The importance of good ventilation

(before, during and after a global pandemic)

Analysis model of the airborne transmission risk

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1 Abstract

From the start of the COVID-19 worldwide pandemic, there has been an international consensus on the transmission mitigation measures: social distancing, hand hygiene and use of a face mask. Such measures arise from the accepted transmission mechanisms, namely the inhalation of infectious droplets and direct contact with contaminated surfaces. Nonetheless, an increasing number of scenarios are being exposed where transmission can only be explained by aerosol transmission. On this matter, several health authorities have recently started accepting aerosols as a likely transmission mechanism – as described in the most recent literature –, therefore including ventilation fundamental measure to reduce virus transmission. This fact has created an intense debate in society about the desirability of natural ventilation versus mechanical ventilation. Natural ventilation (considered in this study as equivalent to opening windows) appears to have the advantage of zero cost, at the expense of sacrificing energy efficiency (disregarding international agreements to fight climate change), thermal comfort of occupants, the presence of polluted air in urban environments and the lack of control in its functioning (ventilation rates achieved).

Despite all the above, the present study focuses on the comparison between different ventilation strategies only in terms of their effectiveness in reducing the airborne infection risk. The natural ventilation rates chosen simulate the effect of opening windows while mechanical ventilation replicates the ventilation rates defined by the applicable standards. Three potential infection scenarios are analysed: a classroom, a bar/restaurant and an office, with their corresponding occupation densities and event characteristics (exposure time, breathing rates, etc.) comparable to real scenarios. The Wells-Riley model is used to relate the room aerosol concentration to the infection probabilities. The infectious particles exhalation rate ($\text{quanta}\cdot h^{-1}$) is taken from literature. For each of the scenarios, the aerosol concentration as well as the infection probabilities are analysed as a function of the ACH for several exposure times. The results show that, to obtain very low infection probabilities, the ventilation rates recommended by the standards should increase (it is important to note that such requirements were not devised during a pandemic). However, it concluded that the ventilation rates recommended by the standards can decrease more than twofold the infection probabilities resulting from natural ventilation.

2 Introduction

The 31st of December of 2019, China reports to the World Health Organization (WHO) a cluster of atypical pneumonia cases in Wuhan. On the 9th of January, the outbreak is identified as caused by a novel coronavirus (SARS-CoV-2) [1]. Immediately after, the first health representatives meet to analyse this new virus and, on the 11th of January, the genetic sequences for the novel coronavirus are obtained [1]. First, the possible human-to-human transmission was doubted. However, the 21st of January, human-to-human transmission was confirmed [1]. Nevertheless, WHO did not declare a global pandemic until the 11th of March [1].

At the beginning, WHO suggested social distancing, the use of a face mask and hand hygiene to fight and reduce virus transmission. These recommendations arise from the fact that, at that moment, WHO considered the direct contact of the mucous membranes located in nose, mouth and eyes with infected droplets/particles [2] as the principal mechanism for virus transmission. This particles may come from:

1. Droplets released while talking, breathing or sneezing. Thereby, the transmission through these droplets seems unlikely at distances larger than two meters.

2. Surfaces contamination and later direct contact with the mucous membranes (touching such surfaces). Thus, the survival time of the virus on different materials is studied.

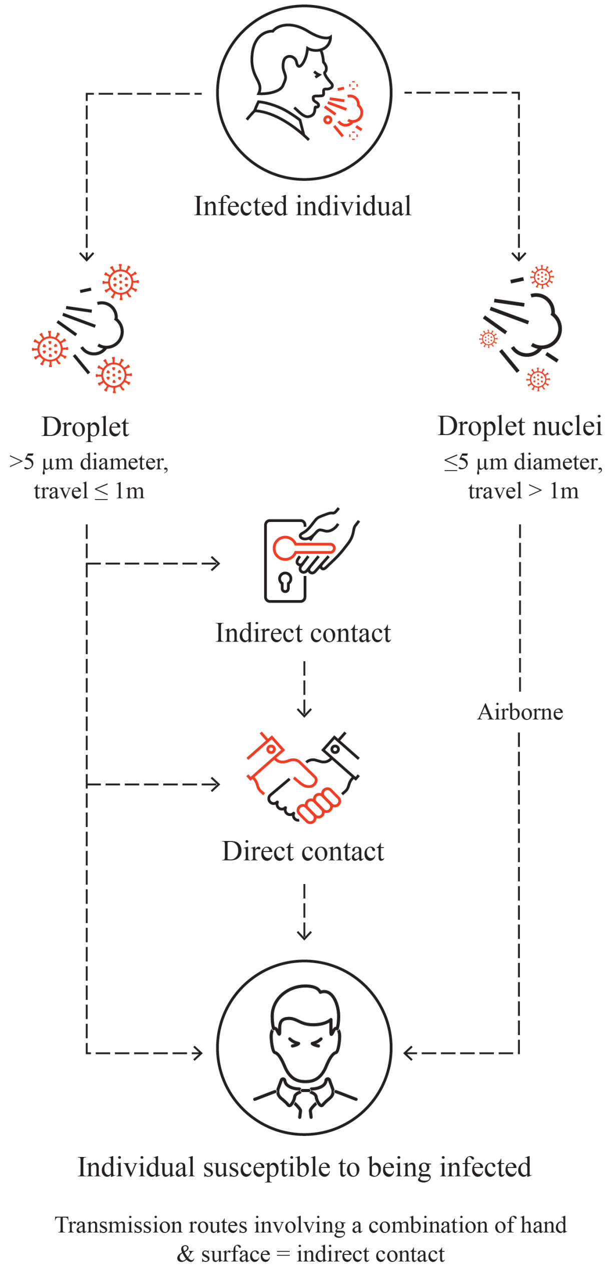

Figure 2.1. COVID-19 Transmission Methods (inspired in [3]).

