

New ventilation design criteria for energy sustainability and indoor air quality in a post Covid-19 scenario

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ABSTRACT

The Covid-19 outbreak raised great attention to the importance of indoor air quality in buildings. Even if the Covid-19 epidemic is nearing an end, all stakeholders agree that increasing outside air flow rates is beneficial for decreasing the likelihood of contagion, lowering the risk of future pandemics, and enhancing the general safety of the interior environment. Indeed, diverse concerns raised about whether the ventilation standards in place are still adequate. In this context, this research intends to assess the suitability of current ventilation standards in addressing the current pandemic scenario and to offer novel criteria and guidelines for the design and operation of HVAC systems, as well as useful guidance for the creation of future ventilation standards in a post-Covid-19 scenario. To that end, a comprehensive analysis of the ANSI/ASHRAE 62.1 is carried out, with an emphasis on its effectiveness in reducing the risk of infection. Furthermore, the efficacy of various ventilation strategies in reducing the likelihood of contagion has been investigated. Finally, because building ventilation is inextricably linked to energy consumption, the energy and economic implications of the proposed enhancements have been assessed. To carry out the described analysis, a novel method was developed that combines Building Energy Modelling (BEM) and virus contagion risk assessment. The analyses conducted produced interesting insights and criteria for ventilation system design and operation, as well as recommendations for the development of future standards.

1. Introduction

Among all the highly energy-intensive sectors, such as communities [1], transport [2], and buildings [3,52], the latter is one of the most impactful, being responsible for high primary energy consumption and CO₂ emission [4,51]. In this context, the relevance of the ventilation system in buildings, and in general in enclosed spaces, is well understood and researched in the scientific community since it aids in preventing the spread of common pollutants, viruses, bio effluents, etc. [5–7]. However, its impact on the buildings' energy demand is remarkable [8]. For such a reason, a trade-off is usually made, when designing HVAC systems, between outdoor air ventilation rates (and thus Indoor Air Quality level – IAQ) and energy consumption. Nonetheless, due to the Covid-19 outbreak, renewed attention and interest have been raised on the topic [9–12] due to the critical role played by ventilation in reducing the risk of infection in enclosed spaces [13,14]. Specifically, stakeholders, health organisations and the scientific community started questioning the current ventilation standards, suggesting

that augmenting the outdoor air flow rates could be helpful not only for reducing the Covid-19 contagion risk but also in decreasing the risk of future pandemic and improving the overall safety of our living environment [15,16]. Therefore, even if the Covid-19 pandemic is coming to an end, the attention raised on the role of mechanical and natural ventilation in buildings seems to be at a new beginning [17], and the scientific community appears to agree on the need of overcoming the existing standards, enhancing the ventilation flow rates currently adopted [18]. In this framework, to identify the latest development of this topic in the scientific community, a comprehensive analysis of the works investigating the connection between Covid-19 infection risk in enclosed spaces and outdoor air ventilation flow rates is conducted.

1.1. Covid-19 and ventilation in buildings

Several studies investigate the connection between Covid-19 contagion risk and ventilation in enclosed spaces. In this scenario, a general agreement on the importance of adequate air changes per hour is detected. A first example is the work presented in Ref. [19], dealing with

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating & Air-Conditioning Engineers
A_z	Net area of the zone
BEM	Building Energy Modelling
b_r	Breathing rate
CDD	Cooling Degree Day
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
D	Exposure time to the virus
d_s	Virus that drops onto room surfaces
E_p	Infectious quanta emission rate
E_{pb}	Infectious quanta emission rate for the first variant
ER	Quanta emission rate
E_{ee}	Electrical equipment power load intensity
g_l	Lighting power load intensity
$g_{l,p}$	Latent heat gain per person
$g_{s,p}$	Sensible heat gain per person
HDD	Heating Degree Day
HEPA filters	High-Efficiency Particulate Air filters
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ISR	Incident Solar Radiation
IR	Inhalation rate
l_r	Infectivity loss rate
m_c	Effect due to additional control measures for virus removal
n	Inhaled quanta
n_s	percentage of sitting people

n_{st}	percentage of standing people
n_{ob}	percentage of oral breathing people
n_{sp}	percentage of oral speaking people
n_{lsp}	percentage of loudly speaking people
N	Number of people in the room
OPEX	Operating Expenditures
P	Infection Probability
p_{inf}	Number of infected and infectious people
PS	Proposed System
Q_{act}	Correction factor linked to the subject activity
q_c	Average quanta concentration
Q_{var}	Correction factor to take into account of the virus variants
R_0	basic reproduction number of the infection
R_a	Outdoor airflow rate per area
R_p	Outdoor airflow rate per person
RS	Reference System
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
UV-C	Ultraviolet C
V	Room Volume
V_{bz}	Breathing-zone ventilation
V_{out}	Outdoor air ventilation flow rate
$\Delta\epsilon$	Economic saving

Greek symbols

η_{er}	Quanta emission rate
η_{ex}	Exhalation filtration efficiency of the face mask
η_{in}	Inhalation filtration efficiency of the face mask
η_{wm}	Percentage of people wearing a facemask
λ	Virus infectivity loss rate

Covid-19 risk in scholarly facilities. Here, it is investigated the probability of a student getting infected in the case of two existing schools located in the north of Italy. The analysed buildings are equipped with a radiator-based heating system while fresh air is provided through natural ventilation only. For two classrooms, experimental tests were conducted to gather values of indoor air temperature, relative humidity, and CO₂ concentration. Lately, the collected data are exploited to evaluate the Covid-19 infection risk for a 100-people group, by using a modified Wells-Riley model. Diverse ventilation strategies, and filtration technologies (only in the case of a system with recirculated air), were investigated in this study, concluding that mechanical ventilation plays a crucial role in the Covid-19 contagion risk reduction. School facilities are investigated also in the work reported in Ref. [20] studying the Covid19 contagion risk in diverse schools in New York. Specifically, the average infection probability has been assessed by using both epidemiologic data and the Wells-Riley model. The highest transmission rates have been discovered in new buildings, in wealthy areas, and during the winter season. The study concludes that these results are connected to the lower ventilation occurring in new buildings, with air-tighter windows, without adequate mechanical ventilation, suggesting an increase in the mechanical ventilation rates. Another contribution adopting the Wells-Riley model to assess the Covid19 contagion risk is reported in Ref. [16]. Here it is investigated the role of mechanical ventilation for the contagion risk reduction in the case of an institutional high-rise building located in Montreal (Canada). Specifically, for diverse quanta emission rates, it was estimated the outdoor air flow rate necessary to drop the contagion risk below 1%. The results of the study show that in case of high quanta emission rates the ventilation needed would be impossible to be guaranteed with the originally installed fans, requiring invasive HVAC system revamping actions. It is worth noticing that in this work some considerations regarding the energy aspects are presented. Specifically, it is stated that a demanded controlled ventilation can reduce the contagion risk while retaining the unavoidable energy

consumption increase. Energy aspects related to Covid-19 diffusion are discussed also in Ref. [21], where the relation between the contagion risk and the occupation schedules is investigated. More precisely, the research aims at optimizing the occupancy profile to minimize the crowding index, thus reducing the Covid19 contagion risk. As a case study, it is considered a University building located in Tehran, for which a multi-objective optimization with the scope of minimizing the virus contagion risk and the energy consumption is conducted. The outcome of the research underlines that higher outdoor ventilation rates return contrasting outcomes: lower contagion risk, but higher energy consumption. The achieved outcomes show that by optimizing the occupation schedule (e.g. by increasing the building operating hours and reducing the occupancy density) it is possible to reduce the Covid-19 contagion risk by 56% and to reduce the energy consumption increase by up to 30%. A different approach, based on the adoption of Computational Fluid Dynamics (CFD) methods, is presented in the work reported in Ref. [22]. Here, it is underlined how the augmentation of the outdoor air flow rate can certainly reduce the Covid-19 contagion risk, but also that the systems usually installed in standard applications are not able to provide the required amount of outdoor air flow rate (similarly to what stated in Ref. [16]). Additionally, it is emphasised that the sole outdoor air flow rate increase (and the avoidance of recirculating system) can lead to an infection risk reduction from 27% to 3% by switching from 10% to 100% of outdoor air. Another work adopting a CFD-based approach is reported in Ref. [18], where an epidemiological study on a specific event that occurred in a restaurant in Guangzhou (China) at the beginning of 2020 is conducted. CFD simulations have been adopted to investigate the spatial distribution of the virus inside the restaurant concluding that a crucial role in spreading Covid19 was played by the air recirculation and by the poor outdoor air ventilation rate. In addition, it is also underlined that the theoretical outdoor air flow rate to reduce the contagion risk to an acceptable level, evaluated by adopting the Wells-Riley model, is equal to 38,6 l/s. Such value is

