Assessment of Contagion Risk due to Covid-19 for a Multi-Zone Building Model of Offices

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Abstract

In this research, a probabilistic model was applied to a building model of a public building located in Bolzano, Italy, for the assessment of the airborne contagion risk due to Covid-19. Different ventilation strategies were investigated in terms of risk reduction, as well as the effectiveness of the Pfizer vaccine. TRNSYS and TRNFLOW models of the public building were created to evaluate the internal airflows, necessary to calculate Covid-19 concentrations in the offices. Both building and airflow models were calibrated against measurement data collected with temperature sensors located in some of the building offices and hallways, prior to coupling with a Monte Carlo model for the risk assessment process. The results were reported in terms of infection risk, both for occupants located in the same office, as well as for occupants in adjacent spaces. It was observed that the current operational modes of both natural and mechanical ventilation are able to limit the spread of Covid-19 only in case of vaccination coverage presence and if the Delta variant is considered. If vaccination coverage is not present or if the Omicron variant is concerned, a higher frequency of windows opening, and a schedule based on occupancy profiles for mechanical ventilation should be adopted.

1. Introduction

In the literature, some references about airborne contagion risk assessment due to Covid-19 are available. One example is given by the work of Buonanno et al. (2020a), on which the "Airborne Infection Risk Calculator" (AIRC) is based, for risk

Fig. 1 – Case study building located in Bolzano, Italy

Part of
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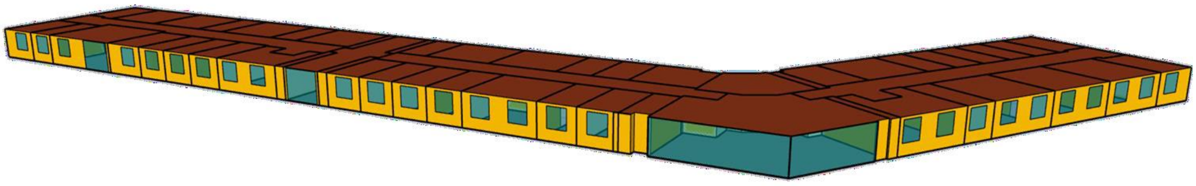

Fig. 2 – 3D model of the second floor of the case study building

assessment due to airborne diseases, including Covid-19. The AIRC tool, as well as other works regarding risk assessment for airborne contagion due to Covid-19, have some limitations. Firstly, it is possible to perform risk assessment only for one room at a time, not considering in this way potential infections in adjacent rooms due to the spread of the Covid-19 virus through doors, or ducts in the mechanical ventilation system. Secondly, one of the major assumptions needed to perform risk assessment is static conditions. For this reason, in Albertin et al. (2022a), a Monte Carlo model was developed to overcome the aforementioned limitations. The probabilistic method proposed is based on the coupling of TRNSYS and TRNFLOW, a building simulation software and a plugin for the evaluation of airflows and infiltrations, respectively, and an algorithm based on the AIRC tool developed in MATLAB® environment. The airflows evaluated with the building and airflow models were utilized for the calculation of Covid-19 concentrations in the internal zones of the building. Then, a Monte Carlo model was used to evaluate the risk of infection for the occupants under different environmental conditions by simulating several scenarios 1000 times each. The whole process was subsequently enhanced in Albertin et al. (2022b), giving the possibility of also considering different Covid-19 variants (Alpha, Delta, Omicron), vaccines (AstraZeneca, Pfizer, Moderna), air purifiers and other features.

In this work, the enhanced version of the probabilistic model is further expanded with the Page algorithm for the randomized creation of occupancy profiles for each occupant and applied to a public building containing offices.

