each risk reduction strategy is summarized in **Fig. 22**. It is shown that the best environmental control strategy is the semi-open space, and it is the only strategy which can reduce the risk of infection (by 55%) more than the cloth mask (50%). The other six strategies, displacement ventilation, increased total supply airflow rate, 100% outdoor air, MERV 13 filter, UVGI, and air cleaner, can reduce the infection risk by 29%, 37%, 35%, 27%, 47%, and 48%, respectively.

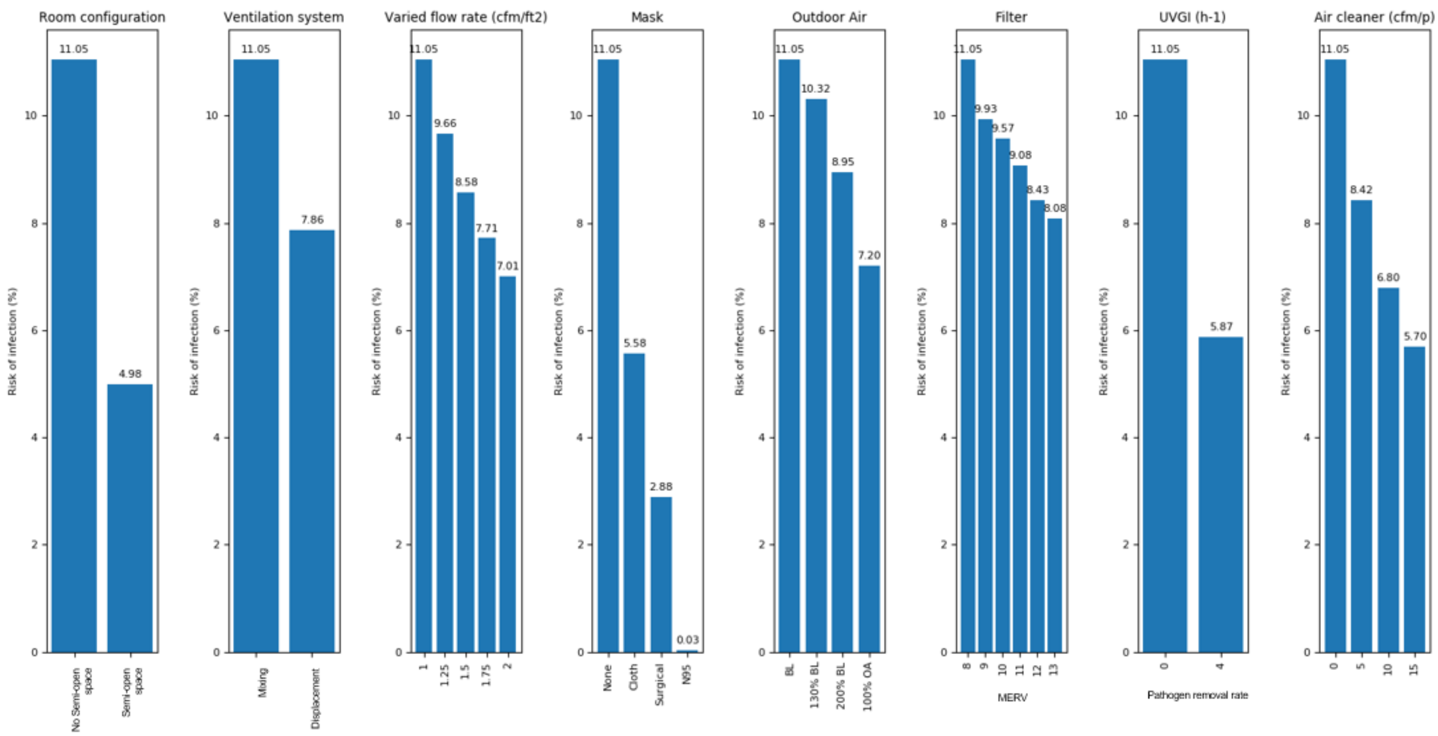


Fig. 21 Effects of individual risk reduction strategies for conference room/small classroom