Therefore, at first, most of the States recommended these measures to try to reduce the high transmissibility of the virus. Nonetheless, many scientists started to alert of the possibility of airborne transmission of the virus by aerosols ([4], [5], [6]). Aerosols are smaller particles than droplets, which do not fall as fast and stay floating in the air for a longer time. Aerosols are quickly dispersed across the room and they may have viral load, similarly to the droplets mentioned before. Different studies have detected the presence of SARS-CoV-2 in aerosols [7]. The importance of this transmission method arises from considering that an adult person breathes between 18,000 and 20,000 times per day, breathing (and filtering) around 8,000 liters of air per day. Thus, a great quantity of aerosols present in the ambient air are inhaled.

Airborne transmission attains greater relevance after the study of different events ([8], [9], [10]), where all the transmission mechanisms mentioned and accepted by WHO do not provide an explanation for the high number of people infected after such events.

From this type of events, Prof. José L. Jiménez of Colorado University developed a model to estimate the transmission of COVID-19 by aerosols [5]. Prof. Jiménez and many other scientists ([4], [11], [12]) have been working for a long time trying to raise awareness among authorities of the importance of COVID-19 airborne transmission. WHO included airborne transmission of COVID-19 under specific circumstances during October 2020 [13].

It is out of the scope of this paper to analyze all the transmission methods. Instead, the discussion focuses on the importance of aerosols in airborne transmission that cannot be prevented by neither social distancing nor hand hygiene.

The tools to conduct the present study are based on the model described in [5], implemented in Python and upon which new features have been added, allowing for a wider range of study cases as well as more data-visualization capabilities. The goal of this article is two-fold: on the one hand, to analyse the infection risk when there is an infected person inside a known room (volume, ACH, amount of people, etc.); on the other hand, to provide a valid tool to size the ventilation rate of any room according to the characteristics of the activity occurring in it.

Thereby, this article seeks to answer the following questions: is natural ventilation (understood as opening windows) enough to mitigate infection risk or is forced ventilation through a mechanical ventilation system required? On the other hand, is it enough to ventilate following the current standard specifications? To answer these questions, three different examples are analyzed (a classroom, a small bar/restaurant and an office).

This work tries, on one side, to raise awareness among all the readers and public administrations of the importance of proper ventilation: before, during and after a global pandemic. On the other side, it tries to validate if the current regulations are enough to reduce the risk of infection by aerosols to acceptable levels.

3 Risk Analysis

3.1. Model Introduction

3.1.1. Key Concepts

The key concepts of the model are described below:

- **Quanta:** pathogen dose in aerosol form, the inhalation of which leads to an infection with a probability of 63.3%. Discrete and present in very low concentrations, analogous to an aerosol particle with a certain pathogen load.

- **Quanta exhalation rate:** rate at which an infectious person emits quanta through exhaled air. Dependant on age group and physical activity [14] [15].

- **Breathing rate:** airflow generated by a person's inhalation and exhalation process. Dependant on age group and physical activity.

- **Inhaled quanta:** total quanta inhaled through breathing by a person after a given exposure time.

- **Mask effectiveness:** effectiveness with which a mask can prevent both the inhalation of airborne quanta and the release of quanta to the environment by an infectious individual [16].

- **Infection probability:** individual probability of infection, dependant on the total quanta inhaled.

- **Quanta concentration average:** to obtain the infection probability, the model uses the concentration of quanta equivalent to a constant quanta concentration throughout the duration of the event.

- **Accumulated probability:** valid for multiple repetitions of the same event or for an event with non-equiprobable segments. It is equivalent to the infection probability during the first event combined with the infection probability during the second event (conditioned to no infection occurring during any of the prior events) and so forth until the last event is considered.

3.1.2. Ventilation Standards

To answer the question "*is it necessary to ventilate more?*", it is relevant to consult the appropriate standards for ventilation in different spaces. The standards that regulate the amount of air changes per hour (ACH) to ensure an adequate indoor air quality are:

- For a classroom a ventilation airflow between 8 and 9 $dm^3 \cdot s^{-1}$ or 28.8 and 32.4 $m^3 \cdot h^{-1}$ per person is defined by Building Bulletin 101, *Guidelines on ventilation, thermal comfort and indoor air quality in schools.*

- For an office a ventilation airflow of 7 $dm^3 \cdot s^{-1}$ or 25.2 $m^3 \cdot h^{-1}$ per person is defined by EN 15251: 2007. The highest required airflow has been considered (category I).

- For a bar/restaurant a ventilation airflow of 10 $dm^3 \cdot s^{-1}$ or 36 $m^3 \cdot h^{-1}$ per person is defined by Building Regulations Part F.

3. 2. Analytical Model

The tool presented herein is based on the "*One Box Model*", a common analytical approximation used in chemistry and atmospheric science to model the chemical equilibrium of a set of species as if they were enclosed by a box. The species are assumed to be instantaneously and uniformly distributed along the volume. Hence, the focus of the model lies on determining the evolution of the total concentration with time instead of the spatial distribution of the species.

- **Inflow and outflow:** the airflow entering and leaving the enclosure. Defines the Air Changes per Hour (ACH). Denoted by F_{in} and F_{out}, in $m^3 \cdot h^{-1}$.
- **Emission:** amount of chemical species generated by direct release into the enclosure. Denoted by E, in h^{-1}.
- **Chemical production:** the amount of chemical species generated by chemical reactions involving other species. Denoted by P, in h^{-1}.
- **Chemical loss:** the amount of chemical species that are inactivated due to the effects of ambient temperature, UV radiation level, chemical reactions with other species, etc. Denoted by L, in h^{-1}.
- **Deposition:** the amount of chemical species removed by surface deposition. Denoted by D, in h^{-1}.