remarkably higher than the one suggested by the current standards (e.g. 5,1 l/s in the case of ASHRAE 62.1–2019). The Wells-Riley model is used also in the work reported in Ref. [14] investigating the waiting rooms of a hospital building located in Shenzhen (China). Here, the Wells-Riley model is modified to also consider the risk due to the proximity. Using this model, an analysis of 20 waiting rooms is conducted by focusing on the role of face masks and ventilation rates in Covid-19 contagion risk reduction. The results show that an augmented outdoor air ventilation flow rate can reduce the Covid-19 contagion risk by up to 75% in case of all the occupants wearing surgical masks. The work presented in Ref. [23] investigates the quanta emission rate for SARS-CoV-2 to be adopted for the infection risk assessment. Specifically, the viral load emitted by contagious people based on the respiratory activity, the physiological parameters, and the activity level, is estimated. The achieved results were then adopted to assess, by exploiting the Wells-Riley model, the contagion risk in diverse buildings located in Italy (pharmacies, supermarkets, restaurants, post offices, and banks), concluding that mechanical ventilation plays a crucial role in reducing the Covid-19 contagion risk. Another work quantitatively assessing the risk of SARS-CoV-2 infection is reported in Ref. [24]. Here, a new approach exploiting the Monte Carlo method for the evaluation of the viral load emission and the consequent contagion risk is proposed. By using such a method, an analysis of naturally ventilated crowded spaces is conducted, concluding that in such a scenario it is difficult to have an acceptable contagion risk ($R_0 < 1$), and that even in the case of highly ventilated buildings, the safe exposure time is limited below 1 h. Another work underlining the importance of ventilation strategies in dealing with the Covid-19 contagion risk, and adopting a modified Wells-Riley model, is reported in Ref. [9]. In this study, the adopted quanta values have been calibrated on real case pandemic scenario, and it is underlined that the minimum ventilation to be guaranteed should be tuned as a function of exposure time, interpersonal distance, vent location, etc. Another work using a modified Wells-Riley model is the one presented in Ref. [25]. Here, a ventilation rates design method for respiratory infection risk reduction is presented and adopted to evaluate, for diverse indeed use, the optimal ventilation flow rate to meet a certain infection risk goal. The investigated case studies were focused on offices, schools, and universities located in Estonia, and the ventilation criteria suggested in the EN 16798-1 standard were examined. From the achieved results it is concluded that in some cases the standard should be updated to reduce the covid-19 contagion risk. However, due to the high difference among the investigated case studies made it is impossible to state a general rule for the ventilation rate estimation. In the work reported in Ref. [26], diverse natural ventilation strategies to avoid Covid-19 transmission are investigated, by adopting the Wells-Riley model, in the case of a school building. Specifically, the performance of windows opening rates, location, and also climate conditions are explored. The obtained results suggest that with an optimal window-opening strategy the Covid-19 infection risk can be reduced. However, HVAC system energy consumption is affected (increased by 10% by increasing the standard ventilation rates to 6.51 h^{-1}). The contagion risk occurring in a gym is instead investigated in Ref. [27]. Here, diverse ventilation strategies, and air cleaning technologies, are investigated aiming at reducing the particle concentration. Results show that a combination of both increased ventilation and cleaning technologies is the optimal choice. One of the few works investigating different space typologies in terms of SARS-CoV-2 contagion risk is the one reported in Ref. [18]. Results of the study, show that the infection probability can be significantly lowered by adopting: i) a face mask; ii) HEPA filters; iii) and by augmenting outdoor air ventilation. Further works demonstrating the role of ventilation in reducing the diffusion of airborne viruses are reported also in Refs. [28,29].

1.2. Considerations and gaps of knowledge

The conducted review highlights that the Covid-19 outbreak, and the

consequent pandemic, developed the common idea, among the scientific community, that the ventilation rates currently adopted in buildings are not adequate to ensure a sufficiently safe indoor environment. Several studies criticise the current ventilation standards, underlining the need for enhancement that considers the lessons learnt from the almost-overcome pandemic. Indeed, it is a general belief that independently from the current pandemic evolution, the standards should be adequate following the renewed awareness about the safety of our living environment and Indoor Air Quality, also in the event of future pandemic scenarios. However, most of the existing research on the topic investigates only very specific case studies, without assessing comprehensive analyses on a wide range of building typologies, crowded indexes, etc. The lack of extensive analysis implies the impossibility of determining general yet effective design criteria or defining novel guidelines. In addition, among the number of works investigating the effectiveness of augmented outdoor air ventilation on the Covid-19 contagion risk, it is very uncommon to find ones that quantitatively assess the related energy impact (with the only exception of a few works [30,31]). Due to the well-known relation between ventilation and energy consumption in buildings, this is a severe lack of knowledge since solutions effective in increasing the occupants' safety could be unviable from the energy and economic point of view. Thus, the scientific community studying this topic agree about the convenience of increasing outdoor air ventilation, on the fact the energy impact would be not negligible, and that there is a need of upgrading the current standards, however, no comprehensive and extensive analysis capable of suggesting novel design criteria, by also providing the related energy implications, have been made so far.

1.3. Aim of the research

In this context, this research has the twofold aim of i) evaluating the adequacy of current ventilation standards in dealing with the present pandemic scenario; and ii) providing all the stakeholders with novel criteria and guidelines for the design and operation of the HVAC system, also giving useful guidance for the development of future ventilation standards in a post Covid-19 scenario. To reach this goal, to fill the identified gaps of knowledge, and to contribute to the state of the art on the topic, the relationship between ventilation rate and Covid-19 contagion risk in buildings has been extensively investigated. Specifically, a comprehensive analysis covering all the building categories presented in the ANSI/ASHRAE Standard 62.1 has been conducted by considering, for each indeed uses, the related crowding indexes, occupancy schedules, and outdoor air ventilation rates suggested by the standard. By doing so, it has been possible to assess the Covid-19 contagion risk for each of the investigated building typologies and to draw conclusions on the adequacy of the current standard. It worth noticing that to assess the risk of infection, only the airborne transmission has been considered (neglecting the close contact one). Additionally, to provide useful insights and criteria for ventilation system design and operation, and to develop recommendations for the development of future standards, higher outdoor air flow rates have been tested by assessing their effectiveness in reducing the probability of contagion. Finally, since ventilation in buildings is strictly connected to energy consumption, and due to the meaningless of providing design criteria without energy insights, the energy implications of the proposed enhancements have been assessed. To carry out the described analysis, a novel method, based on dynamic simulation, which couples together the Building Energy Modelling (BEM), and the virus contagion risk assessment, has been developed. Specifically, to assess the Covid-19 contagion risk, the Wells-Riley model [32,33], largely adopted by the scientific community, has been implemented in a purposely developed Matlab routine, whereas for the building energy simulation, a dynamic simulation model has been purposely developed in EnergyPlus environment.

2. Method and mathematical model

The method adopted to carry out the previously mentioned analyses is summarized in Fig. 1, where a schematic diagram of the developed workflow is presented. Specifically, to conduct an exhaustive analysis for a wide range of building categories, a Matlab routine capable of managing at the same time the simulation of the examined room energy performance, and the assessment of the Covid-19 infection probability, was purposely developed. Indeed, as shown in Fig. 1, the Matlab script is intended to manage either the inputs and outputs of the detailed simulation model of the building (taking into account the geometry, the thermophysical parameters, etc.) or the infection risk calculation model (based on the Wells-Riley model).

The building energy simulation, relies on three different tools: Autodesk Revit [34], OpenStudio [35], and Energy Plus [36]. Specifically, in Autodesk Revit, the building 3D model is detailed developed, by including building elements, as well as thermal zone data. The building model is then exported, by exploiting the gbXML file, in the OpenStudio [35] suite (which is an energy simulation software built on the Energy Plus engine). Simultaneously, also the assessment of Covid-19 contagion risk, for the same building and operating condition is performed. This is conducted into a purposely developed Matlab subroutine, based on the Wells-Riley model. Both the energy consumption and Covid-19 contagion risk assessment methods will be detailed described in the following.

