Contagion Risk Assessment For COVID-19 Variants With A Dynamic Approach For A Multizone Building Model Of University Classrooms

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ABSTRACT

Due to the ongoing COVID-19 pandemic, different strategies have been employed to reduce the risk of contagion for the occupants of the built environment, in particular in educational buildings. The adoption of higher ventilation rates and personal protection devices, such as facial masks, are among the most common solutions to reduce the infection risk and allow students to keep attending classes. Since several studies, dedicated to developing strategies to limit the COVID-19 airborne transmission, have been focusing on isolated environments under steady-state conditions, the possibility for pathogens to spread to adjacent environments or the effects of dynamic occupancy schedules have been marginally investigated, albeit being of special interest for school buildings.

In a previous work, a statistical model able to evaluate the risk of infection was coupled with a TRNSYS building simulation model of three classrooms at the campus of the Free University of Bozen-Bolzano (UNIBZ), Italy. Two out of three classrooms are part of the UNIBZ Living Labs, where the indoor environmental conditions are monitored by a network of sensors. Different scenarios had been investigated, by varying ventilation strategy, number of occupants and mask utilization, and assessing for each case the airborne contagion risk. The study showed a strong correlation between a poorly ventilated environment and high risk of infection, underling also the possibility for the pathogen to spread into the adjacent environments in case of dynamic occupancy or if the classrooms doors are left open.

Drawing on the results of the previous research, this work expanded the scope of TRNSYS and TRNFLOW, extending the building model and the airflow network to the whole floor, including classrooms of different size and some offices. In such a way, the internal airflows were assessed dynamically by considering also cross-ventilation effects, improving the accuracy of the calculated infiltration rates and concentrations of COVID-19 pathogen. After a new calibration and validation against the experimental data collected in the UNIBZ Living Labs, a series of transient scenarios were simulated by accounting for the strategies listed before, as well as by considering the effects of three different vaccines – Pfizer, Moderna, AstraZeneca – with a fixed coverage percentage of full/partially/not-vaccinated occupants, new COVID-19 variants, and introducing portable air cleaners. The spread of new COVID-19 variants, which in some cases have proved to be more easily transmitted, made it necessary to re-evaluate and, possibly, adapt the strategies implemented so far, also accounting for different relative vaccination efficacies.

High risk of infection was found related to environments with poor ventilation, especially if the Omicron variant was present, even with the additional protection provided by the vaccines. Air purifiers were a viable solution to reduce the risk of infection in those cases where mechanical ventilation and/or natural ventilation was missing also for the Omicron variant, especially if combined with the effects of a mixed ventilation strategy and mask utilization.

1. INTRODUCTION

COVID-19 outbreak has been widely analyzed in the recent years to understand how to hinder the spread of the virus, especially in crowded places, as classrooms and offices, where the occupants spend long periods of time. An example is given by Di Gilio *et al.* (2021), who assessed the risk of contagion for 11 classrooms in 9 schools using the CO_2 concentration as a proxy. Similarly, Park *et al.* (2021) assessed the risk of contagion under different ventilation strategies, employing a tracer gas to evaluate the airflow rates. Finally, Buonanno *et al.* (2020a) developed the “Airborne Infection Risk Calculator” (*AIRC*), a tool able to evaluate the individual contagion risk for occupants in a room under different ventilation rates. As a whole, the researches in the literature prioritized the development of strategies aimed at lowering the probability of contagion due to the airborne transmission of COVID-19, among which there is the possibility to remove some of the airborne particles in indoor spaces with air purifiers, as investigated by Burgmann and Janoske (2021).
Despite the availability of different solutions, it is however important to remember that ventilation-based strategies may be compared in terms of airborne contagion risk reduction only if it is assumed that the airborne transmission is the main route of contagion (Buonanno *et al.*, 2020b). Usually, the tools able to evaluate the risk of contagion in a specific scenario focus on one room with a fixed occupation schedule and a given ventilation rate. Furthermore, these tools cannot account for probabilistic aspects as the presence of asymptomatic infected occupants or a vaccination coverage, as well as for dynamic aspects related to ventilation rates and occupancy schedules.
In order to overcome these limitations, in a previous work a Monte Carlo (*MC*) model was developed to evaluate different ventilation strategies in terms of contagion risk reduction for three rooms of the Free University of Bozen-Bolzano (Albertin *et al.*, 2021). The model was able to account for multiple zones, dynamic factors (such as occupancy schedules and ventilation rates), presence of asymptomatic infected occupants, variable contagious period and symptoms onset day, and the possibility for the infected to be contagious also before the symptoms onset day. The aim of the present work is to expand the capability of this model by considering also (1) the possible movements of the students from one classroom to another, (2) the vaccination coverage and the effectiveness of three popular vaccines (Pfizer, Moderna, AstraZeneca), (3) the latest COVID-19 variants (Delta and Omicron), and (4) the usage of portable air cleaners.

