Population simulations of COVID-19 outbreaks provide tools for risk assessment and continuity planning

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Abstract:

Essential industrial sectors, healthcare systems, and government agencies must continue operations despite the risk of COVID-19 infection. They need tools to assess risks associated with operations, so they can devise emergency plans. We developed a population-based simulator to study COVID-19 outbreaks in enclosed environments and evaluate the effectiveness of preventative measures and action plans, such as pre-dispatch quarantine and removal of symptomatic cases.

Availability: The simulation tool is publicly available at http://github.com/ictr/covid19-outbreak-simulator and is free for non-commercial use.

Introduction

The worldwide COVID-19 pandemic has paused social and economic activities in many countries. Gathering at parks and restaurants can easily be put on hold; however, major industrial sectors, healthcare facilities, and government agencies have to function. They need tools to estimate risks of various operations and to help develop operational plans in the event of an outbreak.

While numerous epidemiological simulators are available, none are designed specifically for risk management and continuity planning. Partly in response to industry requests, we developed a population-based simulator to study the outbreak of COVID-19 at an individual level and subject to various preventative measures and post-outbreak operations. Statistics summarized from the simulations have been used to create emergency response plans for environments, such as Floating Production Storage and Offloading (FPSO) vessels.

Methods

The basic assumption of the simulator is a population in which everyone is susceptible although certain groups could be more infectious or more susceptible than others. One or more virus carriers are introduced to the population at the beginning of the simulation or after a certain period of quarantine. If anyone shows symptoms, he or she can be removed/quarantined or be kept in the population. A simulation stops when no one gets infected or shows symptoms or when everyone in the population is infected.

We model the incubation period of infected individuals with a lognormal distribution (Lauer, et al., 2020). Because it was reported that most pre-symptomatic transmission exposure occurred 1–3 days before a person developed symptoms and that viral loads are already at peak and declining at the onset of symptoms (Wolfel, et al., 2020), we designed an infectiousness model with transmissibility intensities that peak before the onset of symptoms and decline to a safe level 7 days later (Fig 1A).

Carriers who stay asymptomatic during their entire disease course tend to have much lower viral loads than symptomatic carriers (Liu, et al., 2020) and are less infectious, yet they could be a major factor for how wide-spread COVID-19 infection is. We allow asymptomatic cases to have production time (R0) ranging from 0.28 to 0.56, which is one-fifth the R0 of symptomatic cases, with transmissibility probabilities that peak at 4.8 days and stop after 10 days. Because the exact proportion of asymptomatic transmissions is currently unknown and expected to vary from population to population, we allow asymptomatic transmission to be set as a constant or vary along a distribution, with default values set to a normal distribution centered at 25%, with a 95% confidence interval (CI) from 10% to 40% (Ferretti, et al., 2020).

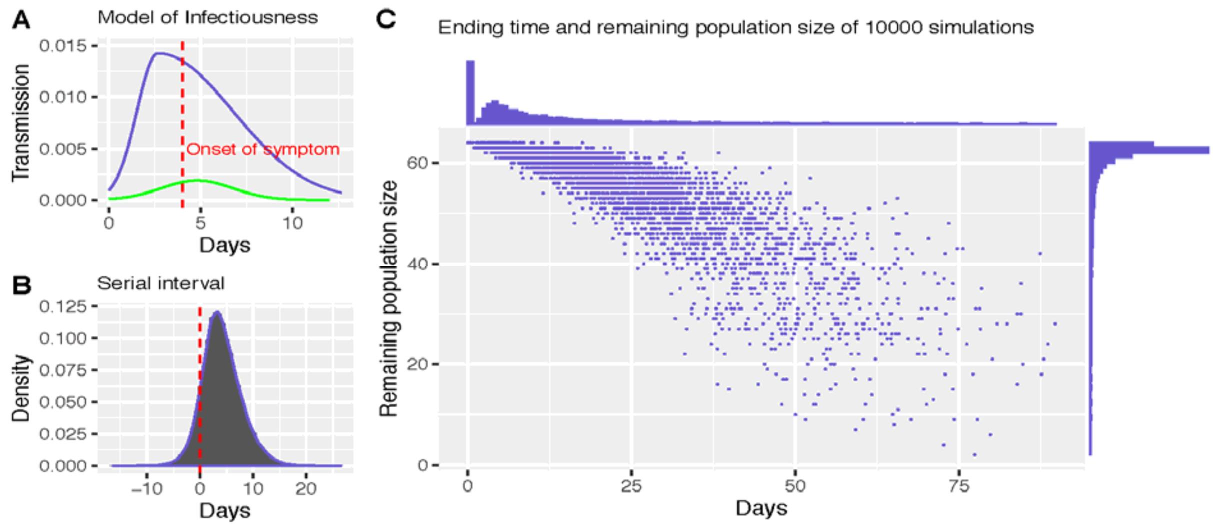
We validated our model with extensive simulations and compared characteristics of simulated datasets, such as generation time, serial intervals, and proportions of asymptomatic, pre-symptomatic, and symptomatic infections, with other reports and models. For example, Fig. 1B shows the distribution of serial intervals of 10,000 simulations. The distribution follows a normal distribution with about 12% of pairs showing negative serial intervals (the infected individuals show symptoms before the infector), which is consistent with the observed data (Du, et al., 2020). The proportions of asymptomatic, pre-symptomatic, and symptomatic transmissions are 6%, 48%, and 44%, respectively, with default parameters (Ferretti, et al., 2020) .

