Combining Epidemiological Models and Supply Chain Management on a National Level

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1 Abstract

In times of a pandemic, especially one that has disrupted supply chains nationally and internationally, continuing to function becomes very difficult for businesses and organizations managing their own supply chains with as little inventory as possible. This paper discusses the integration of epidemiological models with supply chain management as an argument against this supply chain management strategy. More specifically, it recommends that governments maintain an inventory of swabs in case of the emergence of a potential epidemic. It also suggests that to reduce the number of required swabs the government responds to a pandemic with policy actions in conjunction with the supply chain response.

2 Introduction

When the first outbreaks of SARS-CoV-2 (Covid-19) occurred in the United States in early 2020, one of the many challenges facing many hospitals, state health departments and federal agencies was the lack of inventoried supplies, especially personal protective equipment (PPE) (Momper). By that time, Covid-19 had already broken out in Europe and in China. The nature of the measures taken to slow the spread of Covid-19 at the time (such as shut-downs and export-bans) and the international presence of the virus (including sick workers) had a severe negative impact on supply chains across the globe (Mahmoodi). As a result, many of those organizations were forced to compete against each other to purchase necessary supplies (Momper).

The lack of resiliency in the supply chains of US-based businesses can be attributed to several trends before and during the Covid-19 outbreak. Before the outbreak, there was a general trend to minimize physical inventory as a cost-saving measure ("Impact of the Global Medical Supply Chain"). Inventory would be minimized through systems such as Just-In-Time inventory, where replenishment shipments would arrive just as the required item would run low. Such management systems are cheaper and more efficient than traditional inventory. JIT management also has faster turnover rates.

However, JIT systems come with increased fragility, and global supply chain disruptions can leave such businesses with only very thin inventories as they search for alternative suppliers (Mahmoodi). This issue is especially acute in the healthcare industry, as the vast majority of supplies required by hospitals are essential to providing efficient, effective, and sanitary care to patients. Lead times also increase ("Impact of the Global Medical Supply Chain"). As illustrated by the COVID-19 pandemic, it is easy for hospitals to find themselves without sufficient gloves, masks, or gowns. This report suggests the creation of a standing inventory of such supplies, specifically swabs. Swabs are critical for conducting tests, and having a standing inventory of them will give healthcare organisations and governments a head-start on testing in the event of a potential outbreak.

Using compartmental models that include the possibility for various government responses, this report suggests a specific quantity of swabs be held in inventory. Section 3 goes into detail on the types of compartmental models used in this report. Section 4 of this paper discusses the methodology and the process of combining compartmental models and supply chain models. Section 5 details the combination of epidemiological and supply chain models on a national level, as well as some of the actions that can be taken on a national scale.

3 Compartmental Models

Compartmental Models contain several compartments, in which portions of a population are placed as they progress through the stages of a disease. Such a model can have any combination of compartments, depending on the progression. The simplest is the SIR model, in which a population moves from those who can still get the disease (S—Susceptible), to those who are transmitting the disease (I—Infectious), to those that can no longer get the disease (R—Removed, which includes deaths and recoveries). Table 1 and Table 2 detail the definitions of the various compartments used in these models, as well as the rates at which populations move from one compartment to another. The basic model used in this paper is a variation of the SIR model, called the SEIR model. The "E" or Exposed compartment accounts for a disease's incubation period between exposure and infectiousness.

1. SEIR Model.

$$S \xrightarrow{\beta} E \xrightarrow{\gamma} I \xrightarrow{\lambda} R$$

   Due to COVID-19's incubation stage, which usually lasts between 2-14 days from when a person is exposed to when they begin to exhibit symptoms, a SEIR model is an appropriate base model since it includes the "Exposed" compartment (CDC, 2020). However, a SEIR model does not account for those who isolate themselves or are isolated in hospitals from the Susceptible population, either to avoid exposure or transmission.

