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# Assessment Of The Covid-19 Contagion Risk In University Classrooms With TRNSYS And TRNFLOW Simulations

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## ABSTRACT

*The ongoing covid-19 pandemic has drawn the attention on the importance of providing adequate fresh air to the occupants of the built environment, in particular in educational buildings. Higher ventilation rates and personal protection devices like facial masks are among the strategies and procedures to reduce the infection risk, allowing the fruition of school spaces despite the epidemic progression. Nevertheless, the problem of airborne transmission has been usually dealt with considering each environment alone and assuming steady state conditions. Indeed, the contagion risk among adjacent environments, under dynamic occupancy or with variable ventilation rates has not been discussed in detail.*

*In order to investigate those aspects, this research focused on a floor with three adjacent classrooms at the campus of the Free University of Bozen-Bolzano, Italy (UNIBZ). The case-study is part of a modern high performance building, served by a mechanical ventilation system and equipped with building automation solutions. Furthermore, two out of three classrooms are part of the UNIBZ Living Labs, where a network of sensors is deployed for the constant monitoring of the indoor environmental conditions.*

*A TRNSYS and TRNFLOW air flow network model was developed, calibrated and validated against the experimental data collected in the UNIBZ Living Labs. Then, a series of transient scenarios were simulated by varying the probability of windows' opening, mask utilization and ventilation typology. For each scenario and each room, the infection risk was assessed according to the Airborne Infection Risk Calculator tool (AIRC).*

*High risks of infection were found related to poor ventilation, as it can be the case during lectures if windows and doors are kept closed and the mechanical ventilation system is not operating. When open doors are simulated, pathogen propagation in adjacent environments was observed, even if with a lower associated risk if compared to the room where the pathogen source is located.*

## INTRODUCTION

Although the SARS-CoV-2 virus outbreak occurred only in late 2019, some references in the literature are already available assessing the contagion risk for airborne transmission, and evaluating the maximum exposition time given a threshold of risk acceptability and the number of occupants (or vice versa). An example of such works is given by Buonanno *et al.* (2020), who focused on the risk assessment in micro-environments, such as small classrooms and offices. Tools such as the "*Airborne Infection Risk Calculator*" (*AIRC*) based on Buonanno *et al.* (2020) are now available for the assessment of the contagion risk for a susceptible subject located in an environment where at least one infected

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subject is (or was) present.

Even if these tools and models from the literature are particularly useful to quantify the threat posed by the SARS-CoV-2, they show also some limitations. First, they generally focus on a single room, preventing the possibility to assess the contagion risk also in environments adjacent to the room where the infected subject is located or connected to it by means of a mechanical ventilation system or through openings. Then, approaches like the one implemented in the *AIRC* tool require to specify the number of infected subjects and the related emission of quanta; in that respect, more detailed findings can be expected adopting a probabilistic approach by accounting for the probability for an infectious person to be present in a room also in consideration of occupancy times and schedules.

Considering all the above, the aim of the work is to evaluate the individual contagion risk depending on a series of different probabilities, such as the probability of having asymptomatic subjects or the probability for an infected subject of emitting a given quanta rate. A dynamic approach for the evaluation of the dose received from the susceptible subjects has been adopted by means of multi-zone building performance simulation, leading to the possibility to investigate the contamination also in adjacent spaces. Furthermore, the efficacy of strategies aimed to lower the contagious risk (as for example the utilization of masks or the adoption of natural ventilation) have been addressed by the analysis of different scenarios starting from a set of adjacent classroom at the Free University of Bozen-Bolzano adopted as study-case.

## CASE STUDY

The case-study consists of three classrooms (namely E5.20, E5.21, E5.22) in the last floor of the main building of the Free University of Bozen-Bolzano, Italy, located in the city center and surrounded by buildings almost as much as tall. The three classrooms are adjacent (with classroom E5.21 being the one in the middle) and connected to the hallway by the same kind of door with an opening area of 1.98 $m^2$. The classrooms are equal in size, with a total volume of about 200 $m^3$ each. Classrooms E5.21 and E5.22 are part of the Living Labs of the Free University of Bozen-Bolzano and equipped with air temperature, humidity and $CO_2$ sensors for the characterization of the indoor environmental conditions. The installed instrumental setup is completed with a weather station located on the roof of the building, collecting data about ambient air temperature and humidity, as well as global horizontal solar irradiance. Further pieces of information about the Living Labs and room E5.21 can be found in (Pernigotto and Gasparella, 2021).

