A system dynamics analysis about the relationship between ventilation and the spread of COVID-19 in indoor spaces

Introduction

Our work presents a model still under development that captures the relationship between three key areas in connection to the management of airborne disease indoor transmission. These are: 1) ventilation characteristics, 2) infectious pathogen characteristics, and 3) required social activity. With our model, we expect to provide a learning platform for evaluating the effects of adjusting variables in order to create a COVID-19 safe indoor environment. Questions that can be answered by the use of our models are, for example, 1) for how long can the room be considered safe given level of activity and ventilation system, 2) what standards must be met by a ventilation system, and 3) what physical activities can be carried out in room given a specific ventilation system.

An increasing amount of empirical studies indicate that a significant fraction of COVID-19 transmissions happens indoors (Lelieveld et al., 2020; Bulfone et al., 2020; Bhagat et al., 2020). Dependent upon their size, infectious particles can linger in the air for hours or settle on surfaces which can lead to indirect COVID19 transmission between individuals (Zhou and Ji, 2021). There is now an increased consensus that especially smaller particles (less than 5 microns) are the main responsible of transmission and continuous growth of the pandemic (Eiche and Kuster, 2020).

Ventilation has been highlighted as an efficient method for reducing the transmission of airborne pathogens (Borro et al., 2021). However, the ventilation requirements that have so far been issued are generic (Sze To and Chao, 2010), present varying degrees of transparency about their scientific basis, and do not incorporate recent scientific information about particle emission patterns per respiratory outflow, ventilation system performance or personal protective measures (Mitze et al., 2020; Chu et al., 2020).

In Denmark, the population experienced a second wave of COVID-19 spread, which has declined to a level where the government, together with other parties, believe is sufficiently low to incrementally relax current restrictions. Suggested actions include the opening of public schools and technical academies for physical teaching on location. However, public schools have notoriously been identified as having poor indoor ventilation, condition in which airborne pathogens thrive (Morawska et al., 2020).

To effectively enable a safe and efficient return to indoor activities, infectious disease public policy should consider and include the effect of ventilation on the transmission of COVID-19 infection. Scientifically grounded guidelines are needed to define when is it safe to reopen group activities indoors and for which activities, what are the ventilation requirements for specific indoor activities, or what type of activities can be carried out given specific ventilation characteristics, for example. However, present global ventilation guidelines and precautionary measures such as the 1 meter rule or 15 minute limit definition of close contact (Jones et al., 2020), are of more uni-dimensional in character (Atkinson et al., 2009).

Methodological approach

By using system dynamics, we primarily build a model based upon an existing deterministic mathematical model for airborne contagion (Gammaitoni and Nucci, 1997), and its modifications to consider first enclosed spaces (Noakes et al., 2006), and the emission rates of infective particles depending on activity type and activity level (Buonanno et al., 2020). We aim to reproduce the results of these research with the intention of validating both our model structure and behaviour, to then extend the model by incorporating the physics of aerosol transmission under diverse ventilation conditions.

System dynamics has been used to represent the COVID-19 pandemic to model the effectiveness of social measures in pathogen transmission (Niwa et al., 2020) including isolation measures (Feng and Lu, 2020), explore the influence of prevention and control policies on pathogen transmission(Zhao et al., 2020). Our literature review did not reveal published work about system dynamics models representing relationship between ventilation characteristics and pathogen transmission.

Current state and partial results

The current version of the model is shown in Figure 1. Following a system dynamics representation, the model considers three main accumulations, the `Susceptible` and `Exposed` persons and the `Quanta` accumulation in a room. One quantum equals the infectious dose which is by definition the amount of viral particles which will infect 63% of the `Susceptible` exposed to it (Miller et al., 2020). Additionally, the model considers that the `Exposed` do not become infectious within the simulation time window (Noakes et al., 2006). The current model includes a mask scaling factor with an effect both on the quanta production by infected individuals and on the inhaling of quanta by the `Susceptible` (Buonanno et al., 2020). Decrease of airborne quanta in the room happens through several mechanisms being 1) new air brought in by the ventilation system, 2) particle filters in the ventilation system, 3) settling of droplets on surfaces, and 4) deactivation of quanta due to natural degradation, UV light and/or disinfectants (Bazant and Bush, 2020).

Figure 1 shows an example run of the model, representing the dynamics of an application example in Buonanno et al., (Buonanno et al., 2020). This example is of a $75m^2$ pharmacy with 14 customers inside. One infected person arrives at hour 2 and stays for 1 hour inside the pharmacy. All the people involved wore face masks.