Symbol	**Population**	**Definition**
S	Susceptible	People who can contract the disease.
E	Exposed	People who have been exposed to someone with the disease, but cannot yet infect others.
I	Infectious	People who usually exhibit symptoms and can infect others.
R	Removed	People who have recovered or passed away from the disease.
Q_E	Quarantined (Exposed)	People who have the disease but have little or no chance of infecting others. Also known as Isolated.
Q_U	Quarantined (Unexposed)	People who are susceptible but have little or no chance of being infected.

Table 1: Compartments for a Disease

2. SEQIR Model.

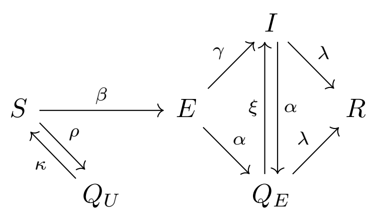
$$\begin{tikzcd}
 & & I \arrow[dr, "\lambda"] \arrow[dd, shift left, "\alpha"] & \\
S \arrow[r, "\beta"] & E \arrow[ur, "\gamma"] \arrow[dr, "\alpha"'] & & R \\
 & & Q_E \arrow[ur, "\lambda"'] \arrow[uu, shift left, "\xi"] &
\end{tikzcd}$$

   The SEQIR model includes a "Quarantine (Exposed)" compartment, which decreases the likelihood of transmission by removing a portion of the Infectious population from contact with the Susceptible population. For example, this would be the compartment for those isolated in hospital rooms or intensive care units. It would also include those who are tested and isolate themselves at home. It is assumed that an Exposed or Infectious people will have a higher quarantine rate than people in the Susceptible compartment.

Rate	Path	Formula	Components
β	S—E	$P_T * N_{Contacts}$	Probability of Transmission $\times$ Contacts per day
γ	E—I	$\frac{1}{D_E}$	One over the number of days before becoming infectious
λ	I—R	$\frac{1}{D_I}$	One over the number of infectious days
ρ	S—Q_U	P_{QU}	Probability that a person will enter mandated quarantine
κ	Q_U—S	$P_{LQU} * \beta$	Probability that a person will leave mandated quarantine and rejoin the Susceptible compartment
α	E—Q_E I—Q_E	$P_{QE} * T_E$	Probability an Exposed/Infectious person will be quarantined $\times$ Testing Efficiency
ξ	Q_E—I	P_{LQE}	Probability that an infectious person will leave quarantine

Table 2: Rates of Transition between Compartments

3. SQEQIR Model



The SQEQIR adds an another Quarantine compartment, this time for those who are still susceptible but are isolating to avoid exposure. The rates at which population flows in and out (α and κ, respectively) of the Q_U compartment are different from those for the Q_E compartment to allow the possibility of modeling personal or government action, specifically self- or mandatory quarantining.

The compartmental models used in this report are stochastic, which means that they have the following properties (using the SQEQIR model as an example):

$$1 = S + Q_U + E + Q_E + I + R \tag{1}$$

$$\frac{dS}{dt} = (-\beta * S * I) - (\rho * S) + (\kappa * Q_U) \tag{2}$$

$$\frac{dQ_U}{dt} = (\rho * S) - (\kappa * Q_U) \tag{3}$$

$$\frac{dE}{dt} = (\beta * S * I) - (\gamma * E) - (\alpha * E) \tag{4}$$

$$\frac{dI}{dt} = (\gamma * E) + (\xi * Q_E) - (\alpha * I) - (\lambda * I) \tag{5}$$

$$\frac{dQ_E}{dt} = (\alpha * E) + (\alpha * I) - (\lambda * Q_E) \tag{6}$$

$$\frac{dR}{dt} = \lambda * (Q_E + I) \tag{7}$$

$$s.t\ 0 = \frac{dS}{dt} + \frac{dQ_U}{dt} + \frac{dE}{dt} + \frac{dI}{dt} + \frac{dQ_E}{dt} + \frac{dR}{dt} \tag{8}$$

The sum of all the compartments is one, so each compartment represents the percent of the population in that compartment. Since the total population is assumed not to change drastically through births or non-disease related deaths over the time period in question, the rate of change of each compartment sums to zero.

