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

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Introduction

Our ongoing work presents a model that captures the relationship between three key areas related to airborne disease transmission indoors. These are 1) ventilation characteristics, 2) infectious pathogen characteristics, and 3) social activity. With our model, we aim to provide a learning platform for evaluating the effects of adjusting variables in order to create a pathogen (here: COVID-19) safe indoor environment. Questions that can be answered using our model could be 1) for how long can a room be considered contagion safe given certain levels of activity, 2) what standards must be met by a ventilation system, and 3) what physical activities can be carried out in room given specific ventilator settings.

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

Ventilation has been highlighted as both a cheap and efficient method for reducing transmission of airborne pathogens (Borro et al., 2021). However, recommended ventilation requirements issued by our health authorities are generic (Sze To and Chao, 2010). Furthermore, the guidelines present varying degrees of transparency about 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 second wave of COVID-19 spread that started in November 2020, had, in April 2021, eased off to a level that allowed for an incremental relaxation of COVID-19 restrictions. Suggested actions included the opening of public schools and technical academies for physical teaching on site. It is important to note that public schools have notoriously been known as having poor indoor ventilation; conditions in which airborne pathogens thrive (Morawska et al., 2020).

To effectively enable a safe and efficient return to indoor activities, public policies must consider the effect of ventilation on airborne disease transmission. Scientifically grounded guidelines are needed to define when it is safe to reopen indoor group activities considering activity levels and ventilation characteristics. 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). More granular detail into room specific conditions is required for conducting a reopening plan with better control over airborne disease transmission.

Methodological approach

System dynamics has been used to represent the COVID-19 pandemic to model the effectiveness of social measures to restrict 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.

Using system dynamics, we are building a model which translates the deterministic mathematical model for airborne contagion by Gammaitoni and Nucci (1997). The model is extended by considering enclosed spaces (Noakes et al., 2006) and the emission rates of infectious particles depending upon activity type- and level (Buonanno et al., 2020). Our current status is to reproduce their results with the intention of validating both our model structure and behaviour.

Current state and partial results

The current version of the model is shown in Figure 1. The model considers three main accumulations; people being either `Susceptible` or `Exposed` and the amount of viral particles (i.e. `Quanta`) accumulating in a room. One quantum equals the infectious dose which, by definition, is the amount of viral particles that leads to a

63% chance of infection (Miller et al., 2020). The model assumes that `Exposed` people do not become infectious within the simulation time window (Noakes et al., 2006). Included in the model is a mask scaling factor with an effect on both the quanta production exhaled by infected individuals and the inhaling of quanta by the `Susceptible` individuals (Buonanno et al., 2020). A decrease in airborne quanta can happen through several mechanisms, which are through 1) new air being 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.

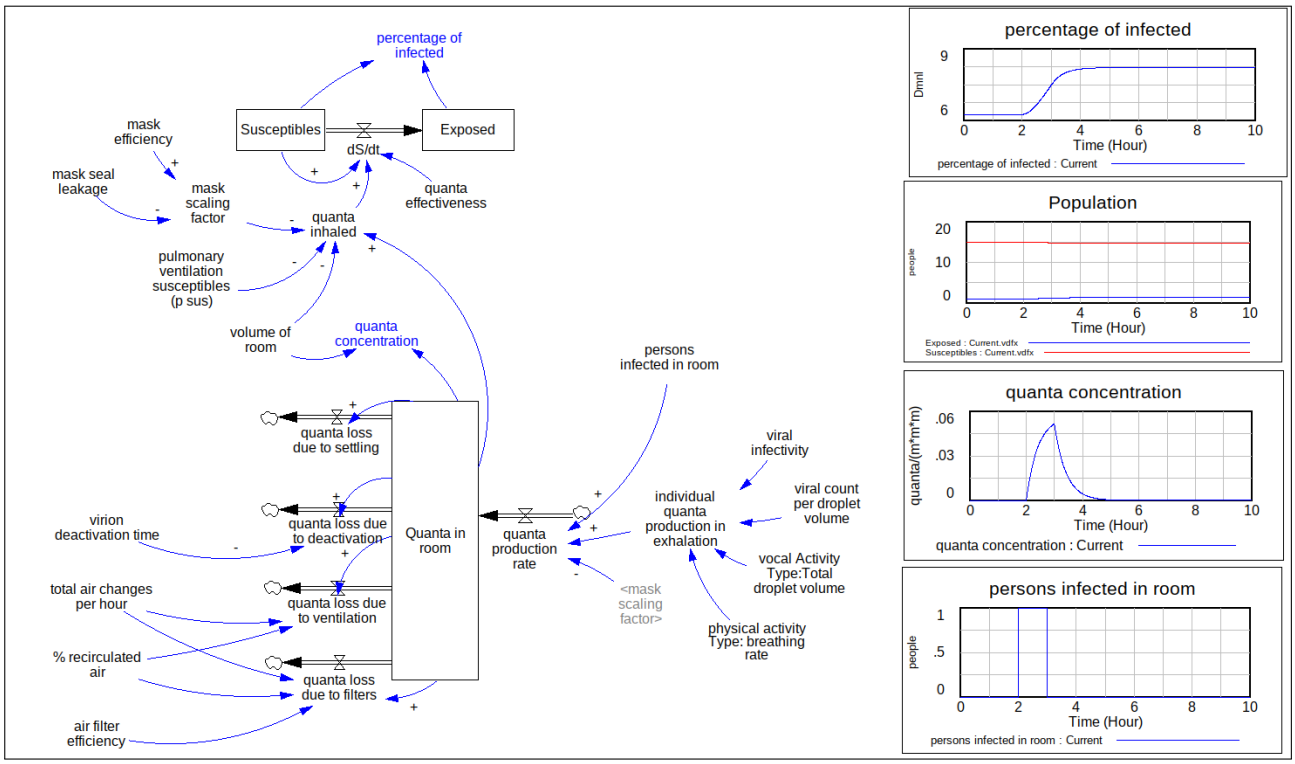

Figure 1: Model of ventilation effect on transmission

Current challenges and issues

We are now in the process of validating the current model's behaviour against empirical studies, as per example in Figure 1. Also, we work towards including more relevant problem variables. We would appreciate feedback on 1) the representation of continuous, non-time-related variables and 2) the chosen level for model aggregation. These are elaborated upon below:

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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