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The Effect of Suggested Ventilation Approaches After Covid-19 on The Probability of Infection, Number of Cases and Ventilation Rates in University Classrooms

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Abstract

After COVID-19, two ventilation approaches have been adopted for infection control. The first is the EN 16798-1 ventilation standard recommended by international organizations. The second is ventilation design, determined according to the risk of infection. This study investigated the effects of various post-COVID-19 ventilation scenarios on the probability of COVID-19 infection, the number of cases, and ventilation rates in four separate university classrooms. Ventilation rates based on infection risk and infection risk were determined by the Wells-Riley mathematical model calibrated to the SARS-CoV-2 virus. The findings showed that the EN 16798-1 ventilation standard may be inadequate in terms of infection risk in classrooms. It showed that ventilation rates determined based on infection risk may not be met by existing HVAC system capacities, even in LEED-certified schools. In possible future pandemics, current ventilation standards and air conditioning system designs in schools should be reviewed in order to control the outbreak.

Keywords: *Ventilation, COVID-19 infection risk, Wells-Riley Model, classrooms.*

Covid-19 Sonrası Önerilen Havalandırma Yaklaşımlarının Üniversite Dersliklerinde Enfeksiyon Olasılığı, Vaka Sayısı ve Havalandırma Oranlarına Etkisi

Öz

COVID-19 salgını sonrasında enfeksiyon kontrolü için iki havalandırma yaklaşımı benimsenmiştir. Birincisi, uluslararası kuruluşlar tarafından önerilen EN 16798-1 havalandırma standardıdır. İkincisi, enfeksiyon riskine göre belirlenen havalandırma tasarımıdır. Bu çalışmada, dört ayrı üniversite sınıfındaki çeşitli COVID-19 sonrası havalandırma senaryolarının, COVID-19 enfeksiyon olasılığı, vaka sayısı ve havalandırma oranları üzerindeki etkilerini araştırıldı. Enfeksiyon riskine dayalı havalandırma oranları ve enfeksiyon riski, SARS-CoV-2 virüsüne göre kalibre edilen Wells-Riley matematiksel modeliyle belirlenmiştir. Bulgular, EN 16798-1 havalandırma standardının dersliklerde enfeksiyon riski açısından yetersiz olabileceğini gösterdi. Enfeksiyon riskine dayalı belirlenen havalandırma oranlarının, LEED sertifikalı okullarda bile mevcut HVAC sistem kapasiteleri tarafından karşılanamayabileceğini gösterdi. Gelecekteki olası pandemilerde, salgının kontrol altına alınabilmesi için mevcut havalandırma standartlarının ve okullardaki iklimlendirme sistem tasarımlarının yeniden gözden geçirilmesi gerekmektedir.

Anahtar kelimeler: Havalandırma, COVID-19 enfeksiyon riski, Wells-Riley Model, derslikler.

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1. Introduction

Various studies have hypothesized that the SARS-COV-2 virus can also be spread through the air and persist in the air for up to 3 hours (Lipinski et al., 2020). Thus, during the COVID-19 pandemic, the risk of airborne infection should also be considered in closed places with many users and common areas such as classrooms. In enclosed indoor situations, one of the best ways to reduce the risk of airborne viral transmission, in addition to taking personal precautions, is to provide ventilation conditions that can lower the virus concentration. Hence, the parameters that determine the indoor environment's air quality and ventilation strategy and the particular actions to be performed as part of the COVID-19 pandemic measures occupy a crucial position.

With the global COVID-19 outbreak, the World Health Organization (WHO) deems inadequately ventilated rooms to be at high risk. For education to continue safely after the reopening of schools during the COVID-19 pandemic, existing facilities should be ventilated as effectively as possible (Bhagat et al., 2020). These developments have proven the need for fresh ventilation design in buildings during the COVID-19 pandemic.

Before the COVID-19 pandemic, two key parameters determined the amount of fresh air that should be provided to the indoor environment in international ventilation standards. The first is the recommended amount of fresh air per person to eliminate the effect of pollutants released by individuals on the ambient air. The second is the amount of fresh air that must be provided per unit area to eliminate the effect of the pollutants generated from the building materials on the surrounding air. Before the COVID-19 pandemic, the fresh ventilation rate required for most indoor spaces was determined per ASHRAE 62.1, ISO 17772, EN 16798, and EN 15251 standards, and sizing an air conditioning system was straightforward.

Although the effect of SARS-CoV-2 viral load on the risk of infection with infection in closed indoor environments is unclear following the COVID-19 pandemic, a clear standard for calculating minimum ventilation rates has not yet been produced. The potential danger of airborne infection indoors has, however, been acknowledged by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the European Federation of Heating, Ventilation and Air Conditioning Societies (REHVA), the WHO, and a number of researchers. Hence, he proposed various ventilation techniques during the COVID-19 pandemic.