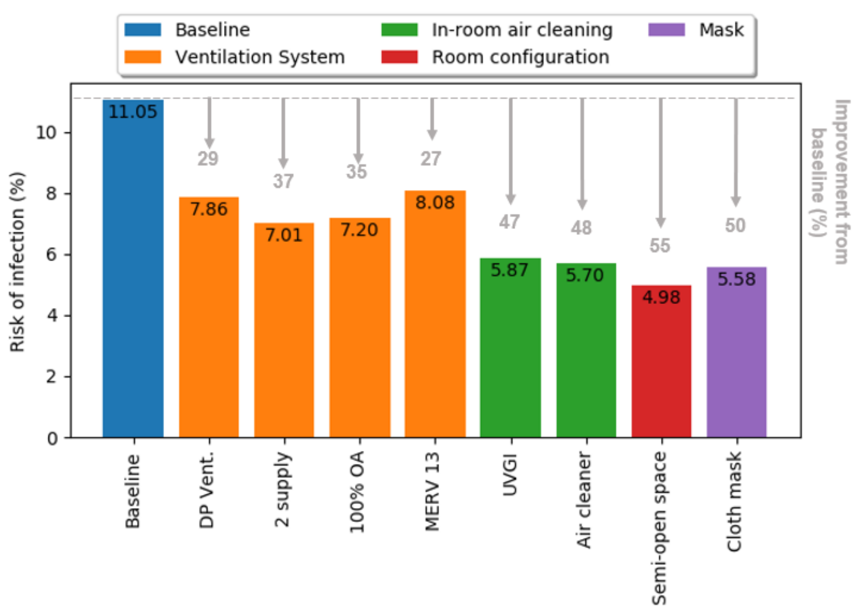


Fig. 22 Potential of individual risk reduction strategy for conference room/small classroom

4.4.6. Hotel/cruise line guest room

The performance of each control strategy in the hotel/cruise line guest room is summarized in **Fig. 23**. Because the room is only occupied by two people and very limited amount of outdoor and supply airflow rate, the infection risk of the baseline case is as high as 90.71%. By wearing the N95 mask, the risk can be reduced to 0.59% which is the most significant reduction. With the cloth mask, the risk of infection is still 68.79%. The potential of each risk reduction strategy is summarized in **Fig. 24**. It was shown that none of the control strategies can reduce the risk of infection by more than 50%. The best environmental control strategy is using the semi-open space which can reduce the infection risk by 27% while the cloth mask can only provide 24% reduction in risk. However, implementing semi-open space in the guest room is usually not possible. The other six strategies, displacement ventilation, increased total supply airflow rate, 100% outdoor air, MERV 13 filter, UVGI, and air cleaner, can reduce the infection risk by 10%, 16%, 17%, 12%, 25%, and 10%, respectively.

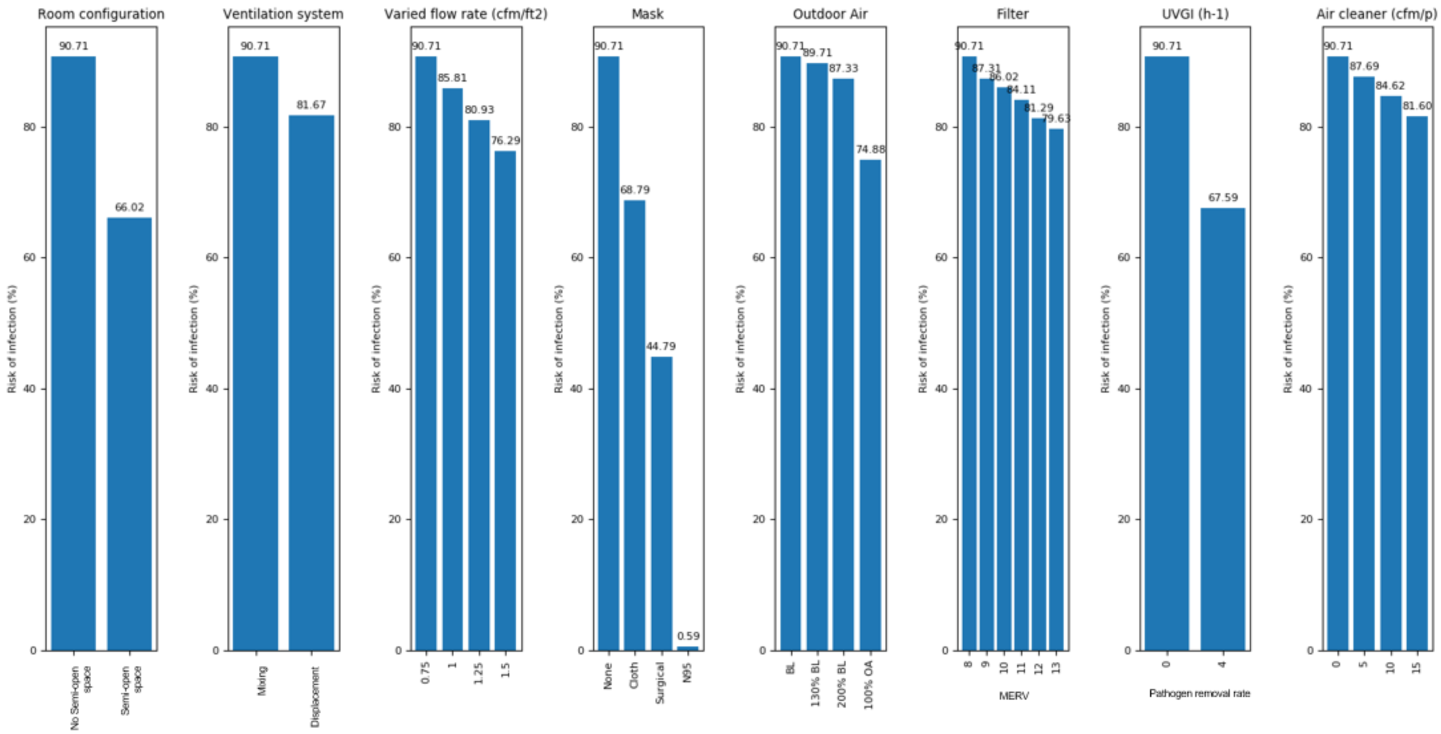


Fig. 23 Effects of individual risk reduction strategies for hotel/cruise line guest room