2. CASE STUDY

The case-study is based on three classrooms located on the fifth floor of the main building of the campus of the Free University of Bozen-Bolzano, Italy. The three rooms, namely E5.20, E5.21, E5.22, are connected by a hallway and are adjacent to each other, with E5.21 being the one in the middle. All classrooms have a floor area of approximately 56 m^2, a door with an opening area of 1.98 m^2 and share the same mechanical ventilation system, with a nominal supply of fresh air of 0.1 $m^3 s^{-1}$ (or 1.8 ACH). The mechanical ventilation system is operative only during occupancy hours, which have been scheduled from Monday to Friday, from 8 am to 12 pm and, in the afternoon, from 2 pm to 6 pm. The openable window area has been limited to two turn windows present in all classrooms, with an opening area of 1.2 m^2 each. An openable tilt window is also present in each classroom; however, it has been neglected since the occupants rarely use it for space ventilation.
The classrooms are part of the Living Labs of the University, equipped with sensors that continuously monitor indoor air variables such as temperature, humidity and CO_2 concentration. Furthermore, a weather station is installed on the roof, collecting data on the external ambient conditions (Pernigotto and Gasparella, 2021).

3. MODEL DEVELOPMENT

The original statistical model able to evaluate the risk of contagion due to airborne transmission of COVID-19 (Albertin *et al.*, 2021) has been modified in order to reduce the computational time required to evaluate each scenario, and to account for new features, such as vaccine coverage and utilization of portable air purifiers. Furthermore, the building model that was previously limited to the three classrooms and the hallway has been extended to the whole floor, in order to evaluate also the impacts of the airflows exchanges with the other rooms on the COVID-19 pathogenic concentration in the hallway.

3.1 Building Simulation Model

The building model of the previous work, developed in TRNSYS 18, has been extended to the whole floor, considering the airflow couplings with several other rooms and the hallway.

The airflow network (*AFN*), previously developed in TRNFLOW to dynamically evaluate the airflows in the building, has been expanded to the whole floor as well. It is important to specify that, while the doors of the additional rooms have been fully included in the airflow network, for those spaces not used for teaching purposes (e.g., bathrooms, storage rooms, offices) the windows have been modelled as always closed due to the lack of a representative opening schedule. For these spaces, only the infiltration rates have been simulated.
These additional rooms have not been included in the risk assessment calculations since a preliminary analysis showed that the COVID-19 concentrations in these rooms due to a contagious occupant in E5.20, E5.21 or E5.22 were negligible. However, they allowed to properly evaluate the airflows coupling of the three main classrooms with the airflow network and to ensure a realistic air change of the hallway.
The introduction of the new rooms in the model has come with the definition of new connections. The same components used for the three main classrooms have been utilized also for the new rooms, in order to simplify the model calibration carried out with the data provided by the sensors of the Living Labs. Specifically, the air temperature profiles in the three classrooms have been used to calibrate the infiltrations across the windows, the discharge coefficient of the doors and the mechanical ventilation efficacy. The results have been found similar to those of the previous calibration (Albertin et al., 2021). In detail, the crack air mass flow coefficient *Cs* has been set to $6e^{-5}$ kg s^{-1} m^{-1} at 1 Pa, the doors' discharge coefficient to 0.56 and the mechanical ventilation efficacy to 61 %.
The calibrated model has been used to create a database of airflows for each room and for each scenario, for a simulation period of one month and a time-step of 5 minutes. The database has been then utilized in the Monte Carlo model for the evaluation of COVID-19 concentrations in the three classrooms and in the hallway through an air mass balance.

