

15.879 Advanced System Dynamics Modeling

Spring 2025

Exercise 2- Modeling Epidemics with Vaccination and Behavioral Response

Submit your model (and potential report) to the shared dropbox before the class on Friday 2/14/2025

This is the first modeling exercise of the course, so we start structured, focusing on expanding an existing model, the Susceptible-Infectious-Removed or SIR. This is a classical model with a rich history going back to 1920s which has been the backbone of mathematical epidemiology and has informed models of diffusion more broadly across different fields. You should be familiar with this model from your introductory System Dynamics course, but if you don't know the basic model by heart, refresh your memory by reading through chapter 9.2 of Business Dynamics. You can find many alternative expositions of the model online, though Sterman's conceptually helpful separation of 'Contact Rate c ' and 'Infectivity i ' is not universal and often, to minimize free parameters, other domains use a single parameter (e.g. β or Attack Rate) that reflects the multiplication of the two.

SIR provides a high-level model of the spread of an infectious disease in a population. The basics are simple: infections happen when an infected person comes into contact with a susceptible one. After a while infected individuals are 'removed' from the transmission dynamics through recovery or deaths. SIR makes several important assumptions that offer a parsimonious but also limited model. For example, assuming that anybody in the population may interact with anybody else, and that people are homogeneous (in terms of their contact patterns, susceptibility, and infectivity), the model can break the population into only 3 stocks of susceptible, infectious, and removed (or recovered). Among others, it also assumes no quarantine or vaccination, no movement of population in/out of the area modeled, no waning of immunity, and no changes in behaviors in response to perceived risk of infection.

In this assignment you model simple relaxations of three of these assumptions. To keep your work concrete, focus on COVID-19 as an empirical context to inform your parameterization of the model, though you do not need to spend time on searching for empirical data or parameter estimates. Expand the SIR model in the following order, while adhering to the iterative modeling process: understand each structure fully before adding the next chunk.

- A) Incorporate the impact of behavioral responses to perceived risk. Specifically, the SIR model assumes contact rate and infectivity are constant, but increasing cases and specially deaths (below 1% of cases lead to deaths in case of COVID-19, while the rest recover) will make people more cautious, reduce social interactions, prompt the use of personal protective equipment, and thus will reduce both contact rate and infectivity. On the other hand, reduced case counts would prompt the relaxation of those measures. The risk perception depends on recent new cases/deaths, though people are typically more sensitive to rising risk levels than when risks subside, creating an asymmetry in risk perception dynamics. Try to use simple formulations and analytical (rather than table) functions in formulating how perceived risk impacts infections.
- B) Next, remembering that most people have contracted COVID-19 more than once, you decide to incorporate the waning of immunity in your model. You can assume an average six-month immunity period after infection.
 - a. With waning of immunity captured, the model could have an endemic steady state, where the disease circulates in the population indefinitely. See if, with some plausible simplifications (e.g. ignoring changes in population due to deaths), you can find an analytical expression for the fraction of people who are sick at any time in the steady-

state. Also calculate how many times, on average, a person will get sick per year. How do these quantities depend on the basic parameters of the model?

- C) Finally, add vaccinations to the model. Vaccinations have three distinct benefits. First, they reduce the risk of infection (conditional on contact) for the vaccinated individual. So those vaccinated are less likely to get sick. Second, those vaccinated, even if they get sick, are partially protected against severe disease and mortality. Finally, the vaccinated, when they get sick, are less likely to infect others. For this exercise only focus on the first two of the benefits from vaccines. A few additional considerations are helpful in modeling vaccinations:
- a. Just as natural immunity, vaccine efficacy also wanes. In case of COVID-19 the vaccine efficacy period is in the same range as the natural immunity.
 - b. You will need to make a choice on vaccination rates. For now, assume a fraction of population is interested in vaccines, so when their vaccine efficacy has waned, they will be interested in receiving vaccinations. You can also consider a maximum capacity for vaccination (e.g. vaccination facilities can serve a fraction of total population per day).

As always, start by considering the key architectural choices:

- 1- Who is your audience and what is a good problem definition?
- 2- What is a good time horizon for the problem?
- 3- What high level mechanisms should be included in the model, and what should be left out?
- 4- What is the right level of aggregation?
- 5- What are the key sources of inertia and what are good stock variables?

The structured nature of this assignment has partially addressed many of the architectural choices, reducing your workload, and flexibility. Nevertheless, being explicit about them will help you in your formulation choices, especially in deciding how stylized to keep your model and where to add more detail and new parameters.

Submission Instructions

Put your Vensim models for parts A-C in the shared dropbox folder under session 2. Please name your model submissions as: S02-**<Last Name>-SIRsb-<Part>.mdl**
for example, “S02-Rahmandad-Rahmandad-C.mdl”. If you are submitting a report for finding the equilibrium, name the file consistently, e.g. “S02-Rahmandad-SIRsb.pdf”.

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