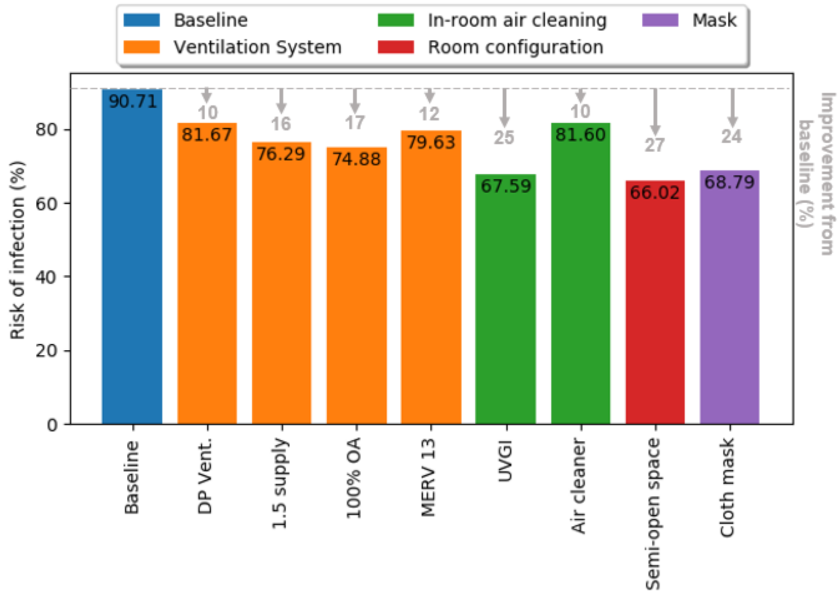


Fig. 24 Potential of individual risk reduction strategy for hotel/cruise line guest room

4.4.7. Open plan office

The performance of each control strategy in the open-plan office is summarized in **Fig. 25**. The infection risk of the baseline case is 6.32%. The most effective strategy is still wearing N95 mask, but the risk of infection while wearing N95 mask is 0.02%. The cloth mask can also reduce the risk by around 50% to 3.15%. The potential of each risk reduction strategy is summarized in **Fig. 26**. Increasing the total supply airflow rate, UVGI and semi-open space can reduce the risk of infection by 59%, 53%, and 55%, respectively, which outperform the cloth mask. The best environmental control strategy is increasing the total supply airflow rate to 3 cfm/ft^2 which can reduce the infection risk by 59% while the cloth mask can only provide 50% reduction in risk. The other four strategies, displacement ventilation, 100% outdoor air, MERV 13 filter, and air cleaner, can reduce the infection risk by 29%, 47%, 38%, and 11%, respectively.