It is important to note that both the gains and losses in chemical species are modelled as first order. Hence, they are independent of the quanta concentration inside the enclosure. Therefore, through the "*One Box Model*", the inflow and outflow can be converted to a loss and subsequently combined with the remaining losses in a λ factor, such that:

$$\lambda = \frac{F_{out}}{V} + D + L$$

With $F_{in} = F_{out}$, where V is the enclosure volume and considering that the inflow only introduces clean air (without pathogen load). In addition, and for this particular case, species gains from chemical production are omitted, as the infectious particles cannot be generated from chemical reactions between the remaining species within the volume. Then, the quanta concentration as a function of time, $C(t)$, can be captured by the following differential equation:

$$\frac{dC(t)}{dt} = \frac{E}{V} - \lambda C(t)$$

Solving the differential equation analytically to find $C(t)$ yields:

$$C(t) = C_0 e^{-\lambda t} + \frac{E\eta}{\lambda V}\left(1 - e^{-\lambda t}\right)$$

Where η represents the mask efficiency and C_0 the initial quanta concentration. To obtain the infection probability during a given time interval, the average concentration value is required and obtained by integration as follows:

$$\overline{C}\Big|_{t_0}^{t_1} = \frac{1}{\Delta t}\int_{t_0}^{t_1} C(t)dt = \frac{C_0}{\lambda \Delta t}\left(1 - e^{-\lambda \Delta t}\right) + \frac{E\eta}{\lambda V}\left[1 - \frac{1}{\lambda \Delta t}\left(1 - e^{-\lambda \Delta t}\right)\right]$$

Introducing the mask efficiency η, the ratio of masked people f and the breathing rate Q, one can derive the quantity of inhaled quanta by:

$$q_{inh} = \overline{C}\Big|_{t_0}^{t_1} Q\Delta t(1 - f\eta)$$

Finally, the probability for a single event or a given time interval is calculated by using the Wells-Riley equation:

$$p = 1 - e^{-q_{inh}}$$

If the desired output is the accumulated infection probability after a multi-segment event or after several repetitions of the same event, then the individual infection probability for each event or segment needs to be calculated beforehand. Afterwards, the latter can be combined to yield the accumulated probability by:

$$p = p_0 + \sum_{i=1}^{n}\left(p_i \prod_{k=0}^{i-1}(1 - p_k)\right)$$

Where the i and k suffixes correspond to the probabilities of the i–th and k–th segment, respectively.

3. 3. Applications for the Ventilation Sector

For all the above, the analysis capabilities given by the model can be summarised as:

1. Risk analysis: as already mentioned, the model is a practical tool to estimate the infection probability in a room for a given set of conditions.

2. Sizing ventilation installations: setting the conditions of a room (number of people, dimensions, mask efficiency, activity…) and the infection risk that one is willing to accept, the ACH necessary to obtain such a scenario can be obtained.

3. Comparison between two types of installations: given two installations with different airflows, the infection probability can be obtained for each case, always assuming that there is one infectious person in the room.

4 Cases of Study

Different configurations are studied for each case (classroom, bar/restaurant and office). Focusing on ACH, the following conditions are analysed:

1. Natural ventilation: an airflow of 0.75 ACH is used for this case. As it was established in [17] [18], natural ventilation varies significantly depending on the exterior conditions. Therefore, the ACH used is only a reference value to analyse a configuration with natural ventilation. As previously stated, natural ventilation has been assumed as the recommendations of opening windows carried out by administrators.

2. Ventilation defined by the standards.

3. Ventilation needed to reduce the infection risk to 1% [19].

4. 1. Relevant Information

This section defines all the parameters from the model that are constant or extracted from the reference literature reviewed for the present article. Table 4.1 contains a summary of the characteristic variables for each case of study.

Concerning the first order losses, the deposition ratio is taken as $D = 0{,}3$ while the chemical loss is taken as $L = 0{,}56$ (see Table 4.1), both according to the recommendations given by [20] and [21], respectively.

With regards to the face mask efficiency, a 50% efficiency is taken as the reference value for all cases, as recommended by [16]. Despite the theoretical efficiency of face masks being much higher (e.g. >95% for FFP2 face masks), research [16] proves that, without a proper fit, exhaled and inhaled air leaks through the openings, some aerosol particles are not filtered by the face mask and its efficiency is drastically reduced.

The breathing rates have been selected accounting for age and physical activity groups, according to what is recommended by Standard ASHRAE 62 [22]. For the classroom case of study, the breathing rates are lower as the susceptible group is entirely composed by children. Regarding the quanta exhalation rates, the most uncertain parameter, reference values are taken according to what is exposed in [14] and [15]. Accordingly, the teacher and the students present different quanta exhalation rates. For the bar/restaurant case, a higher exhalation rate is assigned to the waiter as they are exercising and their metabolic rate is higher than that of rest.

The summary of the remaining parameters, i.e., room dimensions, number of occupants, breathing rate and quanta exhalation rate is shown in Table 4.1.

	Volume $[m^3]$	N. people	Breathing rate $[m^3 \cdot h^{-1}]$	Quanta exhalation rate $[quanta \cdot h^{-1}]$
Classroom	192	24	0.66	25/12.5
Bar - 1	270	35	0.72	38.3
Bar - 2	270	35	0.72	25
Office	780	40	0.72	25

Table 4.1. Characteristic parameters for each of the study cases.

4. 2. Classroom

One of the most interesting cases to study is that of a school's classroom. A typical classroom measuring 8 x 8 x 3m, occupied by 24 students and a teacher, is taken. The latter is considered as the infected person and all the students are wearing a face mask. A timeline of the event is created to reproduce the typical occupation pattern in a school. The event comprises 4 time segments: 2 hours of lectures in the morning, 30 minutes of playground break followed by another 2 hours of lectures after which a 2-hour long lunch break happens. Finally, the lectures are resumed for another 2 hours after lunch. It is important to note that during the segments where the classroom is empty, the concentration of quanta decreases progressively as there is no further quanta release.