3.2 Occupancy Scenarios

It is necessary to make some hypothesis before being able to run the statistical model. Also these hypotheses have been slightly changed with respect to the previous work and are briefly summarized in this paragraph. To this end, students of each classroom are from now on designed as class-group to differentiate it from the physical space of the classroom.
The number of students is 25 for each class-group and does not change in number among simulations, iterations or scenarios. Prior each iteration, a randomly generated schedule assigns each class-group to the three classrooms, simulating the movement of students between classrooms that might happen during the break. Each class-group has a designed weekly schedule that might change randomly from iteration to iteration, allowing the class-group to change classroom at break hours during a day, and from day to day during a simulation. No classroom is left empty at any time.
Additionally, 5 professors for each class-group have been set with a random schedule created at the beginning of each iteration. All 40 hours of occupancy are covered by the professors, for a total of 8 hours of lecture each. The class-group schedule affects also the professors' ones: if a class-group changes classroom within a day, if the professor associated with that class-group is the same from morning to afternoon, then also the professor changes the classroom, following the class-group.
All other hypotheses have been left unchanged. Occupancy hours are set from 8 am to 12 pm and from 2 pm to 6 pm, with break hours set from 12 pm to 2 pm, from Monday to Friday, to represent as a worst-case scenario an intensive course's schedule. It is supposed that the doors are opened only during the break hours and left closed otherwise. With respect to the previous work, only the winter schedule was kept for the natural ventilation. When active, the windows are opened with an opening fraction of 70 % of the total area. The winter schedule set the windows as open during the break hours and for 15 minutes in the morning (9:45 am – 10:00 am) and in the afternoon (3:45 pm to 4:00 pm).
Additionally, air purifiers have been introduced in a subset of simulations. The model selected for this work is suited for rooms up to 79 m^2 and has a clean air delivery rate of 333 m^3 h^{-1} when operating at nominal capacity. When present, a portable purifier is active only during occupancy hours for each classroom.

4. MONTE CARLO ANALYSIS

The Monte Carlo model was modified with respect to its previous version to account for vaccines, COVID-19 variants, air purifiers, random schedule of the class-group and to lower the computational time required to evaluate the airflows. These modifications did not affect the general structure of the algorithm, which is described in this chapter.

4.1 Scenario Initialization

Firstly, a scenario is initialized: the selected ventilation strategy (defined by the scenario) is automatically implemented in the airflow network, which evaluates the airflows of each room with a time step of 5 minutes for a period of a month. After the end of the simulation, a database is created with the airflows for each time step and for each component of the airflow network. After the creation of the airflows database, the first iteration is initialized.

4.2 Iteration Initialization

The schedules for each class-group are created, as well as the schedules for the professors. While a schedule for a class-group defines the classroom where the class-group is located for each half day of the week, the schedule for the professors defines in which half days each professors has lecture hours with a specific class-group. So, the definition of a class-group schedule determines also the location of the relative professors.
Then, the quanta emission rate (*QR*, defined as "the dose of airborne droplet nuclei required to cause infection in 63 % of susceptible persons" by Buonanno *et al.*, 2020a) is evaluated for all the occupants. The *QR* calculation is done *a priori* for all subjects (students and professors), before the start of each iteration, to save computational time. During the simulations, if a subject is not infected, or if he/she is infected but the simulation day is outside his/her contagious period, the *QR* for this subject is set temporarily equal to zero. The *QR* is randomly calculated with a lognormal distribution curve which parameters depend on the activity performed by the subject (Buonanno *et al.*, 2020b). The activities are divided into primary and secondary activities for both students and professors. The primary activity is supposed to be carried out for at least 70 % of the time. The effective time associated with the secondary activity is evaluated with a normal distribution curve, with mean value equal to zero, and three standard deviations equal to 30 % (the maximum percentage of time that can be possibly allocated to the secondary activity). At this point, the percentage of time of the primary activity is obtained by 100 % complement. Then, two *QR* are evaluated, one for the primary activity and one for the secondary with a lognormal distribution curve whose parameters depend on the selected activity (Table 1). Finally, the effective *QR* for a subject is the scalar product of the *QR* values of the two activities with the respective fractions of time.

Table 1: list of activities with relative parameters and typology.