Regarding the hallway, it has a total volume of 700 $m^3$ with no external openings and it is connected to four additional classrooms, two offices, a computer science lab and the restrooms.

Each room has two equal windows for a total area of 12 $m^2$. Each window in E5.20 includes two portions, one entirely openable (turn window) about 1.2 $m^2$ wide, and the second one openable as a tilt window. Windows in classrooms E5.21 and E5.22 are divided into 3 portions each, with a fixed one and a smaller tilt window (Figure 1) instead of the single tilt part, and the same turn openable portion as in E5.20. Despite the alternatives provided by the installed windows, the occupants usually interact only with the portion which is entirely openable.

The classrooms are conditioned primarily by means of mechanical ventilation, with a fresh air supply of 0.07 $m^3/s$. The fresh air supply is provided only during occupancy hours. Regular lectures are usually scheduled from Monday to Friday, in the morning between 8 am to 12 pm and in the afternoon from 2 pm to 6 pm.

## MODEL DEVELOPMENT

In order to quantitatively assess the individual infection risk of susceptible subjects to SARS-CoV-2 airborne transmission pathway of contagion, a Monte Carlo *MC* model has been developed in MATLAB® environment and coupled with a building simulation model of the case-study developed with TRNSYS 18.

As a whole, 12 different scenarios have been developed (Table 1). For each scenario, a total of 1000 iterations of the *MC* model were required. During each iteration, several simulations (whose number depends on the stopping criteria) are performed by means of TRNSYS, each one representing a day (24 h from 0 am). A total computational time of 6-8 hours was required for each scenario. At the end of each *MC* iteration, the number of infected subjects was calculated for each classroom and globally, as well as the number of days elapsed from the start of the first simulation (day I).

Finally, for each scenario, the probability distribution function of infections after a certain number of days has been determined and the final number of infected people divided by the total number of the occupants to assess the individual risk of contagion (or "attack rate").

## Building simulation model

The case-study building model has been developed starting from an existing EnergyPlus model of classroom E5.21, previously calibrated with a multi-stage approach and validated with measured data provided by indoor air temperature and $CO_2$ concentration sensors (Pernigotto and Gasparella, 2021). The single room model has been replicated with TRNSYS and extended by considering also classrooms E5.20 and E5.22, and the adjacent hallway. Given that the initial source of Covid quanta is located in classroom E5.21, as well as the large volume of the hallway compared to the three classrooms, only the adjacent classrooms to E5.21 have been considered for the simulations, since the results are representative for any other room which is connected to the same hallway

After preparing the TRNSYS multi-zone model, an Airflow Network *AFN* has been added for the detailed simulation of air flow exchanges by means of TRNFLOW. A single external node has been modelled with standard pressure coefficients for a shielded building according to the TRNFLOW Manual. Infiltration rates for closed windows have been modelled by means of the TRNFLOW *crack* component while internal airflows through the doors or external airflows in case of open windows have been evaluated by means of the TRNFLOW *large opening* component. Finally, the mechanical ventilation system has been modelled through the TRNFLOW *test data* component, which has allowed the definition of a scheduled constant fresh air supply and exhausted air removal, taking also in consideration the ventilation efficacy. The *crack* air mass flow coefficient $C_s$, the partial opening fraction of doors and the ventilation efficacy have been calibrated by means of the same indoor measurements and weather data utilized for the calibration process of the single room model (Pernigotto and Gasparella, 2021). After the calibration, a *crack* $C_s$ of 8e$^{-5}$ kg s$^{-1}$ m$^{-1}$ at 1 Pa, a value of 0.45 associated to the partial opening fraction for the large opening of the doors, and a ventilation efficacy of 59 % have been selected.

With the calibrated model, air flows and quanta concentrations have been simulated for each room every 5 minutes for each scenario. Finally, these data have been used by the *MC* model as inputs to assess the pathogenic dose received by students and professors and to calculate the associated probability of infection.

**Figure 1** On the left: two set of classroom E521 windows; on the right: focus on one of the two set, with the turn window opened.

## Occupancy scenarios

Some hypotheses have been made regarding the number of students, professors, and related occupancy schedule.