In its assessment of schools and universities after COVID-19, ASHRAE did not give a specific figure for ventilation rates but said that more ventilation is required than the minimum ventilation rates for schools determined by the ASHRAE 62.1 Standard (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2020). REHVA states that a category I ventilation standard (10 L/h per person) with a higher rate among the three recommended categories in the "EN 16798-1: 2019" ventilation standards in non-hospital buildings may be a solid start for minimizing the risk of infection (REHVA, 2021). The World Health Organization, on the other hand, recommends a minimum ventilation rate of 10 L/s per person, citing the EN 16798-1: 2019 standard for naturally ventilated structures outside the dwelling after COVID-19 (World Health Organization, 2021). Another study discussing the steps to reopen schools suggests that 3 ACH (air exchange rate) ventilation rates in classrooms should be low, that ventilation rates should be between 4 and 6 ACHs, and that 6 ACH is the best-case scenario (Jones et al., 2020).

Kurnitski et al. (2021), stated that constant ventilation rates in classrooms are insufficient under all circumstances and that a general ventilation criterion based on infection risk should be devised using the Wells-Riley model calibrated according to SARS-CoV-2. According to the Wells-Riley model, Dai & Zhao (2020), in their study, the ventilation rate required to keep the probability of infection below 1% according to the Wells-Riley model when staying in a school classroom for 2 hours was found to be between 2-7 ACH. Park et al. (2021), on the other hand, showed that with the Wells-Riley model, with a fresh ventilation rate of 6.51 ACH, the probability of individual infection in classrooms can be kept below 1% if the masked exposure time is 3 hours. In a study in which the risk of infection was estimated according to the CO_2 level, it was stated that the external ventilation threshold to prevent the spread of COVID-19 aerosol differs according to the space volume and the number of users, and varied between 3-8 ACHs for 3 different classes (Hou, Katal & Wang, 2021).

Two distinct ventilation approaches emerge when the studies on ventilation are analyzed after COVID-19. The first approach is to increase the fixed ventilation rates to the recommended standards of international organizations such as ASHRAE, REHVA, and WHO before COVID-19. The second approach is to give recommended ventilation rates based on the risk of infection.

When the studies on both ventilation approaches mentioned above in the COVID-19 pandemic conditions are examined, it has been determined that the ventilation rates have increased compared to the pre-COVID-19 pandemic conditions. However, there are significant uncertainties between the proposed ventilation rates due to spatial differences. These uncertainties result in a poor understanding of the sizing of air conditioning systems in university buildings and the possible risk of infection in classrooms. In higher education institutions, students are subject to education in diverse classrooms regarding the volume and number of users. This allows for different pedagogical approaches from the undergraduate to the doctoral education process. Hence, fixed ventilation rates defined in international guidelines or randomly determined ventilation rates may be sufficient in some classrooms regarding airborne infection management but may constitute a risk regarding infection control in some classrooms.

In prior studies, the Wells-Riley model was used to evaluate the risk of infection in university classrooms. However, no study has been identified examining the relationship between the fixed ventilation rates determined after COVID-19 and the ventilation approaches determined based on the acceptable risk of infection and the ventilation rates determined according to classrooms and infection risks.

This research examined the impacts of recommended ventilation approaches following COVID-19 on the probability of infection, the number of COVID-19 cases, and the ventilation rates in various types of classrooms at higher education institutions. The study's findings may contribute to the planning of the use of prepared classrooms and the reevaluation of the air conditioning system's capacity in university buildings, so improving future preparedness for other potential airborne pandemics such as COVID-19.

2. Material and Method

The study methodology comprises two parts. In the initial phase, design guides for higher education learning spaces were researched, and four classrooms representing university learning spaces were determined. In the second stage, the ventilation rate in classrooms, the probability of infection, and the number of COVID-19 cases of the ventilation approach based on the acceptable risk approach with the EN 16798-1 ventilation standard recommended by WHO and REHVA following COVID-19 were computed. It was then compared to the period prior to COVID-19.

The proposed Wells-Riley mathematical model determined the probability of COVID-19 infection in classrooms and the number of cases. The Wells-Riley model is typically employed in studies examining the quantitative risk of infection of infectious respiratory illnesses in indoor environments (Foster & Kinzel, 2021; Nazaroff, 2022; Yan et al., 2017; Zhang & Lin, 2021).

According to the ASHRAE 62.1 standard, the minimum ventilation rates recommended for pre-COVID-19 have been determined. Following COVID-19, the ventilation rate in the WHO and REHVA ventilation approach was determined based on category I of the "EN 16798-1: 2019" standard. With the approach of infection risk based on infection risk, the ventilation rates were determined based on the acceptable infection risk level.