2. Case Study

The case study selected for this work is part of the second floor of a public office (Fig. 1) located in via

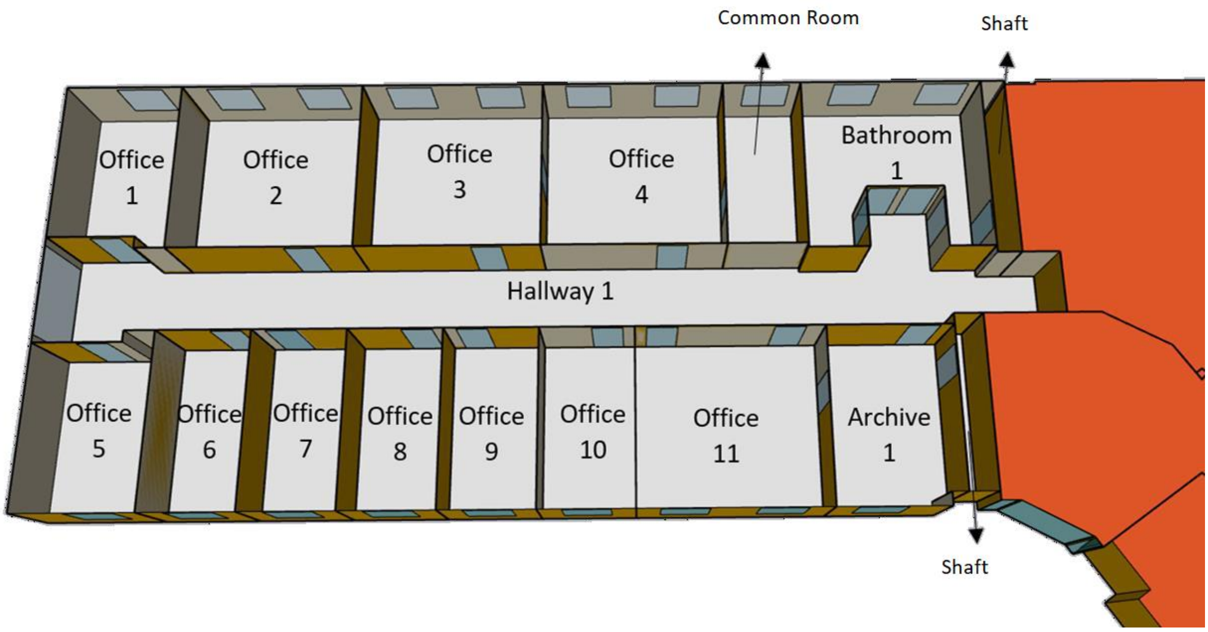

Fig. 3 – Highlight of the second floor of the office block selected for the risk assessment

Vincenzo Lancia, Bolzano, Italy. The second floor is composed of three blocks, and the one selected for the risk assessment is represented in detail in Fig. 3. The surface area of the block is about 564 m^2, for an internal height of 2.7 m and, therefore, a total internal volume of 1523 m^3.

Different ventilation systems are installed for each block, with a low air-flow velocity setting, integrated dehumidification system and crossflow heat recovery unit. However, it has been observed that the mechanical ventilation system is not utilized during working hours, especially in summer, due to issues regarding thermal comfort. For this reason, mechanical ventilation is operative only early in the morning, during lunch hours and in the evening after 6 pm.

All the office windows are composed of a double-glazed glass and an aluminium frame. Given their large dimension and proximity to a busy street, a source of air pollution and acoustic discomfort, it has been observed that the windows are rarely opened and just for short periods of time.

Temperature, relative humidity, and CO_2 sensors are present in three different offices to monitor the environmental parameters (offices 4, 8 and 9 in Fig. 3), and only temperature sensors are present in the relative adjacent rooms for calibration and validation purposes. The sensors used are ONSET HOBO MX1102A for the three offices and ONSET HOBO U12-013 for the adjacent rooms.

3. Model Development

3.1 Building Model

An existing model of the case study building developed in TRNYS was adapted for the calculation of the internal airflows and infiltrations prior to coupling with the probabilistic model. While, in the original model, several rooms were characterized in detail, including offices, bathrooms, hallways, archives, etc. (Fig. 2), in the model used for the risk assessment, only one of the three blocks of the building was considered (Fig. 3). In the selected block, eleven offices, one archive, a hallway, one bathroom, a common room and two shafts are located. As mentioned before, CO_2 was monitored in three offices (offices 4-8-9), while the temperature was also monitored in some adjacent spaces (offices 3-7-10, the hallway and the common room). The data collected from the adjacent rooms was used to set the boundary conditions of the three main offices during the calibration process. The period selected for calibration goes from November 30th to December 15th, 2021, while the validation was carried out in the period starting from December 15th to December 24th of the same year. Calibration and validation were performed on the measured temperature.

