ORIGINAL ARTICLE

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A theoretical study of air change in Italian schools: energetic aspects, air quality and Sars-CoV-2 infection risk assessment Part 2

Approccio teorico sul ricambio d'aria nelle scuole italiane: aspetti energetici, qualità dell'aria e valutazione del rischio di infezione da Sars-CoV-2 Parte 2

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Abstract

Schools are definitely among the highest densely occupied indoor environments with continuous occupation. According to the present knowledge about airborne carried diseases, the infection risk for SARS-CoV-2 could reach significant values especially under poor ventilating conditions. The infection risk can be reduced by dilution of the viral agent concentration, provided by air-change, whether by infiltration, manual aeration (windows opening) or mechanical ventilation. The present work, after a brief survey on ventilation requirements for schools in Italy, compares different strategies to account for dilution both in terms of infection risk control and of energetic and comfort aspects. The paper is split into two parts: this part 2 examines air quality and Sars-CoV-2 risk assessment, while the first one dealt with energetic aspects. Each part has its own specific nomenclature and methodology.

Keywords:

- SARS-CoV-2
- Mechanical ventilation
- Air change
- Infection risk
- Airborne disease
- Schools

Sommario

Le scuole sono sicuramente tra gli ambienti a più elevato tasso di occupazione continuo. Secondo le attuali conoscenze a proposito delle infezioni che si possono diffondere per via aerobica, il rischio di contagio per SARS-CoV-2 può raggiungere valori elevati soprattutto negli ambienti con scarsa ventilazione. La riduzione del rischio si può ottenere anche attraverso la diluizione della concentrazione dell'agente virale, che avviene per infiltrazione d'aria, aerazione (apertura delle superfici mobili, finestre), ventilazione meccanica. Il lavoro, dopo una sintetica disamina dei requisiti italiani di qualità dell'aria nelle scuole, confronta le diverse strategie per la diluizione sia in termini di contenimento del rischio di contagio sia in termini energetici e di comfort. L'articolo si divide in due parti: questa parte 2 tratta i temi della qualità dell'aria e del rischio di infezione da Sars-CoV-2, mentre la prima parte ha analizzato gli aspetti energetici. Ciascuna parte ha la propria terminologia e metodologia.

Parole chiave:

- SARS-CoV-2
- Ventilazione meccanica
- Ricambio d'aria
- Rischio di infezione
- Malattie trasmesse per via aerea
- Scuole

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NOMENCLATURE

- *C:* volume concentration of infectious quanta [quanta m^{-3}]
- *k:* removal contribution factor in space by deposition (gravitational settling) [h^{-1}]
- *N:* number of successive equal events, considered independent
- n_0: initial level of infectious quanta present in volume V (at t = 0) [quanta]
- *P:* probability of infection referred to any exposed fully susceptible individual
- *p:* pulmonary inhalation rate by one susceptible individual [m^3h^{-1}]
- *q:* infectious quanta emission rate by one asymptomatic infected individual [quanta h^{-1}]
- *R*:* average number of susceptible potentially infected people from one contagious person (reproduction index under the specific situation)
- *t:* time [h]
- *V:* schoolroom volume [m^3]
- *λ:* removal contribution factor in space by viral inactivation [h^{-1}]
- *T:* temperature [°C]

Introduction

Recently a wide scientific production has taken place on peer-reviewed journals on the subject of risk assessment for Sars-CoV-2 infection in indoor environments.

It is ever more widely supported that the SARS-CoV-2 virus can survive as airborne [1]. A consistent review study [2] analyzes how different factors, such as ventilation rates, direction of airflows, and relative position of susceptible and infected individuals can affect the probability of infection in the indoor environment with several airborne diseases. Several papers were published on the probability of infection in indoor environments according to different HVAC plant types [3], and special attention was also given to the context of school rooms. Virologist Christian Drosten recently stressed on the importance of ventilation for German schools [4], stating that ventilation is a major prerequisite to run schools in a healthy mode.

ASHRAE published a consistent set of papers from March to June 2021, dealing from both technical and computational points of view, with the aspects of infection risk in indoor environment served by single zone HVAC systems. The first two papers focus on the description of the mechanism of infection and the of quanta emission rates [5] and on the aerosol distribution [6]. The following two papers draw the attention on minimizing the disease transmission in high occupant density environments, through the Wells-Riley model [7]. A modified version of this model is presented to deal with specific and distinct airborne exposure scenarios and to protective measures [8], those being both facility-related ones such as increased air change rates or filters on recirculated air, and occupant-related ones such as different filtration levels of protective face masks.