The number of students for each classroom has been fixed to 25 in all scenarios, assuming that students do not move from classroom to classroom during the day or the week, consistently with the current health safety policies. As mentioned before, lectures are held all weekdays from 8 am to 12 pm, and from 2 pm to 6 pm. For sake of simplicity, students have been assumed to stay in the classrooms during lectures and leave the floor during the break time from 12 pm to 2 pm.

Considering the typical university semester courses in Italy, a maximum of 5 different professors have been assumed to be present in a given classroom during a week, for a total of 8 h of lectures per week per professor, determined according to a random schedule at the start of each iteration and, so, equal for all its simulations.

The doors have been assumed to stay closed during occupancy hours and during nighttime, with opening scheduled only during the break time from 12 pm to 2 pm and for one hour after the end of the lectures in the afternoon. In the base case, windows have been simulated as kept always closed and scheduled openings have been included only in those scenarios in which natural ventilation is present, distinguishing between a winter schedule (windows are opened with an opening fraction equal to 70 % of the total area for 15 minutes after the start of the lectures in the morning and in the afternoon, as well as during the break time) and a summer one (windows are kept completely open from 8 am to 6 pm).

## Monte Carlo analysis

The building model specified above has been coupled with a MATLAB model to run the iterations, to modify TRNSYS input files and to launch the simulations, and finally to read and elaborate the simulations' results. For each of the 1000 iterations of each scenario, the same initial condition is assumed: an asymptomatic infected student (*subject 0*) during its contagious period is present in the central classroom (E5.21). For sake of simplicity, the first simulation of each iteration is associated with the first day of the week, i.e., Monday.

Before starting the first simulation of each iteration, a random value of quanta emission rate is associated to *subject 0* from a probability distribution whose parameters depend on the subject activity. The initial concentration of quanta is then set equal to zero in all the internal environments. After the simulation starts, the *subject 0* emits the selected fixed amount of quanta during occupancy hours. At the end of the simulation (which represents a day 0 am – 12 am), the data regarding quanta concentrations for each room evaluated by the building model is read by the *MC* model.

At this stage, the *MC* model evaluates the doses received by students and professors who held lectures during the simulated day as in Equation 1 (Buonanno *et al.* 2020):

$$D_q = IR \sum_t n(t) \qquad (1)$$

where *IR* is the inhalation rate, equal to 0.49 m$^3$/h for students and 0.54 m$^3$/h for professors, and *n(t)* the quanta concentration at each time-step *t*.

After the dose evaluation, the infection probability is assessed for each subject at risk, i.e., those subjects who are not infected or were not previously infected (Buonanno *et al.* 2020).

$$P_i(\%) = 1 - e^{-D_q} \qquad (2)$$

A uniform distribution is adopted to associate a value between 0 and 100 to each subject at risk (i.e., the students and professors that have not been infected during a given iteration yet), and, if the chosen random value is less than the risk, then the subject is considered to be infected. For each new infected subject, the following factors are established: (a) quanta emission rate, (b) day of symptoms onset, (c) if the subject is asymptomatic or not, and (d) contagious period.

At the end of each simulation (and so, at the end of each simulated day), it is checked if a symptomatic infected subject reaches the synthoms onset day. It is supposed that all the classrooms will close the day after the onset of symptoms of a symptomatic subject, with the subsequent ending of the iteration. If no subjected reaches the onset day, then the *MC* model proceeds again with the initialization of the values of initial concentrations and total quanta emission rate, required to start the simulation of the next day.

If the next day of simulation is not Saturday or Sunday, the quanta concentration in each classroom at the last time step of the previous simulated day is used as initial concentration for the current one. The new total emission rate is evaluated by summing those of all the infected subjects for whom the current day is inside the contagious period. If the next day is Saturday or Sunday, the initial quanta concentration is set equal to zero.

The whole process is repeated until one of the two stop criteria is met: (1) a symptomatic subject reaches the onset of symptoms (assuming all the people who came in contact are then quarantined) or (2) the contagious period of the last asymptomatic subject ends (meaning no further infection is possible).

The quanta emission rates have been assumed as constant for all the occupancy hours inside the contagious period and their values have been determined by means of a lognormal distribution, whose parameters, i.e., mean and standard deviation of logarithmic values, depend on the subject's activity (Buonanno *et al.* 2020). In this research, two different activities have been considered: (a) a resting-breathing activity for students, with a mean of -0.43 and standard deviation of 0.72, and (b) a higher activity for professors, with a mean of 1.08 and the same standard deviation of 0.72. The onset day has been calculated with a gamma distribution with a shape value of 5.807 and a scale value of 0.948 (Lauer *et al.* 2020).

