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The impact of retrofitted ventilation approaches on long-range airborne infection risk for lecture room environments: design stage methodology and application

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ABSTRACT

There is a continued need to improve the energy (and by extension carbon) performance of the existing building stock in Europe and globally. Recent experiences with the COVID-19 pandemic have demanded even more of the built environment disciplines when it comes to air quality and ventilation rates particularly in teaching environments which are seen as necessary developmental sectors for the learning of the population. As such it is important that these spaces are safe for students and staff where, until now, infectious disease risk assessments were not typical. In addition to this, there is a risk that envelope refurbishment (which is critical for energy performance) without the provision of adequate ventilation may lead to high-risk scenarios for occupants in university spaces and additional measures may be required. This study presents a design stage risk assessment methodology and applies this to evaluate different retrofitted ventilation approaches combined with additional control measures for a lecture room environment. A real case study lecture room in Ireland was used to demonstrate the methodology for evaluating the airborne infectious disease risk (using the Wells-Riley model) under different ventilation approaches (natural and mechanical), infiltration rates (existing and upgraded), class sizes and times, mask efficiencies as well as the use of an air cleaner. The methodology that was adopted was shown to be flexible and capable of considering a wide range of different retrofit and user specific combinations. The results from the evaluation indicate a wide range in event specific reproductive numbers, however, the use of a well-designed natural or mechanical ventilation system was seen as significant in stabilising or suppressing virus transmission and reducing the likelihood of highly reproductive events. It was found that combinations of measures with ventilation were the most effective at suppressing reproductive numbers. It is recommended that during known pandemics (in the short-term) infectious control strategies should use filtration (through masks or air cleaners) and adequate ventilation. Long-term refurbishment strategies should consider the provision of hybrid ventilation systems which integrate key energy saving measures (such as heat recovery and demand-controlled ventilation), virus control (such as HEPA filtration) and low energy cooling solutions (such as passive cooling).

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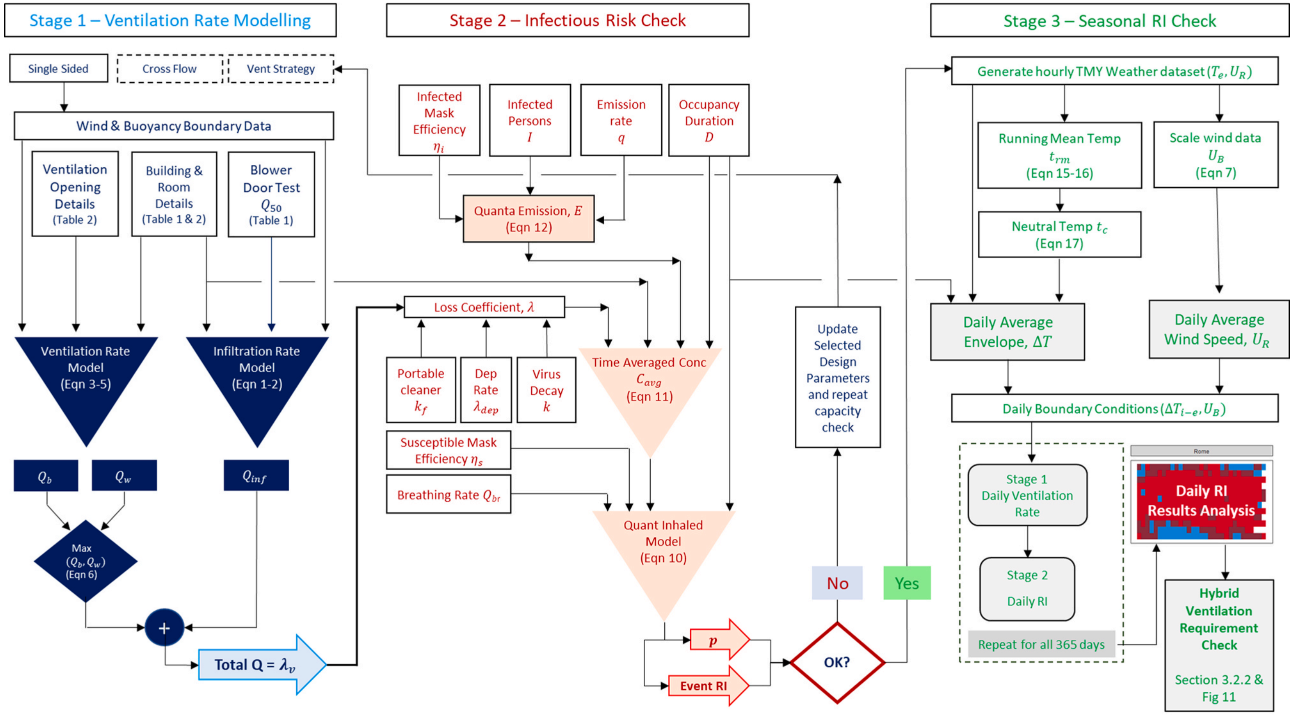

Fig. 1. Flowchart describing general methodology applied to assess airborne infection risk at design stage. (Note: depending on the ventilation strategy chosen stage 1 will have different steps involved. For the particular application evaluated in this paper a single sided strategy was adopted).

1. Introduction

The ongoing low-energy refurbishment of existing educational lecture rooms in northern Europe to reduce operational CO_2 emissions is an essential climate change risk mitigation strategy. However, reducing the longer-term climate change and energy security risks originating with a building's energy demand may be at conflict with the short-term health risks of its occupants. This is due to several competing factors. On the one hand there is a need for low energy resilient solutions such as passive ventilation/cooling [1]. Conversely, the reduction in conductive dissipation of internal heat build-up through the low energy fabric; the reduction of contaminant dilution from higher levels of envelope airtightness [2] and, most importantly, the need for reliable ventilation approaches that limit the airborne infectious risk of SARS-CoV-2 by its occupants [3], all lead to a high expectation on low energy passive strategies to deliver effective ventilation performance. Until recently, evaluating the risk of airborne infection did not typically feature as part of the assessment of building energy refurbishment choices. The challenge in post-COVID lecture rooms is to choose refurbishment strategies that reduce long-term climate change risk without leading to an increased risk of infection for those attending lectures. Occupant behaviour (through deliberate purge ventilation) and the effective ventilation rate both influence infectious risk [4–6]. Mechanical ventilation (MV) strategies can lead to better infectious risk control [4] while causing higher CO_2 emissions impact compared with passive strategies. These are also more vulnerable to grid power outages [7], poor maintenance and component failure. However, recent research focused on educational environments have demonstrated that effective ventilation management (mechanically or naturally) can reduce indoor CO_2 levels considerably [8,9] which demonstrates the need to consider both [10]. The increase of ventilation rates in buildings has been identified as a key mitigation measure for limiting airborne infectious disease spread [11–16]. Existing reviews of the literature support the need to have adaptable ventilation systems which use fresh air as part of their strategy [11,12]. Some have identified natural ventilation (NV) as an effective method for ventilating buildings in the context of infectious diseases [12,13,17]. However, others are critical of NV as a solution which may need fan assistance or additional air purification to reduce infectious risks [12,13,18]. In some of the literature, MV systems have been seen as the preferred choice for future ventilation needs, particularly if they can adjust fan speeds and allow for filtration in their systems or adopt heat recovery for optimal winter performance [11,12,15]. However, any wide-spread adoption of MV systems needs to be balanced with the functional resilience and financial benefits of simplified approaches such as openable windows, even when their intermittent performance can require additional behavioural interventions to mitigate infectious risk for occupants. Given the current and historic retrofit rates as well as current cost-of-living and inflationary circumstances in Europe and further afield it is likely that the decision to choose an MV retrofit strategy could now come under renewed scrutiny. Furthermore, with evidence emerging which suggests we should design our MV systems to reduce virus reproduction [12] and the lack of clear guidance on how to size NV systems to reduce infectious risk, there is a need to consider infectious risk at the early design stage particularly for existing systems in the context of retrofits and upgrades to buildings. To analytically investigate the potential airborne infectious risk in lecturing environments for different low energy refurbishment approaches a lecture room at an Irish university was chosen as a case study. A section of the case study building has previously been refurbished to nearly zero energy fabric performance levels under a separate pilot study [19,20] and the decision regarding its extension to other parts of the building should be assessed based on both climate change risk as well as occupant respiratory safety. The aims of this study are:

1. To develop an early design stage methodology to assess infectious disease risk for teaching spaces such as lecture room environments,
2. To evaluate what airborne infection risk currently exists with existing ventilation systems and determine what measures will be required to reduce this risk in retrofitted spaces in the future,
3. To determine whether there exists seasonal variability in infectious risk related to the performance of natural ventilation and what is required to reduce this risk.

The subsequent sections of the paper outline a detailed description of the design stage methodology used for the study (Section 2), the results (section 3), and the interpretation of findings to assist with future refurbishment choices (Section 4).