4 Methodology

4.1 Constructing Compartmental Models

The models discussed in Section 3 were based on the SEIR and SUQC models derived in "Compartmental Models of the Covid-19 Pandemic for Physicians and Physician-Scientists" (Abou-Ismail). Starting with the SEIR, the SEQIR and SQEQIR were created to model the possibility of multiple quarantine compartments. As with the neural network model used by Dandekar and Barbastathis, these models start with 500 infectious individuals.

4.2 Calculating the required number of Swabs

To combine the compartmental models with a supply chain model, the number of swabs required must be a product of the compartmental models. In an ideal setting, there would be enough swabs so that everyone who enters the Exposed category is tested and then enters the Exposed Quarantine compartment instead of the Infectious compartment (i.e. Confirmed Cases = Actual Total Cases). Thus, the required number of swabs should be the number of people entering the Exposed compartment:

$$Required\ Swabs = \hat{S} = \sum_{d=0} round(\beta * S_d * I_d * N) \tag{9}$$

where d is the number of days since there were 500 infectious individuals and N is the total population. The round function operator ensures that only integer values are taken into account (i.e. only new additions to the Exposed compartment).

However, shortages in swabs means that not everyone can be tested. This is reflected in the "Testing Efficiency" value T_E within the rate α. In this case, T_E is equivalent to the percent of the population that could receive a swab test if needed. Thus, it prorates the probability that an exposed or infectious person would enter quarantine based on the availability of tests. More available tests means a higher percentage of the Exposed/Infectious population will enter quarantine at the P_{QE} rate.

4.3 The Disease

This report uses a hypothetical disease on which possible government actions and responses are based. The disease is similar to Covid-19 in transmission methods (i.e. a respiratory virus). It also has incubation and infectious periods similar to those of Covid-19. The disease uses the following values:

Rate	Value	Notes
β	0.75	.15 transmission chance $\times$ 5 contacts/day
γ	.125	D_E=8 Days before symptoms arise
λ	.1666	Remain infectious for 6 days

Table 3: Epidemiological Rate Values for a Hypothetical Disease

4.4 Assumptions of the Model

Since this report is focused on a national scale model, it makes some assumptions on the functioning of a national-scale response. These assumptions are further detailed in National Model. This report assumes a greater resource availability as well as the ability of governments to take policy actions, such as mandating mask-wearing, that would effect the compartmental or supply chain portion of the model. It also assumes that for an emergency stockpile program (see Supply Chain Actions) that there is only a demand for the supplies within the stockpile in times of an emergency.

The model operates as if the swabs within the stockpile are the only swabs available. While this would of course not be the case in an actual pandemic as private companies will have some of their own, the swabs in the stockpile will likely be the most accessible and easily distributed.

There are also inherent assumptions within the compartmental models. SEIR and similar models assume a "homogeneous mixing of sub-populations" (Dandekar and Barbastathis). For simplicity, many of the initial values such as β, the duration for which people are exposed or infectious (D_E and D_I, respectively), and the probability that people will quarantine are set as constant values. In many cases, these are average values that in fact represent a probability distribution.

5 National Model

5.1 Overview of National Model

As a pandemic grows and the surge in demand of medical supplies can no longer be met by the inventories and suppliers of hospitals and local governments, the federal government has the ability to support those organizations with needed supplies. This is in the hopes that the supplies will last until the organizations can reestablish functioning supply chains. Therefore, the role of entities such as the Strategic National Stockpile is to temporarily buoy hospitals and states who are embattled with a medical emergency.

With this role in mind, a scenario can be created on which to base the government's response. This scenario, the National Model, stipulates that there has been an outbreak of the disease discussed in Section 4.3 has occurred. The three epidemiological models mentioned earlier are then used to track the progression of the disease. The SEIR model shows what would happen without government intervention. The SEQIR model illustrates the use of swabs to confirm exposures and then quarantine exposed individuals. Lastly, the SQEQIR model shows how a mandate that slows the spread of the disease (quarantining susceptible individuals in this case) can reduce the number of swabs needed. It is assumed that the models begin at a point in time where hospitals inventories are depleted. Similarly, it assumes that the disease in question has disrupted international medical supply chains in a manner akin to Covid-19. Thus, the goal is to show that between a balance of swabs and mandated quarantining will slow the spread of the disease such that hospitals and local governments have a chance at recovering.