2.1. Determination of Classrooms

According to pedagogical requirements, higher education learning spaces are typically split into seminar classrooms, traditional classrooms where didactic education takes place, active learning classrooms, lecture halls, and auditoriums (Arizona State University, 2019; University of Michigan, 2012; University of Toronto, 2012). As learning spaces, two various sizes (small and large classrooms) and lecture halls classrooms that can be utilized for seminars, traditional classrooms, or contract learning classrooms were determined in this study.

The recommended classroom capacity has been determined based on design recommendations provided by higher education institutions (Mcgill University, 2020; The University of British Columbia, 2014; University of California, 2015). Unit space required for classrooms based on recommended capacities, ASHRAE 62.1 determined based on the density of people seated in the ventilation standard. According to ASHRAE 62.1, the minimum ventilation rate in classrooms is recommended to be 0.66 m^2 per person for lecture halls and 1.53 m^2 per person for other classrooms. The permissible ceiling height for classrooms is 3.5 m^2. Table 1 lists the users and locations of the classrooms.

Table 1. User and location information of the classrooms

Classroom type	**Floor space (m^2)**	**Space Ceiling height (m)**	**Before COVID-19 conditions**		**After COVID-19 conditions**	
			Total number of people	Number of people per area (m^2)	Total number of people	Number of people per area (m^2)
Seminar	30.60	3.50	20	1.53 m^2	10	3.06
Small Classroom	91.80	3.50	60	1.53 m^2	30	3.06
Large Classroom	153.01	3.50	100	1.53 m^2	50	3.06
Lecture Hall (fixed seat)	66.66	3.50	100	0.66 m^2	50	1.32

After COVID-19, in the process of returning to face-to-face education in schools, many precautions have been taken to avoid being infected with the SARS-COV-2 virus indoors. Some of these measures are maintaining physical distance, called social distancing of 1.5−2.0 meters (Welsch et al., 2020), and halving the user density indoors (Li et al., 2021). That's why it has been diluted by 50% for capacities to implement social distance in classrooms after COVID-19.

2.2.Determination of Estimated Infection Risk and Ventilation Rate in Classrooms

2.2.1.Basic Wells-Riley model

The Wells-Riley model is a mathematical model based on the concept of infection quantum that is used to model the probability of transmission of airborne infectious particles to an individual in a well-mixed indoor environment at a steady state. The quantum in this risk model is an estimated unit of infectious dose derived from observational epidemiological studies (Azimi & Stephens, 2013).

The Wells Riley mathematical model for calculating the probability of infection after COVID-19 is shown in equation (1).

$$P_I = \frac{C}{S} = 1 - \exp\left(-\frac{Iqpt}{Q}\right) \tag{1}$$

where P_I is the probability of infection risk (In certain studies, it is referred to as R-value); C is the number of cases that develop infection (It is referred to as the basic reproduction number Ro in certain studies); S is the number of susceptible people; I is the number of infected persons; q is the quanta emission rate depending on the activity; p is the pulmonary ventilation rate of exposed susceptible persons; t is the duration of stay and Q is the volume flow of pathogenic free air. In the original Wells-Riley model, the factors affecting the risk of infection are limited to the parameters specified in the equation.

2.2.2.Calibrating the Wells-Riley model according to SARS-COV-2

The COVID-19 Task Force of REHVA's Technology and Research Committee (REHVA, 2021), has calibrated the airborne infection risk model according to SARS-COV-2 in line with data obtained from COVID-19 studies to calculate the risk of SARS-CoV-2 infection based on the Wells-Riley equation developed by Gammaitoni & Nucci (1997) Subsequently, Kurntiski et al. (2021), derived Equation (2) to calculate ventilation rates for acceptable infection risk levels from the event reproduction number to develop a ventilation design method based on respiratory infection risk. In this equation (2), in addition to the original Wells-Riley equation, the surface deposition loss and virus decay parameters of the virus are considered when calculating the infection probabilities and aeration rates.

$$Q = \frac{qQ_bD}{ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k\right)V \tag{2}$$

Where q is the quanta emission rate per infected person (quanta/(h pers); Q_b is the volumetric breathing rate of an occupant (m^3/h); D is the duration of the occupancy (h); I is the number of infectious persons; n is the quanta inhaled; p is the probability of infection for susceptible persons; λ_{dep} is depostion onto surfaces (1/h); k is virus decay (1/h); V is volume of the room (m^3).