2. Materials and methods

2.1. General methodology and scope

To address the objectives of the study, a three-stage methodology (shown in Fig. 1) was developed which consisted of: 1) a natural ventilation airflow rate modelling stage, 2) a design stage airborne infectious risk modelling check, based on static system capacity sizing and 3) a seasonality check stage. The methodology utilised an analytical multi-permutation static simulation approach, where the ventilation rate is obtained through a combination of infiltration and ventilation rate modelling based on established validated ventilation and infiltration models. Calculated ventilation rates are then used as one of the many inputs into the widely used Wells-Riley model [21] to determine the likely airborne infectious risk when several internal and external boundary conditions are considered for a lecture room indoor environment. The Wells-Riley model presented in this paper, was verified using two different literature sources, the reference value calculated by Guo et al. [16] as well as the table of input and output values presented by Kurnitski et al. [22] for different spaces. For both approaches similar probability values were attained when compared to those calculated in previous literature (within 1% in absolute terms generally overpredicting risk compared with others). The following approach uses a natural ventilation model which is likely to a lead to uncertainty of around $\pm 20\%$ in predicted airflow rates. When this uncertainty is introduced into the Wells-Riley model this can lead to uncertainties of $\pm 1\%$ on average in probability terms and ± 0.1 in reproductive terms. Using this approach, a series of ventilation retrofit scenarios are considered which include: 1) the existing case study building scenario; using top hung outward opening windows with single-sided NV only (i.e. the original 1974 building/envelope design), 2) upgrades to the ventilation openings (i.e. with an airflow guiding louvre or different NV components), 3) upgrades to building air-tightness levels, and 4) the use of an MV system. With this approach it is assumed that comfortable conditions can be maintained for occupants (i.e., a constant indoor temperature is assumed). The sedentary nature of lecture room environments enables reasonable evaluation of infectious risk using models that assume the internal air is well mixed with contaminants homogeneously distributed. There is evidence to suggest that under conditions where forced convection is not the main driving force for ventilation that this assumption (and the accuracy of the Wells Riley model spatially) is reasonable [23]. It is also reasonable to expect low levels of internal air motion/local airflow regimes during lecturing etc. It should be noted that there are many simulation-based approaches that could be used to simulate the airborne infectious risk, including the use of dynamic indoor environmental and energy modelling and simulation methods, which typically occurs during the detailed design stages. The method presented in this study (shown in Fig. 1) is designed to be applied by design practitioners (i.e. architects or engineers) to make some decisions about ventilation design at the early design stages. In addition to this, it should be noted that vaccination has a key role to play in reducing the spread of viral pathogens, such as COVID-19, in the community [24–26] and it can have a substantial effect in reducing the need for other infection prevention control measures [27]. However, there are limitations to this as the sole approach to infection prevention and control as, for example, protection from infection from subsequent variants of COVID-19 (or other airborne viruses) may not be guaranteed, where current evidence for COVID-19 suggests that protection from reinfection decreases after vaccination [24,25]. The general approach adopted in this method and demonstrated in further sections of this paper therefore presents and focuses on the airborne risk in the worst-case and likely scenarios where the population are susceptible to infection or reinfection. Furthermore, the scope of the method applied here considers the probability of infections and virus reproduction using a scenario-based approach including multiple personal factors (mask wearing, class size limitations, exposure times etc), though it should be noted that deviations may (in reality) occur through personal choices to adopt these measures, this could be the case for any of these measures. In addition to a static approach, the performance of all selected NV systems was evaluated in four different representative cities located in Europe (Dublin, Stockholm, Rome and Budapest) to consider whether there is a seasonality bias in airborne infection risk for retrofitted approaches for different climates. Finally, the provision of hybrid ventilation (HV) was assessed for the Dublin climate only.

2.2. *Ventilation and infiltration modelling*

To consider the above question and problem, a combined infiltration and ventilation model was created based on existing published models and was subsequently parameterised based on verified building information or sources from the literature. Models were chosen based on their practical useability for practitioners involved at the early building design stages and as such static models were adopted. Equation (1) defines the infiltration airflow rate (in m^3/s) which was based on the work of Sherman and Grimsrud [28] and was taken from the latest edition of the ASHRAE fundamentals guidebook [29].

$$Q_{inf} = \frac{A_L}{1000}\sqrt{C_s|\Delta T| + C_w U^2} \tag{1}$$

Where, C_s is the stack coefficient [in $(L/s)^2/(cm^4 K)$], C_w is the wind coefficient [in $(L/s)^2/[cm^4\ (m/s)^2]$], A_L is the effective leakage area (in cm^2), ΔT is the average indoor-outdoor temperature difference for the time interval of calculation, U is the average reference wind velocity. All values used for pre- and post-retrofit scenarios are indicated in Table 1 and Table 2. The effective leakage area (A_L) is calculated based on the work of Sherman, Turner and Walker et al. [30] by using Equation (2) and existing building leakage measurement data.

$$A_L = Q_{50}\left(\frac{4Pa}{50Pa}\right)^n \sqrt{\frac{\rho}{8}} \tag{2}$$

Where, Q_{50} is the ventilation rate taken from a blower test (in m^3/s), n is the flow exponent, and ρ is the air density (in kg/m^3, taken as 1.2 kg/m^3). The flow exponent for the post-retrofit scenario is obtained from a blower test, for the pre-retrofit scenario the standard flow exponent of 0.65 was taken which was typical of buildings of the time in Ireland and further afield [2,31,32] (see Table 1). To account for natural ventilation the work of Warren and Parkins [33] is used which was evaluated later by Larsen et al. [34] and by Albuquerque et al. [35]. Warrens model for single-sided NV evaluates airflow rates independently for two momentum sources: buoyancy and wind. The most widely used buoyancy driven airflow equation is shown in Equation (3) (taken from Ref. [36]) and, for wind driven airflow, indicated in Equation (4) (using reference wind speeds). There are many limitations in the use of the wind speed

Table 1
Infiltration parameters used in study.

Parameter	Units	Existing (1974)	Retrofit	Reference or source
n	–	0.65	0.71	[29], Test data
Q_{50}	$m^3/h/m^2$	14.77	1.76	Test data
Q_{50}	m^3/s	0.62	0.07	Calculation
A_{ext}	m^2	107	107	Calculation
A_L	cm^2	329	39	Calculation (Eq. (2))
C_s	$(L/s)^2/(cm^4K)$	0.00029	0.00029	[29]
C_w	$(L/s)^2/(cm^4K)$	0.000231	0.000231	[29]

Table 2
Natural ventilation parameters used in study.

Parameter	Units	Existing Window	Louvre	New Window	Reference or source
Opening height	m	0.92	1.6	1.6	[40,41]
Opening width	m	1.14	0.3	0.9	[40,41]
$A_{aperature}$/opening	m^2	1.05	0.48	1.44	–
Opening depth	m	0.155	NA	0.20	[40]
A_{free}/openings	m^2	0.32	0.20	0.50	–
No openings	–	3	6	7	–
A_{free}	m^2	0.96	1.2	3.5	–
POF_{free}	%	1.2	1.5	4.4	Floor area = 79m^2
H	m	0.9	1.6	1.6	–
C_d	–	0.422	0.61	0.422	[39,42,43]
F_r	–	0.025	0.039	0.025	[39,42,43]

Table 3
Ventilation and retrofit scenarios considered.

Ventilation Scenario	Retrofit	Ventilation Type	Opening Type	Infiltration
Scenario 1	No	None	None	Pre-retrofit
Scenario 2	Yes	None	None	Retrofit
Scenario 3	No	NV - Existing	Top hung (outward)	Pre-retrofit
Scenario 4	Yes	NV – Existing	Top hung (outward)	Retrofit
Scenario 5	Yes	NV – New	Louvre with door (side hung inward)	Retrofit
Scenario 6	Yes	NV - New	Top hung (outward)	Retrofit
Scenario 7	Yes	MV (demand controlled)	None	Retrofit

local at the opening, (also recommended by Warren and Parkins) not least that data on the local wind at the opening is seldom available to practitioners or may not be suitable for a given location. Therefore, the reference conditions were used to calculate NV airflow rates.

$$Q_b = \frac{1}{3} C_d A_{op} \sqrt{gH \frac{T_i - T_e}{T_i}} \tag{3}$$

$$Q_w = F_R A_{op} U_R \tag{4}$$

Q_b is the volumetric airflow rate due to buoyancy (in m^3/s), C_d is the discharge co-efficient (–), A_{op} is the effective opening area (in m^2), T_i is the internal temperature (in K), T_e is the external air temperature (in K), H is the opening height in metres, U_R is the reference wind velocity (in m/s). Typical values of local and reference flow numbers are indicated in Table 2. It was proposed by Warren and Parkins [37] that for single-sided flow with one opening (typically abbreviated as SS1) that the maximum of either buoyancy or wind driven flows be taken, as is indicated in Equation (5).

$$Q = \max\left(Q_b, Q_w\right) \tag{5}$$

In this study, the total ventilation rate by infiltration and natural ventilation are considered as the sum of both infiltration and ventilation flows. To examine the seasonal variance in infection risk, typical meteorological year (TMY) datasets were used for four interpolated cities (described earlier). This was generated using Meteonorm version 8.1 [38] with "Contemporary" weather data, with radiation data from 1996 to 2015 and other relevant parameters from 2000 to 2019. To scale the wind velocities to the building height, Equation (6) (taken from CIBSE AM10 [39]) was used:

$$U = U_{met} k z^a \tag{6}$$

Where, U is the wind speed (in m/s) at height z (in m) and k and a are coefficients determined by the terrain in which the building lies. For all seasonal risk assessments considered in this paper a value of $k = 0.35$ and $a = 0.25$ was used with a building height of 10 m. This represents a two-storey building in an urban environment.