Activity	Log mean	Log standard deviation	Subjects	Type
resting-breathing	-0.43	0.73	Students	Primary
resting-speaking	0.24	0.72	Students and Professors	Secondary
standing – loudly speaking	1.08	0.72	Professors	Primary

When a COVID-19 variant is considered in a given scenario, the mean value of the activities' distribution curves is multiplied by a factor of 2, as suggested in the AIRC tool's manual.
Then, all the occupants are categorized *a priori* as either asymptomatic or symptomatic, even if they are not infected at this point. The early categorization is done to save computational time and does not imply that a not infected subject is contagious. The asymptomatic subjects are selected with a random sorting from a uniform distribution and from a normal distribution curve with mean 40.5 % and standard deviation 3.5 % (Ma *et al.*, 2021). If the value obtained from the uniform distribution curve is lower than the value of the normal distribution curve, then the subject is considered asymptomatic.
All the occupants are then further categorized in fully (2 received doses), partially (1 received dose) or not vaccinated with respect to a vaccination coverage set accordingly to the global database of COVID-19 vaccinations (Mathieu *et al.*, 2021). The vaccination coverage selected for all scenarios is equal to 72 % fully vaccinated, 5.8 % partially vaccinated and 22.2 % unvaccinated, representative of the situation in Italy on November 1st, 2021. Furthermore, the vaccination effectiveness for the fully and partial vaccinated is selected with respect to the COVID-19 variant set by the scenario and to three different vaccines: Pfizer, Moderna and AstraZeneca (Andrews *et al.*, 2022). A random extraction from a uniform distribution is done to determine the status of each occupant. If the extracted value falls below a given threshold, the subject cannot be infected anytime during the iteration. The threshold is selected with a normal distribution curve, which mean and standard deviation depend on the vaccination typology (fully or partial), the COVID-19 variant (Delta or Omicron) and the received vaccine (Pfizer, Moderna or AstraZeneca).

Some additional hypotheses are made at the beginning of each iteration: the initial concentrations of COVID-19 quanta are zero for all internal rooms and an asymptomatic infected student is located in classroom E5.21, being part of the class-group assigned to this specific classroom on the morning of the first day. From now on, the first infected student will be referred as subject 0. It is also hypothesized that day 1 corresponds to the symptoms' onset day of subject 0, which implies that subject 0, even if asymptomatic, is contagious. The concepts of contagious period and symptoms' onset day are further detailed in the next paragraphs.
At this point, the initialization process of an iteration is complete, and the first simulation starts.

4.3 Simulation Start

Each iteration starts at day 1, set to be a Monday, and the first 12 hours of the day are simulated. For each time-step a COVID-19 quanta mass balance calculation of the three classrooms and the hallway is performed. To this mean, the database of airflows is used to evaluate the air exchange from one room to another. Within the mass balance, it is accounted also for Covid-19 quanta generation due to the presence of infected subjects within their contagious period, and only during occupancy hours. If active, the air purifiers are also included in the balance, one in each classroom acting as a COVID-19 quanta sink.
At the end of the first 12 hours, it is checked if the class-groups change classrooms. If so, class-groups previously not in contact with COVID-19 virus might be located in the afternoon in a classroom with a COVID-19 quanta concentration different from zero. Furthermore, it is also checked which professors of each class-group has lectures in the afternoon. Then, the remaining hours of the day are simulated until 12 am. At this point, the simulation ends, and before starting with a new day, the risk assessment analysis is performed.
Firstly, it is evaluated the dose received from all the subjects with Equation 1 (Buonanno *et al.*, 2020b):

$$D_q = IR \sum_t n(t) \tag{1}$$

where *IR* is the inhalation rate and *n(t)* the quanta concentration at time-step *t*. The dose received changes from class-group to class-group, and also from professor to professor within each class-group, dependently to the assigned schedule and to the COVID-19 quanta concentrations in the three classrooms. The inhalation rate was not changed with respect to the previous work and kept to 0.49 $m^3\ h^{-1}$ for students and 0.54 $m^3\ h^{-1}$ for professors. Given the dose received by the susceptible subjects (i.e., the subjects that can be infected), it is possible to evaluate the probability of infection as in Equation 2 (Buonanno *et al.*, 2020b):