The contagious period of an infected subject depends on the onset: regardless an infected subject being asymptomatic or not, the starting day of the contagious period is selected according to a gamma distribution (shape 97.188, rate 3.719, shift 25.625) with respect to the onset day (He *et al.* 2020). In this way, also symptomatic subjects can contribute to the spread of the contagion during an iteration. The gamma distribution provides also the number of days in which a subject is contagious before the onset day, with a maximum of 5 days. The starting day of the contagious period cannot be under any circumstances in the first two days following the infection. The ending day of the contagious period is needed only for asymptomatic subjects and is always equal to 9 days after the onset. Finally, a new infected subject is considered asymptomatic with a probability given by a gaussian distribution with mean 33 and standard deviation 12.5. The choice to utilize a gaussian distribution for the probability of being asymptomatic has been made starting from the proportion of asymptomatic (33.3 % with a 95 % confidence interval: 8.3 – 58.3 %) related to Japanese citizens evacuated from Wuhan (Nishiura *et al.* 2020). The asymptomatic subjects are still considered infected after the contagious period and for this reason they cannot be reinfected during the iteration and, so, to emit quanta again after the contagious period. In the total count of infected subjects at the end of each iteration both symptomatic and asymptomatic subjects are included.

## Simulation Plan

A total of 12 scenarios have been evaluated with the *MC* model (Table 1). The factors that have been accounted for are the ventilation type (i.e., (a) mechanical ventilation, (b) natural ventilation, (c) both, or (d) none) and the utilization of mask by all the subjects. Scenario n.1 has been designed as the worst-case scenario by removing both mechanical and natural ventilation, and by not taking into consideration mask utilization. Infiltrations are still present due to the crack of the windows and due to the door in the classrooms. During break time, the doors are still open, allowing the concentration of the classroom to be diluted by the air of the hallway. Since the hallway has a volume of 700 m$^3$, the concentration of quanta is expected to be low enough to significantly reduce the probability of infection in the classrooms after the air exchange during break time. In scenario n.2, mask utilization has been accounted for by reducing the probability of being infected by 33 % (AIRC User's Manual). In scenarios n.3 and n.4 mechanical ventilation has been added to the infiltrations due to the cracks in the windows. The ventilation system is active during occupancy hours and off otherwise. In scenarios n. 5-6-9-10 the mechanical ventilation system is off, and the ventilation requirements are satisfied by opening the windows with two different schedules: winter schedule (*VN_win*) and a summer schedule (*VN_sum*). It has been observed that during winter the windows are opened few times during the day, and often not completely. For this reason, the choice to set an opening fraction equal to 70 % of the total openable area has been made, with opening schedule as previously defined (15 minutes after the start of the lectures both in the morning and in the afternoon, and during break hours). During summer, the opening fraction has been considered equal to 1, and the window are supposed to be open the whole day during the weekdays (8 am – 6 pm) and closed during the night and at the weekends. Finally, scenarios n.7-8-11-12 are respectively equivalent to scenarios n. 5-6-9-10 with the addition of mechanical ventilation. For each scenario results have been plotted as histograms counting the *MC* iterations for which a given number of infected is observed at the end of the 1000th *MC* iterations (Figure 2). Furthermore, the attack rate values in the three classroom and for classroom E5.21 have been plotted for each scenario in Figure 3.

**Table 1 Scenario overview. The ventilation types are referred as: mechanical ventilation (VM), natural ventilation with winter schedule (VN_win) and natural ventilation with summer schedule (VN_sum).**

| Scenario | ***ventilation type*** | ***mask utilization*** |
|---|---|---|
| ***1*** | - | - |
| ***2*** | - | yes |
| ***3*** | VM | - |
| ***4*** | VM | yes |
| ***5*** | VN_win | - |
| ***6*** | VN_ win | yes |
| ***7*** | VM & VN_ win | - |
| ***8*** | VM & VN_ win | yes |
| ***9*** | VN_sum | - |
| ***10*** | VN_sum | yes |
| ***11*** | VM & VN_sum | - |
| ***12*** | VM & VN_sum | yes |

## RESULTS AND DISCUSSION

Mask utilization may have a strong impact on simulation results in those cases where high concentration of quanta is present in the classrooms. From Figure 3, by observing scenarios n.1 and n.2 (which differs only by mask utilization) it is possible to notice that the utilization of masks by all the subjects enable a reduction of the attack rate spread with respect to the median value. For this reason, mask utilization may be fundamental to drastically reduce the possibility of unacceptable outcomes in those cases where high quanta concentration may occur (as, for example, an attack rate of 20 % for classroom E5.21 for the present study-case). The same effects of mask utilization can be observed in scenarios n.3 and 4 and again in scenarios n.5 and 6.