As shown in Equation (3), the amount of inhaled quantum (n) depends on the average of the quantum concentration (C_{avg}), a person's volumetric respiratory rate (Q_b, m^3/h), and the length of time people stay in the area (D, h).

$$n = C_{avg}Q_bD \tag{3}$$

Assuming that the quanta concentration is 0 at the beginning for the occupancy of the space, the average concentration is determined as shown in Equation (4) and Equation (5):

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

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

where t is time (h); Λv is the outdoor air change rate (1/h); E is quanta emission rate (quanta/h). E değeri denklem 6'daki gibi hesaplanıır. The first order loss amount coefficient (λ, 1/h) for quanta/h is determined according to Equation (7) (Yang & Marr, 2011) below:

$$\mathrm{E} = \mathrm{Iq} \tag{6}$$

$$\lambda = \lambda v + \lambda_{dep} + k \tag{7}$$

The infection probability and aeration rates calculated with the improved Wells-Riley model (Kurnitski et al., 2021; REHVA, 2021) may differ from the original Wells-Riley model, as the surface depositional loss and virus decay parameters of the virus may affect the average concentration of quanta in the indoor environment.

2.2.3.Calibrating the Wells-Riley model according to SARS-COV-2

Uncertainties about the features and transmission mechanism of the SARS-CoV-2 virus induce various variations in the Wells-Riley model (Guo et al., 2021). To effectively forecast infection risk and ventilation rates, the values of all parameters in the modified Wells-Riley mathematical model must be determined. In this section of the study, the pertinent literature on the SARS-CoV-2 virus was thoroughly read, and the parameters in the Wells-Riley model were calibrated according to SARS-COV-2.

The measurement of the virus emission rate (q), which determines the virus's contagiousness, is one of the most critical difficulties in using the Wells-Riley mathematical model. The quantum emission rate (q) is estimated epidemiologically during an epidemic (Sze To & Chao, 2010). The quanta emission rates of SARS-Cov-2, which change depending on specific activities, have been researched by several researchers. According to the research of Buonanno et al. (2020) the average value of the quantum emission rate lecture rates (6.85 q/h) was accepted in this study. Subsequently, using a conversion factor coefficient of 3.30 for the SARS-CoV-2 Omicron BA.2 variety, the determined quantum emission rate by Lyngse et al. (Lyngse et al., 2022) has been adjusted to 22.60 q/h. The number of people vulnerable to the virus was determined for classrooms before and after COVID-19, and the capacities of the demonstrations were accepted in Table 1, Table 2 summarizes recent studies and accepted values for the parameters of the Wells-Riley equation.

Table 2. Determination of Wells-Riley model parameters

Parameters	Unit	Value	Related Studies
Virus Inactivation Rate (k)	1/h	0.63	(van Doremalen et al., 2020; Fears et al., 2020)
Accumulation Loss Rate of Virus on Surfaces (Λ_{dep})	1/h	0.24	(Buonanno, Morawska & Stabile 2020; Buonanno, Stabile, et al., 2020; Chatoutsidou & Lazaridis 2019; Diapouli, Chaloulakou &Koutrakis 2013; Miller et al., 2021; Thatcher et al., 2002)
Quantum Emission Rate (Q)	quantum/h	22.6	(Buonanno, Stabile, et al., 2020; Dai & Zhao 2020; Park et al., 2021)
Volumetric breathing rate of an occupant (Q_b)	m^3/h	0.60	(Adams, 1993; Binazzi et al., 2006; Chen, Chang & Liao 2006; Gao et al., 2021; Stephens, 2012; Yılmazoğlu, 2020)
Number of Infected Persons (I)	person	1	(Guo et al., 2021; Park et al., 2021; Stabile et al., 2021)
Exposure time to the virus	hour	4	

The exposure time to the virus in the classrooms was determined by considering the daily usage times of the school. Lessons usually occur between 08:00-12:00 and 13:00-17:00. Therefore, the exposure time to the virus has been determined as 4 hours.

2.2.4.Calibrating the Wells-Riley model according to SARS-COV-2

According to ASHRAE 62.1, the recommended ventilation rates for classrooms before COVID-19 were 3.8 l/s per person and 0.30 L/m^2 space. Considering the classroom capacities, the minimum ventilation rates required are 2.78 L/(s m^2) in the seminar, small and large classrooms, and 6.05 L/(s m^2) in the lecture hall.

REHVA indicates that a category I ventilation standard (10 L/h per person) with a higher rate of infection among the three recommended categories in the "EN 16798-1:2019" ventilation requirements in non-hospital buildings may be a good start for minimizing the risk of infection (REHVA, 2021).

The World Health Organization, on the other hand, recommends a minimum ventilation rate of 10 L/s per person, citing the EN 16798-1:2019 standard for naturally ventilated structures outside the dwelling after COVID-19 (World Health Organization, 2021). In light of the classroom capacity, the required ventilation rates are 3.26 L/(s m^2) in the seminar, small and large classrooms, and 7.57 L/(s m^2) in the lecture hall.