2.1. Building energy model

The building energy modelling relies on the OpenStudio software kit. Specifically, the geometry and parameters of any buildings can be imported from Autodesk Revit, where the investigated building should be previously modelled from the geometrical point of view. The energy model resulted in a well-mixed air single-zone building equipped with ideal air loads systems capable to provide the exact thermal energy required to keep the temperature setpoints. The HVAC system also guarantees the minimum outdoor airflow rate (V_{bz} , breathing-zone ventilation), specified using equation (1) which depends on the number of people in the zone (N), the outdoor airflow rate per person (R_p), the net area of the zone (A_z) and the corresponding outdoor airflow rate

required for unit of zone area (R_a).

$$V_{bz} = R_p \cdot N + R_a \cdot A_z \tag{1}$$

Furthermore, the influence of people, lighting and electrical equipment on the heat balance algorithm is accounted for using characteristic heat gains parameters such as sensible and latent heat fraction per person ($g_{s,p}$ and $g_{l,p}$, $W/person$), lighting power load intensity (g_l , W/m^2) and electrical equipment power load intensity (g_{ee} , W/m^2). Appropriate schedules complete the model to take into account the actual operating regime of the buildings under investigation.

2.2. Modified Wells-Riley model

To assess the Covid-19 contagion risk, the Wells-Riley model [32,37, 38] has been adopted. This model is based on a standard aerosol Wells-Riley infection model, opportunely modified to consider the hypothesis of well-mixed air volume. Following this model, the Covid-19 infection probability P can be expressed as:

$$P = 1 - e^{-n} \tag{2}$$

Where, n represents the inhaled “quanta”, which is the concentration of infectious doses of the virus which are inhaled by a person. Note that a quantum is defined as the dose necessary to cause an infection in 63% of the persons susceptible. The Covid-19 infection probability expressed by equation (2) is valid under a certain hypothesis: the quanta emission rate from the infectious individual is constant; no prior quanta are in the investigated environment; the quanta aerosol is evenly distributed in the environment; close-proximity infection is neglected. The number of quanta inhaled by a person depends on a wide range of parameters, as follows:

$$n = q_c \cdot b_r \cdot D \cdot (1 - \eta_{wm} \cdot \eta_{in}) \tag{3}$$

where η_{in} is the mean filtration efficiency of the face mask for inhalation, η_{wm} is the percentage of people wearing a facemask, D is the exposure time to the virus, b_r is the breathing rate, and q_c is the average quanta concentrations, in turn, equal to:

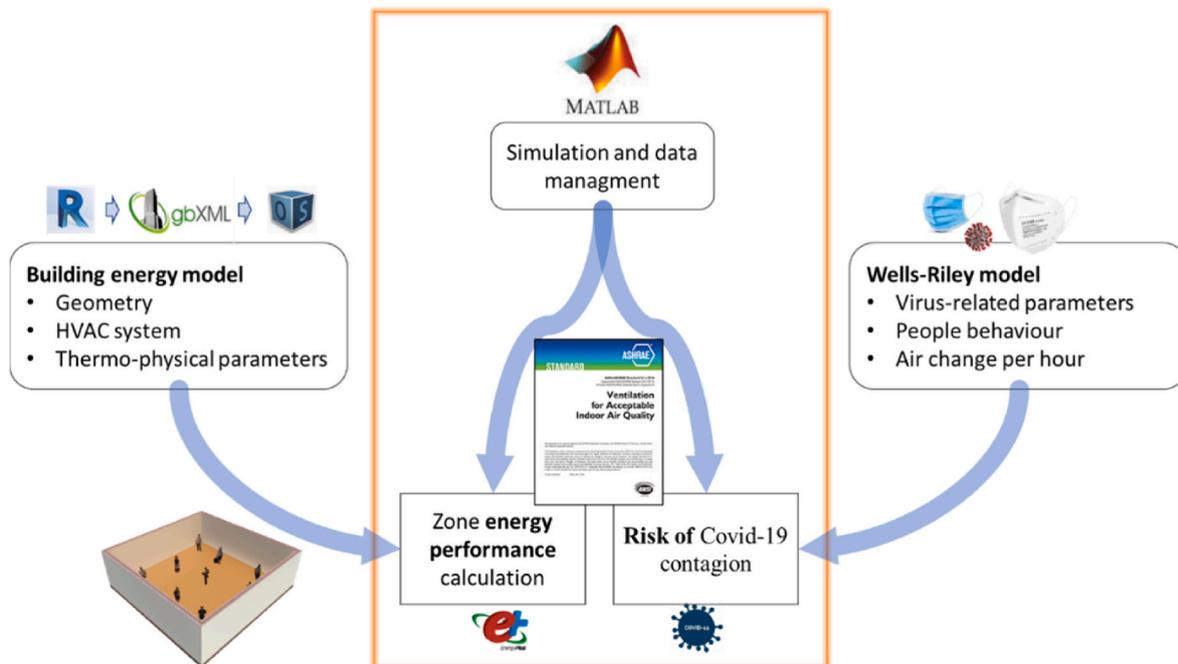


Fig. 1. Schematic workflow of the methodology adopted.

Table 1
Summary table of parameters involved in equations (2)-(7)

Symbol	Unit	Description	Value
P	[-]	Infection probability	Calculated (equation (2))
n	[-]	Inhaled quanta	Calculated (equation (3))
η_{in}	[-]	Inhalation filtration efficiency of the face mask	Table 5
η_{wm}	[-]	percentage of people wearing a facemask	1
D	[h]	Exposure time	1, 2, and 3
b_r	[m ³ /h]	Breathing rate	Table 3
q_c	[quanta/m ³]	Average quanta concentrations	Calculated (equation (4))
V	[m ³]	Room volume	300
η_{er}	[quanta/h]	Quanta emission rate	Calculated (equation (6))
l_r	[h ⁻¹]	Infectivity loss rate	Calculated (equation (5))
V_{out}	[h ⁻¹]	Outdoor air ventilation flow rate	Calculated from Table 2
d_s	[h ⁻¹]	Virus that stops onto room surfaces	0.3
m_c	[h ⁻¹]	Effect due to additional control measures for virus removal	0
λ	[h ⁻¹]	Virus infectivity loss rate	2.8
p_{inf}	persons	Number of infected and infectious people	1
η_{ex}	[-]	Filtration efficiency of the face mask for exhalation	Table 5
E_p	[quanta/persons-h]	Infectious quanta emission rate	Calculated (equation (7))
Q_{var}	[-]	Correction factor to take into account the virus variants	1 (original variant), 2 (Delta), and 2.5 (Omicron)
Q_{act}	[-]	Correction factor linked to the subject activity.	Table 3

$$q_c = \left(\frac{n_{er}}{l_r \cdot V} \right) \cdot \left(1 - \frac{1}{l_r \cdot D} \right) \cdot (1 - e^{-l_r \cdot D}) \quad (4)$$

where V is the considered room volume, η_{er} is the quanta emission rate, and l_r is the infectivity loss rate. The infectivity loss rate can be estimated as:

$$l_r = V_{out} + d_s + m_c + \lambda \quad (5)$$

where V_{out} is the outdoor air ventilation flow rate, d_s is the virus that stops onto room surfaces, m_c is the effect due to additional control measures for virus removal, and λ is the virus infectivity loss rate. The quanta emission rate, η_{er} , is evaluated by the following equation instead:

$$n_{er} = E_p \cdot (1 - \eta_{ex} \cdot \eta_{wm}) \cdot p_{inf} \quad (6)$$

where p_{inf} is the number of infected and infectious people in the considered environment, η_{ex} is the filtration efficiency of the face mask for exhalation, and E_p is the infectious quanta emission rate, in turn, assessed by the following:

$$E_p = Q_{var} \cdot (E_{pb} \cdot Q_{act}) \quad (7)$$

where E_{pb} is the infectious quanta emission rate for the first SARS-CoV-2 variant; Q_{var} is a correction factor to take into account the virus variants, and Q_{act} is a correction factor linked to the subject activity. The described set of equations has been included in a purposely developed Matlab subroutine capable to assess the number of quanta in the confined space and also to evaluate the number of quanta inhaled by a person. As a consequence, by equation (2), it is possible to determine the Covid-19 infection risk. For the sake of clarity, all the parameters involved in equations (2)-(7) and described in this section are summarized in Table 1.