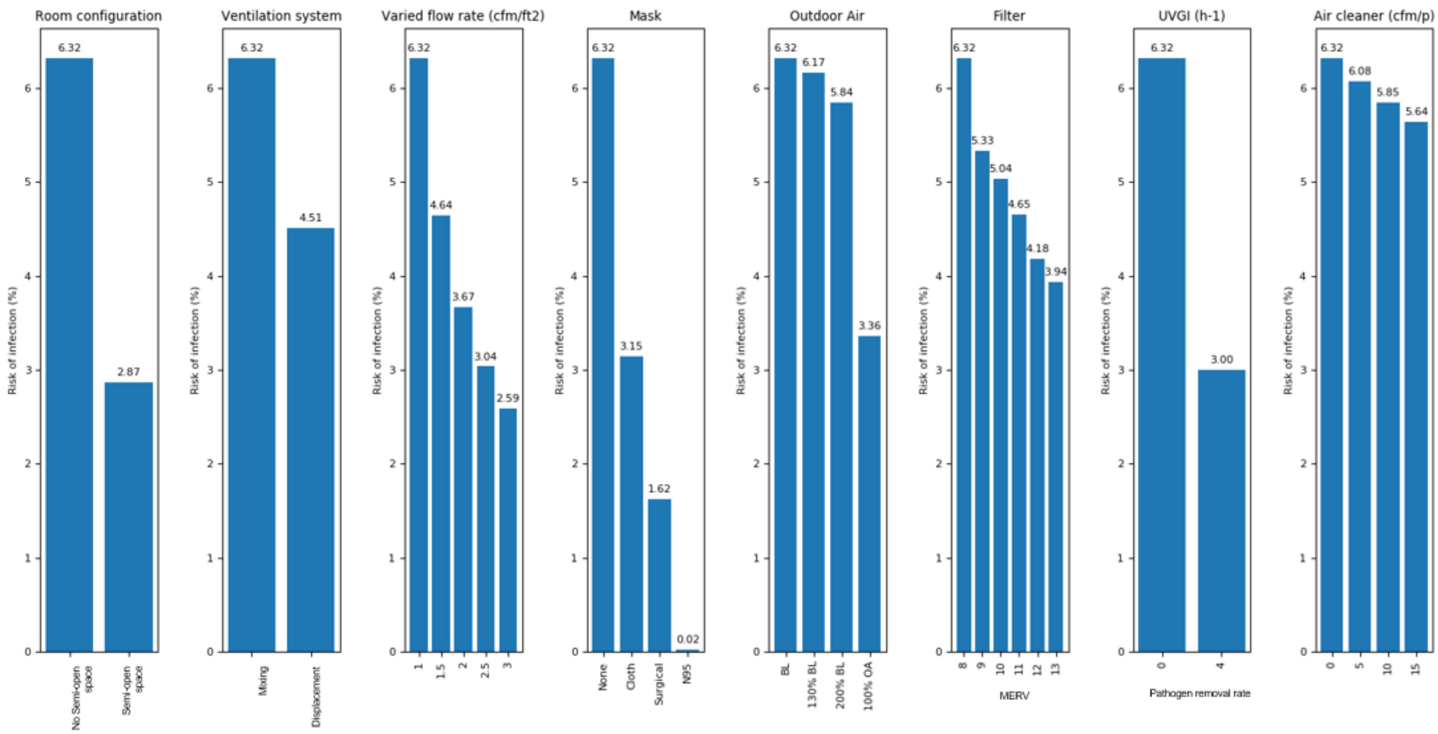


Fig. 25 Effects of individual risk reduction strategies for open-plan office

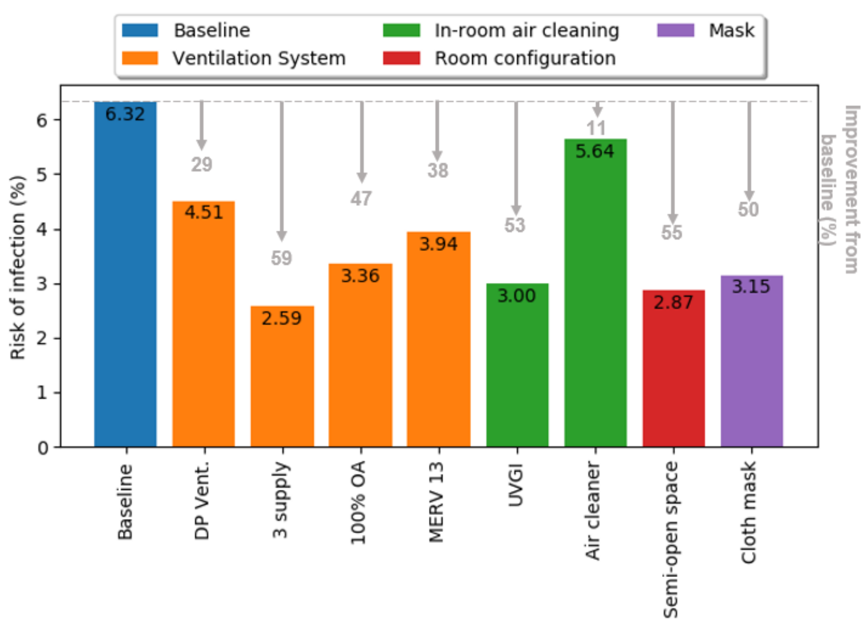


Fig. 26 Potential of individual risk reduction strategy for open-plan office

4.5. Performance evaluation of combined control strategies on Carrier baseline case

The most commonly used building engineering strategies include increased outdoor air, improved filtration system (filter with better efficiency), and portable air cleaner. **Fig. 27** summarizes the risk reduction potential of these three strategies in seven Carrier cases. All these risk reduction potentials were calculated relative to the baseline case and ranged between 0 and 60%. Similar to the previous findings for the general space types, the combined performance of the three strategies is comparatively small for hotel/cruise line guest rooms. This is because the guest room had the lowest occupancy and therefore lowest baseline outdoor airflow rate, total supply flow rate, and clean air provided by air cleaners (CADR assumed based on occupancy), and yet had the highest fraction of virus carriers among the occupants (1 out of 2) assumed. Increasing the outdoor airflow rate and CADR by air cleaners and improving the filtration system are all very effective ways to reduce the risk. With the increase of the outdoor air, the benefits of the filter for recirculation air diminished. When 100% outdoor air was provided, no improvement could be provided by the better filtration system, because no recirculation air was provided. The benefit of the portable air cleaners also diminished when the CADR increased beyond 10-15 cfm/p. Increasing the outdoor air fraction is not as effective as increasing the equivalent CADR by the portable air cleaners since it reduces the recirculation air and hence the impacts of the MERV filter. In addition, increasing MERV 13 to MERV 16 does not reduce the risk significantly in all the simulated cases, yet it may dramatically increase the retrofit and operation cost of the HVAC system. Therefore, as a basic mitigation strategy. MERV 13 is recommended, which requires no major modification to typical existing air handling systems. MERV 16 or HEPA filters are considered as premium mitigation strategy for further reducing the risk and additional assurance considering the possible conditions where virus-containing particles are primarily below 1 um as was found in the medical PPE change room.