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

The probability of infection is reduced by 1/3 if all the occupants are wearing mask during the occupancy hours (AIRC User's Manual).
At this point, a uniform distribution is used to evaluate the newly infections. Only healthy subjects, who were not previously infected and have no immunity status given by the vaccination, can be infected. A random value is extracted from the uniform distribution for each subject who fulfills the aforementioned conditions, and, if its value is lower than the probability of infection, then the subject is considered to be infected. For all new infections, the symptoms' onset day and the contagious period are evaluated.
The symptoms' onset day for each newly infected subject is calculated with a gamma distribution curve, whose parameters (shape and scale) are set accordingly to Lauer *et al.* (2020). Then, the starting and ending days of the contagious period are evaluated, the former with a gamma distribution curve, whose parameters are set as defined by He *et al.* (2020). It is important to notice that an infected subject can be contagious also before the symptoms' onset day. The ending day of the contagious period is always set 9 days after the onset day (both for symptomatic and asymptomatic subjects), in order to consider the worst-case scenario.
Finally, it is checked if one of the two ending conditions is met: either a symptomatic subject reaches his symptoms' onset day, leading to the discovery of the virus in the classrooms, or all the asymptomatic subjects are no longer contagious, completely halting the spread of the virus. If an ending condition is met, the iteration comes to an end. The attack rate is then calculated as the ratio of the infected subjects with respect to the total number of susceptible subjects. Furthermore, the number of elapsed days from the start of the iteration to its end is evaluated. If no ending condition is met, another day is simulated. The *QR* for each infected subject is set equal to zero if the next day lies outside his/her contagious period, otherwise it is set to the value assigned during the initialization of the iteration.

Once that 1000 iterations have been performed for each scenario, the attack rate and number of elapsed days distributions are evaluated and compared.

5. SIMULATION PLAN

The Monte Carlo model was used to evaluate 48 scenarios, accounting for: ventilation type (none, natural, mechanical, mixed), COVID-19 variant (Delta, Omicron), vaccination (none, Pfizer, Moderna, AstraZeneca) and presence of purifiers in the classrooms (Table 2). Furthermore, all 48 scenarios were evaluated a second time accounting also for mask utilization, a third time by increasing the number of occupants by 30 % and a fourth time by decreasing the classrooms air volume by 30 %, for a total of 192 scenarios.

Table 2: main scenarios settings.

Scenario	Covid variant	Vaccine	Ventilation	Purifiers
1	Delta - Omicron	None	Off	Off
2	Delta - Omicron	None	MV	Off
3	Delta - Omicron	None	NV	Off
4	Delta - Omicron	None	Mixed	Off
5	Delta - Omicron	None	Off	On
6	Delta - Omicron	None	MV	On
7	Delta - Omicron	None	NV	On
8	Delta - Omicron	None	Mixed	On
9	Delta	Pfizer	Off	Off
10	Delta	Pfizer	MV	Off
11	Delta	Pfizer	NV	Off
12	Delta	Pfizer	Mixed	Off
13	Delta	Pfizer	Off	On
14	Delta	Pfizer	MV	On
15	Delta	Pfizer	NV	On
16	Delta	Pfizer	Mixed	On
17	Delta	Moderna	Off	Off
18	Delta	Moderna	MV	Off
19	Delta	Moderna	NV	Off
20	Delta	Moderna	Mixed	Off
21	Delta	Moderna	Off	On
22	Delta	Moderna	MV	On
23	Delta	Moderna	NV	On
24	Delta	Moderna	Mixed	On
25	Omicron	Pfizer	Off	Off
26	Omicron	Pfizer	MV	Off
27	Omicron	Pfizer	NV	Off
28	Omicron	Pfizer	Mixed	Off
29	Omicron	Pfizer	Off	On
30	Omicron	Pfizer	MV	On
31	Omicron	Pfizer	NV	On
32	Omicron	Pfizer	Mixed	On
33	Omicron	Moderna	Off	Off
34	Omicron	Moderna	MV	Off
35	Omicron	Moderna	NV	Off
36	Omicron	Moderna	Mixed	Off
37	Omicron	Moderna	Off	On
38	Omicron	Moderna	MV	On
39	Omicron	Moderna	NV	On
40	Omicron	Moderna	Mixed	On

41	Omicron	AstraZeneca	Off	Off
42	Omicron	AstraZeneca	MV	Off
43	Omicron	AstraZeneca	NV	Off
44	Omicron	AstraZeneca	Mixed	Off
45	Omicron	AstraZeneca	Off	On
46	Omicron	AstraZeneca	MV	On
47	Omicron	AstraZeneca	NV	On
48	Omicron	AstraZeneca	Mixed	On

In the first 8 scenarios the vaccination coverage is set equal to zero. Since both COVID-19 variants are accounted for by doubling the mean value of the *QR* distribution curves, which do not change from scenario to scenario, the first 8 scenarios are representative of both.