2.3. *Airborne infectious risk modelling*

To assess the risk of infectious disease transmission for many airborne diseases many researchers have adopted the Wells-Riley model [21,44] indicated in its classical form in Equation (7).

$$P = \frac{C}{S} = 1 - e^{-Iqpt/Q} \tag{7}$$

Where, P is the probability of infection for a susceptible person, C is the number of infection cases, S is the number of susceptible people, I is the number of infectors, p is the breathing rate of a susceptible person (in m^3/s), q is the quantum generation rate by an infector (in quanta/s), t is the total exposure time (in s), and Q is the outdoor supply rate (m^3/s). Table 4 and Table 5 indicate typical values used by REHVA in reference to airborne transmission of COVID-19. Recent work completed by REHVA on the development of a ventilation risk assessment tool applies the Wells-Riley model, however in an modified format [22] shown in equation (8):

$$p = \frac{N_c}{N_s} = 1 - e^{-n} \tag{8}$$

Where, p is the probability of infection for susceptible cases (−), N_c is the number of disease cases, N_s is the number of susceptible persons in the room, and n is the quanta inhaled (in quanta). Equation (9) describes the calculation of the number of quanta inhaled when considering susceptible occupants are wearing masks.

$$n = C_{avg} Q_b (1 - \eta_s) D \tag{9}$$

Where, C_{avg} is the time-averaged quanta concentration (in quanta/m^3), Q_b is the volumetric breathing rate of an occupant (in m^3/h), η_s is the filtration efficiency of the masks worn by those who are susceptible, and D is the duration of occupancy. Equation (10) indicates the time-averaged quanta concentration calculation.

$$C_{avg} = \frac{1}{D} \int_0^D C(t)dt = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda V}\left(1 - e^{-\lambda D}\right)\right] \tag{10}$$

Where, E is the quanta emission rate (quanta/h), λ is the first order loss coefficient for quanta/h due to the summed effects of ventilation (λ_v, 1/h), deposition onto surfaces (λ_{dep}, 1/h), virus decay (k, 1/h) and filtration by a portable air cleaner if applied (k_f, 1/h), $\lambda = (\lambda_v + \lambda_{dep} + k + k_f)$ and V is the room volume (in m^3). Finally, Equation (11) indicates the calculation of the quanta emission rate.

$$E = (1 - \eta_i) I q \tag{11}$$

Where, η_i is mask efficiency for an infected person, I is the number of infectious persons (−), and q is the quanta emission rate per infected person (quanta/(h pers)). To account for the first order loss rate due to portable air cleaners Equation (12) was used.

$$k_f = \frac{Q_{filter} \eta_{filter}}{V} \tag{12}$$

Where, Q_{filter} is the airflow rate through the filter and η_{filter} is the filtration efficiency. In addition to the calculation of the probability of infection, the study also calculated the event specific reproductive number RI which is defined as the number of new disease cases ($N_c = pN_s$) divided by the number of infectors using Equation (13) adapted from Refs. [22,45].

$$RI = \frac{N_c}{I} \tag{13}$$

Where, N_c is the number of new or secondary cases.

2.4. Indoor temperature assumptions

For all static risk assessments, it is assumed that the building was maintained at 22 °C. Designers should note that this value is selected for the purposes of demonstrating the methodology and is a commonly adopted term for Irish buildings. Careful consideration should be given to the choice of design indoor air temperature so that it reflects the needs of occupants for the purpose of assessment as well as accounting for the influence the ongoing global energy crisis is having on thermal comfort expectations. The indoor air temperature is also non-linearly related to the airflow rate in buoyancy driven NV and for the same indoor-outdoor envelope temperature difference, different indoor air temperatures can lead to different airflow rates. For all seasonal piece-wise risk assessments the indoor temperature was assumed to be close to the operative temperature and varied depending on the exponentially weighted external mean temperature (t_{rm}). The exponentially weighted external mean temperature was calculated using Equation (14) for the first day and using Equation (15) for every day after this according to TM52 [46]. For external mean temperatures of greater than or equal to 10 °C the internal temperature was assumed to follow the neutral operative temperature (t_c) according to EN 16798–1 [47] (see Equation (16)) for external mean values less than 10 °C a fixed threshold of 22 °C was adopted.

$$t_{rm} = (T_{od-1} + 0.8T_{od-2} + 0.6T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2T_{od-7}) / 3.8 \tag{14}$$

Table 4
66th quanta emission rates for different activities taken from [50].

Activity	Quanta emission rate, (quanta/h)
Resting, oral breathing	0.72
Heavy activity, oral breathing	4.9
Light activity, speaking	9.7
Light activity, singing (or loudly speaking)	62

Table 5
Volumetric breathing rates [51,52].

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

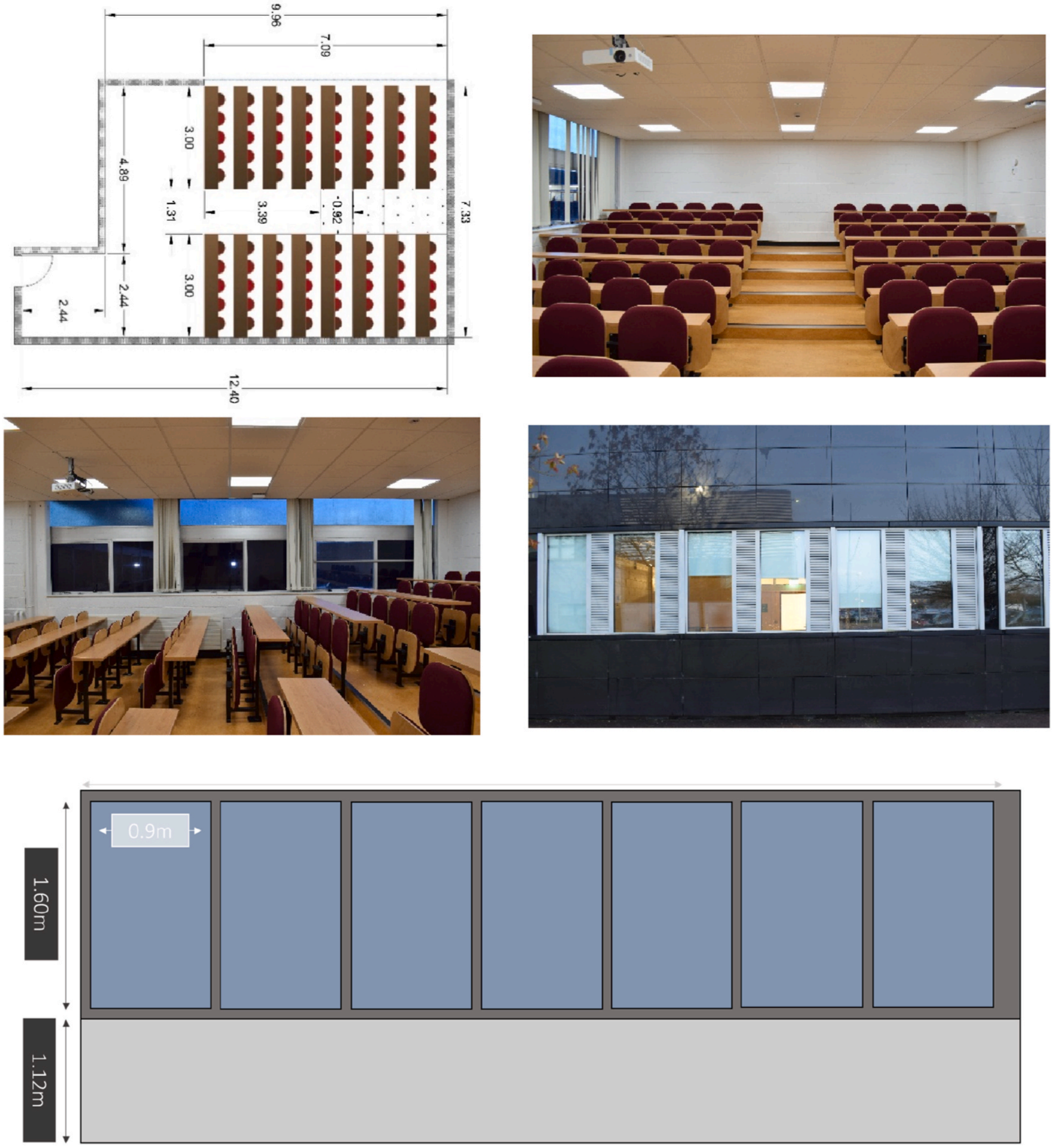

Fig. 2. Case study lecture room used for analysis (Top-left: plan drawing of room, Top-right: Image of classroom while unoccupied, Mid-left: image of the openings in the classroom, Mid-right: image of the low energy building façade, Bottom: Illustrative design of openings for new NV scenario (Scenario 6), which is a maximum opening area scenario).

$$t_{rm} = (1-\alpha)T_{od-1} + \alpha t_{rm-1} \quad (15)$$

$$t_c = 0.33t_{rm} + 18.8 \quad (16)$$

Where, T_{od-1} is the daily average temperature from the day before today and so on, and α is a weighting factor which was assumed to be 0.8.