In 1934 Wells carried out experiments showing that liquid particles expectorated by an individual and greater than 100 µm, called droplets, would fall to the ground quickly, while particles smaller than 100 µm would evaporate before they could reach the ground forming what are called droplet nuclei that could float in the air for hours or even days; his work became fundamental for understanding the transition between droplets and droplet nuclei [9]. In 1978 Edward C. Riley developed an airborne infection model using an epidemiological study of a measles outbreak [10]. Following developments of the so called Wells-Riley model adjusted the technique with dose-response models to provide a more complete risk assessment tool. There has been a lot of discussion on the drawing of a line between droplet and droplet nuclei/airborne transmission. WHO (World Health Organisation) and the CDC (the Centers for Diseases Control and Prevention) set this line at 5 µm of mean particle diameter. However relative humidity RH and air temperature play a great role in determining this transition, by affecting the evaporation and falling rates. With special regard to virus droplet nuclei, temperature has also its biological effect on the survival rate; for example, lower temperature (7-8 °C) seems to be the ideal condition for airborne influenza survival, while moderate (20-24 °C) and higher (> 30 °C) temperatures are associated with an increase in the rate of protein and nucleic acid inactivation.

As to the viral load and infectious dose, in 1955 Wells suggested the concept of quanta infection as the unit of measure of the infectious dose [11]; the quantum of infection is a measurement of the ability of inhaled particles to cause infection, and must not be confused with the number of infectious particles released from the source or inhaled by the recipient. The idea of quantum of infection was used in the Wells-Riley equation, which assumes a well-mixed environment (i.e., droplet nuclei are instantaneously and evenly distributed in a space). Wells defined the quantum of infection as being the infectious dose capable of inducing a probability of infection of 0.632 ($1 - 1/e$) when inhaled by a fully susceptible individual. The main limitation for the Wells-Riley model application is the estimation process of the quanta generation rate by an infected subject. This rate is usually estimated backwards from an outbreak case in which the attack rate is substituted back into the model. This backward estimation assumes that all infection cases are caused by airborne transmission; influencing factors, such as survival rate, deposition rate, etc., can cause the rate to vary widely in different cases. It is possible to build dose-response models following a toxicological approach that overcomes the shortcomings of the Wells-Riley model; a dose-response model is of course more flexible, but it needs the dose rate data that are not available in the early stages of a pandemic, and it takes quite a lot of experimental studies to derive the information needed to run those kinds of models. A dose response model could possibly be able to determine how some people can act as superspreaders, while in the case of Sars-CoV-2 this is not fully understood; however it is believed superspreading is a normal feature of disease spread, and it has been linked to several outbreaks, such as the 2003 SARS-CoV outbreak in Hong Kong and the 2015 MERS-CoV outbreak in South Korea.

When assuming the environment as "well-mixed" one should take into account that every environment represents a complex and dynamic set of interactions among the occupants, appliances, building envelope and furniture, and the HVAC system. Therefore the effects of plumes, convective forces, air supply velocity and people movements through the environment can strongly affect the concentration distribution of droplet nuclei in the space. Different types of air distribution (high induction, displacement) have very different effects that can be somehow defined by their ventilation efficiency; the well-mix assumption can yield accurate outcomes especially when referred to mixing ventilation.

Very interesting outcomes came from the study of face mask efficiency, revealing that common knit cotton masks have very low efficiency, 0.2 at most, while EOC (three-ply spunbound polypropylene mask), procedure and surgical masks scored efficiencies from 0.6 to 0.9. In any case the efficiency is always increased by the use of braces or fitter to enhance mask sealing. An interesting comparison can be carried out between the reduction in infection risk achieved through masks and the same effect of an increased ventilation rate. While an increased mask efficiency from 0.2 to 0.6 reduces the infection risk by one order of magnitude, it needs at least to increase the ventilation rate of an order of magnitude to achieve the same result.