The evolution of the quanta concentration with time is shown in Figure 4.1 for the three ACH values selected. It can be seen, as expected, that the higher the ACH, the faster the equilibrium concentration is reached and at a lower value.

Additionally, Figure 4.1 shows that compliance to the recommendations by Building Bulletin 101 standard in terms of ACH leads to eliminating almost completely the quanta concentration by the end of the intervals where there is no occupancy. In contrast, the natural ventilation scenario leaves residual quanta concentration after the breaks.

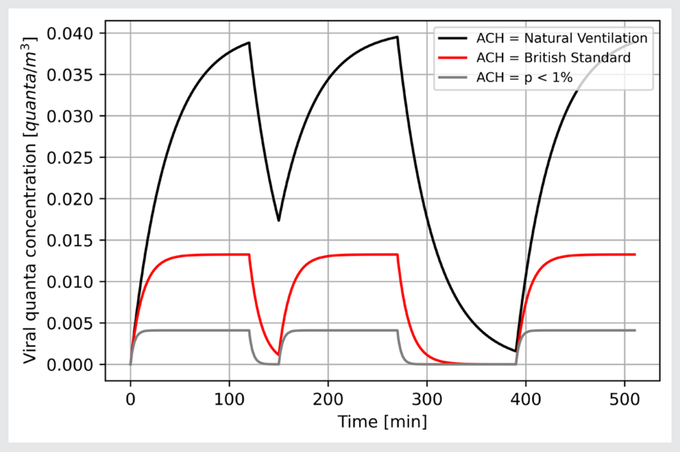

Figure 4.1. Temporal evolution of the concentration for different ventilation rates.

After the analysis of the evolution of the concentration of infectious doses with time, the accumulated infection probability as a function of the available ACH is calculated. The results are displayed in Figure 4.2.

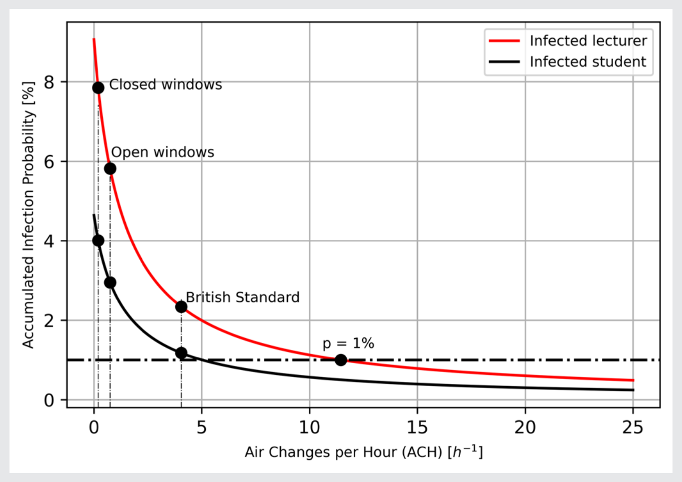

Figure 4.2. Temporal evolution of the concentration for different ventilation rates.

In the natural ventilation case, the infection probability is of about 6%, which means that there would be one infected by the end of the day. For ventilation according to the standard recommendations, the infection probability is more than two times lower than that of natural ventilation (open windows), leading to 1 person infected at the end of the day. For the ACH corresponding to a 1% infection probability, no infections would occur after a school day.

Nevertheless, assuming that the lecturer teaches 4 days in a row while being infectious (a reasonable hypothesis given the typical time elapsed between infection and the first symptoms), the scenario changes as follows: with natural ventilation, the accumulated probability would increase to about 21%; following the recommendations by the standard, the probability grows to 9%; while for the ACH corresponding to a 1% infection probability, the accumulated probability would be approximately 4%. Recalculating the amount of infected people after 4 days yields 5, 2 and 1 infected people for the abovementioned cases, respectively.

When considering the no ventilation scenario and accounting only for the possible leaks within the classroom (taken as 0.2 ACH [17] [18]), the daily infection probability is of 7.8%, much higher than for the rest of scenarios. Hence, after a school day there would be 2 infected students while after the fourth school day there would be 7 infected students.

The next studied scenario is one where the infectious person is a student instead of the teacher. In that particular case, due to the quanta exhalation ratio of a student being approximately half of that of the teacher, the infection probability would be halved as well (see Figure 4.2). Then, after the school day, there would be 1 and 0 infection cases for natural ventilation and the ventilation recommended by the standard, respectively. Additionally, computing the accumulated probability during 4 days yields 3 and 1 infection cases instead.

A last case, consistent with the recommendations given by Spanish authorities following the recent cold wave, is considered. The recommended strategy is based on “intermittent ventilation”, where windows are opened for 10 minutes at the end of every hour. Hence, the time intervals for the present case are modified to adapt to the 50’ – 10’ periods where windows are closed and open, respectively. Moreover, the open windows period is also applied to the playground and lunch breaks. When the windows are closed, a ventilation rate of 0.2 ACH is used [17] [18], equivalent to the air leaking from/to the classroom. In contrast, when the windows are open, the ventilation rate considered is 8 ACH. This ventilation rate was referenced in literature as the maximum rate obtained in a classroom with open windows, A/C on and fans to enhance air circulation [18]. Thus, the results arising from such “intermittent ventilation” case would represent an optimistic case in terms of ventilation rate. As shown by [17], the ventilation rates in natural ventilation scenarios are highly variable and difficult to control.