3. Case study

The previously described method has been adopted to investigate the effectiveness, of the Covid-19 contagion risk, of the ventilation rates proposed by ANSI/ASHRAE Standard 62.1, and then to evaluate possible enhancements. Specifically, a generic room (Fig. 2) characterized by a walkable area of 100 m² (10 m × 10 m), with an eight of 3 m, for a total volume of 300 m³, has been considered. The investigated room, equipped with an ideal HVAC system, is considered located in the core of a generic building. Consequently, all the walls have been modelled as adiabatic. Such a hypothesis has been made to obtain results as little case specific as possible and to take into account the sole effect of

ventilation and internal heat gains on energy performance.

The room has been considered as alternatively belonging to all the 109 occupancy categories reported in the ANSI/ASHRAE Standard 62.1, by taking into account the related outdoor air flow rates and occupancy density values. Note that the analysis of the entire ANSI/ASHRAE standard will provide generalizable results that can be then exploited for a wide range of buildings. The 109 space typologies have been grouped, following the ANSI/ASHRAE Standard 62.1-2019, in 11 categories, as reported in Table 2 where the minimum and maximum outdoor air rates and occupancy density occurring within the group are reported.

Note that the values reported in Table 2 represent the range limits (min and max) of each building category group, however, each of the 109 spaces presented in the ANSI/ASHRAE Standard 62.1 have been singularly simulated. For further details, please, refers to the standard [39]. For each of the considered spaces, the Covid-19 contagion risk resulting from the adoption of the outdoor air ventilation rates, suggested by the standard and calculated by means equation (1), has been assessed. To do so, the following assumptions have been made: i) the occupancy density (N) is set as suggested by the ANSI/ASHRAE Standard 62.1 standard [39]; ii) the infectivity loss rate (λ) is equal to 2.8 h⁻¹, evaluated at the indoor temperature of 20 °C, relative humidity of 50% and UV index as high as in Ref. [38]; iii) the virus surface inactivation (d_s) has been considered equal to 0.3 [24]; iv) the number of infected and infectious people inside the environment is equal to 1; v) the breathing rate (b_r) is calculated according to equation (8) by considering the inhalation rates for sitting and standing people (IR_s and IR_{st} , m³/h) [19] and the corresponding percentage of sitting and standing people in the room (n_s and n_{st} , %) (the values adopted are summarized in Table 3 and Table 4); vi) the quanta exhalation rates ($E_{pb} \cdot Q_{act}$, namely ER , quanta/h) used to evaluate the infection risk are calculated by equation (9), based on values of quanta emission rates for breathing ER_{ob} , speaking ER_s and, loudly speaking people ER_{ls} that are gathered from reference [19] (the corresponding percentage of people (n_{ob} , n_{sp} and n_{lsp}) are summarized in Tables 3 and 4).

$$b_r = IR_s \cdot n_s + IR_{st} \cdot n_{st} \quad (8)$$

$$ER = (ER_{ob,s} \cdot n_{ob} + ER_{sp,s} \cdot n_{sp} + ER_{lp,s} \cdot n_{lsp}) \cdot n_s + (ER_{ob,st} \cdot n_{ob} + ER_{sp,st} \cdot n_{sp} + ER_{lp,st} \cdot n_{lsp}) \cdot n_{st} \quad (9)$$

To investigate diverse scenarios, five pivotal parameters have been supposed as variables: i) three different SARS-CoV-2 variants have been alternatively considered. Note that the variant choice affects the Q_{var} parameter in the equation (7). Specifically, the three investigated variants are: the original variant ($Q_{var} = 1$), Delta ($Q_{var} = 2$); and Omicron



Fig. 2. Investigated room.

Table 2
Outdoor ventilation rates, and occupant density for all the investigated categories.

Occupancy category	People		Area		Occupant	
	Outdoor Air		Outdoor Air		Density	
	Rate [L/s person]		Rate [L/s person]		[persons/100m ²]	
	min	max	min	max	min	max
Animal facilities	5	5	0.6	0.9	20	20
Correctional facilities	2.5	3.8	0.3	0.6	15	50
Educational facilities	2.5	5	0.3	0.9	10	100
Food and Beverage service	2.5	3.8	0.3	0.9	2	100
Hotels, motels, resorts, dormitories	2.5	3.8	0.3	0.6	10	120
Miscellaneous Spaces	2	5	0	0.9	0	100
Office Buildings	2.5	2.5	0.6	0.12	2	60
Outpatient Health Care Facilities	2.5	10	0.3	2.4	5	50
Public Assembly Spaces	2.5	3.8	0.3	0.6	10	150
Retail	3.8	10	0.3	2.4	7	150
Sports and Entertainment	3.8	10	0.3	2.4	7	150

Table 3
Inhalation rate IR (m^3/h) and emission rate ER (m^3/h) for different activity levels.

Activity	IR (m^3/h)	ER (m^3/h)		
		Oral breathing (ob)	Speaking (sp)	Loudly speaking (ls)
Sitting (s)	0,49	14,30	16,50	68,00
Standing (st)	0,54	15,80	18,20	74,90

Table 4
People activity indexes.

Occupancy category	Occupants' behaviour [%]				
	n_s	n_{st}	n_{ob}	n_{sp}	n_{ls}
Animal facilities	60	40	70	20	10
Correctional facilities	70	30	70	20	10
Educational facilities	80	20	70	20	10
Food and Beverage service	90	10	40	50	10
Hotels, motels, resorts, dormitories	90	10	40	50	10
Miscellaneous Spaces	70	30	70	20	10
Office Buildings	90	10	70	20	10
Outpatient Health Care Facilities	90	10	70	20	10
Public Assembly Spaces	90	3.8	70	20	10
Retail	10	90	70	20	10
Sports and Entertainment	10	90	70	20	10

($Q_{var} = 2.5$) [40,41]; ii) three different exposure time (D) have been considered: 1 h, 2 h, 6 h; iii) three different facemask scenarios, affecting the inhalation and exhalation efficiencies in Ref. [7] have been assumed: No mask scenario, all people wearing chirurgical masks, all people wearing FFP2 masks. It is worth noticing that the selected face masks scenarios (only surgical mask or FFP2, and not a mix of them) are in accordance with the most common obligations occurred during the Covid-19 pandemic. Indeed, institutions usually required a very specific mask type rather than a general use of them (in addition, using a face

Table 5
Inhalation and exhalation filtration efficiencies for each face mask scenario [42, 43].

	Inhalation efficiency	Exhalation efficiency
No mask	0%	0%
Chirurgical	30%	65%
FFP2	90%	90%

mask safer than the one suggested represented a “free will” action, which is not possible to foresee and include in the analysis). Nonetheless, starting from the obtained results (reported later), qualitative considerations can still be drawn in case of a face mask type mix. For each mask scenario, the related inhalation and exhalation efficiencies [42,43] have been taken into account, as reported in Table 5.

3.1. Proposed solutions

The described case study, adopting the outdoor ventilation rates suggested by the ANSI/ASHRAE Standard 62.1, is considered as Reference System (RS). To reduce the Covid-19 contagion risk, the convenience of using increased outdoor air ventilation rates is investigated. Ventilation is just one of the different actions that it is possible to take in order to reduce the Covid-19 infection risk in enclosed spaces. As an example, it is possible to adopt filtration, air ionization, and ultraviolet light. Nonetheless, increasing outdoor air ventilation is largely recognized in literature as the most effective method to reduce the Covid-19 contagion risk, and to increase the IAQ, without particular technical issues, while also proven to be safe for human beings (as long as the indoor air velocity is maintained in a certain range [44–46]). In this context, outdoor air ventilation rates augmented three and ten times (Proposed System 1 – PS1, and Proposed System 2 – PS2, respectively) than those suggested by the standard have been considered and tested. These values have been selected by the data found in other scientific contributions, as referenced in the review of the existing studies section. To better describe the technical feasibility of the proposed solutions, it should be underlined that two main HVAC system layouts may occur: i) decentralized systems, in which the air is adopted mainly for IAQ purposes, and the heating and cooling loads are balanced by local devices (e.g. fan coils); ii) centralized (all-air) systems, in which the air is used for IAQ purposes and also to balance the heating/cooling loads. In case of the decentralized systems, the amount of air elaborated by the AHU is usually small and its augmentation during the design phase is not expected to be an issue in terms of ducts encumbrance, vents size, or air handling units' dimensions (since the resulting elaborated air flow rate would be comparable to that of centralized all-air systems). Conversely, in case of centralized all-air systems, the AHU usually elaborates a substantially higher amount of air (outdoor air plus recirculating one). In this case, the proposed outdoor air augmentation occurs by reducing the recirculated air, implying no modification of the total air flow rate elaborated by AHU. Only if the outdoor air flow rate increase overcomes the recirculated flow rate, the total supply air elaborated by the AHU may increase. Nonetheless, this increase would be far from three and ten times the initially elaborated one. As a consequence, in both cases (decentralized and centralized systems) the proposed outdoor air