The ventilation has four possible settings: *none*, which specifies the absence of any kind of ventilation; *MV* (Mechanical Ventilation), which specifies a fixed amount of fresh air supply during occupancy hours (8 am – 12 am, 2 pm – 6 pm); and finally, *NV* (Natural Ventilation), which sets the windows status as open with a winter schedule (9:45 am – 10:00 am, 12:00 am – 2:00 pm, 3:45 pm – 4:00 pm). The last setting is *mixed*, which sets both natural and mechanical ventilation for the given scenario.

A purifier within each classroom might also be considered for a given scenario. If active, it is supposed to operate at maximum capacity, providing 333 $m^3 h^{-1}$ of clean air rate during occupancy hours.

Finally, three vaccines were implemented in the model, each with a specific effectiveness against COVID-19 variants, both for partially and fully vaccinated occupants. If a vaccine is considered for a scenario, it is supposed that only the considered vaccine was used for all the vaccinated occupants, and with a coverage that is always set as 72 % fully vaccinated, 5.8 % partially vaccinated and 22.2 % unvaccinated.

All 48 scenarios described above were evaluated three additional times. Firstly, the mask utilization was accounted for by decreasing the probability of infection of each occupant by 1/3. Secondly, the number of students for all classrooms was increased by 30 % by keeping all the other factors unchanged (for instance, no mask utilization), to simulate an inadequate usage of the rooms. Finally, the volume of the classrooms was reduced by 30 % to simulate a small and crowded environment.

6. RESULTS

In this chapter, the results of the scenarios are compared in terms of attack rate for classroom E5.21 and number of elapsed days. Given the probabilistic nature of a Monte Carlo model, the results are presented with boxplot graphs (1000 values for each metric and for each scenario). It is extremely important to highlight that the numbers of infected occupants that are presented in this chapter are due only to the airborne transmission of the virus, and only during occupancy hours. Furthermore, it was hypothesized that the students do not interact with each other. Given these considerations, it can be safely assumed that, by considering all possible pathway of contagion, the effective number of infected occupants at the end of each iteration may be substantially higher.

Due to space limitations, the graphs representing the number of elapsed days for all cases were omitted, as well as the graphs reporting the attack rate for the two set of 48 cases with increased number of occupants and reduced air volume of the classrooms.

Figure 1 shows the attack rate boxplot for the 48 scenarios of the standard case, which does not consider a reduced volume for the classrooms or an additional number of occupants. As expected, the absence of any typology of ventilation combined with the lack of a strategy aimed at reducing the risk of infection due to COVID-19 variants (as vaccines, purifiers or mask utilization) leads to high values of attack rate. It can be expected form Scenario 1 a number of infected occupants up to 10 people in a range of 2 to 18 days from the start of the iteration. It is worth mentioning that, with the same conditions but without considering a COVID-19 variant, the expected number of infected occupants is approximately half (Albertin *et al.*, 2021). Scenarios 2 to 4 show how mechanical and natural ventilation are not able alone or combined to reduce substantially the attack rate. On the other hand, Scenario 5 shows how an air purifier leads to the same attack rate distribution with respect to a mixed ventilation, highlighting its potential as a strategy to prevent the spread of the virus in locations where the mechanical ventilation is not present, and the natural ventilation is ineffective. Scenarios 9 to 24 also include the effects of vaccines while considering the Delta variant: Pfizer in Scenarios 9 to 16 and Moderna in Scenarios 17 to 24. As it shown in Figure 1, the vaccines are highly effective in terms of risk reduction, especially if combined with an air purifier and any type of ventilation strategy. The number of elapsed days for these cases drops quickly to a range of 9 – 12 days, or