This simulator is provided as a Python package with a command-line interface. It is implemented in Python using an event-driven model that changes the states of individuals in a population. It can run tens of thousands of simulations on multiple processors in a few minutes, but the actual performance of the simulator depends on choice of parameters, especially the population size. The GitHub repository contains installation instructions, usage information, and details of the statistical models.

Results

The simulator tracks events such as quarantine, reintegration, infection, onset of symptom, and removal of symptomatic cases and records outputs, such as time of events and number of infected individuals for each infector. Numerous summary statistics are calculated from replicated simulations to answer critical questions needed for risk assessment and continuity planning.

For example, we used the default parameter settings with a population of size of 64 individuals that enters the FPSO without quarantine, with 10% to 40% of infected individuals never showing any symptoms, and prompt removal of symptomatic cases. Under those parameters and assuming one infected individual enters the FSPO at the start of the simulation, in 18.2% of all cases, the carrier will not infect anyone or show any symptoms. In the remainder of cases, an outbreak will happen, and unless the carrier shows symptoms on the first day, there is a 47.3% probability the virus has already been transmitted to at least one other person by the time of detection, so removal of symptomatic cases is insufficient to stop the outbreak. The probability that a second symptomatic case happens remains high until 1 week after the removal of the first case. Fig. 1C illustrates the duration of outbreak versus the remaining population size in this scenario, showing that a large percentage of outbreaks stop on the first day when the carrier, most likely asymptomatic carriers, are not expected to infect anyone else. Based on the high probabilities of an outbreak under this scenario better approaches to risk management require quarantine prior to boarding the FSPO. A 7-day quarantine prior to boarding the FPSO would avoid 82.1%, and a 14-day quarantine would avoid 99.3% of potential outbreaks.



a) Probability of transmission per day for a symptomatic case with an incubation period of 4 days (purple line), and for an asymptomatic case (green line). b) Distribution of serial intervals of 10,000 simulated infector-infected individual pairs, c) Duration vs remaining population size for 10,000 simulated outbreaks.

Discussion

The simulator is currently designed for an enclosed population that assumes a single entry point for carriers. It allows the simulation of heterogenous populations with millions of individuals but does not yet model scenarios such as continued injection of carriers, testing of virus, hospitalization, and more complex outbreak response operations. Despite these current limitations, the current version of the software could be useful for studying the behavior of outbreaks affecting closed systems that might include nursing homes or jails for which entry is tightly controlled. We are expanding the simulator to handle these cases and those priorities needed for specific application areas.

References:

Du, Z., *et al.* Serial Interval of COVID-19 among Publicly Reported Confirmed Cases. *Emerg Infect Dis* 2020;26(6).

Ferretti, L., *et al.* Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. *Science* 2020.

Lauer, S.A., *et al.* The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. *Ann Intern Med* 2020.

Liu, Y., *et al.* Viral dynamics in mild and severe cases of COVID-19. *Lancet Infect Dis* 2020.

Wolfel, R., *et al.* Virological assessment of hospitalized patients with COVID-2019. *Nature* 2020.