Kurnitski et al. (2021) assessed the probability of infection by updating and calibrating the equation in which ventilation rates were determined during the COVID-19 procedure. The probability of infection and the number of new cases are calculated in equation (8) based on the ventilation infection rates determined before COVID-19.

$$P\iota = 1 - \frac{1}{e^{\frac{qQ_bD}{Q+(\lambda_{dep}+k)V}}} \qquad (8)$$

2.2.5. Estimated ventilation rates based on the acceptable risk of infection

The probability of infection is usually expressed in terms of the baseline reproduction number (R_0) (Vignolo et al., 2022). In the COVID-19 pandemic, the basic reproductive number $R_0 < 1$ is recommended for the reduction of the disease in the susceptible population (Achaiah, Subbarajasetty & Shetty, 2020; Schibuola & Tambani, 2021). The basic reproduction number is determined by Equation (9) below.

$$R0 = S \times R \tag{9}$$

In the equation, R_0 represents the number of reproductions, S represents the number of susceptible individuals, and R represents the individual risk of infection. In order to estimate the minimum ventilation rate based on the acceptable risk of infection following COVID-19, the fundamental reproduction number was accepted as R_0=0.99. The infection probability determined by equation 1 was determined based on the 0.99 basic reproduction number accepted in the classrooms. Then the required ventilation rates were calculated according to equation (2).

3. Conclusion and Suggestions

Allen & Ibrahim (2021) say that ventilation rates of 4-6 ACH (air change rate per hour) should be targeted in classrooms during the COVID-19 period. The study looking at the measures to reopen schools at Harvard states that 3 ACH is too low for ventilation rates in classrooms, they should be between 4-6 ACH and 6 ACH is the most ideal scenario (Jones et al., 2020). Dai & Zhao (2020) stated that the ventilation rates required to keep the probability of COVID-19 infection below 1% when exposed to the virus for 2 hours in classrooms vary between 2-7 ACH. Hou et al. (2021) reported in their study, which was conducted in three different classrooms from three different schools, that ventilation rates varied between 3 and 8 ACH depending on the classroom in order to prevent the spread of SARS-CoV-2. In the ventilation scenarios investigated within the scope of the study, according to the ventilation rates specified in Table 5 and Table 4, the ventilation rates required in classrooms before COVID-19 varied between 2.85-6.22 ACH. In the ventilation scenario recommended by WHO and REHVA after COVID-19, the required ventilation rates in classrooms were between 3.35-7.78 ACH. In the ventilation design determined based on the risk of infection after COVID-19, the ventilation rates in the classrooms were between 3.70 and 10.62 ACH. The findings obtained within the scope of the study show that they are consistent with the results of studies on COVID-19 and ventilation rates, but ventilation rates may vary depending on the physical conditions in the classrooms.

3.1. WHO and REHVA ventilation design

Table 3 displays the ventilation rate in classrooms of the EN 16798-1 ventilation standard recommended by WHO and REHVA and the pre-COVID-19 ventilation standards, the probability of COVID-19 infection, and the number of COVID-19 cases, assuming 4-hour use of the classrooms.

Table 3. WHO and REHVA ventilation approach infection risk and ventilation rates

Classroom Type	Ventilation before COVID-19				WHO and REHVA ventilation			
	Number of People	Ventilation rate (L/s m^2)	Probability of infection (P_I)	Number of COVID-19 Cases (person)	Number of People	Ventilation rate (L/s m^2)	Probability of infection (P_I)	Number of COVID-19 Cases (person)
Seminar Classroom	20	2,78	%11,9	2,38	10	3,26	%10,7	1,07
Small Classroom	60	2,78	%4,1	2,48	30	3,26	%3,7	1,11
Large Classroom	100	2,78	%2,5	2,50	50	3,26	%2,2	1,12
Lecture	231,83	6,05	%1,4	3,17	115,91	7,57	%1,1	1,31

Hall								
Total	411,83	3,59	%2,68	10,53	205,91	4,33	2,15	4,61

Per Table 3, in the post-COVID-19 WHO and REHVA ventilation scenario, the ventilation rates increased by 17.26% in the seminar, small and large classrooms, 25.12% in the lecture hall, and on average 20.61%, compared to the pre-COVID-19 timeframe. Due to the more significant number of pupils per square meter in the lecture hall, the ventilation rate has increased. In classrooms reduced to 50% capacity after COVID-19, the probability of individual infection dropped by 10.8% in the seminar classroom, 9.75% in the small classroom, 12% in the large classroom, 21.42% in the lecture room, and 19.77% in average when all classrooms are included. Under the post-COVID-19 WHO and Rehva ventilation scenario, the number of COVID-19 cases surpasses the R01 limit, which is crucial for infection management in all classrooms. In this ventilation scenario, if the classrooms are utilized for 4 hours, the number of COVID-19 cases drops by 55.04% in the seminar classroom, 55.24% in the small classroom, 55.2% in the large classroom, and 58.67% in the lecture hall compared to pre-COVID-19. COVID-19 cases in all classrooms were reduced by 56.2%.