The occupancy profiles were randomly determined with the Page stochastic algorithm, based on the occupancy probability profiles proposed by ASHRAE standards. An occupancy profile was created in this way for each occupant of the block, considering in the process the day of the week (weekday, Saturday, Sunday) and the hour of the day. With the Page algorithm, it was possible to account for short moment of absence from the office, as well as long periods of absence usually related to sickness or holidays.

The airflow evaluation was carried out with TRNFLOW, a plugin for TRNSYS, based on the software COMIS. Two external nodes were added to the TRNFLOW model (a.k.a. airflow network, or AFN), one for each external side where windows are present. Pressure coefficients were chosen accordingly to the TRNFLOW manual for a semi-sheltered building. Infiltrations were modeled with the *crack* component, both for closed windows and for doors, while internal and external airflows (present in the case of an open window and/or door), with the *large opening* component. Four different opening profiles for the opening and closing of the windows were extrapolated from the data collected in the monitored offices, and then assigned to all the internal spaces. Finally, the *test data* component was used to model the mechanical ventilation, with a constant rate of fresh air supply when active.

3 design variables were considered during the calibration process, and these are related to each component: for the *crack* component, the air mass flow coefficient, the discharge coefficient for the *large opening* component and the ventilation efficacy for the *test data* component were considered. After

calibration, the AFN was used to evaluate both infiltrations and airflows in the block considered for risk assessment.

3.2 Occupancy Scenarios

Some hypotheses regarding the occupancy of the offices were formulated. Firstly, it was supposed that all the occupants of the building were susceptible subjects (i.e., people that can be infected by Covid-19). Only one person was infected and contagious at the start of the risk assessment process: an occupant of office 3 (Fig. 3). In all offices, only one person was present at a time, with the exception of offices 2-3-4, where 2 persons could be present at the same moment according to their occupancy profiles. In total, during occupancy hours, 15 people could be simultaneously present in the block considered for risk assessment. Occupancy hours were scheduled to be from 8 am to 12 pm in the morning, and then from 1 pm to 5 pm in the afternoon. The occupants of the offices did not move from one space to another: whenever an office was scheduled to be empty, the occupants were supposed to be outside the block.

Doors were considered usually closed and briefly open only whenever a change in the occupancy status of a given office occurred (i.e., an occupant entered/left the office according to its occupancy profile). Windows were also observed to be usually closed. Since the expected state of the windows when open was the tilted position, an opening fraction of 30 % was considered for the windows when open. This was necessary to limit the airflows evaluated by the *large opening* component of the AFN, avoiding an overestimation of the air change rate for the internal spaces.

4. Monte Carlo Analysis

The Monte Carlo model used for the risk assessment analysis was based on a previous model, developed for a set of three university classrooms in the Free University of Bozen-Bolzano (Albertin et al., 2022a), where it was used to evaluate the airborne risk of contagion for the students and professors of the classrooms for different scenarios. Some ventilation strategies were investigated in terms of risk reduction, as well as the effect of mask utilization. The probabilistic model was subsequently enhanced in Albertin et al. (2022b), to consider different Covid-19 variants (Delta and Omicron), vaccines (AstraZeneca, Pfizer and Moderna), and the effect of air purifiers, as well. In this work, the Monte Carlo model was adapted to the office building and further enhanced with the Page algorithm for the creation of randomized occupancy profiles for each occupant. The probabilistic nature of the Page algorithm could be fully exploited within the Monte Carlo method, whose simplified schematic is represented in Fig. 4.

The process started with the definition of a scenario, by selecting the ventilation strategy, the presence of vaccine coverage, Covid-19 variants, etc. Then, each scenario was evaluated 1000 times, in this work referred as *iterations*. An iteration consists of a series of simulations, each one representing a day. During the simulations, the airflow database was used to calculate the concentration of Covid-19 in the offices, and, thus, the dose received by the occupants (Buonanno et al., 2020b). Thanks to the dose, it was possible to account on a day-to-day basis for newly infected occupants, who would contribute towards increasing Covid-19 concentrations in the block in the next simulations. The simulations stopped when it was not possible to have new infections, meaning that the infected occupants were either no longer contagious or kept outside the block.