increase results to be technically feasible in terms of AHU, fans, ducts, vents design. It is still worth noticing that the proposed solutions, in case of decentralized HVAC systems (or in case of dedicated ventilation systems) would imply higher space for the installation compared to the reference case one. Besides the technical feasibility, it should be considered that the proposed outdoor rates will imply a substantial increase in the energy consumption for space heating and cooling due to the augmented ventilation loads which can be efficiently reduced by using heat recovery devices [50]. For such a reason, PS1 and PS2 systems have been investigated also as provided of a sensible heat recovery device to reduce the ventilation load. The selected sensible heat recovery device is a commercial device with an average heat recovery efficiency equal to 75%, and nominal pressure drops ranging from 100 to 300 Pa (depending on the elaborated airflow rate). In Table 6 a sum-up of all the investigated systems is reported.

3.2. Energy analysis

To assess the energy consumption associated with the selected ventilation strategies (both RS and proposed systems), the ANSI/ASHRAE Standard 90.1 has been taken into account. Specifically, for each of the investigated occupancy category spaces (see Table 2), the following data have been considered: i) occupancy scheduling; ii) lighting loads density and scheduling; iii) machinery loads density and scheduling; and iv) indoor air setpoints. Concerning the HVAC system, the considered room space heating and cooling are ensured by an air source HPC (heat pump/chiller), sized on the maximum load, with a variable COP [47,48] whose performance maps are implemented into the software. The energy consumption resulting from the conducted analysis is substantially affected by the climate zone, due to the different outdoor air temperatures (it is worth noticing that the room is placed in the core of a conditioned building, so no transmission load is considered). Thus, aiming at assessing the energy impact of the proposed ventilation strategies for diverse climates, three different European weather zones have been considered as representative of hot, mild, and cold weather (see Table 7).

4. Results and discussion

In this paragraph, the results of the carried-out analyses are accurately described. Specifically, first, the Covid-19 results will be presented, and then, the energy and economic implications discussed.

4.1. Contagion risk analysis

With respect to the infection probability analysis, the Covid-19 contagion risk is examined for all the investigated occupancy categories, in the case of the three different face masks scenarios (no mask, on the left, surgical mask in the middle, and FFP2 mask on the right), and in case of three different exposure time (1 h in blue, 2 h in red, and 6 h in yellow). To conduct the analysis it is necessary to define a contagion probability threshold (evaluated as in equation (2)) that can be considered as a “safe” one for all the investigated building categories and occupancy densities. To this aim, it is required to introduce the “basic reproduction number of the infection”, R_0 . Such a number indicates the contagiousness or transmissibility of infectious and parasitic

Table 6
Investigated case studies.

System	Outdoor ventilation rates	Heat Recovery
RS	ANSI/ASHRAE Standard 62.1–2019	No
PS1	Ventilation x3	No
PS1.1	Ventilation x3	Yes
PS2	Ventilation x10	No
PS2.1	Ventilation x10	Yes

Table 7
Investigated weather zones.

Climate	HDD	CDD	ISR
	[Kd]		[kWh/m ² y]
Almeria	763	982	1664
Rome	1475	730	1529
Berlin	3394	262	1001

agents. To control an epidemic the R_0 value must be lower than 1 [24]. The accurate description of this number is out of the scope of this study, nonetheless, it is necessary to specify that it is function of the infection probability (P – evaluated as in equation (2)) and of the number of exposed susceptible people [24]. For simplicity, and for safety sakes, an assumption has been made which consists in considering for the threshold evaluation, for all the investigated building categories, an occupancy density of 100 people (evaluated as the average of maximum occupancies reported in Table 2). By assuming such occupancy, to respect the R_0 limit ($R_0 < 1$), a maximum contagion probability threshold equal to 1% is obtained. Concerning the analysis outcome, numerical results obtained (probability of infection) are reported as boxplots in Fig. 3. Specifically, the distribution of the set of data, the minimum and maximum values (whiskers), as well as the 1st and 3rd quartiles (boxes) and the median are depicted for each of the occupancy category groups. From the figure, diverse considerations can be made. First, it is possible to notice that in case of people not wearing a mask (box on the left of Fig. 3) and for an exposure time of 1 h (blue bars), the infection probability is almost always higher, yet quite close, than 1%. Higher risk occurs in the case of 2 h (red bars), with infection probability rising around 4%. Finally, the highest infection probability in case of no masks worn is obtained for 6 h of exposure time (yellow bars), with contagion risk values rising around 12–14%

By using a surgical mask (central plot in Fig. 3), it is possible to notice that in the case of both 1 h and 2 h of exposure time (respectively blue and red bars), the infection probability is almost always below the 1% value. Nevertheless, in the case of 6 h (yellow bars), the risk is still higher than the threshold value. Lastly, the adoption of FFP2 (right diagram in Fig. 3) ensures a safe environment, with outdoor ventilation rates from standard, also in case of 6 h of exposure time. The reported results show that the ventilation rates suggested by the ANSI/ASHRAE Standard 62.1 are adequate to control the Covid-19 contagion risk only in case of all the occupants wearing an FFP2 mask, whereas higher risk occurs in the case of a surgical mask, and no mask worn. Due to the safe condition reached for all the exposure time in the case of FFP2 masks, no further analysis will be conducted for this scenario, whereas only no mask and surgical mask scenarios will be presented. To reduce the estimated contagion risk, the ventilation rates suggested by the standard have been augmented by 3 times, and the related contagion risk results are shown in Fig. 4.

Here, it is possible to notice that, in the case of the no mask scenario (box on the left of Fig. 4), the contagion risk in case of 1 h exposure time (blue bars) is almost always below 1%, ensuring the occupant safety. Also, the contagion risks relative to 2 h of attendance time (red lines) drop. However, many building categories return infection probabilities still higher than the safe threshold. The contagion risk connected to the 6 h of exposure time (yellow bars) is also reduced with respect to the standard ventilation base case. Still, very high values with respect to the 1% threshold are reached. A different situation occurs in the case of surgical masks worn. In this case, both 1-h and 2 h of exposure time return contagion risks lower than 1%, whereas the 6-h case returns contagion risk higher than the safe threshold, but remarkably reduced with respect to the base case. To further reduce the contagion risk, the ten times increased standard ventilation has been also tested, and the related results are reported in Fig. 5. Here, it is possible to notice that, in the case of the surgical mask worn, the contagion risk probability is lower than the threshold value for almost all the investigated scenarios

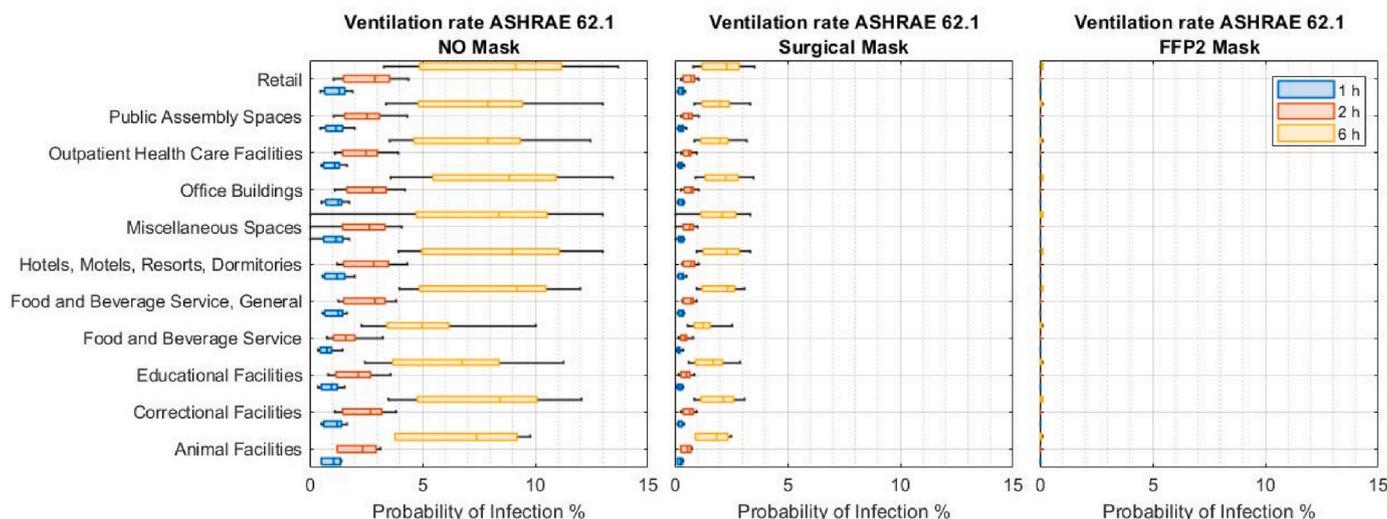


Fig. 3. Covid-19 infection probability for all the investigated case studies (standard ventilation).