2.5. Case study and retrofit measures for static assessment

To evaluate infectious risk in refurbished lecturing environments a typical university classroom was taken as a case study (shown in Fig. 2). The room had three openings on one side of the room, (see Table 2 for more details), with a maximum aperture of 1.05 m^2 per opening and 3.24 m^2 overall and a maximum proportion of openable area to floor area (POF) of 4.1%. The room had a floor area of 79 m^2, an average floor to ceiling height of 2.8 m and a volume of 221 m^3. The lecture room had a maximum seating number of 80. Current occupancy levels are reduced due to social distancing. Recently, an MV system was installed in the room to provide additional ventilation. In this study, seven ventilation retrofit scenarios (indicated in Table 3) were evaluated which consider different combinations of pre and post retrofit infiltration rates (due to different fabric performances) and the use of an airflow guiding component (architectural louvre) or window, as well as an MV system. When considering minimum ventilation rates required for hygienic ventilation there are many standards that can be used (see Table 6). The MV system considered in this study was demand controlled delivering 10 l/s/p using the occupancy level as an indicator. Regarding infectious modelling, the values used by Kurnitski et al. [22] for quanta emission rates in classrooms ($q = 5$ quanta/h), breathing rates ($Q_b = 0.57$ m^3/h), as well as defaults for first order virus deposition rates ($\lambda_{dep} = 0.3$ 1/h) and virus decay ($k = 0.32$ 1/h) were adopted for this study (see Table 4 and Table 5)

In addition to the ventilation measures proposed, variable occupancy levels were evaluated, including; 1) 100% capacity (81 people), 2) 1 chair between occupants (48 people) and 3) 2 chairs between occupants (32 people). Scenarios with and without a portable air cleaner were also examined, where an airflow rate of 650 m^3/h (a cleaning air change rate or k_f of close to 3 1/h) was considered using guidelines provided by the Department of Education in Ireland [48] with a filtration efficiency of 99.97% ($\eta_{filter} = 0.9997$). The application of a face covering (with a filtration efficiency of 30%, 50% or 90%), the consideration of exposure times of one, two and whole day 8 h (typical class times), as well as the consideration of winter and summer conditions for wind speed (0 m/s to 6 m/s) and envelope temperature difference (ΔT from 0 °C to 12 °C) were also considered. Based on a ratio of one infector in 25 people (or 4%) rounded down to the nearest whole infector (leading to 1 (32 and 48 people) or 3 infectors (81 people)). Overall, 20,736 combinations were tested using a code developed in RStudio [49], of these 8,064 combinations are reported in this paper.

2.6. Seasonal risk assessment parameters

The seasonal variation in daily infection risk was considered using the average of conditions between 8am and 6pm which corresponds to typical class times in the university building in question. Two different timescales were assessed with this seasonal risk assessment method: 1) a short-term or expected strategy (when virus presence is known) and 2) a medium to long-term strategy considering a worst-case scenario for NV systems. For the short-term assessment, only the natural ventilation scenarios 4, 5, and 6 were evaluated as the focus of this part of the study was to investigate the vulnerability of NV designs in different climates. In addition to this, a basic risk management plan was considered which included masks (with a 50% filtration efficiency) and NV, the maximum class size (leading to three infectors) and a maximum exposure time of 8 h. Outside of this the same ventilation and infectious risk parameters were used as described above, however, they were calculated daily for each location. For the medium to long-term assessment, one ventilation scenario (Scenario 6) was considered in one location (Dublin). For this scenario, the same climate data and same infectious risk parameters were used as described previously, however, occupants were simulated as wearing no masks (virus presence considered unknown). At this stage, the ventilation rate required to lead to an RI of 1 and 0.5 was considered for the room in question. Using this as target, the need for mechanical ventilation or hybrid systems in addition to changes in occupant density was also considered if NV systems were not satisfactory in keeping room specific RI numbers to below these values.

Table 6
Recommended ventilation rates in buildings.

Standard, group or study [Ref]	Building Type	Recommended ventilation rate (L/s/p, L/s/m^2 or ACR)
Mendell et al. (1993) [53]	Office buildings	10 L/s/p
CIBSE AM10 (2005) [39]	Non-residential buildings	8 L/s/p
Persily et al. (2015) [54]	Bedrooms to Kitchens (Residential)	3.5–10 L/s/p
EN 16798–1 (2019) [47]	Category I/II	14–20 L/s/p (1.4–2 L/s/m^2)
ASHRAE (2021) [55]	Schools and Universities	6 ACR
REHVA (2021) [56]	Common for buildings	10 L/s/p
	Meeting rooms and classrooms	8–10 L/s/p
	Hospital environments	6-12 ACR or (4L/s/m^2)

Table 7
Summary statistics of probability of infection (in percentage terms) with respect to different ventilation scenarios.

Metric	Scenario 1 –No vent.(No Retrofit)	Scenario 2 –No vent.(Retrofit)	Scenario 3 - NV Existing(No Retrofit)	Scenario 4 - NV Existing(Retrofit)	Scenario 5 - NV Louvre(Retrofit)	Scenario 6 –NV New Window(Retrofit)	Scenario 7 - MV(Retrofit)
min	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
q1	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%
median	0.4%	0.4%	0.3%	0.3%	0.2%	0.2%	0.1%
mean	1.8%	2.1%	1.1%	1.2%	0.8%	0.6%	0.3%
q3	1.5%	1.7%	1.0%	1.1%	0.8%	0.5%	0.3%
max	32.9%	32.9%	32.9%	32.9%	32.9%	32.9%	2.2%

3. Results and discussion

3.1. Static risk assessment

3.1.1. Ventilation systems and risk

Table 7 provides summary statistics for the seven ventilation and retrofit scenarios considered. Based on this table it is evident, that all scenarios can reduce the airborne infectious risk substantially in the context of all the measures mentioned. For no ventilation scenarios it is evident that average probabilities of infection are not below 1% (which would be a typical threshold value used in similar fields [57]). It is also likely that there will be limitations in the use of natural ventilation in particular conditions, where additional measures will be required. The use of demand controlled MV system was found to be very effective at supressing the virus under several variable combinations (RI $<$ 1).

Table 8 indicates the potential of secondary infections for different ventilation configurations. This indicates that it is likely that with no ventilation (despite low mean probabilities and RI) the skewness in the distribution (also indicated in Fig. 3) indicates many cases which could be particularly risky and lead to major reproductive events. Table 8 also indicates a higher probability of infection with a fabric upgrade which emphasises the need to ventilate or include secondary measures to reduce infection risk and that this risk is expectedly higher for a more air-tight fabric (even when the existing NV system is considered). Despite all NV scenarios exhibiting the same worst case maximum RI (RI = 8.6) (which indicates a scenario when no wind or buoyancy driven flows are possible), when any ventilation system is employed, this results in a substantial decrease in the average RI number, where all retrofit scenarios with ventilation systems are likely to lead to average RI numbers under 0.5, which should suppress the growth of the virus. The average RI number is reduced by 44%–86% using ventilation systems depending on the ventilation scenario. There are, however, circumstances where the NV ventilation system alone does not lead to a safe internal environment (or the suppression of the virus). Equally, all significant risk cannot be eliminated through single-sided NV alone, even when designed to maximise ventilation rates. Between 3% and 10% of the NV simulations considered led to RI numbers greater than 1 (Scenarios 3 to 6). Fig. 3 illustrates the range of all possible RI values including all other control measures (i.e., masks, air cleaners, variable exposure times and occupancy levels). This points to a considerable reduction in the spread of RI values through increased ventilation. Fig. 4 indicates that if air change rates (ACRs) are achieved in line with recommendations developed by REHVA and ASHRAE (ACR $>$6) (see Table 6) this is likely lead to the suppression or stabilisation of the virus (RI $<$ 1).

Although median values when infiltration only (no ventilation) is considered are low, this is due to the aggregated influence of other control measures, indicating that a safe indoor environment can be maintained with limited ventilation but with more control measures than would be the case for some of the scenarios that adopt ventilation as the only control measure. The intermittency of single-sided NV is a concern for a consistently safe indoor environment. The largest risk of viral growth for this ventilation approach will occur when weak driving forces are present at the opening. Fig. 5 indicates the infection risk for retrofitted single-sided NV strategies (i.e. scenarios 5 & 6 – which represent best case designs for NV) under different weak boundary conditions. The effect of adopting masks is also included. It should be noted that the spread in results indicates the presence of air cleaners, variable exposure times and class sizes also, where the tails in this graph show the extremes (where exposure times and class sizes are largest and air cleaners are not present).

High envelope temperature differences ($\Delta T = 12^{\circ}C$) and high external wind speeds ($v = 3\ ms^{-1}$) were excluded from Fig. 5 given these are lower risk scenarios. Furthermore, combinations of variables where buoyancy and wind were equal were also excluded (i.e.

Table 8
Event specific reproductive numbers (RI) for different ventilation scenarios.