Starting from scenario n.7, it is possible to notice how the effects of mask utilization on the attack rate start to lower until there is almost no difference with those scenarios where natural ventilation with the summer schedule is adopted. This can be due to the reduction of the infection risk probability that is determined as a fraction of the total probability, which is applied to an already low value caused by the high air change rate given by the natural ventilation. Mechanical ventilation helps with the reduction of the total number of infected people at the and of the *MC* iterations (Figure 2: difference in scenario n.1-3) but, by itself, is not enough to lower significantly the attack rate (Figure 3: scenarios n.1-3). If combined with mask utilization, on the other hand, it may help also to decrease the attack rate mean value (Figure 3, scenario n.4).

For what regards natural ventilation, it possible to notice that the winter schedule has almost the same effects in terms of final number of infected people and individual contagion risk as for the mechanical ventilation.

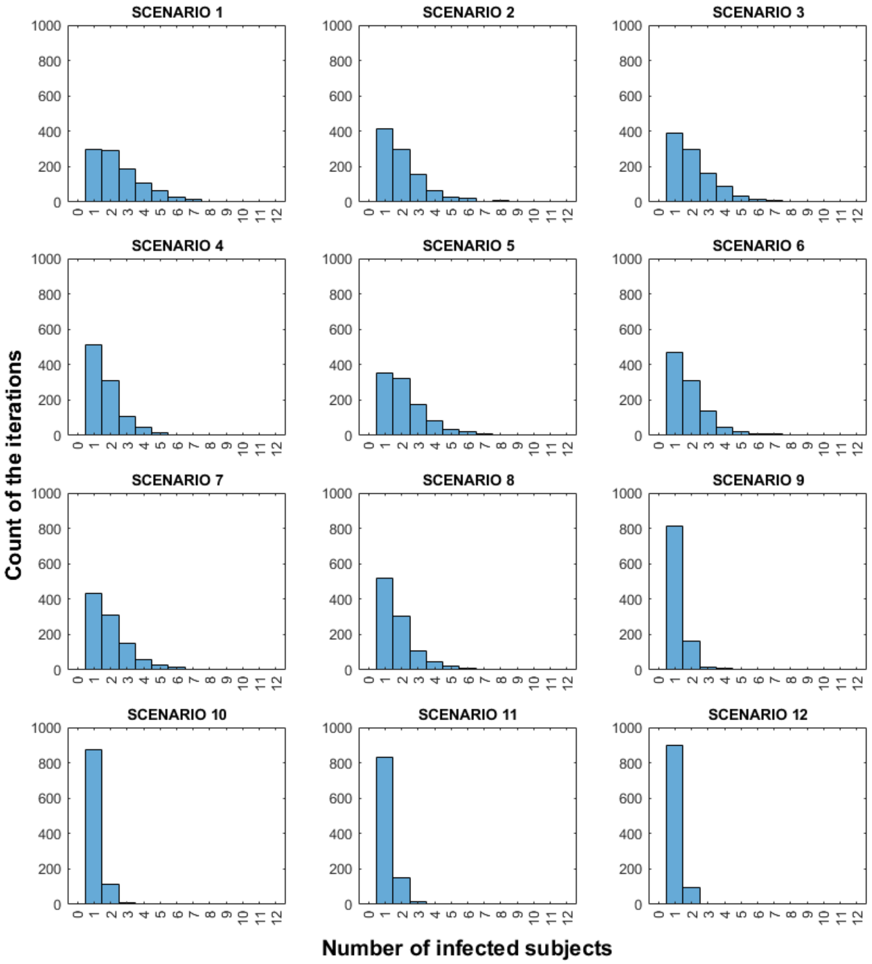

**Figure 2** Count of *MC* iterations ended with a specified number of total infected subjects for each scenario.

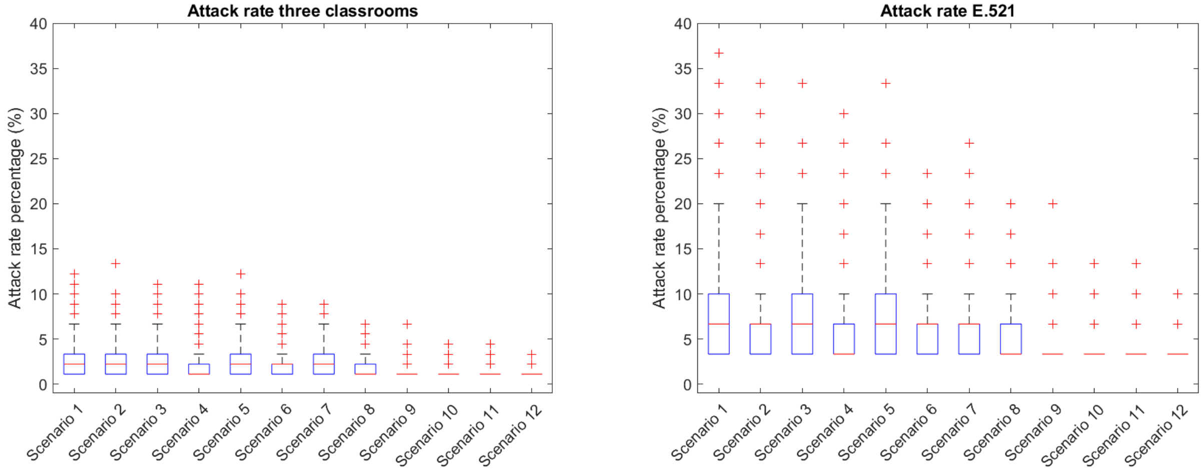

**Figure 3** Boxplots representing the attack rate for all the classrooms (left) and for classroom E5.21 (right) for each scenario. On each box, the red central line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, which are plotted individually using a red cross symbol.

The reason is related to the schedule chosen: windows are open mainly during break time, when also doors are considered open, allowing the air in the classrooms to be partially renovated by the air coming from the hallway, whose high volume ensures a low quanta concentration. A period of 15 minutes of opening in the morning and in the afternoon is not enough to lower the concentration of quanta and, so, to have a significant impact on the results. Still, a combination of natural and mechanical ventilation may help to reduce the attack rate (Figure 3 scenario n. 5-7). The summer schedule for natural ventilation does not present this issue since windows are considered to be always open. Also, in Figure 3 there is almost no difference between scenarios 9-10-11-12 in terms of attack rate. The only difference is observable