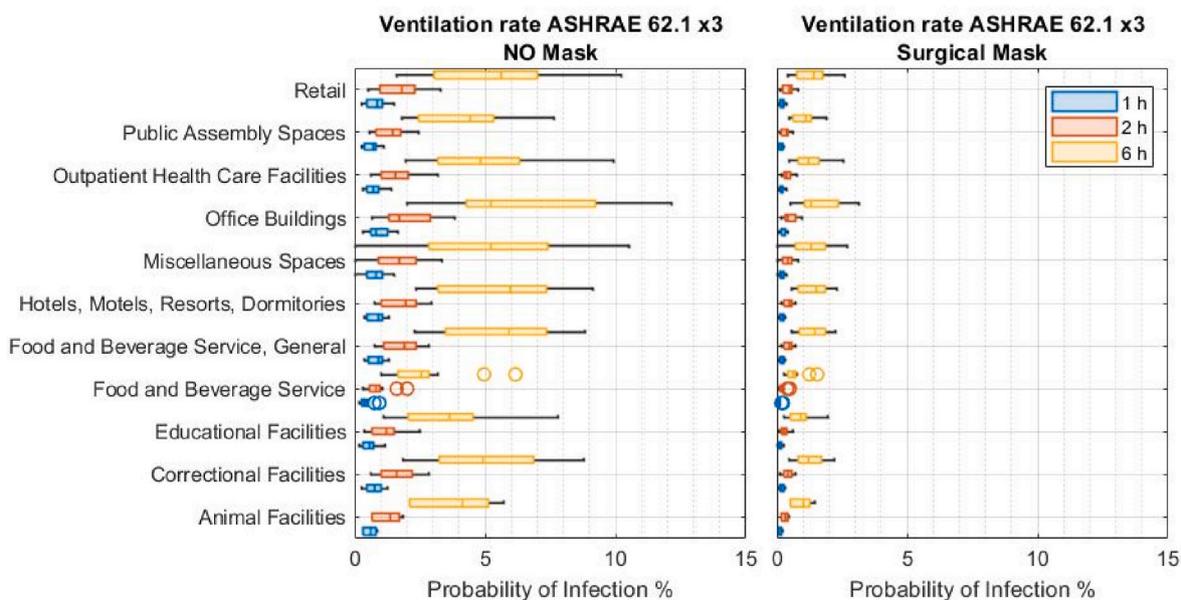


Fig. 4. Covid-19 infection probability for all the investigated case studies (x3 ventilation).

and exposure times. On the contrary, in case of no masks worn, one- and 2-h residency time results be still safe.

It is worth noticing that the absolute values shown in the figures are subjected to uncertainty. This is mainly due to the adopted number of quanta, whose value is still under discussion in the scientific community. For such a reason, relative results are also presented. Specifically, the average relative contagion risk reduction for all the mask scenarios and exposure time is presented in Fig. 6. From the figure, it is possible to notice that, besides the absolute contagion risk value, the contagion risk percentage reduction ranges from 30 to 50% in the case of an x3 ventilation, and from 65 to 80% in the case of x10 ventilation. Such results help in understanding, and quantifying, the great effect that outdoor ventilation rates have on the Covid-19 contagion risk reduction.

4.2. Energy analysis

The described ventilation strategies, due to the augmented ventilation loads, while reducing the Covid-19 contagion risk also increase the energy consumption of the building for space heating and cooling, as

expected. Furthermore, more air treatment leads to higher air handling costs. In this framework, the space heating thermal energy demand for representative space typologies (selected from each category) is presented in Fig. 7 in the case of the building located in Berlin, for all the investigated ventilation strategies. From the figure, as expected, it is possible to notice that the adoption of x3 (PS1) and x10 (PS2) ventilation flow rates (red and light blue bars respectively) always implies a remarkably higher energy demand compared to the RS scenario (blue bar). Different results are instead achieved in the case of the adoption of a Heat Recovery (HR) device (orange – PS1.1, and green – PS2.1, bars in Fig. 7). Here, it is possible to notice that the energy demand increases are remarkably lower than those occurring without HR adoption. It is worth noticing that, in some cases, the PS1.1 energy demand (orange bars) is comparable to the RS one (blue bars).

Similar outcomes can be detected in the case of the thermal energy demand for space cooling, as shown in Fig. 8, where the results in the case of the building located in Almeria are presented.

Nevertheless, by analysing Fig. 8, it is possible to notice that in the case of x3 ventilation, (PS1 and PS1.1 – orange and yellow bars) lower

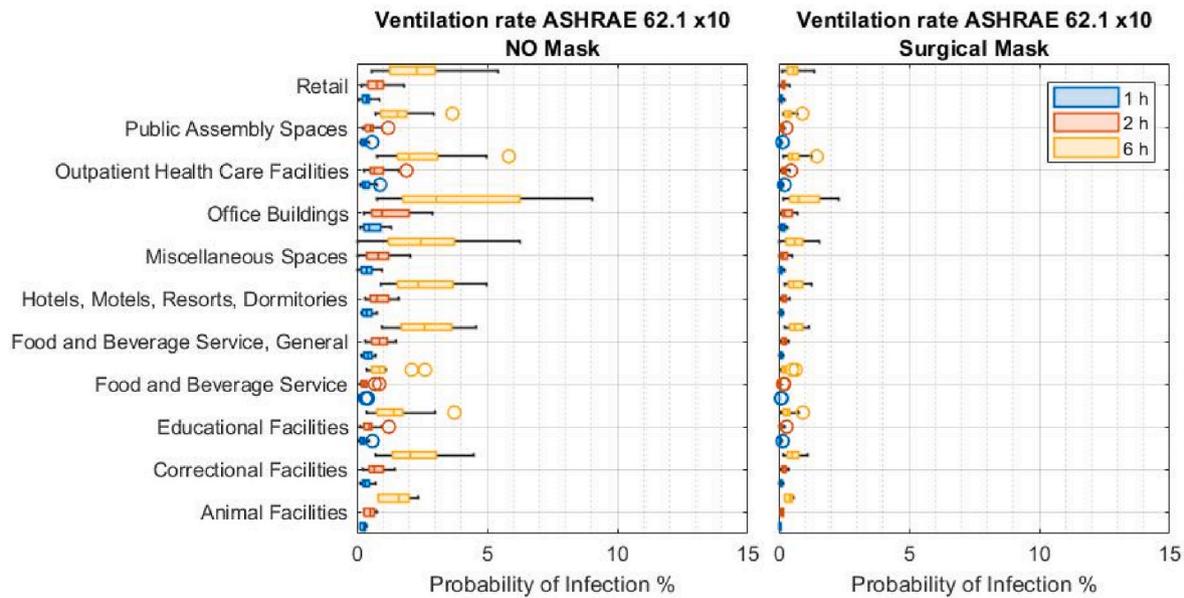


Fig. 5. Covid-19 infection probability for all the investigated case studies (x10 ventilation).