Materials and methods

Ventilation rates

The first part of this work [12] specifically dealt with models and estimation of air change rates by infiltration, manual aeration and mechanical ventilation. This second part deals with the infection risk. Some assumptions were made, as specified hereafter.

As to mask efficiency, a uniform value of 0.5 has been assumed; it's a medium to low value if compared to those reported in [8], but it also accounts for adjustments due to the non hermetic sealing around mouth/nose given by the ability to wear a mask in the correct way: strict adherence to the rules is not likely to be continuously maintained in schools.

The infiltration rate is assumed to be 60 m^3/h, in between the values calculated for class 1 and 2 of glazing systems.

With respect to quanta emission rate the value of 8 quanta/h was assumed for an infected student and 50 quanta/h for the instructor. These values are slightly increased from those in the literature since the Delta variant, most likely to be dominant at the beginning of the school year 2021-22, is reported to be somewhat more contagious than the previous ones.

Unlike in previous papers where the reproduction index is considered, e.g. R^* in [3], here it is by far preferable to give the "individual probability of infection" P, since the exposed subjects can't be considered uniformly susceptible; some of the students might be vaccinated or might have been infected in the past. P refers to "fully susceptible individuals", because individuals who have had previous events of partial immunization respond differently and more attenuated to infectious situations.

All of the calculations were performed assuming the room environment as "well-mixed" [3], and "perfectly and instantaneous mixed flow". So viral (or CO_2) concentrations of the exhaust air, when windows are opened, are calculated by instantaneous mixing with the inlet fresh air. So it is likely that the calculated results can lead to more restrictive conclusions than reality.

Since the school is only attended in the mornings, the question arises as to what is the probability of infection for a single fully susceptible student subjected to several successive identical infections events (N) on a daily basis. The probability can be assessed as that of N independent events as per the following formula:

$$P(N\,events) = 1 - \left[1 - P(single\,event)\right]^N$$

It must be noted that for the specific case, where the probability is expressed with the Poisson formula (Wells-Riley) for evenly probable events, the same result is obtained by calculating the infection probability with respect to the sum of infection doses totally inhaled in the period.

As to the calculation of CO_2 concentration, a constant increase in concentration in respiration is assumed, namely 38 000 ppmv (difference in concentration between exhaled and inhaled air), see [13].

Results

Infection risk assessment

Infectious quanta concentration trend over time is calculated as extensively described in [3]; the same reference describes in detail how the Wells-Riley model is applied to calculate the individual probability of infection P. In agreement with the discussion in Reference 3, the values assigned to the removal contribution factors in space are: by deposition

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$k = 0.24$ h^{-1}; by viral inactivation $\lambda = 0.63$ h^{-1}; the initial level of infectious quanta present in volume V (at $t = 0$) is taken equal to zero. It is assumed that any opening of windows takes place at the end of each lesson hour.

A model was implemented in Matlab environment in order to perform the calculations based on the above discussed assumptions and then calculate the results.

The first results show the comparison of infectious quanta concentration in the room with and without mask for the students, the dilution of quanta being only provided by air infiltration, one student is infected. The inscriptions on the figures also report the individual risk of infection, that after a 5-hour class is equal to 0.086 without mask (Figure 1) and 0.022 with mask (Figure 2), showing a reduction by a factor of 4 due to the use of masks.

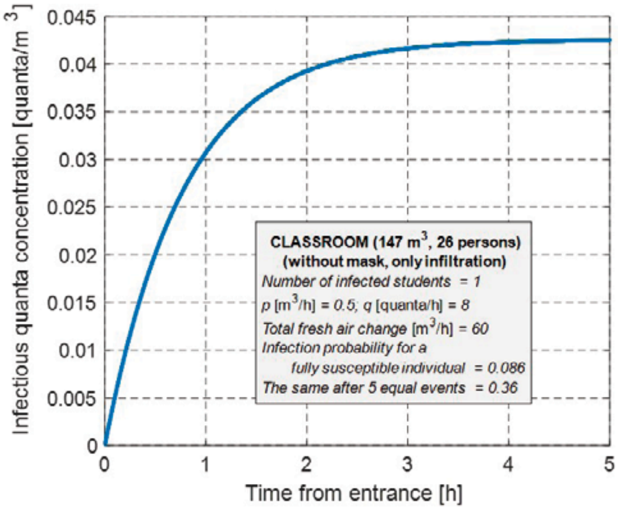

Figure 1 – Infectious quanta concentration; one student infected; infiltration air change only; no masks