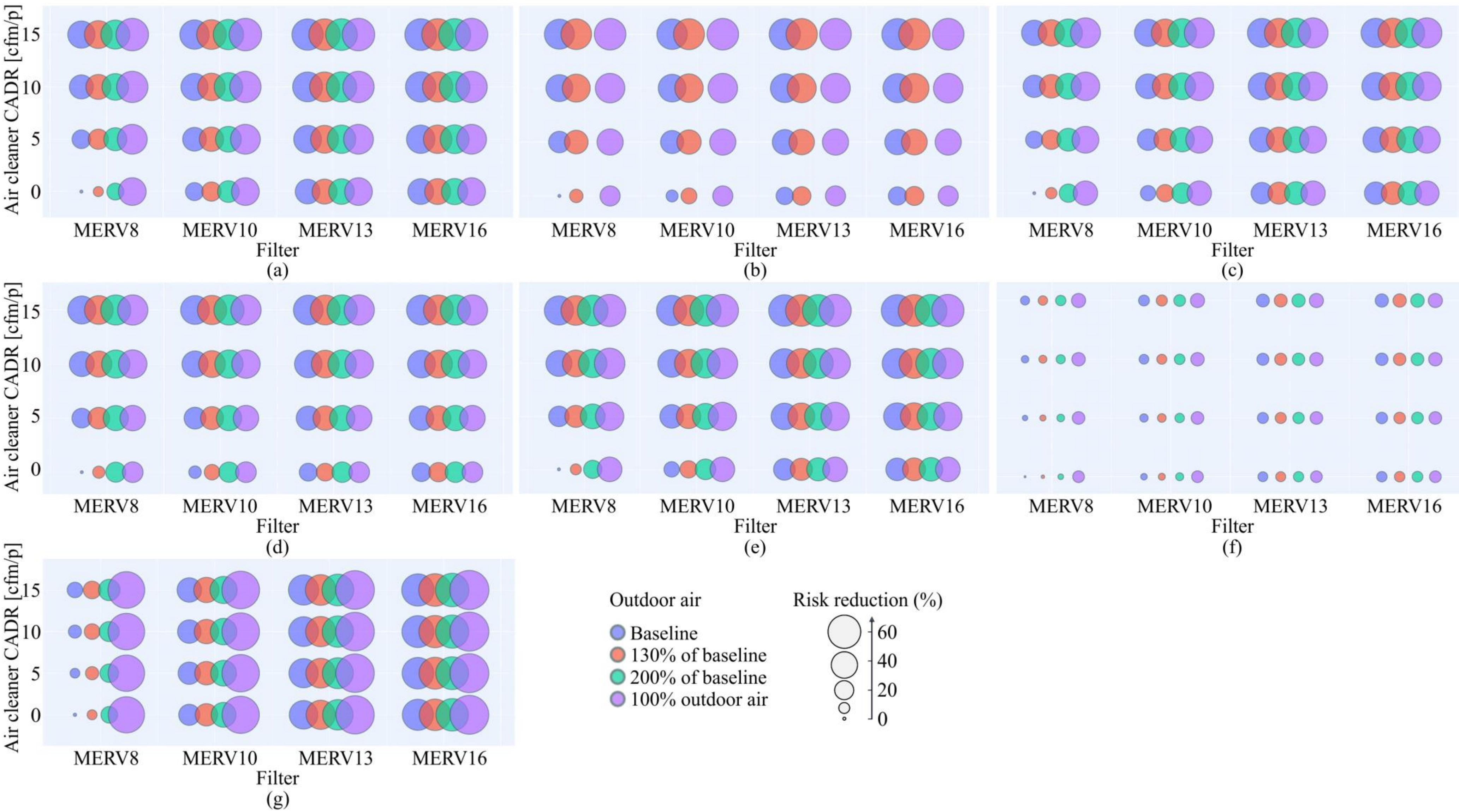


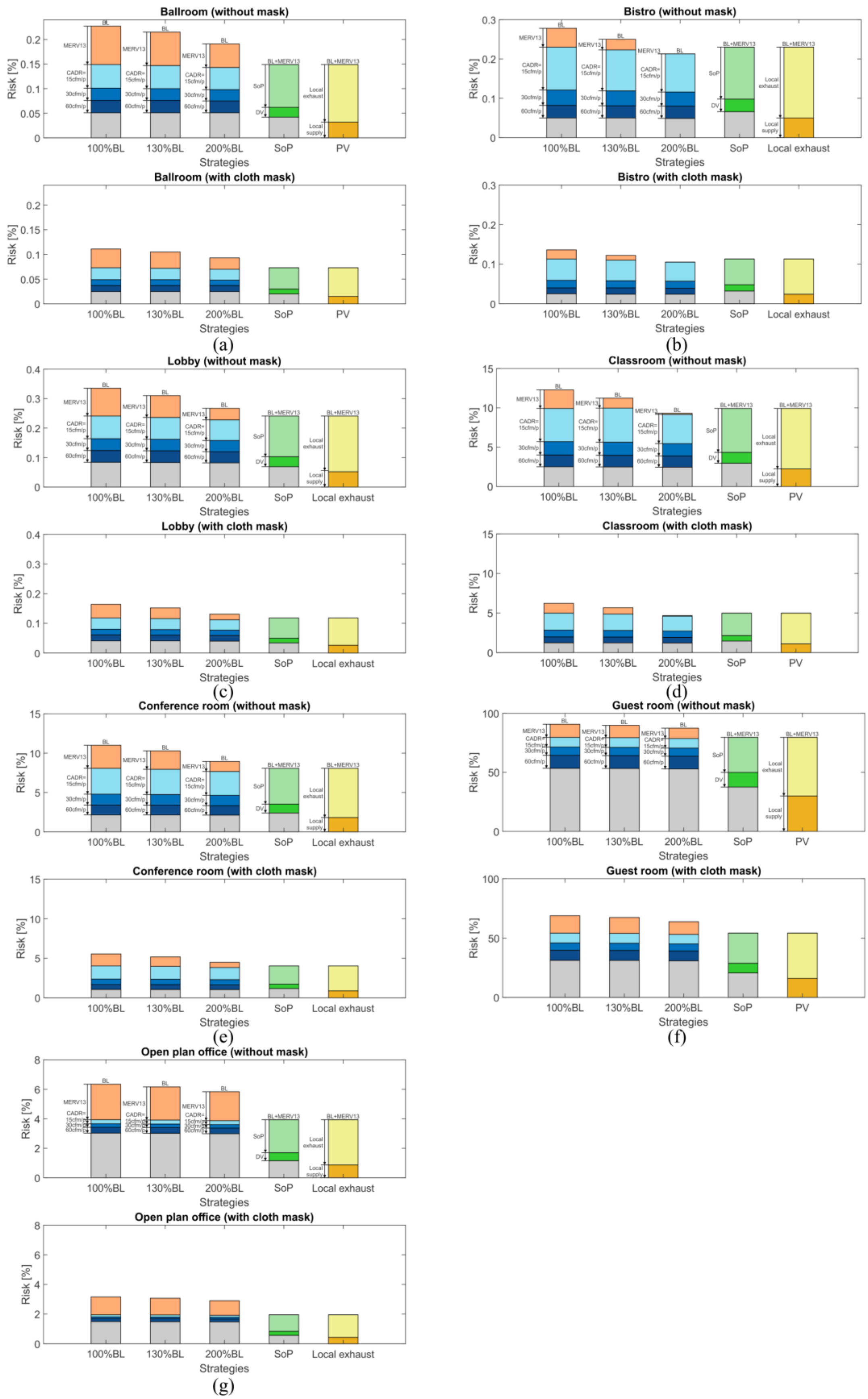
Fig. 27 Potential of Combined Risk Reduction Strategies

4.6. Integrated (Layered) Control Strategies

All the strategies mentioned above require modification or retrofit of either the configuration of the system of the spaces, and therefore some necessary cost. Depending on the efforts and costs needed, three levels of integrated control strategies were proposed and evaluated with selected spaces:

1. Basic (without major system retrofit):
   a) 100%, 130% or 200% BL OA, respectively
   b) a)+MERV 13 (within the capacity of existing system)
   c) b)+15 cfm/p CADR (low-cost standalone air cleaners, flexible, easy to deploy)
   d) b)+30 cfm/p CADR (more standalone air cleaners or supper air cleaners such as higher end UVGI in-duct or upper room UVGI)
   e) b)+60 cfm/p CADR (supper air cleaners/disinfectors)
2. Intermediate – semi-open partition + airflow pattern management (mixing or displacement room air distribution) – require more expertise and some materials
3. Premium:
   f) Personal environmental control
   g) System retrofit to accommodate MERV 16 or HEPA filters. This is only for worst case condition where majority of virus containing particles are <1.0 μm such as found in medical PPE change rooms, or for enhanced safety precaution given the uncertainty in virus distribution among different particle sizes.