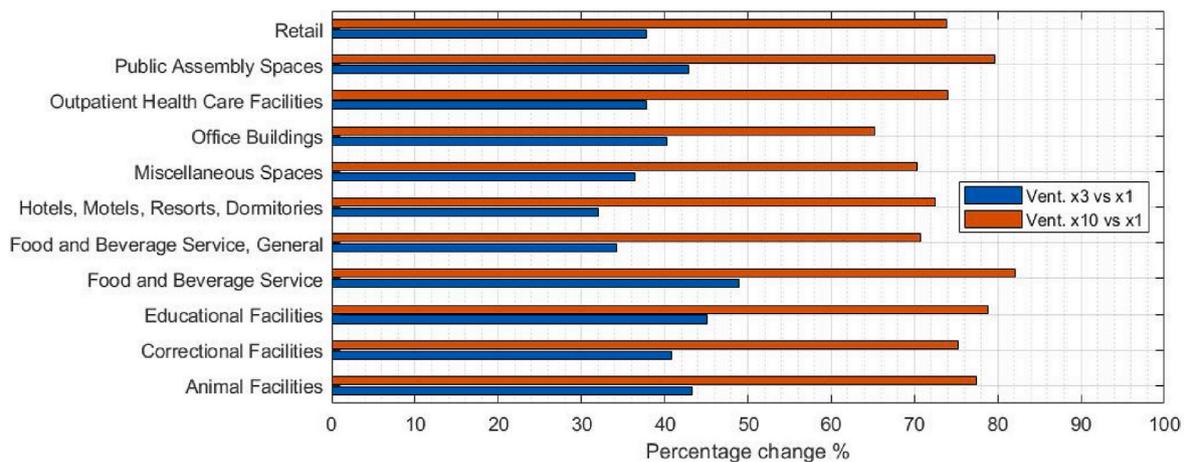


Fig. 6. Average relative contagion risk reduction for all the face mask configurations.

energy demands for space cooling are obtained. Such occurrence is due to the free cooling effect played, in some cases, by the augmented flow rate. The same effect is not noticeable in the case of x10 ventilation (PS2 – light blue bars) since the positive effects connected to the free cooling are overwhelmed by the negative ones occurring in the other hours. However, it is worth noticing that the overall weight of cooling needs increase is remarkably lower than that of heating (the y-axis scale of Fig. 8 is different from that of Fig. 7). In addition, also the benefits of HR are lower due to the lower temperature difference between the outdoor air and the zone temperature during the summer season. The thermal energy demand variations presented in Figs. 7 and 8 imply a variation in the considered room electricity consumption. Specifically, in Fig. 9, the distribution of electricity consumption is presented for all the investigated case studies.

It is worth noticing that, differently from Figs. 7 and 8, the electricity results presented in Fig. 9 take into account also the higher consumption of the fans. Since the specific pressure drop of the duct system remains the same for all the investigated proposed systems, the higher fan consumption is only due to the higher concentrated pressured drop due to the adoption of the HR. Thus, the higher fan consumption is evaluated only in case of those proposed systems including the heating recovery

device (PS1.1 – yellow bars in Fig. 9, and PS2.1 – green bars in Fig. 9). Referring to the median values of the set of data in Fig. 9, as expected, the adoption of PS1 (red boxes) and PS2 (purple boxes) systems always present higher electricity demand vs the RS (blue boxes). The benefits achieved during the cooling season, due to the free cooling effect as shown in Fig. 8, are counterbalanced by the highest consumption during the heating season. Smaller electricity consumption increases are instead detected in the case of PS1.1 (yellow bars) and PS2.1 (green bars) adoption. These reductions are smaller in magnitude with respect to those shown in the case of Figs. 7 and 8 due to the higher consumption of the fans connected to the HR adoption (higher duct system pressure drops due to the HR devices adoption in case of PS1.1 and PS2.1 only).

4.3. Economic analysis

The previously reported energy results imply some economic consequences in terms of investigated system OPERating EXPenditures (OPEX). In this framework, the running cost variations due to the proposed ventilation strategies adoption are evaluated. According to Ref. [49], the electricity costs are considered equal to 299, 207 and 299 €/MWh, respectively for Berlin, Rome and Almeria. On the other hand,

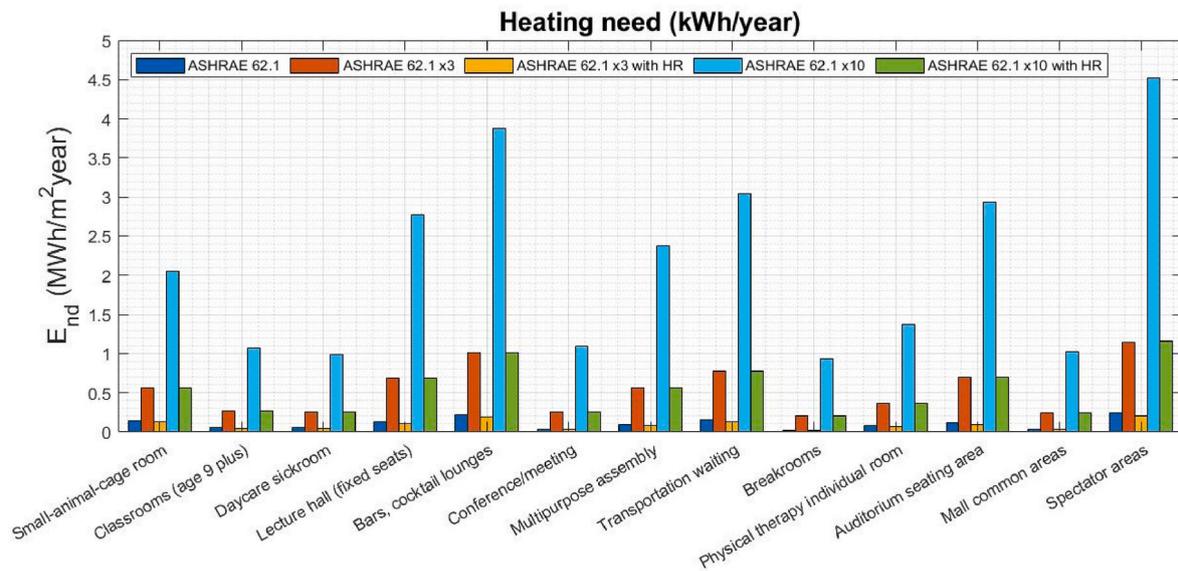


Fig. 7. Space heating needs for all the investigated case studies for the building located in Berlin.

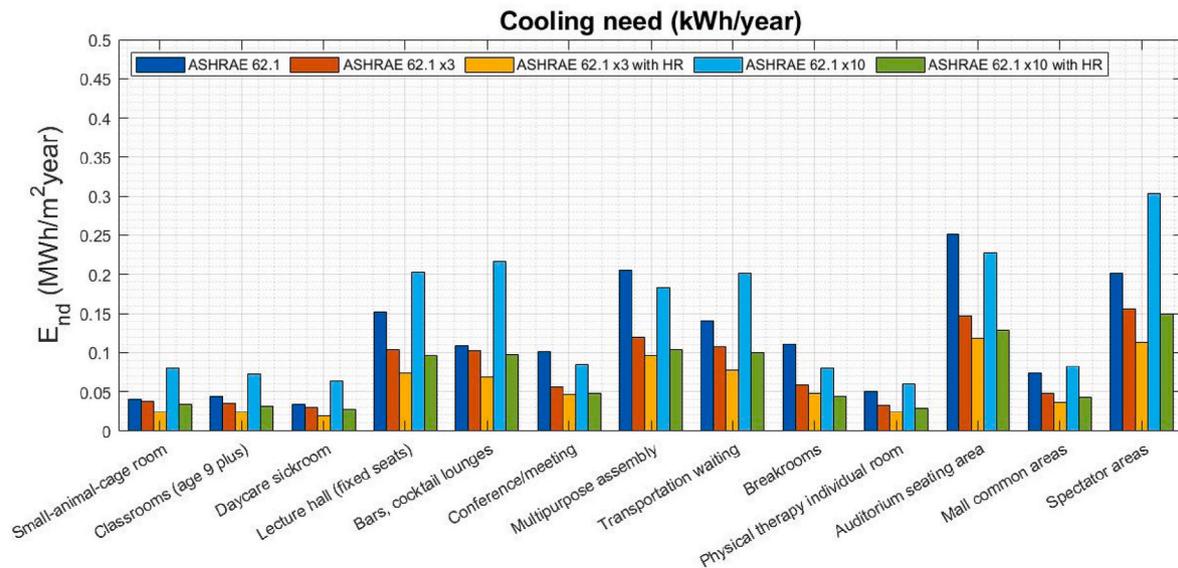


Fig. 8. Space cooling needs for all the investigated case studies for the building located in Almeria.