5.2 Supply Chain Actions

From a supply chain perspective, governments can take a variety of proactive and reactive measures when responding to a national emergency, including pandemics and natural disasters. Proactive measures tend toward preparing for some future event, usually in the form of stockpiling, while reactive measures (e.g. as releasing supplies to areas in need) are taken once the event occurs. It is important to thoroughly plan and maintain both types of actions, since under-planned proactive measures may be insufficient to meet the demands of a catastrophic event, and uncertain reactive measures will lead to confusion and disorder among responders.

Proactive Measures. Proactive measures can take several forms, but generally consist of building and maintaining inventories or coordinating responses with other organizations, public or private, that will also be among the first to react to an emergency event. In the United States, the first of those measures, stockpiling, is readily exemplified by the Strategic National Stockpile (SNS).

The SNS is meant to be a standing inventory of Medical Countermeasures (MCMs) that can be deployed to an area in need of extra medical supplies ("Impact of the Global Medical Supply Chain"). The SNS contains a wide variety of MCMs. Specifically, it contains the necessary supplies and medications to combat a nuclear event, natural disaster, biological or chemical attacks, terrorist attacks, and diseases.

Traditional inventory such as the SNS can become a valuable asset in two ways, making it worthy as a proactive measure. The first is that it provides the necessary supplies when there is a surge in demand. However, the fact that it is a physical inventory located within the United States sets the SNS apart from a highly efficient supply chain, and this is the second benefit. Many medical supplies such as PPE are themselves made in China, and many surgical instruments are made in Mexico and Pakistan ("Impact of the Global Medical Supply Chain"). When a disease or other emergency event has such a widespread impact as Covid-19 has, the supply chains linking domestic distributors and hospitals with international manufactures can quickly break. A US-located physical inventory is not immediately affected by disruptions in international supply chains.

The downside to traditional inventory is that it is expensive. The budget for the SNS alone in 2019 was $575 million dollars, out of a $2.2 billion budget request for the Office of the Assistant Secretary for Preparedness and Response (Dodgen). However, the budget also shows that there is not an infinite amount of money to be had in emergency preparation, especially if the budget is split among all the different types of MCMs and devices that the SNS needs to carry. According to the Public Health and Social Services Emergency Fund, an estimated $350 million (out of $705 million) was budgeted for procurement at the SNS in 2020, $130 million for warehousing costs, $218 million for sustainment, and another $135.5 million for operational costs.

The other most important proactive measure that can be implemented deals with the relationships between all organizations and groups that would be the first to react to an emergency. This goes beyond simply promising supplies to a local government, it includes making sure that the channels for for both supplies and information are well maintained. It means having set plans and partnerships that will come into effect when a crisis arises. Not only will the dispensing of supplies be hindered by uncertainty, uncertainty can also reverberate up the supply chain through the Bullwhip Effect. The Bullwhip Effect gives an impression of more demand than is actually present, and it compounds in each of level of the supply chain if information isn't being properly shared (Kros and Brown 14).

Reactive Measures. As an analogue to stocking the SNS, it is also important to be able to deploy the MCMs stored there. For that reason releasing SNS supplies is one of the main reactive measures. The first supply packages can be deployed within 12 hours of a serious event, and other supplies can arrive within 24 hours of the decision to deploy (Bhavsar et al.).

The process of releasing supplies emphasizes the importance of proactive planning: once the supplies are delivered, the receiving state or local government takes responsibility of managing them. This includes dispensing the materials to the people, keeping climate-sensitive items at the right temperature (especially with vaccines or other medications that need to be kept cold), and keeping track of all deliveries (Bhavsar et al.).