In this chapter, the risk assessment model is described in detail, highlighting the differences with respect to previous works.

4.1 Scenario Definition

The risk assessment process begins with the definition of the scenario. The ventilation strategies considered for the given scenario were automatically implemented in the TRNSYS model, as well as in the AFN, changing the parameters used for the evaluation of both infiltrations and airflows. The building model was then used to create a database of airflows under different conditions (windows and/or door opened or closed). The database was used during the simulation phase to dynamically evaluate the concentrations for each office, necessary for calculating the dose received by the occupants, and thus, to identify new infections.

4.2 Scenario Evaluation Process

Each scenario was evaluated with 1000 iterations. An iteration started with a random process for assigning a quanta emission rate value (QR, where a quantum is defined as "*the dose of airborne droplet nuclei required to cause infection in 63 % of susceptible persons*" in Buonanno et al., 2020b) to each occupant. The process was also carried out for the occupants that were not infected to save computational time. During a simulation, if a subject was not infected, his or her QR was considered to be zero. The QR was then switched to the value assigned only for those occupants that were infected during a simulation. The QR values were randomly selected with a lognormal distribution curve whose parameters depended on the activity performed by each occupant (Buonanno et al., 2020b). The activities were subdivided into primary and secondary activity.

The time allocated to the secondary activity was randomly chosen with a Gaussian distribution, with a process ensuring that the primary activity was carried out at least 70 % of the time. Two values of QR were then randomly extracted for the occupants, one for each activity, and subsequently weighted with the time allocated to the respective activities, and finally added up.

In a similar process, two other values were randomly assigned to all the occupants during the initial phase of an iteration: asymptomatic status and vaccination status.

Asymptomatic status was determined once again for all the occupants, infected or not. Early categorization was performed randomly with a normal distribution curve whose parameters were set according to Ma et al. (2021). Those occupants categorized as asymptomatic and who would get infected during a simulation would increase the Covid-19 concentrations in the block during the whole contagious period, without ever being kept outside the building.

Table 1 – List of activities with relative parameters for the log-normal distribution curve

Activity	Log Mean	Log Standard Deviation	Type
Resting-breathing	-0.43	0.73	Primary
Standing-speaking	1.08	0.72	Secondary

Finally, vaccination status was randomly extracted. All the occupants were categorized in this way as fully vaccinated (2 doses received), partially vaccinated (1 dose received) or not vaccinated. The number of occupants in each category was automatically assigned to match the vaccination coverage according to the global database of Covid-19 vaccinations (Mathieu et al., 2021). The vaccination

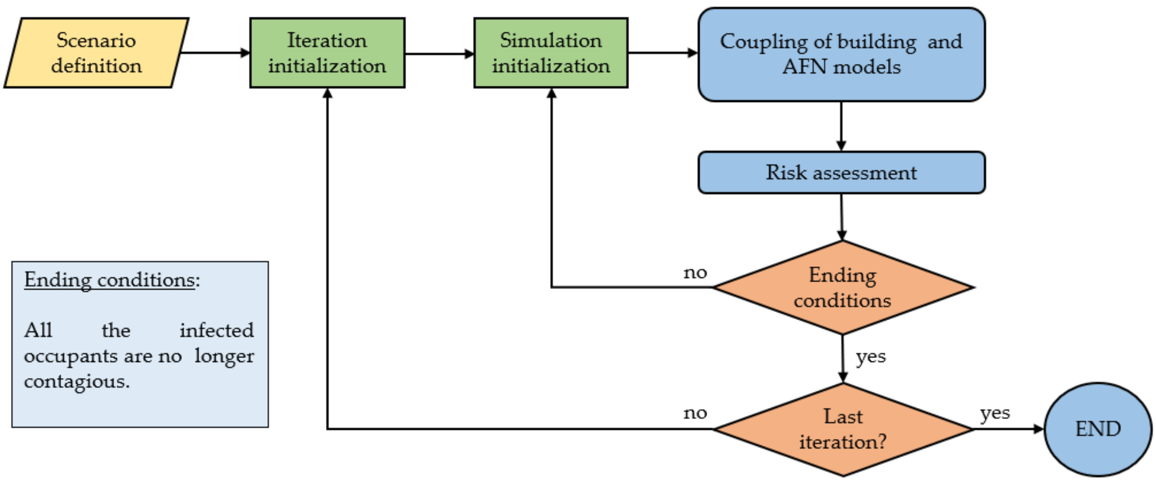

Fig. 4 – Scheme of the Monte Carlo model utilized for the risk assessment process