Figura 1 – Concentrazione di quanta infettanti; uno studente infetto; sola infiltrazione d'aria; senza maschere

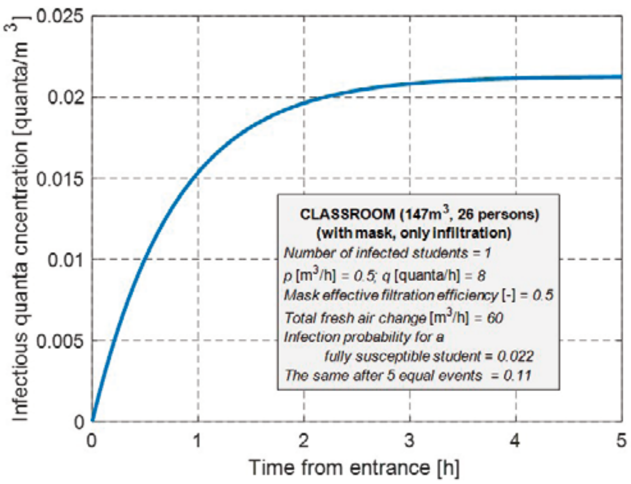

Figure 2 – Infectious quanta concentration; one student infected; infiltration air change only; with masks

Figura 2 – Concentrazione di quanta infettanti; uno studente infetto; sola infiltrazione d'aria; con maschere indossate

The second set of plots reports on the results with the same basic assumptions, but with mechanical ventilation of 40 m³/(h person). It can be appreciated that without mask the infection probability falls from 0.086 (without mechanical ventilation) to 0.017 (Figure 3), and with mask from 0.022 to 0.0042 (Figure 4). It is a reduction factor by 5, half an order of magnitude. Another interesting result is that mechanical ventilation not only can replace but even can exceed the effect of masks (comparing plots in Figure 1 and in Figure 3).

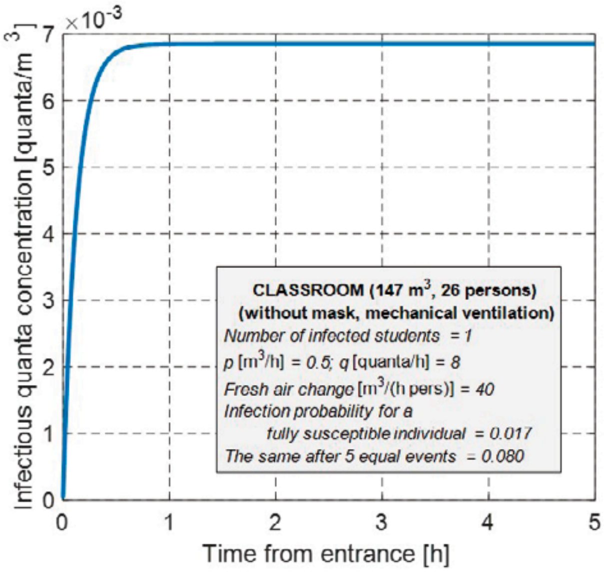

Figure 3 – Infectious quanta concentration; one student infected; mechanical ventilation; without masks

Figura 3 – Concentrazione di quanta infettanti; uno studente infetto; ventilazione meccanica; senza maschere

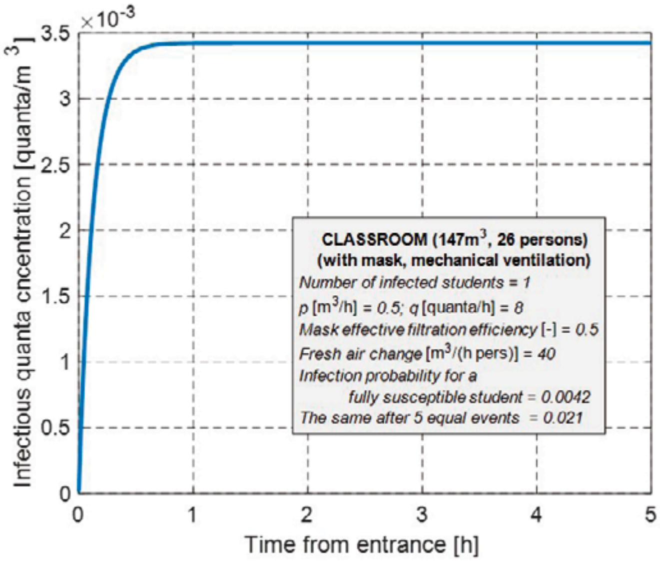

Figure 4 – Infectious quanta concentration; one student infected; mechanical ventilation; with masks