Metric	Scenario 1 -No vent.(No Retrofit)	Scenario 2 –No vent. (Retrofit)	Scenario 3 - NV Existing (No Retrofit)	Scenario 4 - NV Existing (Retrofit)	Scenario 5 – NV Louvre (Retrofit)	Scenario 6 -NV New Window (Retrofit)	Scenario 7 – MV(Retrofit)
min	0.0	0.0	0.0	0.0	0.0	0.0	0.0
q1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
median	0.1	0.1	0.1	0.1	0.1	0.1	0.0
mean	0.6	0.7	0.3	0.4	0.3	0.2	0.1
q3	0.5	0.5	0.3	0.4	0.3	0.2	0.1
max	8.6	8.6	8.6	8.6	8.6	8.6	0.6

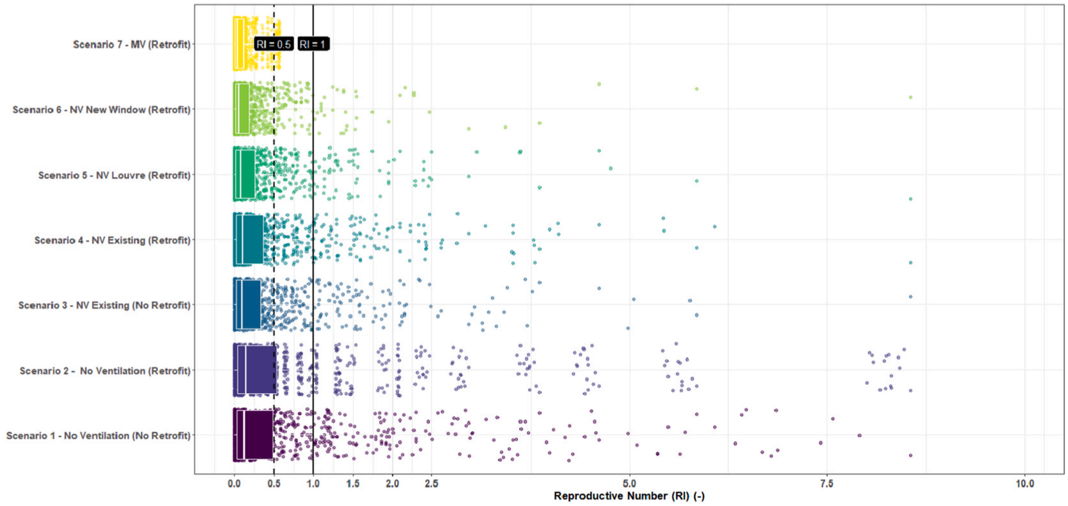

Fig. 3. Boxplots and jitter plots of event specific reproductive numbers for all ventilation scenarios (Vertical lines indicate RI for stability (RI = 1) and suppression (RI = 0.5) scenarios).

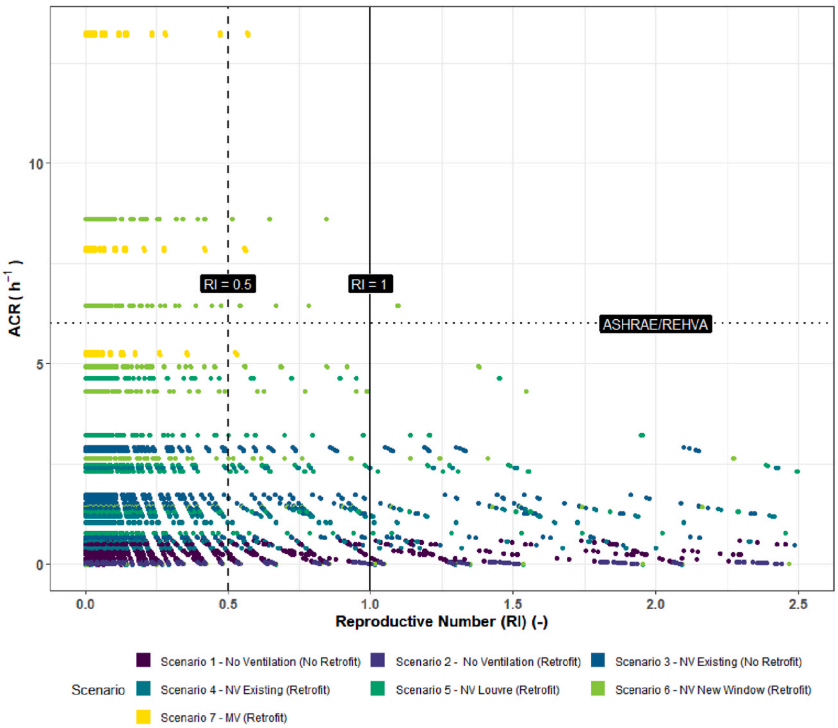

Fig. 4. Scatterplot of air change rate (ACR) and RI (Colour indicates the retrofit and ventilation scenario, lines indicate threshold RI numbers and recommended ACRs for buildings). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

($\Delta T = 0^{\circ}C$) or ($v = 0ms^{-1}$)). For wind-driven ventilation and no mask the average and 90th percentile RI are 0.59 and 1.54 respectively. When a mask is considered with wind driven ventilation this results in an average and 90th percentile RI number of 0.15 and 0.39 respectively. The average and 90th percentile RI number for buoyancy driven ventilation and no mask are 0.53 and 1.38 respectively. When a mask is considered this results in an average and 90th percentile RI number of 0.13 and 0.35 respectively.This highlights that the use of a mask, with a reasonable efficiency, can stabilise or supress this risk substantially under the same external conditions. Alternatively, a supplementary integrated mechanical ventilation system could ensure minimum ventilation rates at the performance limits of the NV strategy. Based on the data in Fig. 5, the combined effect of a newly retrofitted single-sided NV strategy and mask wearing can be observed. The data indicates that when masks are not worn and there are low envelope temperature

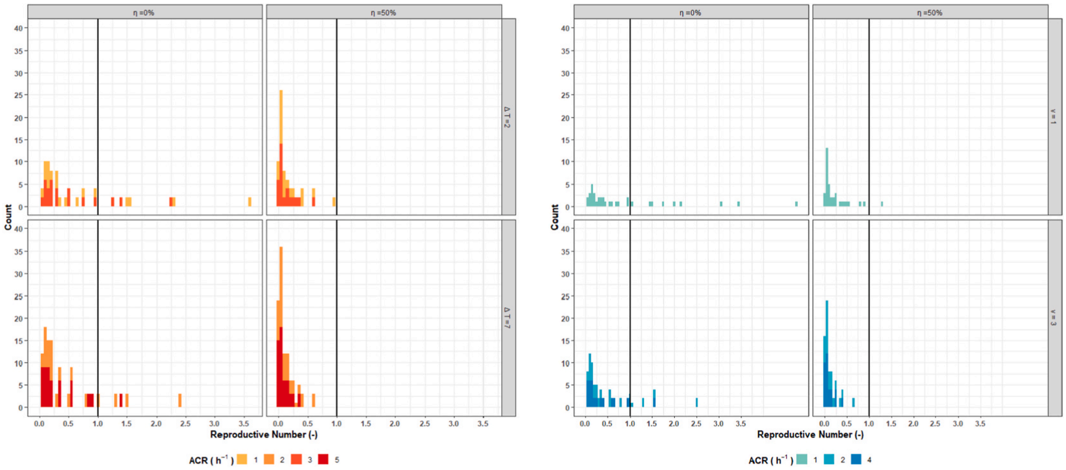

Fig. 5. Histograms of RI with respect to weak boundary conditions when using data from NV scenarios 5 and 6 only. Facets describe the effect of including or excluding masks as part of all strategies shown, which also include variable exposure times, class sizes and air cleaners. (Left: buoyancy driven flow, Right: wind driven flow, Colour indicates ACR rounded to the nearest whole number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

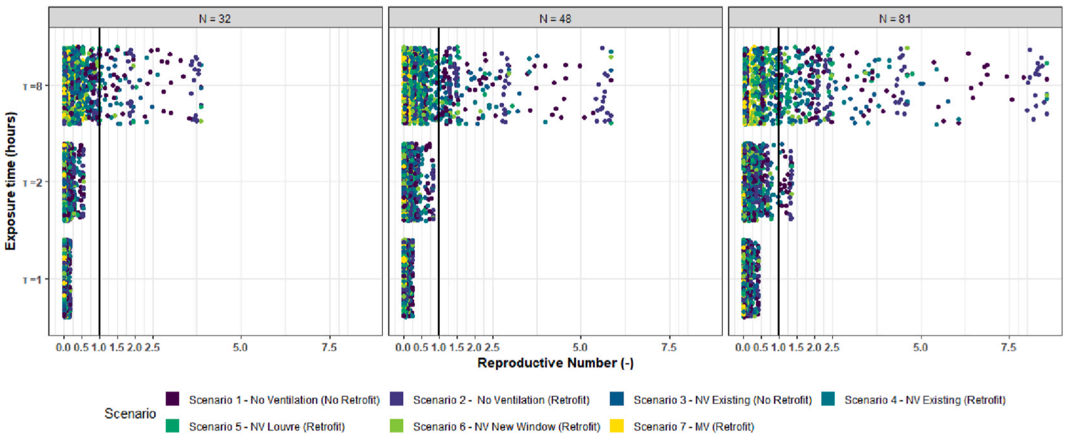

Fig. 6. Jitter plots of RI with respect to exposure time (in hours 1, 2 and 8) and class size (Colour indicates the ventilation scenario, black line indicates RI of 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

differences or low wind speeds, there is a risk of virus growth.

3.1.2. *Effect of time and class size*

When the effect of class duration (or exposure time) and class size are examined (see Fig. 6) several further observations can be made. For long exposure times (i.e. full day training courses or where a room is occupied continuously throughout the day) social distancing measures alone will not be sufficient in mitigating airborne infectious risk without good natural or mechanical ventilation.