in the final number of infected people for classroom E5.20 and E5.22. While in scenario n.1 there is at least 5 % of *MC* iterations where more than 1 person is infected also in the adjacent rooms, in scenario n.12, with the adoption of natural ventilation with a summer schedule combined with mechanical ventilation and mask utilization, the possibility to find an infected subject in the adjacent rooms is nearly zero.

## CONCLUSION

In this work, a Monte Carlo method has been coupled with building simulation to dynamically assess the individual risk of contagion according to a probabilistic approach for a multi-zone model under different scenarios. The case-study chosen for the scenario creation are three adjacent university classrooms at the Free University of Bozen-Bolzano, Italy. A total of 12 scenarios have been modelled by changing relevant factors for the risk of contagion as the type of ventilation or the possibility for the subjects to utilize face masks. For each scenario, a total of 1000 Monte Carlo iterations have been run and, at the end of each iteration, the number of infected subjects has been counted for each classroom and in total. The count of the infected subjects has been used for the calculation of the attack rate knowing the number of students and professor present in each classroom. The results highlight the importance of mask utilization by all the subjects especially in those scenarios where a high concentration of quanta is present. Mechanical ventilation is useful to reduce the individual risk of contagion if combined with mask utilization or natural ventilation but has a limited efficacy in terms of risk reduction by itself. Natural ventilation may provide the greater benefits if the right conditions are met. In order to be effective in terms of risk reduction, the windows must be kept open during most hours of the occupancy period, condition that may not be met especially during the winter season or in locations characterized by high noise pollution.

The approach utilized in the present work for risk assessment may be applied also to more complex case-studies where it is important to optimize strategies aimed to reduce the infection risk and, in those cases where it is not possible to adopt a determinist approach to model occupancy, number of infected subjects and other factors.

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