Fig. 28 shows the calculated risk of infection of the layered approaches for seven spaces, which could be categorized into three groups, i.e. high occupancy and short exposure (ballroom, bistro/cafeteria, lobby), medium occupancy and medium exposure (classroom, conference room, open plan office), and low occupancy and long exposure (guest room). It indicates that consistent with the findings of previous sections, wearing masks can reduce the risk significantly (about 50% with cloth mask). Similar level of risk reduction can be achieved by installing MERV 13 filter and supplement 15 cfm/p with in-room air cleaners. When MERV 13 filter is used, increasing the outdoor air flow rate has reduced effects on risk reduction while may lead to significant increase in heating or cooling energy consumption. The benefit of increasing the CADR by air cleaners beyond 15 cfm/p also diminishes for all the space types except for the guest room scenario. For example, 22% reduction of the risk was achieved by providing 15 cfm/p CADR, but further reducing the risk by 22% requires 45 cfm/p more CADR. Both the basic and intermediate approaches can reduce the risk to almost the same level, especially for high-occupancy-short-exposure and medium-occupancy-medium-exposure spaces, but the additional cost of the basic approach come mostly from minor system retrofit and/or adjustment to the system operation while the intermediate approach's cost comes mostly from modification of the room and duct configurations, and requires more design expertise for space air distribution/diffusion. The premium approach is the most effective one which can reduce the risk to 0% when both local supply and local exhaust are used simultaneously. However, this kind of approach may be too costly and not suitable for all the spaces.



Ballroom (without mask)
Ballroom (with cloth mask)
Bistro (without mask)
Bistro (with cloth mask)
Lobby (without mask)
Lobby (with cloth mask)
Classroom (without mask)
Classroom (with cloth mask)
Conference room (without mask)
Conference room (with cloth mask)
Guest room (without mask)
Guest room (with cloth mask)
Open plan office (without mask)
Open plan office (with cloth mask)
Risk [%]
Strategies
100%BL
130%BL
200%BL
SoP
PV
Local exhaust
BL
MERV13
CADR=15cfm/p
30cfm/p
60cfm/p
BL+MERV13
DV
Local supply
(a)
(b)
(c)
(d)
(e)
(f)
(g)

Fig. 28 Performance of layered control strategies (a. ballroom; b. bistro/cafeteria; c. lobby; d. classroom; e. conference room; f. hotel/cruise line guest room; g. open plan office)

4.7. Estimated risk reduction from air cleaning products identified by Carrier

In addition, the performance of several Carrier selected products (air cleaners) has been evaluated using the proposed model. The experimentally determined CADR of these products are given in **Table 20**. The risks of infection using these products in selected spaces are shown in **Fig. 29**. The results have indicated that the performance of these products is positively correlated to the CADR of the product. Product 1 also provides the best risk reduction. Even in the guest room (baseline infection risk is as high as 91%), this product can still reduce the infection risk to around 0.1%.

Table 20 Product information

Product	CADR [cfm]
Product 1 – 219,544CFM	219,544
Product 1 – 105,381CFM	105,381
Product 2	976
AVLI	45,344
KLARWIND – 2,140CFM	2,140
KLARWIND – 3,075CFM	3,075