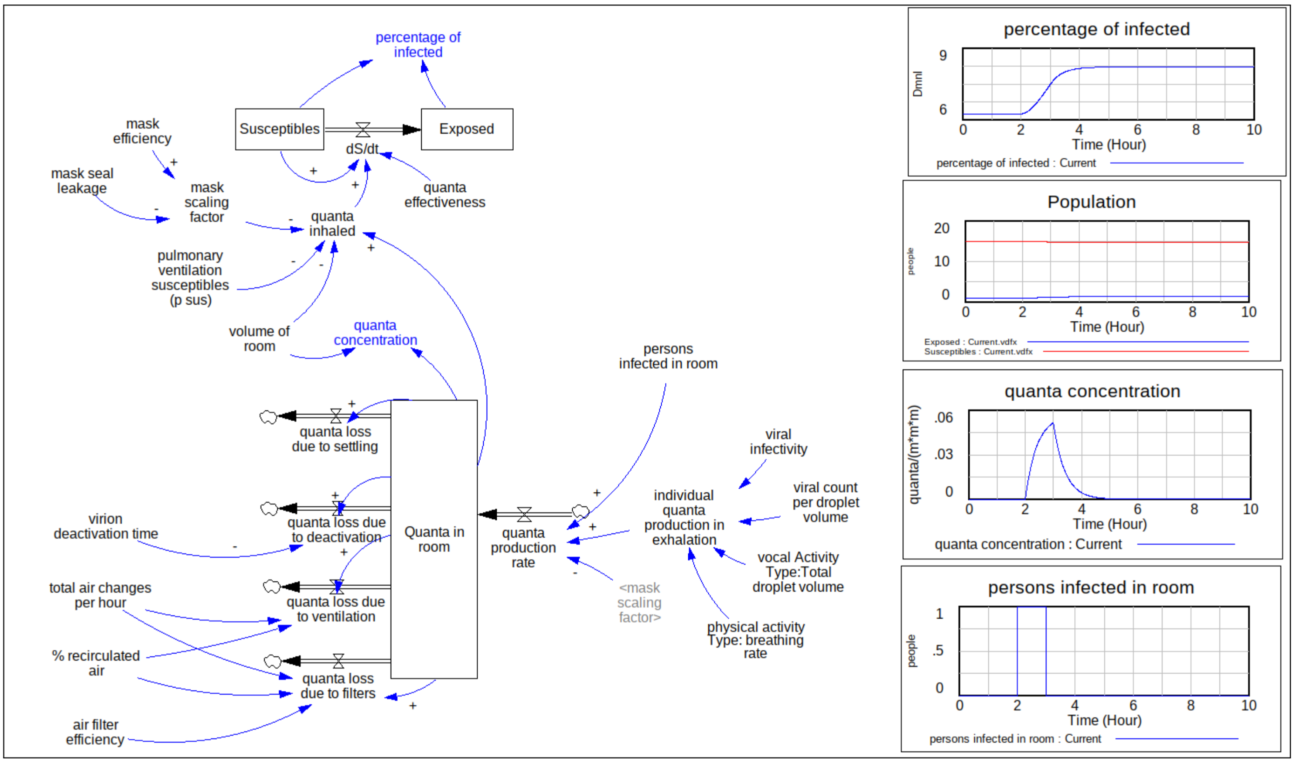

Figure 1: Model of ventilation effect on transmission

Current challenges and issues

Our research, is first in the process of validating the current model's behaviour against empirical studies, as per the example in Figure 1, and second we work towards including more relevant problem variables. We would like to highlight two present challenges: 1) the representation of continuous, non-time-related variables, and 2) the chosen level for model aggregation.

1. Our model represents time-related phenomena in a continuous way. However, this model also needs to represent other continuous phenomena that are not time related. For example, an infected person, when breathing, produces droplets of different sizes. Our model needs to calculate the settling speed of this distribution of droplets, yet we have not found **a way to sum up (integrate) according to a variable which is not time**.

2. Our model represents a level of aggregation that does not delve into individual particle behaviour, with assumptions such as perfect mixing of room air immediately after pathogen-containing air is exhaled by infected persons. The model does however address the contagion risk of a limited number of persons in a room. We would welcome any comments with respect to **the level of aggregations that has been chosen so far for the model**.

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