coverage selected represents the situation in Italy on November 1st, 2021, with 72 % fully vaccinated, 5.8 % partially vaccinated and 22.2 % not vaccinated. Furthermore, the effectiveness of each vaccination category depends on the typology of Covid-19 variants considered, and on the vaccine selected: Pfizer, Moderna, AstraZeneca (Andrews et al., 2022). The effectiveness of the vaccine selected can then vary from occupant to occupant, and it was used to randomly select the subjects who were immune to airborne contagion due to Covid-19 for a given iteration. For example, a fully vaccinated occupant with 2 doses of Moderna had a higher probability of being immune to the Delta variant compared with an occupant with only one dose of AstraZeneca.

Before the start of the simulations, some hypotheses were formulated: all the occupants were not infected and were susceptible to Covid-19 contagion, except for one occupant in office 3, who was already infected, asymptomatic, and contagious. The initial concentrations of Covid-19 in all the internal spaces of the block were equal to zero.

At this stage, the simulations started and were performed until the ending condition is met, which signified the end of the iteration. At the end of each iteration, the number of infected occupants in office 3 and in the whole block were counted, obtaining a distribution of 1000 values. It was then possible to calculate the likelihood of having one or more infected subjects both for the office where the first infected was located (office 3) and for the other offices of the block. The distinction was important, since having new infections in adjacent spaces meant that it was possible for the Covid-19 virus to spread from one room to another, increasing the chances of unacceptable outcomes.

4.3 Risk Assessment

During a simulation, the airflows evaluated with the AFN were utilized to dynamically calculate Covid-19 concentrations in all the internal environments of the block considered. Then, at the end of each day, the dose received by the occupants was calculated, taking into consideration the occupancy profile of each subject and Covid-19 concentration in the respective office. Finally, with the dose received it was possible to calculate the probability of infection for each occupant (Buonanno et al., 2020a), and thus, to randomly account for new infections at the end of each day. Those occupants that were selected as not infectable during the assessment of the vaccination status always had a probability of infection equal to zero for the given iteration.

For each newly infected occupant, the contagious period was randomly determined, as well as the symptom onset day. The process is reported in detail in Albertin et al. (2022b). The occupants that were infected and that were outside the contagious period cannot be infected again during an iteration. The simulations were repeated until all the occupants were no longer contagious. At this stage, the final number of infected occupants was computed for each office and the iteration came to an end.

5. Simulation Plan

A total of 27 scenarios were evaluated with the Monte Carlo model by considering different natural and mechanical ventilation strategies, Covid-19 variants, and the presence of vaccination coverage with the Pfizer vaccine.

There were 3 natural ventilation strategies considered for the scenarios: (1) all the windows were always closed; (2) the opening of the windows was set by profiles based on measured data; (3) the windows were open for 10 minutes every hour and during the lunch break. There were also 3 mechanical ventilation strategies: (1) always inactive; (2) active outside occupancy hours as observed during the monitoring period (7 – 8 am, 12 – 13 pm, 5 – 6 pm); (3) active during occupancy hours (8 am – 12 pm, 1 – 5 pm). Two Covid-19 variants were considered, (a) Delta and (b) Omicron, respectively. Finally, the efficacy of vaccines was investigated by comparing the case where (a) all the people were not vaccinated or (b) with vaccination coverage, performed with the Pfizer vaccine. Cases were coded, with a sequence of two numbers, both in range 1-3, representing respectively the natural and mechanical ventilation strategy considered, followed by a letter D or O, respectively, for the Delta and Omicron variants, or O/D if the case was valid for both variants. Finally, the last member of the sequence was a number: 1 when vaccination coverage was present, and 0 when not. As, for example, code 13O1 represents the case with windows always closed (natural ventilation strategy number 1), mechanical ventilation active during occupancy hours (mechanical ventilation strategy number 3), Omicron variant and vaccination coverage present.