The evolution of the concentration with time in both the “intermittent ventilation” scenario (again, with the infected person being the teacher) and following the recommendations given by the standard is plotted in Figure

4.3. It is observed that the maximum concentration values reached by following the standard recommendations are approximately three times lower than those obtained by “intermittent ventilation”. Moreover, a 4.8% infection probability is calculated for such scenario, which would yield 1 infection case by the end of the school day and 4 cases after 4 days, in contrast to the 1 and 2 infection cases that would result from following the recommendations by the standard.

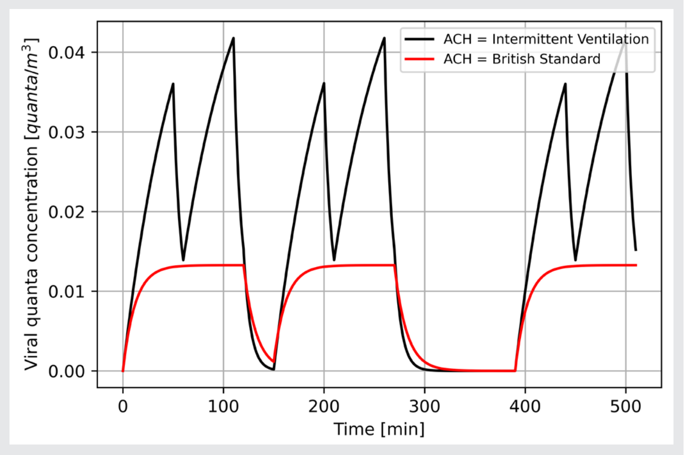

Figure 4.3. Temporal evolution of the concentration for different ventilation rates.

4.3. Bar/Restaurant

Two different situations are analysed for a small bar/ restaurant. A 90 m^2 restaurant with a total volume of 270 m3 is chosen, with a capacity of 35 customers, none wearing a face mask, and one waiter, with a face mask. The restaurant service is divided in two separate shifts of 2 hours each. The first analysed scenario is the case where the waiter is infected. In the second scenario, one of the customers of the first shift is infected and there are no infected customers in the second shift.

Since the customers are different between the first and second shift, the risk of infection must be calculated separately for each, considering that, at the beginning of the first shift, the restaurant’s indoor air would be free of quanta while at the start of the second shift there would be an initial concentration of quanta. Figure 4.4 illustrates the evolution of quanta concentration with time for both cases.

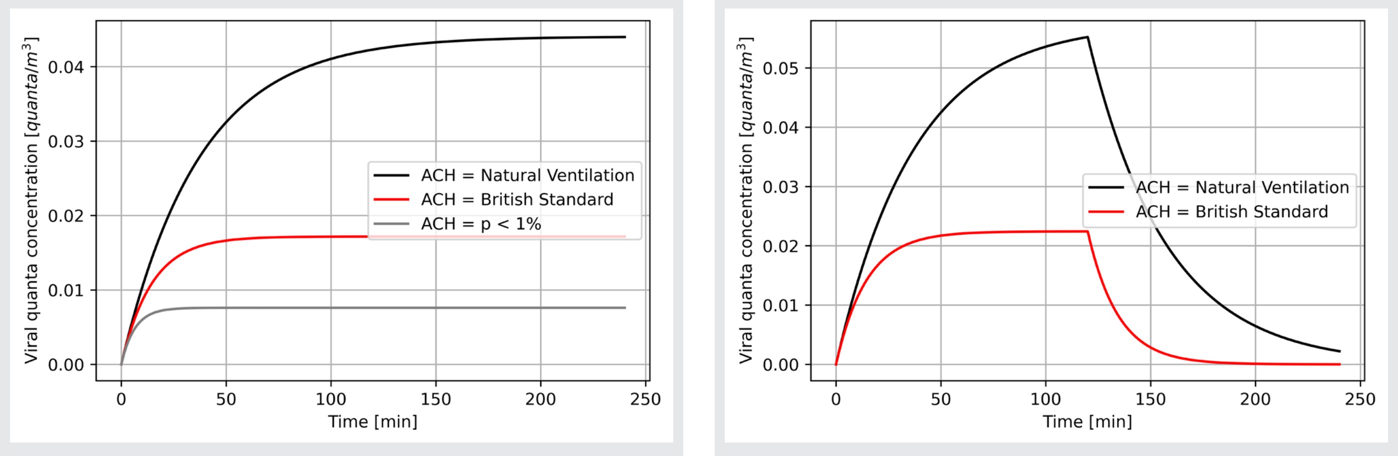

Figure 4.4. Temporal evolution of the concentration for different ventilation rates. Left graph for the infected waiter and on the right for the first shift infected customer.

Figure 4.5 illustrates the evolution of the infection risk for each shift as a function of the ventilation rate for each of the analysed cases. As shown in Figure 4.4 (left), the concentration of equilibrium is reached faster when the ventilation rate is increased. Therefore, the difference in infection probabilities between the first and second shift reduces with the increment in ventilation rate until no difference is appreciated (see Figure 4.5).

For the infected customer case, the infection risk also decreases with the ventilation rate. Nonetheless, as there is no quanta release during the second shift, the infection probability curves decrease is steeper and the offset between the first and second shift curves becomes more visible.

In Figure 4.4 (right), the curve corresponding to the second shift of the infected customer case, the 1% infection probability curve is not plotted as the ventilation rate recommended by EN 15251: 2007 entails a probability already lower than 1%.