The decline in COVID-19 cases was more significant than the probability of individual infection. The results reveal that when the number of persons vulnerable to the virus in classrooms grows, the probability of infection reduces, but the number of new cases increases.

Figure 1 depicts the time-dependent fluctuation of individual COVID-19 infection probability in classrooms, WHO, and REHVA ventilation scenarios.

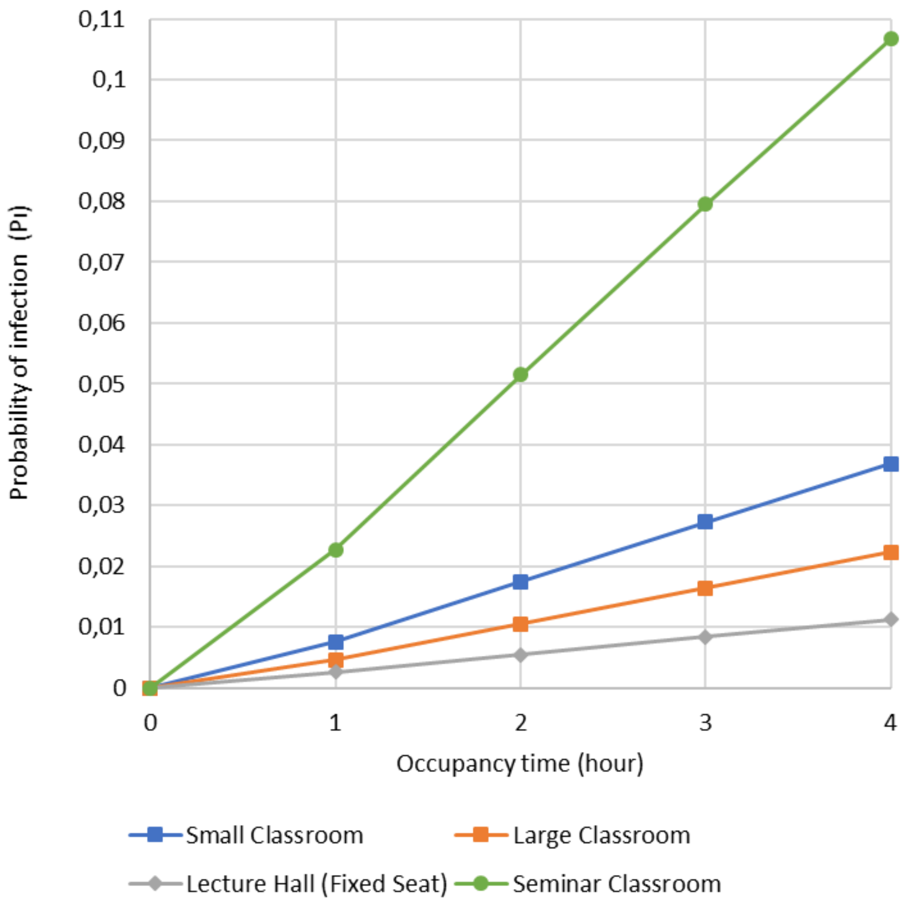

Figure 1. EN 16798-1 ventilation standard time-dependent infection probability

The probability of infection in the seminar classroom surpasses 2% when the SARS-COV-2 virus is exposed for 1 hour, whereas it remains below 1% in other classrooms, as shown in Figure 1. The probability of COVID-19 infection exceeded 1% in all classrooms but the lecture hall by the end of the second hour. The probability of COVID-19 infection cases reached 1.1% in the lecture hall, 2.2% in the large classroom, 3.7% in the small classroom, and 10.7% in the seminar classroom in cases when the virus exposure period was 4 hours. By the end of the fourth hour, the number of COVID-19 cases surpasses the tolerable ro>1 value regarding infection risk in all classrooms. In the first 3 hours, the number of new teachers in all classrooms was below one value.

3.2. Ventilation Design Based on Infection Risk

Table 4 displays the ventilation rates based on the tolerable infection risk and the ventilation rate of the pre-COVID-19 ventilation standards in classrooms, the number of COVID-19 cases, and the probability of COVID-19 cases in the 4-hour use case of the classrooms.