6. Results

The results were reported as the likelihood of having a specific number of newly infected subjects by considering all offices:

- L0, refers to the likelihood of not having new infections,
- L1, refers to the likelihood of having exactly one new infection,
- L2, refers to the likelihood of having exactly two new infections,
- L2+, refers to the likelihood of having more than two new infections.

Furthermore, the likelihood values were colored in shades of red and green, where red represents the lower value, and green the highest value for L0. The colours were inverted for the metrics L1, L2, L2+. In this way, it was easily possible to identify the scenarios with the best and worst possible outcome thanks to the colors of each row in Table 2.

To this end, it was possible to identify the worst-case scenario as 11D/O0. In this case, the windows are always closed, allowing only a small amount of fresh air (infiltrations) to enter the building through the cracks and small openings, since the mechanical ventilation is always inactive, too. Furthermore, in this case, vaccination coverage is not present. The result is a likelihood of 50 % of having a new infection in the block. Most of the time, the infection will occur inside the same office (L1 ~ 27 %) but it can also happen in other rooms, too (L2 ~ 9 %; L2+ ~ 14 %). By taking into consideration the case that represents the actual conditions of the block regarding both mechanical and natural ventilation strategies, in the case of vaccine coverage not being present (22D/O0), the results are similar to the worst-case scenario, with a probability of 42 % of having at least one new infection. The coupling of mechanical and natural ventilation is able to reduce the probability of infection in adjacent rooms from ca. 23 % to 17 %. In the case of windows being opened often, and the mechanical ventilation being active during occupancy hours (case 33D/O0), it is possible to reduce the probability of new infection even further to 25 % (half with respect to the worst-case scenario), and the probability of new infections in adjacent offices to 7 %. The efficacy of vaccination coverage strongly depends on the Covid-19 variant considered. By looking at the table, it is possible to observe how vaccinations are a valid substitute for the optimal ventilation strategies (i.e., strategy number 3 for both mechanical and natural ventilation) when the Delta variant is considered. In fact, the scenario with windows always closed and mechanical ventilation always inactive (11D1) is comparable with the best-case scenario without vaccination coverage (33D/O0). If all the possible counter measures are taken (scenario 33D1), it is possible to reduce the probability of new infections to 10 %, and the probability of having new infections in adjacent rooms to almost 0 %. For the Omicron variant, the considered vaccines are not as effective as for the Delta variant. In this case, the results are slightly better if compared with the scenarios without vaccination coverage.

7. Conclusion

In this work, a Monte Carlo method for the assessment of airborne contagion risk due to Covid-19 was applied to some offices contained in a public building, taking into consideration different ventilation strategies, two Covid-19 variants, and the presence of vaccine coverage. It was observed that the current strategies regarding both window utilization and mechanical ventilation are not able to prevent the spread of Covid-19 virus from office to office. Vaccination coverage alone is able to reduce the risk of contagion due to Covid-19 to acceptable values only when it is a case of the Delta variant.

Table 2 – Likelihood of having exactly 0 (L0), 1 (L1), 2 (L2), or more (L2+) newly-infected occupants for each scenario

Scenario Code	L0 (%)	L1 (%)	L2 (%)	L2+ (%)
11D/O0	50	27	9	14
12D/O0	56	29	7	8
13D/O0	65	24	8	4
21D/O0	54	29	9	9
22D/O0	58	26	9	8
23D/O0	65	21	8	6
31D/O0	70	20	6	4
32D/O0	73	21	4	2
33D/O0	75	19	5	2
11D1	74	19	4	2
12D1	79	18	3	1
13D1	85	13	2	0
21D1	81	16	2	1
22D1	77	18	3	2
23D1	86	12	2	0
31D1	87	12	1	0
32D1	88	11	1	0
33D1	90	8	1	0
11O1	60	25	8	7
12O1	62	25	8	6
13O1	70	21	6	3
21O1	62	24	7	7
22O1	65	24	6	5
23O1	73	21	3	3
31O1	72	21	5	3
32O1	73	21	5	2
33O1	82	14	3	2

In fact, if the Omicron variant is considered instead, the only proper way to contain the spread of the virus is to combine vaccination coverage with an increase in opening frequency of windows, and to adopt an appropriate schedule for mechanical ventilation, preferably based on occupancy profiles.

Acknowledgement

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