Even in the full-day high-occupancy scenarios there are incidences where NV cannot supress the growth of the virus. However, a doubling of exposure time (from 1 h to 2 h) did not result in a change from viral decay to viral growth for 2 out 3 distancing regimes considered. Overall, class size reductions alone were found to reduce RI numbers by a maximum of 55% (from 81 to 32 people), while

Table 9
Summary statistics for all scenarios grouped by class size.

Metric	N = 32	N = 48	N = 81
min	0.0	0.0	0.0
q1	0.0	0.0	0.0
median	0.1	0.1	0.1
mean	0.2	0.3	0.5
q3	0.2	0.3	0.5
max	3.9	5.9	8.6

Table 10
Summary statistics for all scenarios grouped by different exposure times.

Metric	t = 1	t = 2	t = 8
min	0.0	0.0	0.0
q1	0.0	0.0	0.1
median	0.0	0.1	0.4
mean	0.1	0.2	0.8
q3	0.1	0.2	1.0
max	0.4	1.3	8.6

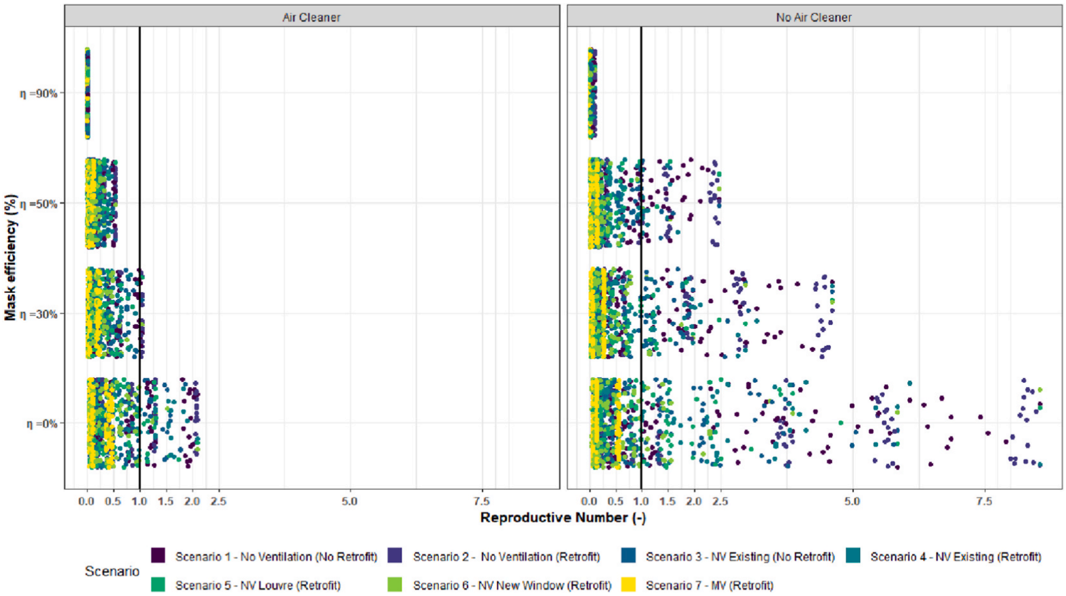

Fig. 7. Jitter plots of RI with respect to mask efficiency (in filtration efficiency terms 0%, 30%, 50%, 90%) and the presence of an air cleaner with a HEPA filter (Colour indicates the ventilation scenario, line indicates RI of 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reducing class exposure times (from 8 h to 1 h) can reduce RI numbers by a maximum of 95% (see Table 9 and Table 10). Although reducing in person classes to 1 h are likely to be prohibitive, the management of these two parameters; reducing class sizes and reducing exposure to less than maximum (one chair spacing) and limiting exposure time in class to less than 8 h are likely to have a great effect on limiting airborne infectious risk.

3.1.3. Effect of mask and HEPA filtration

Fig. 7 indicates the effect mask efficiency and HEPA filtration have on the reproductive number with reference to the ventilation scenarios discussed. Based on this, it is evident that the use of high-grade masks is likely to result in a considerable reduction in the reproductive number, where this single measure alone can result in the suppression of the virus in all scenarios. The use of masks with a 50% and 90% efficiency were found to reduce maximum RI numbers by 71% and 99% respectively for this application (see Table 11).

In addition to this, with much poorer mask filtration efficiencies, (i.e. ill-fitting masks with heavy filter loadings from overuse which would not be uncommon for the general population), the rooms NV systems (Scenario 5 and 6) as well as the MV system can lead to average and median RI numbers less than 1, demonstrating the complimentary importance of the two measures even with newly refurbished low energy spaces (i.e. good ventilation retrofit regimes can compensate for poor mask wearing culture in the buildings future lifecycle and build societal resilience into future pandemics). Fig. 7 also indicates the effect of the use of an adequately sized

Table 11
Summary statistics for all scenarios grouped by mask efficiency.

Metric	η = 0%	η = 30%	η = 50%	η = 90%
min	0.0	0.0	0.0	0.0
q1	0.1	0.1	0.0	0.0
median	0.3	0.1	0.1	0.0
mean	0.8	0.4	0.2	0.0
q3	0.8	0.4	0.2	0.0
max	8.6	4.6	2.5	0.1

Table 12
Summary statistics for all scenarios grouped with and without an air cleaner.

Metric	Air Cleaner	No Air Cleaner
min	0.0	0.0
q1	0.0	0.0
median	0.1	0.1
mean	0.2	0.5
q3	0.2	0.4
max	2.1	8.6

HEPA filtration system or room air cleaner in the context of the ventilation scenarios discussed. Based on this, air cleaners alone are not capable of supressing the transmission of the virus in an airborne sense (i.e. see no ventilation scenarios with 0% mask efficiency).

However, the reduction in RI due to the use of an adequately sized air cleaner with a HEPA filter has a substantial effect on the range of likely RIs. Air cleaners alone (when sized based on existing guidelines) were found to reduce maximum RI numbers by 76% (in a global sense, this would vary location to location within the room, see Table 12). This also indicates that reasonable mask efficiencies and HEPA filtration will lead to virus suppression for the most part. Improved filtration efficiencies through the use of KN95 or higher (under realistic usage and in-use efficiencies [58]) would require lower ventilation rates if the same HEPA filtration system was in place. Equally a higher ventilation rate from adequately sized ventilation systems (NV or MV) and improved mask efficiencies or air cleaning devices are likely to supress the virus also.

3.2. Seasonality dependant risk assessment

3.2.1. Assessment of short-term strategies

Fig. 8 indicates the daily infection risk according to the rounded RI number using suppression (RI $<$ 1), stabilisation (RI $=$ 1), and growth (RI $>$ 1) scenarios to categorise daily risk values, with respect to different locations and retrofitted ventilation scenarios, when a mask with a 50% efficiency is used by both infectors and those who are susceptible. Based on this, it is evident that there is a considerable difference in daily infection risk depending on the ventilation system used and the daily boundary conditions in each location. Seasonally, in winter months the existing NV system is likely to supress or stabilise infection risk in three out of four locations indicated. However, considerable risks exist in the summer and shoulder months in continental and Mediterranean climates for the same NV system (Scenario 4). This is less the case in colder climates; however, the summertime months are likely to be risky in all climates using the existing system (permitted the rooms are occupied for 8 h per day, i.e. summer schools, professional training etc). The use of an airflow guiding component in the opening (Scenario 5) or new window which maximises opening area (Scenario 6) can reduce mean RI numbers by between 39% and 69% depending on the location and the system. The use of these systems leads to a maximum 90th percentile value of 1.02, when all locations are considered.

Between 32% and 76% of the daily RI numbers calculated were greater than 1 for the existing NV system (scenario 4), while the use