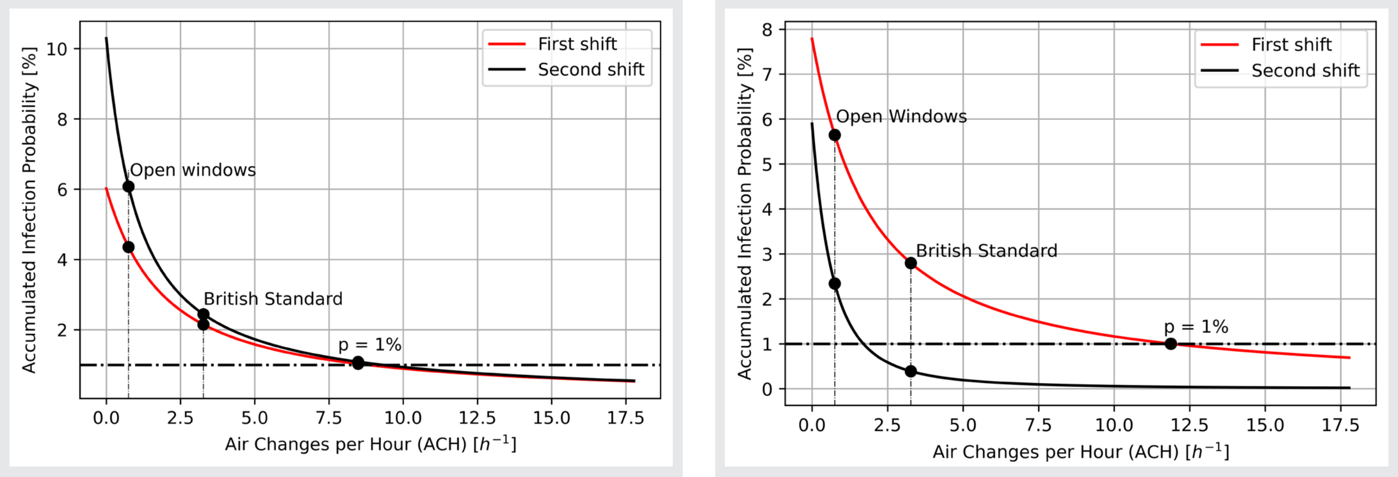

Figure 4.5. Risk of infection evolution for different ventilation rates for the first and second shift. Left graph for the infected waiter and on the right for the first shift infected customer.

It is concluded that an adequate ventilation system is fundamental to minimize infection risk. Specifically, as clients are not wearing a face mask, the quanta infectious doses released must be dissipated as soon as possible to prevent clients from infecting, especially during the subsequent shift.

Figure 4.5 shows, in line with the results of the classroom case, that the risk of infection resulting from compliance to the standard is at least half of that from natural ventilation. Regarding the number of people infected and considering for each case the ventilation rates corresponding to natural ventilation, ventilation rates established by the standard and ventilation required to have 1% risk of infection, the results obtained are shown in Table 4.2.

	Situation 1: Waiter infected wearing a face mask			Situation 2: 1st shift customer infected not wearing a face mask		
Ventilation	Natural	EN 15251: 2007	<1%	Natural	EN 15251: 2007	<1%
First shift	2	1	0	2	1	0
Second shift	2	1	0	1	0	0

Table 4.2. Number of people infected in the bar/restaurant case.

4.4. Office

The last studied case is that of an office. The office is analysed for a period of 7h with different ventilation rates, with an area of 260m^2 and a volume of 780m^3 and occupied by 40 people (where one of them is infected). Two different situations are compared, the first one considering all the employees wearing a face mask and the second one assuming none of them do so.

Figure 4.6 shows that the equilibrium concentrations for the same ventilation rates are twice as high when employees are not wearing a face mask than when they do (for the cases with fixed ACH).

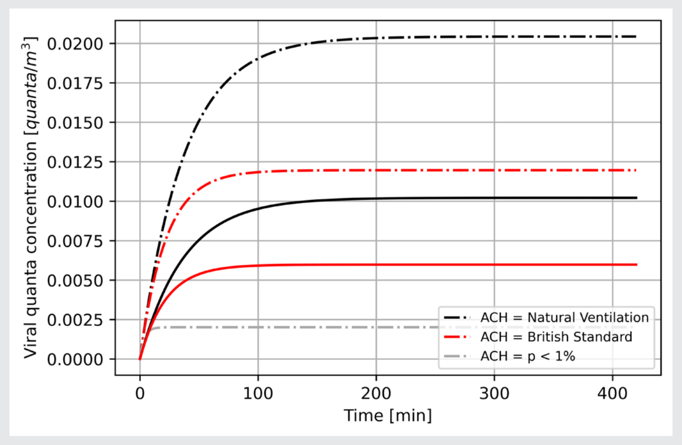

Figure 4.6. Temporal concentration evolution for different ventilation rates (dashed lines corresponds to the NOT wearing mask case).

Since following Building Regulations Part F recommendations coupled with wearing a face mask yields a probability of infection close to a 1%, such concentration curve is not included for better clarity of the results presented in Figure 4.6.

Figure 4.7 clearly illustrates the reduction of the infection risk when wearing a face mask. For instance, the ACH required to reach a 1% infection probability is more than six times lower with face masks on.

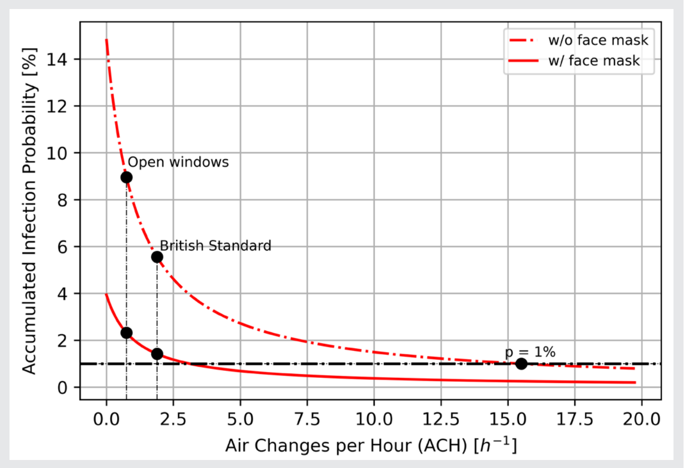

Figure 4.7. Risk of infection evolution for different ventilation rates and employees wearing or not a face mask.