Table 4. Ventilation and acceptable risk of infection before COVID-19

Classroom Type	Ventilation before COVID-19				WHO and REHVA ventilation			
	Number of People	Ventilation rate (L/s m^2)	Probability of infection (PI)	Number of COVID-19 Cases (person)	Number of People	Ventilation rate (L/s m^2)	Probability of infection (PI)	Number of COVID-19 Cases (person)
Seminar Classroom	20	2,78	%11,9	2,38	10	3,6	%9,9	0,99
Small Classroom	60	2,78	%4,1	2,48	30	3,77	%3,3	0,99
Large Classroom	100	2,78	%2,5	2,50	50	3,8	%2	0,99
Lecture Hall	231,83	6,05	%1,4	3,17	115,91	10,33	%0,9	0,99
Total	411,83	3,59	%2,68	10,53	205,91	5,37	1,92	3,96

According to Table 4, in the ventilation scenario determined based on the acceptable risk of infection after COVID-19, the ventilation rates increased by 29.49% in the seminar classroom and 35.61% in the small classroom, by 36.89% in the big classroom, 70.74% in the lecture room, and 49.58% on average in all classrooms compared to the pre-COVID-19 period. In ventilation based on virus risk, the required ventilation rates rise as the number of people susceptible to virus infection in classrooms rises. When all classrooms were considered, the probability of individual infection in classrooms diluted by 50% decreased by 16.8% in the large classroom, 19.51 in the small classroom, 20% in the lecture classroom, 35.71% in the lecture hall, and 28.35% in the classroom. In the ventilation scenario based on acceptable infection risk, the number of COVID-19 cases decreased by 58.40% in the seminar classroom, 60.08% in the small classroom, 60.4% in the large classroom, 68.76% in the lecture hall, and 62.39 percent across all classrooms (6.57) compared to pre-COVID-19. The decrease in COVID-19 cases in all classrooms exceeded the probability of individual infection. The results indicate that as the number of susceptible individuals in classrooms increases, the probability of infection decreases, but the number of new cases rises.

Figure 2 depicts the time-dependent variation of the probability of individual COVID-19 infection in classrooms under the WHO and REHVA ventilation scenarios.

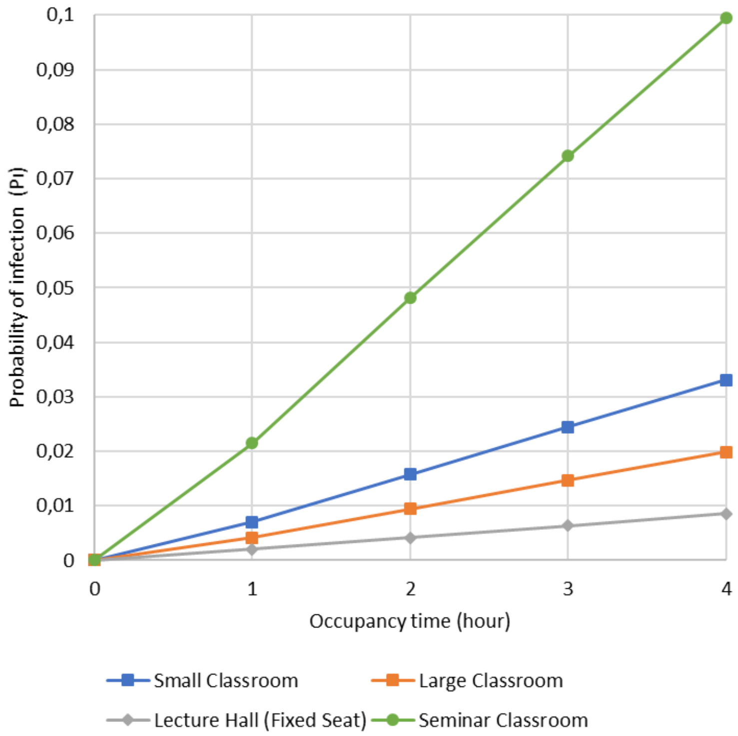

Figure 2. Time-dependent infection probability of ventilation scenario based on acceptable infection risk

The probability of infection in the seminar classroom exceeded 2% after one hour of exposure to the SARS-COV-2 virus, while it remained below 1% in other classrooms, as shown in Figure 2. At the end of the second hour in the classrooms, the probability of COVID-19 infection was 4.7% in the seminar classroom, exceeding 1% in the small classroom but still below 1% in the other classrooms. At the end of the third hour, the probability of COVID-19 infection exceeded 1% in the large classroom and reached 1.5%, while 7.4% in the seminar classroom. The probability of COVID-19 infection reached 0.9% in the lecture hall, 2% in the large classroom, 3.3% in the small classroom, and 9.1% in the seminar classroom in cases where the virus exposure time was 4 hours. At the end of the fourth hour in the lecture hall, the probability of infection remained below 1%. Findings showed better results in infection probability and new cases in ventilation design based on infection risk than in REHVA and WHO ventilation design.

3.3.Comparison of Ventilation Designs After COVID-19

The probability of COVID-19 infection and the number of COVID-19 cases in the classrooms for 4 hours of usage is shown in Table 5, along with the ventilation rates based on the tolerable infection risk and the EN 16798-1 ventilation standard.