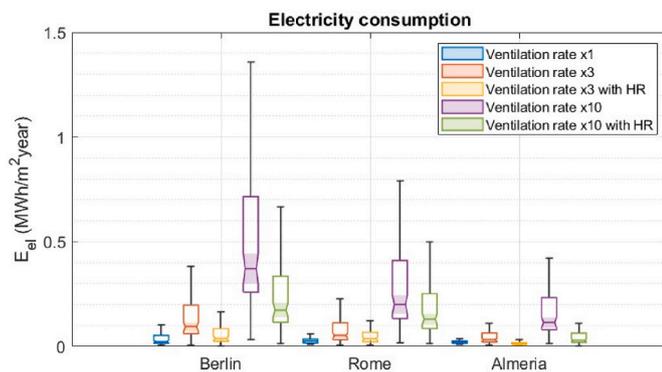


Fig. 9. Electricity needs for all the investigated case studies.

Table 8

Proposed systems economic results.

		Almeria	Rome	Berlin
		$\Delta\epsilon/\text{m}^2\text{year}$	$\Delta\epsilon/\text{m}^2\text{year}$	$\Delta\epsilon/\text{m}^2\text{year}$
PS1 - ASHRAE 62.1 x3	min	-4.8	-1.3	-1.8
	median	3.5	6.4	21.2
	max	52.0	62.4	168.7
PS1.1 - ASHRAE 62.1 x3 with HR	min	-13.2	-1.4	-2.1
	median	-2.0	2.9	5.2
	max	-0.5	32.4	43.3
PS2 - ASHRAE 62.1 x10	min	-2.0	0.2	6.1
	median	27.8	36.2	104.6
	max	277.1	308.1	793.7
PS2.1 - ASHRAE 62.1 x10 with HR	min	-7.3	-1.0	-0.4
	median	3.0	21.9	45.6
	max	60.7	220.0	394.7

potentially higher CAPEX that may occur due to the possibility of higher system size (especially in case of decentralized systems - see section 3.1) have been neglected. Such assumption is justified by the lack of information in the standard on the HVAC system to be considered (it is designer's choice), and thus to the impossibility of estimating the CAPEX for all the investigated building categories. Nonetheless, it is worth noticing that the conducted economic analysis is intended as a tool for all the stakeholders to quantify the running cost of the proposed solutions, whereas the initial cost difference depends on the specific project and on the choice of the HVAC system designer. The analysis outcomes are reported in Table 8 for all the investigated scenarios and weather zones. Particularly, the minimums, the medians, and maximums values of economic savings between PSs and RS are shown. From the table, it is possible to notice that the adoption of both the x3 and x10 ventilation (PS1 and PS2 systems) imply a general increase of the OPEX for all the considered weather zone. Nevertheless, in some cases, it is possible to achieve an economic savings. This saving is higher in the case of the PS1 system (x3 ventilation), and for those climates where cooling loads impact more (hot weather zones). Lower economic expenditure increases (and higher savings) are obtained by considering the PS1.1 (x3 ventilation and HR adoption) and the PS2.1 (x10 ventilation and HR adoption), as expected (see Table 8).

In general, the adoption of the proposed solutions, especially PS1 and PS2, imply not negligible OPEX increases. The adoption of a heat recovery system (PS1.1 and PS2.1) allows for an interesting reduction of such increase making the proposed solutions more viable. Lastly, it should be considered that in some specific cases, also economic savings over RS could be obtained.

5. Conclusions

In this study, the effectiveness of the ventilation rates proposed by the current ANSI/ASHRAE Standard 62.1 in dealing with the Covid-19 contagion risk is comprehensively investigated. More precisely, this research has the twofold aim of i) evaluating the adequacy of current ventilation standards in dealing with the present pandemic scenario; and ii) providing all the stakeholders with novel criteria and guidelines for the design and operation of the HVAC system, also giving useful guidance for the development of future ventilation standards in a post Covid-19 scenario. To reach this goal, a comprehensive analysis dealing with all the building categories presented in the ANSI/ASHRAE Standard 62.1 has been conducted by considering, for each indeed uses, the related crowding indexes, occupancy schedules, and outdoor air ventilation rates suggested by the standard. By doing so, it has been possible to assess the Covid-19 contagion risk for each of the investigated building typologies and to draw conclusions on the adequacy of the current standard. Additionally, to provide useful insights and criteria for ventilation system design and operation, and to develop recommendations for the development of future standards, higher outdoor air flow rates have been tested by assessing their effectiveness in reducing the probability of contagion. Finally, the energy and economic implications of the proposed enhancements have been assessed. To carry out the described analysis, a novel method, based on dynamic simulation, which couples together the Building Energy Modelling (BEM), and the virus contagion risk assessment, has been developed. Specifically, to assess the Covid-19 contagion risk, the Wells-Riley model, largely adopted by the scientific community, has been implemented in a purposely developed Matlab routine, whereas for the building energy simulation, a dynamic simulation model has been purposely developed in the EnergyPlus environment. From the carried-out analyses, several considerations can be made:

- The ventilation rate values proposed in the current ANSI/ASHRAE Standard 62.1 are not capable to ensure a safe indoor environment in case of no face mask is worn. Specifically, infection risk probability higher than 1% is almost always obtained by the conducted analysis,

regardless of the considered exposure time. The same is true for surgical mask adoption, which gives lower infection risk probability, but very often still higher than the safe threshold;

- The current standard adoption returns a very low contagion risk probability only in case of all occupants wearing an FFP2 mask (which is, nowadays, a rare occurrence). Therefore, it is suggested to revise the current standards by increasing the suggested outdoor air flow rate;
- The adoption of higher ventilation rates (x3 and x10) always returns interesting infection risk reduction, respectively ranging between 30 to 50% and 65–80%. Nevertheless, x3 ventilation is effective only for an exposure time to the virus of 1 h, whereas in case of 2 and 6 h, the resulting contagion risk is always higher than 1%;
- Ten times augmented ventilation vs. ANSI/ASHRAE Standard 62.1 values reduces the contagion risk below 1% for both 1- and 2-h exposure time (whereas 6 h is often still too high). Nonetheless, some technical issues for the components (AHU, ducts, etc.) installation may be experienced, especially in case of decentralized or ventilation-only systems, due to the higher space requirements;
- By increasing the ventilation, it is possible to reduce the Covid-19 risk below the 1%, without wearing facemasks, only for 1- and 2-hours attendance time, whereas in case of 6 h this is not possible. Consequently, in case of certain indeed use characterized by long occupancy time (e.g. classrooms), additional solutions aimed at deactivating the virus should be adopted;
- From the energy point of view, the proposed ventilation strategies return a remarkable electricity demand increase, with consequent very high economic expenditures.
- The adoption of a heat recovery device allows for a remarkable reduction of the energy and economic impact of the proposed ventilation strategies, making both x3 and x10 ventilations more feasible than the same solutions without the HR.
- The best trade-off solution by energy, indoor air quality, and technical feasibility points of view is represented by x3 outdoor air ventilation increase coupled to a heat recovery system.

From the results obtained through the carried-out analysis it is possible to conclude that the current standard is not adequate to ensure a low contagion risk. Even if the current epidemic is nearing an end, this is still an issue since the attention raised on the role of ventilation in buildings lifted general concerns about whether the ventilation standards in place are adequate to reduce the risk of future pandemics and to improve the overall safety of our living environment. In this context, the results achieved in this research can be used as guidelines for the design and operation of the HVAC system, and also as useful guidance for the development of future ventilation standards in a post-Covid-19 scenario.

Credit author statement

All authors have contributed equally.

Annamaria Buonomano: Conceptualization; Methodology; Software; Formal analysis; Data curation; Writing – original draft; Writing – review & editing; Visualization, **Cesare Forzano:** Conceptualization; Methodology; Software; Formal analysis; Data curation; Writing – original draft; Writing – review & editing; Visualization, **Giovanni Francesco Giuzio:** Conceptualization; Methodology; Software; Formal analysis; Data curation; Writing – original draft; Writing – review & editing; Visualization, **Adolfo Palombo:** Conceptualization; Methodology; Software; Formal analysis; Data curation; Writing – original draft; Writing – review & editing; Visualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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