Figura 4 – Concentrazione di quanta infettanti; uno studente infetto; ventilazione meccanica; con maschere indossate

The third set of results in Figure 5 and Figure 6, shows the effect of manual aeration by windows opening. From [12] an aeration air change of 200 m³ for a 5-min opening time was selected as an average value. The comparisons between plots in Figure 3 and Figure 5, and subsequently between plots in Figure 4 and Figure 6, show how mechanical ventilation let the individual infection probability fall by a factor of 3, both with and without masks, with respect to natural ventilation by infiltration alone.

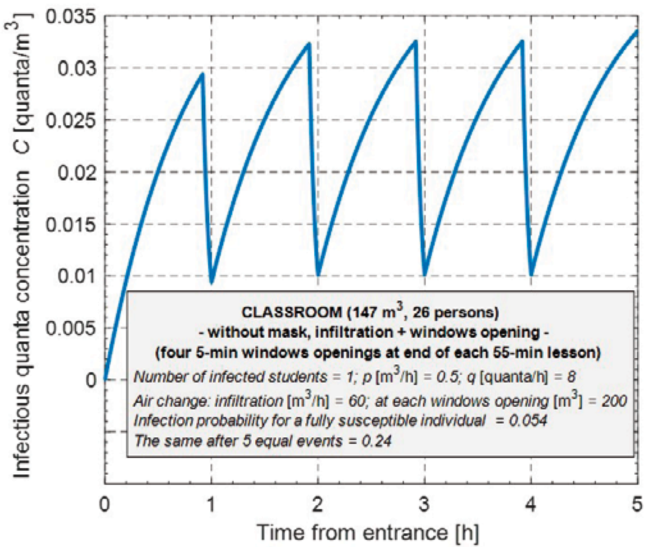

Figure 5 – Infectious quanta concentration; one student infected; infiltration and manual aeration; without masks

Figura 5 – Concentrazione di quanta infettanti; uno studente infetto; infiltrazione e aerazione manuale; senza maschere

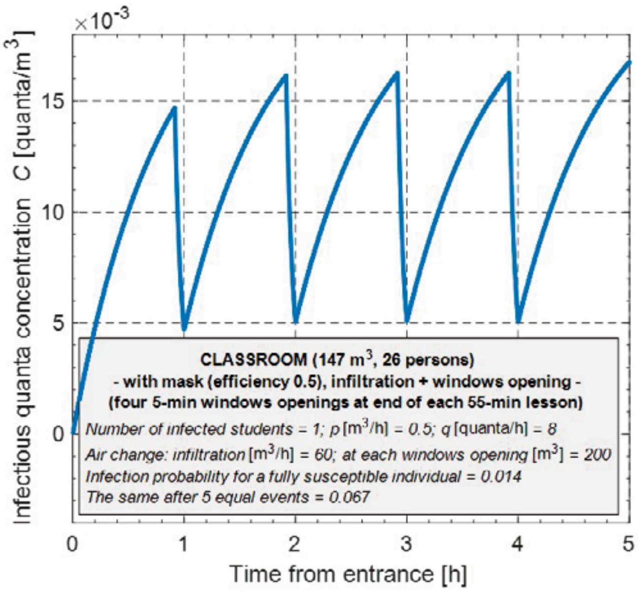

Figure 6 – Infectious quanta concentration; one student infected; infiltration and manual aeration; with masks

Figura 6 – Concentrazione di quanta infettanti; uno studente infetto; infiltrazione e aerazione manuale; con maschere indossate

The previous considerations are drawn for a single day event, and only for the exposure to the contaminated environment during the five hours of daily teaching. In the presence of an asymptomatic spreader, the same situation can repeat itself day after day. This situation is dealt with in the plots of Figure 7 and Figure 8. Only the case of infiltration and manual aeration is considered, for sake of brevity and due to the fact that Italian schools are seldom equipped with mechanical ventilation systems. As it can be seen, the effect of the amount of air supplied by aeration is relevant; if the manual aeration is low, due to climatic conditions or to short-term windows opening, the risk of infection can increase significantly by almost a factor of 2. As it could be expected, wearing masks reduce the infection risk by a factor of 4.