even collapse to a single value equal to 10 days. Lowering the number of days of an iteration means that not only the occupants infected through an airborne transmission of virus are less, but also the occupants infected by any other virus pathway.
Scenarios 25 to 48 show the attack rate in case of Omicron variant, for three vaccines: Pfizer (25 - 32), Moderna (33 - 40), AstraZeneca (41 - 48). The overall effectiveness of vaccines coverage is lower with respect to the Delta variant. If no ventilation system is present, nor the air purifier, the attack rate is just slightly lower with the respect to the case with no vaccines. The only effective way to lower the risk of contagion is to adopt a combined action of vaccines, mixed ventilation and air purifiers.
Figure 2 show as mask utilization greatly reduce the risk of infection for the occupants. However, Scenario 1 shows how their effect is still limited in cases without any kind of ventilation. If adopted in combination with a ventilation strategy and an air purifier, the results on the reduction of the attack rate are similar to the effects of Pfizer or Moderna vaccines (Scenarios 6 - 8). Furthermore, even if an air purifier is not present but a ventilation strategy is, the number of elapsed days is greatly reduced, lowering also the risk of infections through a different pathway of contagion. The combined adoption of mask utilization, mixed ventilation strategy and a vaccine coverage leads to a risk value which is almost zero (Scenarios 16 and 24). Since the effect on the contagion risk of mask utilization is independent with respect to the considered COVID-19 variant, from Scenarios 25 to 48 it is possible to observe how mask utilization is extremely useful to lower the risk of contagion in case of Omicron variant. Not only the scenarios with a ventilation strategy and the utilization of an air purifier are comparable to the respective cases with Delta variant, but it is now sufficient to have at least one ventilation strategy to greatly reduce the likelihood of an unacceptable outcome, especially if air purifiers are used (Scenarios 25 to 27, 33 to 35, 41 to 43).
The results of other two sets of scenarios (a case with an increased number of occupants and another with an air volume of the classrooms reduced by 30 %, which could not be reported due to space limitations) highlight the importance of the combined action of a mixed ventilation strategy, air purifier and vaccines, especially with the Omicron variant. An increase in the number of the occupants leads to an overall higher mean value of attack rate with respect to the standard case, while the spread of the distribution curves is higher in the case of a reduced air volume. It is important to mention that a given value of attack rate represents a different number of infected occupants in the two cases, since the total number of susceptible subjects is different (30 occupants in the former, 38 in the latter).

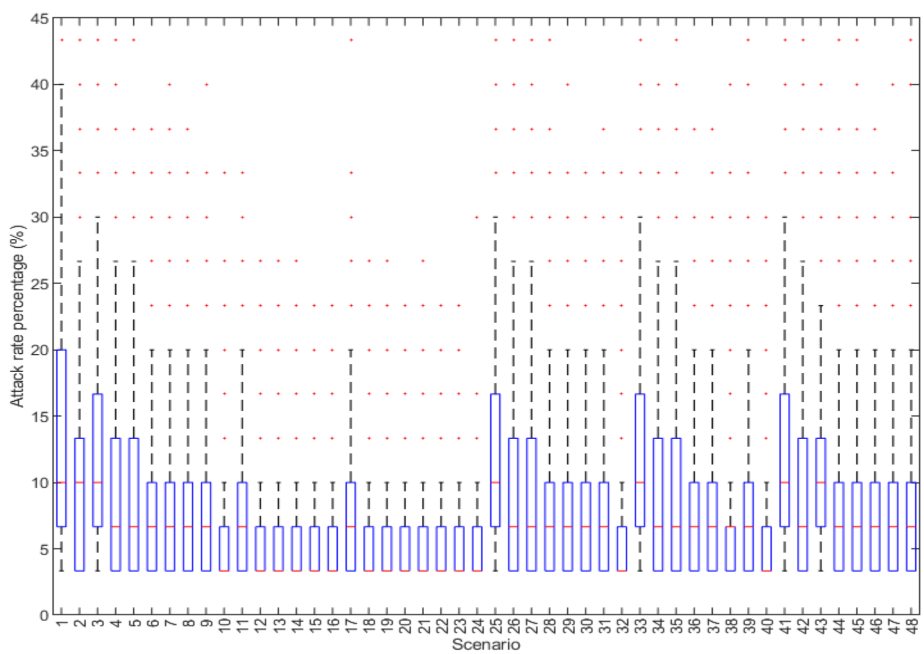

Figure 1: attack rate of each scenario for the standard case.