Thereby, when employees are not wearing a mask there would be 4, 2 and 0 infections for the natural ventilation case, ACH established by the standard and ACH corresponding to a 1% infection probability, respectively. However, if all the employees are wearing a mask, there would be 1 person infected both for the natural ventilation case and the ventilation rate recommended by the standard (which in this case entails an infection probability of approximately 1.5%).

Again, if the assumption exposed above in the classroom case in which an employee goes to the office for four days while being infectious, there would be 13, 8 and 2 people infected when no employees are wearing a face mask respectively for the natural ventilation, standard recommendation and 1% risk of infection case. However, assuming that all employees are wearing a mask, the number of people infected would be 4 for the natural ventilation and 2 for the ACH established by the standard.

4.5. Sensitivity of the results

The model used in this article is particularly appropriate to perform relative analyses or comparison of the impact of several risk mitigation strategies, as opposed to performing absolute analyses for which the uncertainties in several parameters need to be propagated to the calculated infection probabilities.

Such uncertain parameters are, for example, the inactivation and deposition rates. Furthermore, the breathing rate also entails some variability as, despite being described as a function of age and type of physical exercise, it depends on individual metabolic and pulmonary variables that are hard to quantify and generalize. Nevertheless, the parameter with the highest uncertainty is the quanta exhalation rate ([14] and [15]). In particular, proposed values range from a few tenths of quanta per hour to approximately a thousand quanta per hour for a super spreader.

For all the above, it is important to note that the probabilities given by the model should not be taken as an exact prediction but rather as an order of magnitude. To prove the latter, the office study case is revisited focusing on two variables, ACH and quanta exhalation rate. Now, instead of a probability curve, the desired outcome is a cloud of points (infection probability) for different pairs of ACH and quanta exhalation rates.

The ACH are modelled as a uniform distribution bounded between two arbitrary values, chosen at 0 and 6 ACH, where every possible value is equiprobable. In contrast, the quanta exhalation rate is modelled as a normal distribution with an average of 25 quanta·h^{-1} and a variance such that 0 quanta·h^{-1} and 50 quanta·h^{-1} match the 3σ probability.

Figure 4.8 shows the results of a statistical analysis with N=10000 points for both of the abovementioned variables. For the sampling of ACH and due to its distribution being uniform, points can be taken randomly from the interval defined. However, for the quanta exhalation rate, values are sampled according to its probability density function. Thus, during the sampling more points are obtained that are close to the average than to the ends of the distribution.

Finally, the quanta exhalation rates to bind the cloud of points with two infection probability curves are calculated. This allows quantifying the potential variability in the results for the chosen parameter modelling.

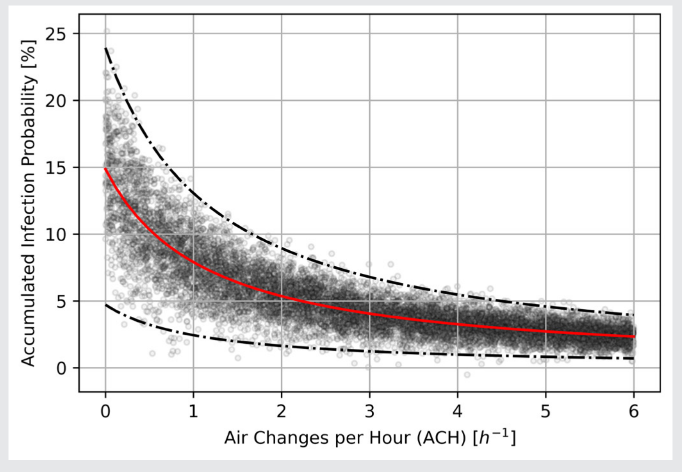

Figure 4.8. Results of a statistical analysis with N=10000 for pairs of quanta exhalation rates (normal distribution) and ACH (uniform distribution).

It can be concluded that the variability is lower at higher ACH values, which is in line with the results presented earlier in the quanta concentration analyses. At 0 ACH the variability is at its highest and the infection probability varies between 5% and 24% with 15% for an average quanta exhalation rate (25 quanta·h^{-1}). Nonetheless, the area with a higher density of points includes probabilities ranging from 10% to 18%.

5 Conclusions

It is shown that the model presented herein is not only an effective tool to analyze and size a mechanical ventilation system (airflow requirements) in the context of the current pandemic, but also to evaluate the relative effect of different measures to prevent the spread of the virus (exposure time, use of face masks, number of ACH).

The model consists of an extension of that already mentioned in the Analytical Model section. On the one hand, the model has been implemented in Python to offer a greater flexibility when setting the study cases and the possibility of a further detailed analysis using the presented plots and figures. On the other hand, the base features of the model have been extended by adding the possibility to define events by segments or intervals with variable parameters (quanta exhalation rate, air changes per hour, breathing rates, etc.), for which the accumulated infection probabilities can be computed. Additionally, the “One Box Model” equations have been modified to include initial quanta concentrations of arbitrary value.

The results show the importance of adequate ventilation and reinforce the advantages of mechanical ventilation systems. In particular, mechanical ventilation allows to obtain higher ventilation rates than natural ventilation (in most cases), which leads to a lower infection risk. Furthermore, mechanical ventilation prevents noise and pollution from outdoors (if air is filtered) from entering the room. Although literature shows that natural ventilation, considered as open windows, may vary from almost 0 to more than 10 ACH under specific conditions, it also highlights the limited control over such conditions and, thus, on the amount of ACH provided. Therefore, mechanical ventilation is especially appropriate thanks to its ability to set the ventilation rates accurately and according to the requirements regardless of external factors (number, size and position of the windows, interior-exterior thermal gradient, etc.).