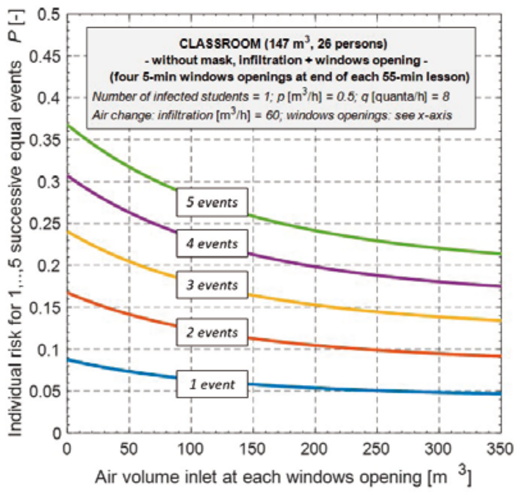

Figure 7 – Individual infection risk; one asymptomatic student infected; infiltration and manual aeration; without masks

Figura 7 – Rischio individuale di infezione; uno studente asintomatico infetto; infiltrazione e aerazione manuale; senza maschere

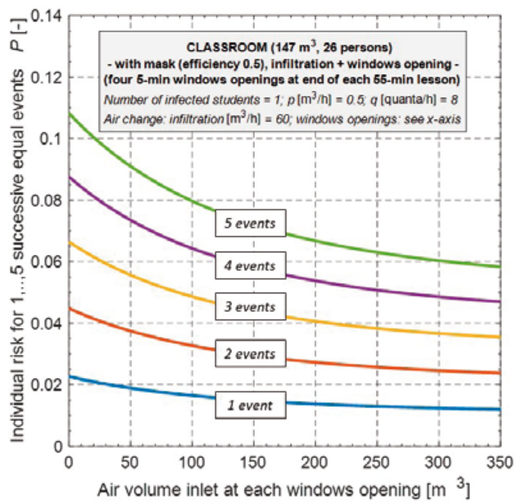

Figure 8 – Individual infection risk; one asymptomatic student infected; infiltration and manual aeration; with masks

Figura 8 – Rischio individuale di infezione; uno studente asintomatico infetto; infiltrazione e aerazione manuale; con maschere indossate

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A fifth set of results accounts for a different scenario, where the instructor is infected (instead of one student), and infiltration and aeration by windows opening are considered.

This situation is illustrated in the diagrams and inscriptions in Figure 9 and Figure 10.

It should be noted that, according to current Italian law, people under the age of 12 cannot be vaccinated. In this situation, in primary and secondary schools, it may happen that all students must be considered as fully susceptible. In this case, the calculation of the reproduction index R^* shows that, even with full mask on, an infected instructor can cause at least one infected student after a 2-hour lesson, while without mask an infected instructor could infect from 3 to 6 students, in the absence of mechanical ventilation.

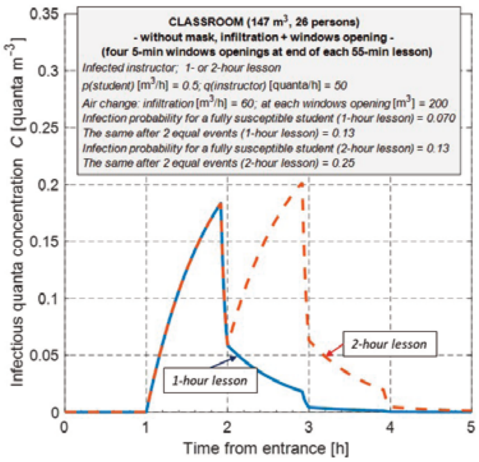

Figure 9 – Infectious quanta concentration; instructor infected; infiltration and manual aeration; without masks

Figura 9 – Concentrazione di quanta infettanti; docente infetto; infiltrazione e aerazione manuale; senza maschere