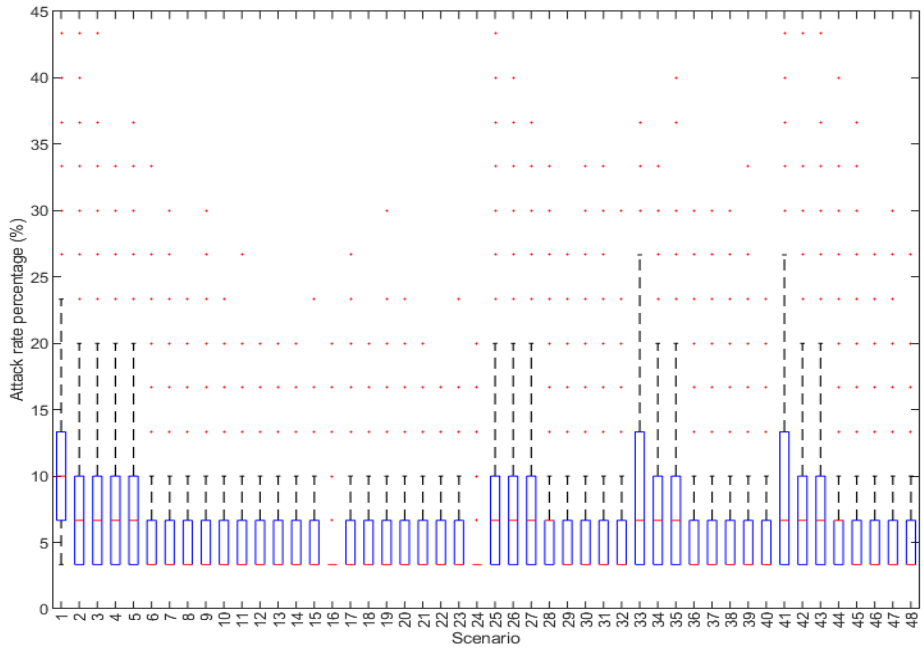

Figure 2: attack rate of each scenario for the case which consider mask utilization.

7. CONCLUSION

In this work, a previously developed Monte Carlo model able to assess the risk of contagion due to the airborne transmission of COVID-19, was further expanded to consider also vaccine coverage, utilization of portable air purifiers, COVID-19 variants and the possible movement of students between classrooms. The case-study are three classrooms of the Free University of Bozen-Bolzano campus' main building, as for the previous work. However, the building model used to assess the airflows needed to evaluate COVID-19 quanta concentrations was extended to the whole floor, as well as the airflow network required for the airflow's dynamic evaluation. The additional complexity introduced with the new rooms and their connections in the airflow network led to the necessity to perform a new calibration, which was carried out against measured data. The calibrated building model was successively used to create a database of airflows for each room, required by the Monte Carlo model to evaluate with a mass balance the concentrations of COVID-19 quanta for the three classrooms and the hallway that connects them. The airflows database allowed to evaluate a total of 48 scenarios according to a probabilistic model based on 1000 iterations for each scenario. We got as outputs the attack rate (i.e., the number of final infected occupants with respect to the total number of susceptible subjects) and number of elapsed days from the start of each iteration. Furthermore, all 48 scenarios were considered three additional times by also considering mask utilization, increasing the number of students in all classrooms by 30 %, and, finally, by reducing the air volume of the classrooms by 30 %, for a total of 192 scenarios. The results showed the danger posed by the COVID-19 variants, especially in environments without any kind of ventilation. The portable air purifiers showed some potential to effectively reduce the risk of contagion, whenever mechanical ventilation is not present and/or natural ventilation is not efficient. Vaccines were observed to be able to greatly reduce the risk of contagion, especially if used in combination with air purifiers, but only in case of the Delta variant, due to a low effectiveness of the vaccines relative to the Omicron variant. If the Omicron variant is considered, the only possible solution to keep the attack rate to low values is by combining the effects of vaccines, air purifiers, as well as a mixed mechanical ventilation. Mask utilization was identified as being able to greatly reduce the risk of contagion also due to Omicron variant, and, so, masks should be employed when possible to keep the risk of contagion contained, also in those buildings without purifiers or an adequate ventilation strategy. Finally, two additional set of the main 48 scenarios, which consider an increased number of occupants or a reduced air volume for the classrooms, show that, in both cases, the combined action of mixed ventilation strategy, air purifiers, and vaccines coverage, is not able anymore to keep the risk of contagion at an acceptable value, discouraging an improper use of the classrooms and limiting the occupancy densities.

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