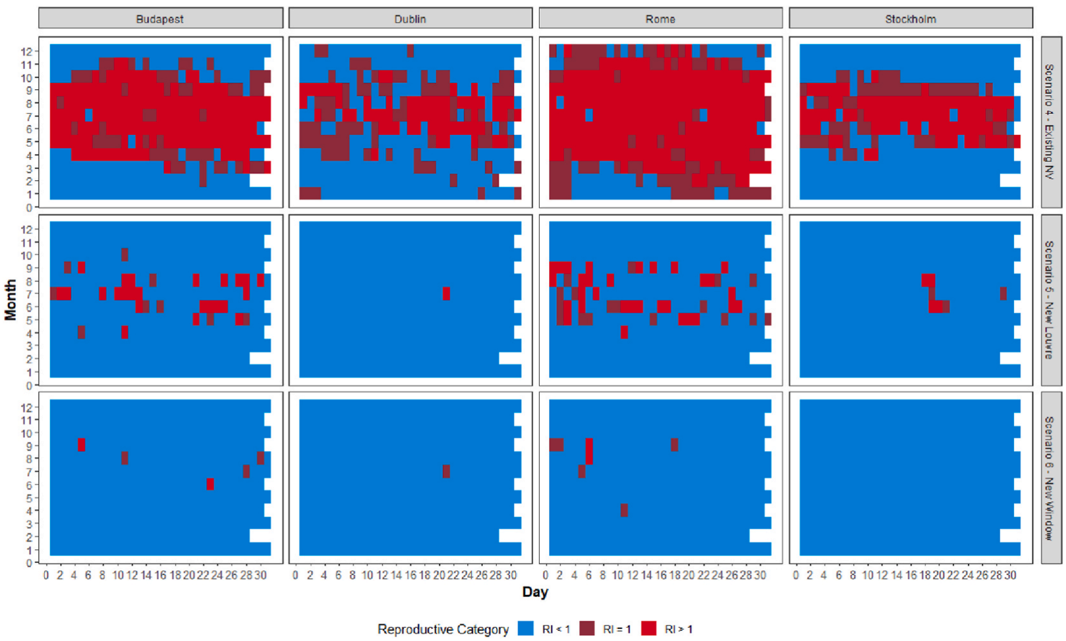

Fig. 8. Daily infection risk for four different European cities and different NV scenarios (i.e. 4, 5 & 6) (Colour indicates reproductive category (suppression (blue), stabilisation (maroon), and growth (red)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of a purpose provided louvre design led to between 0.3% and 11.0% of daily RI numbers greater than 1, and a new maximum opening window design (scenario 6) leading to between 0% and 1.1% of daily RI numbers greater than 1. This demonstrates that it is likely that existing ventilation systems may need to be upgraded in the future to ensure year-round suppression or stabilisation of virus reproduction, even when a virus is known to be in circulation and masks are adopted as a control measure to reduce spread. For warmer climates, this could mean that other flow regimes or principles (cross ventilation, stack ventilation) may be required. For milder and colder climates single-sided NV could be sufficient (if masks are adopted). Comparing this dynamic approach to the static approach in the previous section illustrates that for NV systems it is critical that a wide distribution of boundary conditions (representative of the location where the building being designed is located) is needed to evaluate NV systems as this can reveal potential deficiencies in the NV system design. Although the use of masks is likely when a virus is known to be in circulation, if an unknown virus is in circulation, it could be the case that occupants will not be wearing masks. When a "no masks" scenario was simulated under the same conditions with the scenario 6 ventilation system (the best single-sided NV system considered) between 53% and 96% of daily RI numbers were greater than 1 (depending on the location). Considering this it is likely that additional structural changes may be required in future retrofits for all locations this may lead to a need for reductions in occupant density or the provision of supplementary mechanical ventilation.

3.2.2. *Assessment of medium to long-term strategies (vulnerability)*

Considering the above seasonal evaluation, it is evident that single-sided NV is likely to be unable to keep RI numbers to less than 1 (if no masks are worn). To assess the additional structural measures highlighted above, the case study building was simulated in Dublin with the best-case single sided NV scenario (Scenario 6). In this regard, the effect of occupancy density and the provision of hybrid ventilation were evaluated. Fig. 9 indicates the resulting daily occupancy density necessary to retain RI numbers at 1.0 and 0.5, (i.e. occupancy levels are adjusted to accommodate the maximum available NV ACR).

Based on Fig. 9 it is evident that if existing densities (~1.0 m^2/p, which is similar to other buildings for a similar application [59]) are increased to values greater than 3.5m^2/p it is likely that the single-sided NV system (Scenario 6) will be able to supress the growth of COVID-19 in Dublin. Doubling the allowable floor area per occupant could generally stabilise infection risk, however, this clearly has practical limitations. Additionally, concern should be taken as occupancy density management may be limited in heat wave conditions where daily external temperatures are likely to exceed indoor comfort thresholds (and lead to poor conditions for NV performance). For the university lecture room described above, it is likely that, with no masks and the baseline maximum (Baseline) occupancy density, an ACR of 7.3 h^{-1} (>1605 m^3/h) and 15.3 h^{-1} (>3383 m^3/h) (see Scenario 7 in Fig. 4 above) will be required to keep RI levels are 1 and 0.5 respectively. Despite the new maximum opening window design (Scenario 6) being capable of delivering on average 6.2 h^{-1} and being the best solution in this regard (see Fig. 10) the variability in outside conditions leads to a wide distribution in air change rates for this scenario. The range of ACRs that were simulated using this system were between 1.2 h^{-1} and 11.5 h^{-1} which highlights this variability.

A supplementary MV system is one approach to address the variability with adopting NV strategies alone. Fig. 11 indicates the daily relative contribution from MV and NV to maintain the daily RI at stable levels. Based on this, the MV system would be required to supply 16% of the daily ventilation rate on average to maintain RI at 1.0 and 59% of the daily ventilation rate on average to maintain RI to 0.5, where on individual days MV may not be needed or may be required to deliver 90% of the daily ventilation rate. It is likely that, for the room evaluated here, that an ACR of 1.2 h^{-1} on average (min = 0 h^{-1}, max = 6.0 h^{-1}) would be required from the supplementary MV system to keep RI to 1.0, however, an additional 9 h^{-1} on average (min = 3.8 h^{-1}, max = 14.1 h^{-1}) would be required from a supplementary MV system to keep RI to 0.5. It is therefore important that variable or demand-based hybrid ventilation be prioritised in future retrofits to take advantage of the energy and comfort potential of NV while also allowing for a consistent delivery of air in the space to reduce to risk of infection.

4. General discussion, limitations and future work

This study demonstrates the importance of ventilation and infiltration in relation to other control measures such as personal filtration (through masks or HEPA filters), exposure times and class sizes for lecture room environments. The importance of ventilation and airborne infectious risk has previously been stressed for many settings [3,23]. The results shown indicate that combinations of measures are required to ensure a stabilisation or suppression scenario when it comes to the reproduction of the virus at lecture or classroom level and considerations for retrofitted ventilation systems should be made where limitations apply (i.e. high numbers of occupants, no ventilation system, extended class times – many conditions present in older universities and secondary schools suffering from capacity issues). This finding is also supported by other studies indicating that more than one control measure is required or recommended to mitigate long range airborne risks [5,6,11,18,22,23,57,60–65]. Regarding the use of NV as a mitigation measure, this work indicates that on average NV and MV systems can result in similar virus risks in a static sense (when evaluated in combination with other control measures), however, the uncontrolled intermittency of NV system performance leads to issues under certain boundary conditions (low wind speeds and envelope temperature differences) particularly when no masks are worn. It should be noted that low envelope temperature differences will often occur at times of the year where occupancy levels are lowest in university settings (i.e. summertime). In addition to this, there is a climate variability in boundary conditions that are likely to require additional ventilation rates for warmer climates. Previous work has highlighted that NV purging can be adequate for school or educational settings [65–67] and can reduce the airborne risk by 50% [65]. It is also worth noting that some have advocated for the use of hybrid or mixed mode ventilation systems which combine the benefits of NV and MV systems combined to deliver reliable and demand driven ventilation rates [6,17]. Our work indicates that, in a setting where single sided NV is typically applied (i.e. education facilities), hybrid ventilation solutions may be the most reliable solution to deliver the best year-round performance from an infectious risk perspective,

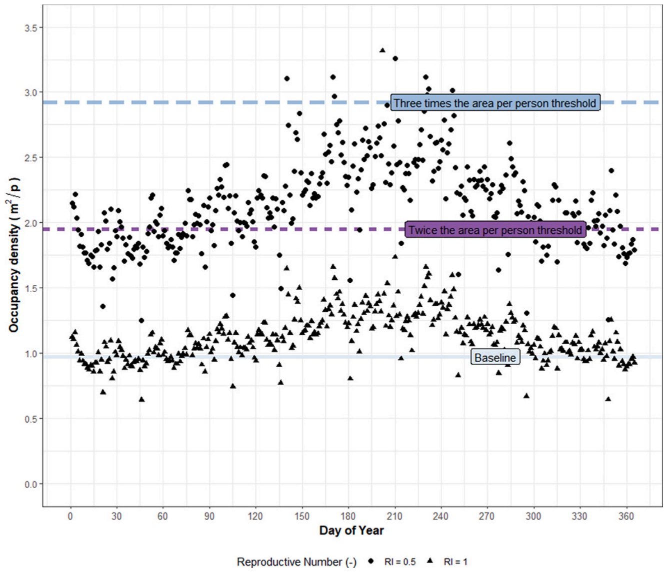

Fig. 9. Time series of daily occupant density (in m^2/ p) necessary to maintain an RI of 1.0 and 0.5 respectively using a single sided NV system (Scenario 6) when using this system in Dublin. (Lines indicate the Baseline occupancy density (i.e. 81 people) as well as reference lines for doubling and tripling the area per person, one outlier was removed for the RI = 0.5 dataset which was for one day in the summer).