Table 5. Acceptable infection risk and EN 16798-1 ventilation standard

Classroom Type	Ventilation before COVID-19				WHO and REHVA ventilation			
	Number of People	Ventilation rate (L/s m^2)	Probability of infection (P_I)	Number of COVID-19 Cases (person)	Number of People	Ventilation rate (L/s m^2)	Probability of infection (P_I)	Number of COVID-19 Cases (person)
Seminar Classroom	10	3,26	10,7	1,07	10	3,6	9,9	0,99
Small Classroom	30	3,26	3,7	1,11	30	3,77	3,3	0,99
Large Classroom	50	3,26	2,2	1,12	50	3,8	2	0,99
Lecture Hall	115,91	7,57	1,1	1,31	115,91	10,33	0,9	0,99
Total	205,91	4,33	2,15	4,61	205,91	5,37	1,92	3,96

According to Table 5., ventilation rates increased by 10.42% in the seminar classroom, 15.64% in the small classroom, 16.56% in the large classroom, by 36.45% in the lecture hall. When the whole classroom was evaluated, the average increased by 24.01% according to the WHO and REHVA ventilation design in ventilation design based on the acceptable risk of infection after COVID-19. The findings indicate that as the number of people vulnerable to the virus in classrooms increases, so do the ventilation rates required for infection control. In the ventilation design developed based on the risk of individual infection after COVID-19, the probability of individual infection decreased by 7.47% in seminar classrooms, 10.81% in small classrooms, 9.0% in large classrooms, 18.18% in the lecture hall, and by an average of 10.69% when all classrooms are taken into account. The probability of COVID-19 infection has further decreased as a result of the increase in ventilation rate in the lecture hall compared to other classrooms. Under the ventilation method based on an acceptable infection risk scenario, the number of COVID-19 cases drops by 7.47% in the seminar classroom, 10.8% in the small classroom, 11.60% in the large classroom, 24.42% in the lecture hall, and by 14.09% (0.65) in all classrooms. In ventilation design based on virus risk, it is seen that the number of new cases of infection decreases as the number of persons vulnerable to the virus in classrooms increases. Results indicated superior results in infection probability and new cases in ventilation design based on infection risk than in REHVA and WHO ventilation design.

4. Conclusion

In the post-COVID-19 ventilation scenarios, when classrooms are utilized for 4 hours, the probability of infection and the average number of cases dropped by 19.77% and 56.22 %, respectively, compared to the pre-COVID-19 ventilation scenario. In the same condition, it decreased by an average of 28.35% to 62.39% in the ventilation scenario based on the tolerable risk of infection. Under the WHO and REHVA Ventilation scenario, the ventilation rates of classrooms rose by an average of 20.61 percent compared to pre-COVID-19. In ventilation design based on the tolerable risk of infection, ventilation rates rose by an average of 49.58 percent compared to before COVID-19. In the ventilation design based on the risk of infection, it was noted that the increase in ventilation rates was more significant as the number of classroom users grew so much that the ventilation rate necessary for infection control in the lecture hall was 70.74 percent greater than before COVID-19.

With the current air conditioning system capacity in schools, supplying the necessary ventilation rates following COVID-19 under actual settings is challenging. The COVID-19 pandemic's suspension of face-to-face schooling has highlighted the significance of air conditioning system design. Hence, educational buildings that will be constructed or renovated in the future should be equipped with air conditioning systems that allow ventilation rates to increase as necessary, notwithstanding future pandemics.

Ventilation rates in LEED-certified buildings are supposed to be 30% greater than the minimum fresh ventilation rates necessary to guarantee interior air quality. In this way, in LEED-certified schools, the requisite ventilation rates can be delivered in select classrooms under the REHVA and WHO ventilation scenario. Nevertheless, in this ventilation scenario, the number of COVID-19 cases in all classrooms surpasses the baseline production scenario (R0) value of 1 assessed for infection management. Managing the number of COVID-19 cases and the fundamental reproduction number in crowded indoor contexts such as schools is crucial for epidemic control. The category I ventilation rate in the EN 16798 standard suggested by REHVA and WHO should thus be evaluated in light of pandemic dynamics. In this instance, extra filtration and air purification methods should be considered in some classrooms, particularly packed classrooms like lecture halls.

Assessing the risk of airborne infection is a detailed step in the COVID-19 process. In some research, the infection risk is assessed based on the likelihood of individual infection, but in others, it is assessed based on the reproductive number. The probability of individual infection is higher in classrooms with fewer users than in other classrooms, although the basic reproduction rate is lower. While COVID-19 infection is low in packed classrooms, the basic reproduction number is larger. Thus, the infection risk assessment should be considered independently based on regional disparities.

Defining ventilation requirements based on infection risk is complex throughout the pandemic phase. Since this problem involves several scientific fields, including virology, fluid mechanics, immunology, building design, building ventilation systems, and building ventilation methods. There is a need for extensive multidisciplinary research in order to be better prepared for future probable airborne epidemics like COVID-19.

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All authors contributed equally to the article. There is no conflict of interest.

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