The impact of complying with the standards has been evaluated in terms of infection risk. It is shown that the ventilation requirements set by British standards can reduce more than twofold the infection risk when compared to the open-windows case. If a lower infection risk is desired, the installation must then deliver higher ventilation rates than those defined by the standard. However, it is important to note that this standards was not devised in the context of a global pandemic with the associated risk of airborne transmission.

Concerning the uncertainty of the results, section 4.5 shows the complexity of quantifying the quanta exhalation rate, leading to a significant variability of the results. Nonetheless, the sensitivity analysis performed on the results of the studied cases allows to evaluate the infection probabilities relatively (one case versus another) as well as absolutely, by accounting for the upper and lower limits of the confidence interval for any given case.

Due to the amount of media attention received, the school case of study is the most appropriate to draw a conclusion on the requirements for infection risk mitigation. In that sense, it is shown that mechanical ventilation delivering ventilation rates according to the standards manages to eliminate most of the viral concentration during a playground break (30min) and completely removes the infectious particles during the two hour-long lunch break. In comparison, the natural ventilation scenario (open windows) is not capable of completely removing the concentration of virus during any of the breaks.

6 Bibliography

[1] "Organización Mundial de la Salud," [Online]. Available: https://www.who.int/es/news/item/29-06-2020-covidtimeline. [Accessed 12 2020].

[2] "Organización Mundial de la Salud," [Online]. Available: https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations. [Accessed 12 2020].

[3] J.L. Jimenez, COVID-19 *transmission patterns only seem explainable by aerosols*, https://docs.google.com/document/d/1Kx4Mka_nORa8LlEwziRYZxOX0J8_fFfgnt-9TBjxusc/edit.

[4] J.L. Jimenez, FAQs *on Protecting Yourself from COVID-19 Aerosol Transmission*, http://tinyurl.com/faqs-aerosol, Versión 9/12/2020.

[5] J.L. Jimenez, COVID-19 *Aerosol Transmission Estimator*, https://tinyurl.com/covid-estimator, Versión 28/11/2020.

[6] R. Zhang, Y. Li, A. L. Zhang, Y. Wang and M. J. Molina, "Identifying airborne transmission as the dominant route for the spread of COVID-19," *PNAS*, vol. 117, no. 26, pp. 14857-14863, 2020.

[7] Liu, Y., Chen, Y., et al, "Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals," *nature*, vol. 582, pp. 557-560, 2020.

[8] S. L. Miller, W. W. Nazaroff, J. L. Jimenez, A. Boerstra, G. Buonanno, S. J. Dancer, J. Kurnitski, . L. C. Marr, L. Morawska and C. Noakes, "Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event," *Indoor Air*, 2020.

[9] Yuguo Li, et al., "Evidence for probable aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant-full," *medRxiv*, 2020.

[10] S. E. Hwang, J. H. Chang and J. Heo, "Possible Aerosol Transmission of COVID-19 Associated with an Outbreak in an Apartment in Seoul, South Korea, 2020," *International Journal of Infection Diseases*, 2020.

[11] K. Nissen, K. Janina, D. Akaberi, T. Hoffman, J. Ling, A. Lundkvist, L. Svensson and S. Erik, "Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards," *Nature: Scientific Reports 10*, 2020.

[12] G. Jiang, C. Wang, L. Song, X. Wang, Y. Zhou, C. Fei and H. Liu, " Aerosol transmission, an indispensable route of COVID-19 spread: case study of a department-store cluster," *Frontiers of Environmental Science & Engineering*, vol. 15, no. 46, 2021.

[13] "Organización Mundial de la Salud," [Online]. Available: https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-how-is-it-transmitted. [Accessed 12 2020].

[14] G. Buonnano, L. Stabile and L. Morawska, "Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment," *Environment International*, vol. 141, 2020.

[15] G. Buonanno, L. Morawska and L. Stabile, "Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications," *Environment International*, vol. 145, 2020.

[16] A. Davies, et al., "Testing the efficacy of homemade masks: would they protect in an influenza pandemic?," *Disaster Med Public Health*

Preparedness, vol. 7, no. 4, pp. 413-421, 2013.

[17] C. Howard-Reed, L. A. Wallace and W. R. Ott, “The Effect of Opening Windows on Air Change Rates in Two Homes,” *Journal of the Air & Waste Management Association*, vol. 52(2), pp. 147-59, 2002.

[18] H. Guo, L. Morawska, C. He and D. Gilbert, “Impact of ventilation scenario on air exchange rates and on indoor particle number concentrations in an air-conditioned classroom,” *Atmospheric Environment*, vol. 42, no. 4, pp. 757-768, 2008.

[19] H. Dai and Z. Bin, “Association of the infection probability of COVID-19 with ventilation rates in confined spaces,” *Building Simulations*, vol. 13, pp. 1321-1327, 2020.

[20] Suit M., et al., “Airborne SARS-CoV-2 Is Rapidly Inactivated by Simulated Sunlight,” *The Journal of Infectious Diseases*, vol. 222, no. 4, pp. 564-571, 2020.

[21] T. L. Thatcher, A. C. Lai, R. Moreno-Jackson, R. G.Sextro and W. W.Nazaroff, “Effects of room furnishings and air speed on particle deposition rates indoors,” *Atmospheric Environment*, vol. 36, no. 11, pp. 1811-1819, 2002.

[22] ANSI/ASHRAE, *The Standards for Ventilation and Indoor Air Quality*, ANSI, 2019.