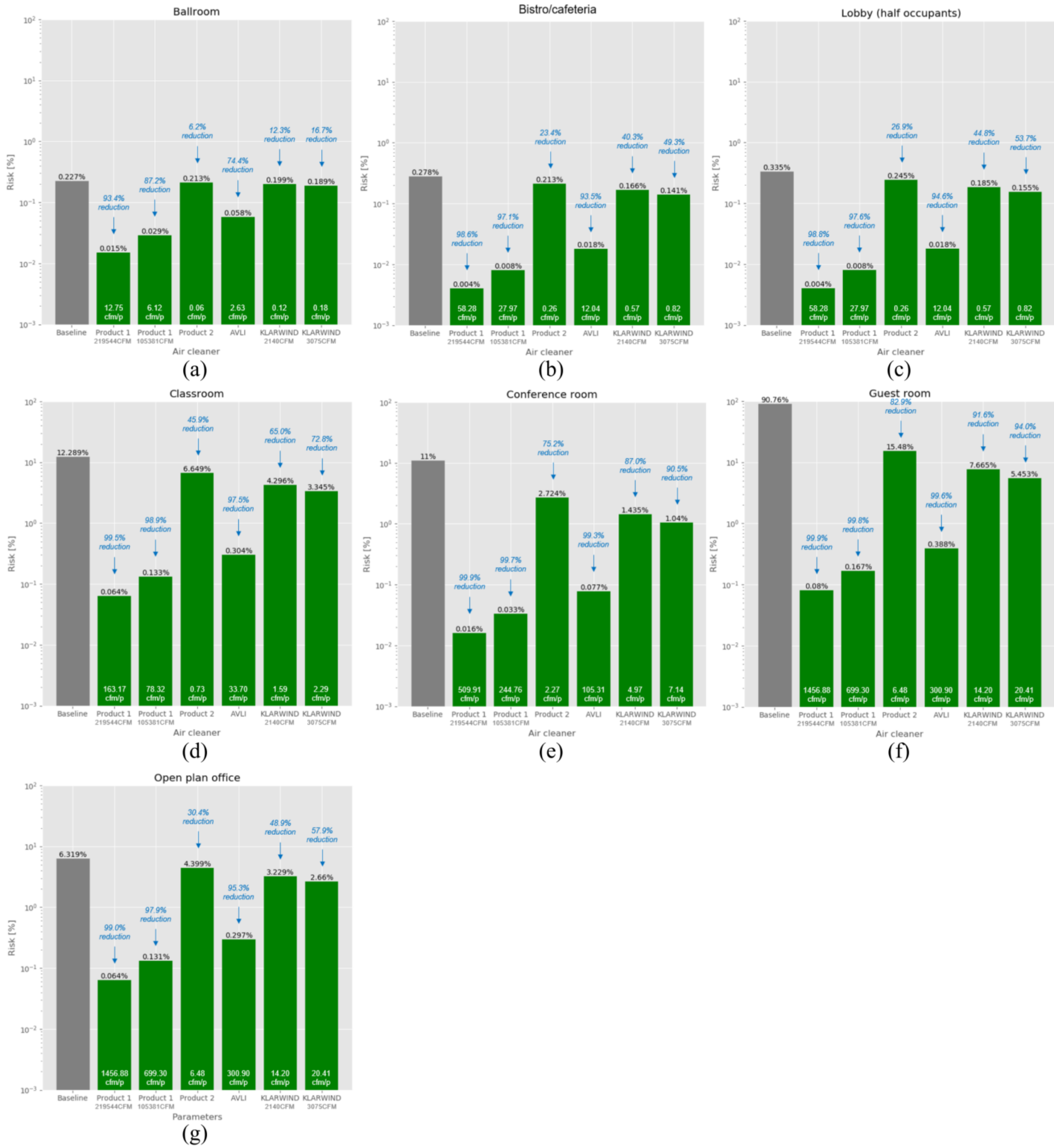


Fig. 29 Performance of selected products (a. ballroom; b. bistro/cafeteria; c. lobby; d. classroom; e. conference room; f. hotel/cruise line guest room; g. open plan office)

5. Conclusions

A method and procedure has been developed for estimating the COVID 19 infectious risk due to exposure to SARS-CoV-2. We used a widely adopted airborne disease infection risk model (Wells-Riley equation) to investigate the infection risk of the SARS-CoV-2 in some typical indoor spaces in office buildings, educational buildings, hotels, and cruise ship. Risk analysis were also performed for the seven (7) specific space types defined by Carrier to evaluate the effectiveness of different levels of increased ventilation, enhanced filtration and equivalent clean air delivery rate (CADR) by using room air cleaners. The original Wells-Riley equation was modified to account for the effects of mask filter efficiency, virus distribution in different size of particles, recirculated air filter efficiency, particle deposition rate in the space, room air ventilation efficiency (as affected by the space air diffusion, internal partitions, and locations of susceptible and infectors) as well as the outdoor ventilation rate. The quantum generation rate per infector for SARS-CoV-2 was derived from the published SARS-CoV-2 case studies available to date. Baseline cases were established based on the literature and online survey as well as Carrier's previous projects to represent the typical configurations in selected types of indoor spaces. The IAQ control strategies, including increasing the ventilation rate, improving the ventilation efficiency by changing the air distribution system, improving the air filtration system, the use of the personal protection equipment, etc., were evaluated for their individual and combined effectiveness in risk reduction against the baseline cases. Some major findings are summarized below:

1. Wearing the mask is the most cost-effective way to provide protections. A cloth mask can usually reduce the infection risk by 50%. A similar level of risk reduction is achievable by installing MERV 13 filter and supplement 15 cfm/p CADR with room air cleaners.
2. Depending on the space type, some engineering approaches including more total supply air, UVGI, portable air cleaner and semi-open space can provide more protection than a cloth mask.
3. The benefit of increasing total supply flow rate and clean air delivered by the air cleaner and upgrading the filtration system decreases with the increase of the total "equivalent" clean air delivery rate.
4. The benefit of the portable air cleaners also diminished when the CADR increased beyond 10-15 cfm/p for all the space types studied except for the guest room case where high baseline infection risk was present.
5. Increasing the outdoor airflow rate is not as effective as increasing the same amount of CADR provided by the portable air cleaners since increasing the outdoor airflow rate will also reduce the recirculation air which can also help reduce the risk when properly filtered.
6. Installing a MERV 13 filter in the recirculation air duct is recommended as a basic mitigation strategy. Increasing MERV 13 to MERV 16 does not further reduce the risk significantly for all the cases studied but it may dramatically increase the retrofit and operation cost of the HVAC system.
7. With the MERV filter in place, increasing the outdoor air flow rate has less effect in reducing the risk because it deceases the amount of air through the MERV filter.
8. The basic and intermediate approaches can reduce the risk to almost the same level while the premium approach is the most effective one which can reduce the risk to 0% although it may not be applicable for all the spaces.
9. The performance of portable air cleaner is positively correlated to its CADR. Product 1 can reduce the infection risk to below 0.1% level.

Further studies will focus on extending the current model to include unsteady-state conditions and account for uncertainties in the model parameters such as the quantum generation rate, virus distribution among different particle size ranges, inhalation flow rates, and occupant exposure times, and test and validate the performance of the selected mitigation strategies by experiment. In addition, the inter-zonal cross-contamination and detailed zonal virus distribution under different room configurations, and for specific application scenarios are also needed to understand the spatial distribution of virus inside a room and its impact on the dose exposure and associated infection risk.

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