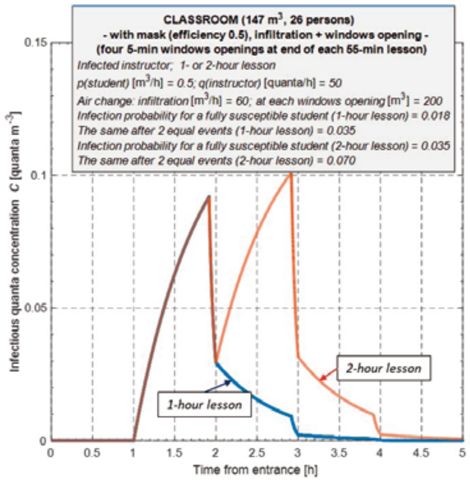

Figure 10 – Infectious quanta concentration; instructor infected; infiltration and manula aeration; with masks

Figura 10 – Concentrazione di quanta infettanti; docente infetto; infiltrazione e aerazione manuale; con maschere indossate

CO_2 concentration

Further calculations were carried out to determine the trend with time of CO_2 concentration in the classroom, in the presence of infiltration and manual aeration.

The assumption of perfect mixing is also maintained in these simulations. The plot in Figure 11 shows how infiltration does not provide a sufficient air change in order to maintain the target CO_2 concentration of 1000 ppmv. Shortly after entrance CO_2 concentration exceeds 1000 ppmv, and the assumed manual aeration by windows opening isn't able to bring this value below 1000 ppmv at the end of each opening. Figure 12 shows how even at the highest aeration rates (350 m³ in 5-min) the mean value of CO_2 concentration in 5-hour classes can't be possibly lower than 2000 ppmv.

Although an exact comparison is not possible due to some differences in the situations treated, these results of the trend in indoor CO_2 concentrations seem to be quite consistent with the experimental measurements reported in [14].

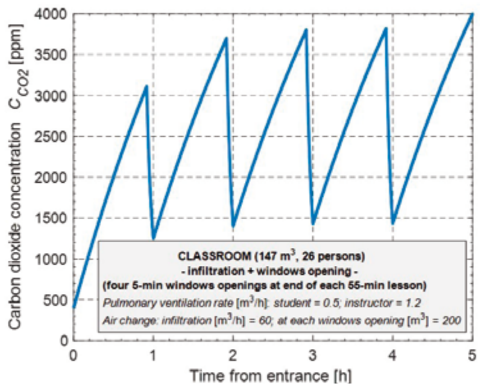

Figure 11 – CO_2 concentration; infiltration and manual aeration

Figura 11 – Concentrazione di CO_2; infiltrazione e aerazione manuale

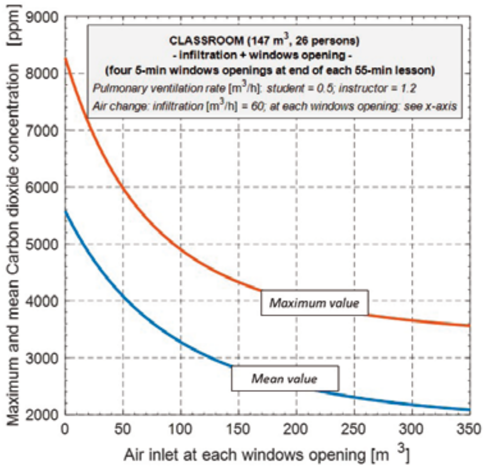

Figure 12 – Maximum and average CO_2 concentration; infiltration and manual aeration

Figura 12 – Concentrazioni di CO_2 massima a e media; infiltrazione e aerazione manuale

Discussion and conclusions

Although affected by the "well-mixed" assumption, which is common to most modelling in this field, the results presented above are interesting in many respects, namely:

- the effect of wearing masks is significant, allowing a reduction in quanta concentration and in individual probability of infection by a factor of 4;
- mechanical ventilation not only can "replace" the effects of masks, but can even exceed it;
- mechanical ventilation let the individual probability of infection drop by a factor of 3 with respect to natural ventilation/manual aeration;
- manual aeration isn't an effective way to prevent infections;
- manual aeration/natural ventilation can't provide acceptable indoor air quality, with respect to appropriate levels of CO_2 concentration.

CONFLICT OF INTEREST

The Authors declare the absence of economic or other types of conflicts of interest in all of the phases of the paper preparation.

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