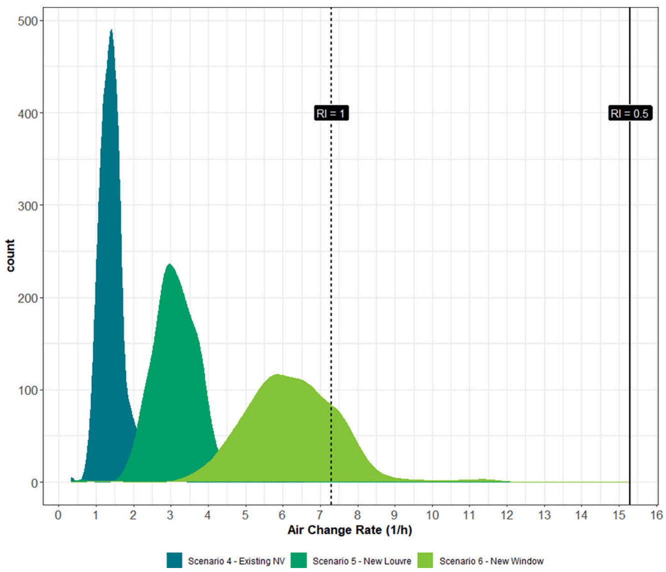

Fig. 10. Density plot of air change rates for scenarios 4, 5 and 6 using Dublin climate data for scenario 6. (Fill indicates scenario, vertical lines indicate ACR requirements in the room studied to allow for RI values of 1 and 0.5 respectively).

particularly under suppression scenarios. The mask filtration efficiencies presented indicate that as a single preventative measure, mask wearing can be very effective and their use is supported largely in the literature [5,22,57]. However, it should be noted that good practise in mask wearing is required as some research has indicated that ill-fitting masks can have up to 50% greater leakage rates [61], there are also clear differences in mask efficacy depending on the material choices [68]. In addition to individual mask filtration, the use of filtration in general at room level or in dedicated ventilation systems can be very effective and could reduce the need for increased ventilation rates [60,62], however, this study shows that a properly designed and operated retrofit solution can minimise the need for reactive strategies such as localised air cleaners.

The application of the findings presented here are limited to the scope of the study and should be interpreted in their context. However,some of the results considered could be applied to other environments with largely sedentary occupants. The consideration for one NV flow regime (i.e., single-sided) presents the worst case (though the most ubiquitous approach) for NV in education environments. Other solutions such as cross-ventilation or stack ventilation are likely to provide much higher ventilation rates [67] and a

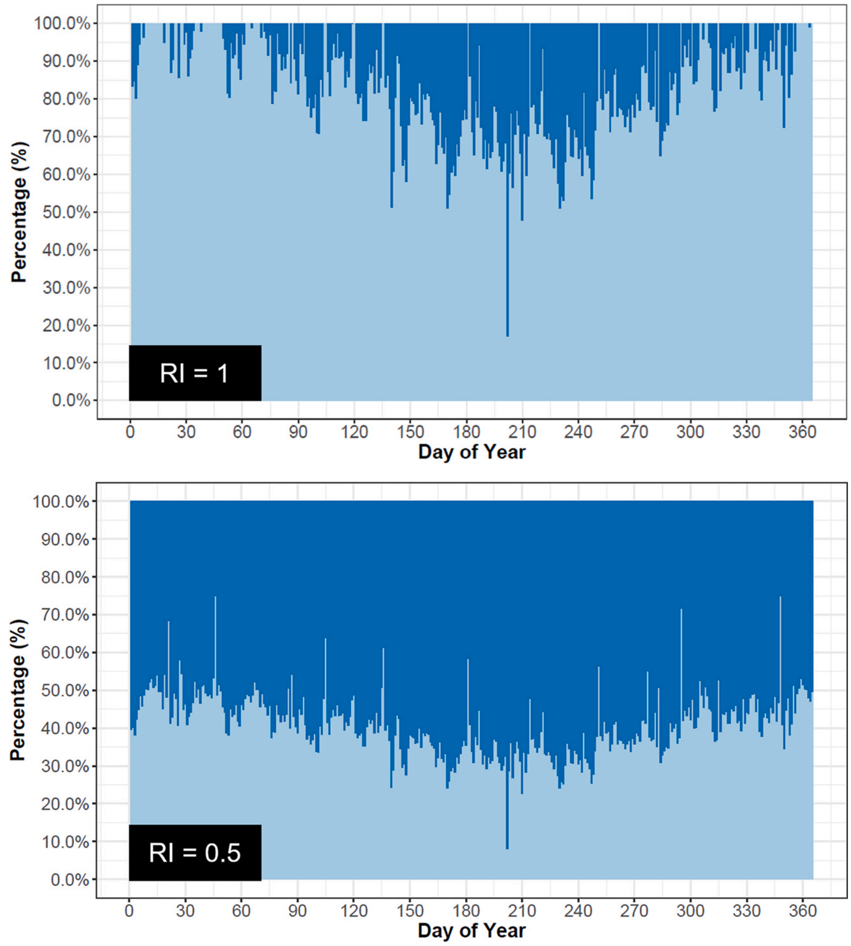

Fig. 11. Percentage of time with respect to the day of year when NV systems (in light blue) or MV systems (in dark blue) can maintain RI at 1 (top graph) and RI at 0.5 (bottom graph) respectively, when conditions for a typical meteorological year in Dublin are used and when the NV system used is a new window system (i.e. Scenario 6). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reduction in opening ratios [57,69]. NV systems will have reduced operation with low external temperatures, and while large temperature differences will drive higher ACRs, the draft risk may limit the operation of typical windows (but may not affect louvre operation with the same external conditions due to reductions in turbulence intensity) [42]. O' Donovan et al. considered this by using a low limit of 10 °C to correspond with lower limits in adaptive comfort standards [47,70]. The purpose of this framework was to demonstrate the potential risks and so an external low limit was not considered. However, more work is needed in demonstrating solutions which examine draft risk with NV or MV systems in cold conditions. It should also be noted that unless internal conditions are maintained within set-points, that the potential for NV to be utilised may be limited. This study did not consider the energy consequences (for heating or cooling) of airflows into the indoor space. There are as such potentially significant energy implications for such decisions depending on the retrofit strategy adopted. In addition to this, in this study we did not consider the effects of other indoor environmental parameters (such as temperature and humidity) and the energy consequences of such decisions which was completed by [71]. It is evident from the literature that in addition to their being a higher risk when it comes to a larger number of potential infectors (and susceptible people) that under a maximum occupancy scenario there could also be additional risks for particles of larger sizes. Consideration as to the variation in quanta emission rates for the teacher speaking were not considered also, there are also considerations as to virus variants which were not considered. However, while most static approaches consider one infector, it is more likely that one infector is present in the student population within the classroom environment given the overwhelming sample of students to teacher ratio. There are also likely to be differences amongst age cohorts in terms of age specific incidence that can be time dependent. Finally, it is also evident that future weather will likely lead to a reduction in NV potential [72] across many climates, which will have a knock on effect on virus risk. This has not been considered in this case.

5. Conclusion and recommendations

The following paper presented a demonstration or application of a three-stage infectious risk assessment modelling methodology for use at the design stage when considering different ventilation systems and other infection control measures. The approach adopted highlights the benefits of adopting tools which allow for rapid decision making at the early design stage, especially given "vulnerability lock-in" can be an unintended consequence at this stage of the building process [73]. Based on the results of the evaluation presented for lecture room environments, multiple measures are required in ensuring a safe lecture room environment in educational buildings retrofitted to low or very low energy performance standards. The reduction in infiltration rates with envelope refurbishment leads to a more pronounced need for effective ventilation systems. Based on the findings of the study the following conclusions can be drawn:

1) Many existing infectious risk methods utilise arbitrary ventilation rates when assessing the probability of infection in indoor spaces without evaluating whether the arbitrarily chosen ventilation rate is achievable for natural ventilation applications. The early design stage methodology presented here integrated natural ventilation capacity sizing with evaluating the probability of long-range airborne infection in indoor spaces. The method is easily instantiated using universally available engineering design tools such as Excel, R, Python and so on, and was shown to be versatile and insightful when comparing multiple ventilation retrofit scenarios. It can assist building design practitioners when incorporating infectious risk checks to their existing ventilation design scope.
2) Natural ventilation is often seen as the preferred energy conservation strategy to ventilate lecturing spaces when cooling needs are low. However, results from this study show that, based on many design permutations, while natural ventilation can suppress viral growth under certain conditions, it cannot provide consistent protection against airborne transmission of respiratory viruses such as SARS-CoV-2. As indicated previously, poorly performing NV systems could lead to higher infectious risk (32%–76% of daily RI numbers greater than 1), however, when designed correctly, this underperformance can be limited (0%–11% of daily RI numbers greater than 1, depending on the location and system). Complimentary measures such as protective masks, further extend its suppression capacity, though the intermittency in the supply of clean air to the indoor space needs to be carefully considered in future building designs. This means natural ventilation designers need to extend their performance criteria to include infectious risk and make choices regarding system redundancy to improve the health resilience of the indoor environment, for example, the inclusion of NV-MV hybrid or mixed-mode systems to build in adaptive capacity in the event of a viral outbreak.
3) There are many complimentary measures that can be adopted when retrofitting existing lecture rooms with new external envelopes. The selection of different natural ventilation openings leads to different outcomes for infectious risk. While retrofit designs are often constrained by the existing structure and architectural layouts, resulting in non-invasive easily applied solutions such as single sided ventilation being adopted, this study demonstrated that significant improvements in further mitigating long range airborne transmission are achievable by designing ventilation openings based on the probability of infection as a design criterion and selecting components that enhance the airflow rate into the space (either passive or hybrid passive-active approaches). Evidence based assessments of the potential of a natural ventilation strategy can lead to a reduction in the size and infrastructure of supplementary backup systems.

Author statement

Adam O′ Donovan: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing - Original Draft, Visualization, Project administration, Funding acquisition, **Paul D. O' Sullivan:** Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

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

No data was used for the research described in the article.

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