5.3 Policy Actions

Governments have the authority to institute temporary policies such as states of emergency, travel bans, and quarantine. During the COVID-19 pandemic, policies such as mask wearing and social distancing, as well as mandates on gatherings and events, have also been instituted. When confronted with another potential outbreak, or in the course of a pandemic, governments can use this authority to slow the rate of transmission between populations. These actions slow transmission rates in various ways. Mask wearing and social distancing decrease the probability of exposure and infection, and the number of contacts per day. This can drastically reduce the β rate and thereby slow the disease. Similarly, quarantining portions of the population that have yet to be exposed decreases the number of people in the susceptible category, making it more difficult for the disease to spread.

In this model, mandated quarantining is used as the government response to slow transmission. In the figures in the next section, the model assumes rather conservative values of quarantining (i.e. only 10% actually obey the mandate). This allows for the strength of the quarantine a variable that can be adjusted based on how strictly compliance with the mandate is enforced.

5.4 Models

Hypothetical Disease SEIR Model. Figure 1 shows the stochastic SEIR model for the disease with the values defined in Table 3. Figure 1 illustrates how the population will move through the compartments, starting with a mainly Susceptible population which transitions to a mainly Removed population as the Exposed and then Infectious population peak around 60 days after 500 infectious.

This is representative of a complete lack of response, without any testing, quarantining, or other mandatory preventative measures. As such, much (99%) of the population is placed into the Removed compartment.

Swabs and the SEQIR Model. As was discussed in the Section 4.2, the rate at which exposed or infectious people enter the Quarantined Exposed compartment is dependent on the Testing Efficiency. By using swabs to diagnose individuals and move them into the Quarantined Exposed compartment, governments can reduce

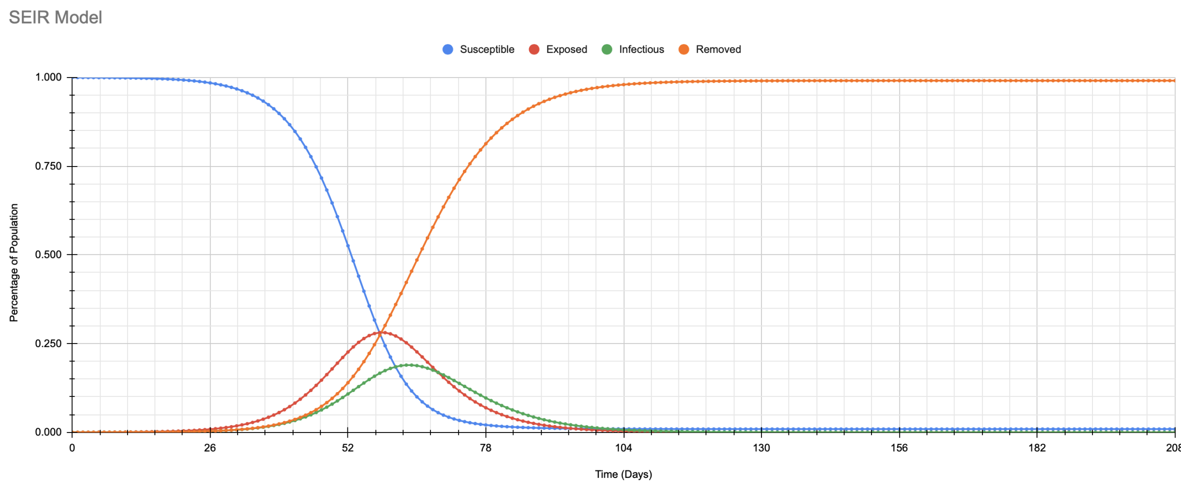


Figure 1: SEIR Model

the impact of the disease. With the introduction of the Quarantined Exposed compartment, two new rates need to be defined for the disease: T_E is left undefined since it is dependent on the number of swabs available

Rate	Value	Notes
α	$T_E * 0.4$	$T_E \times P_{QE}$
ξ	.05	5 percent of people will break their quarantine

Table 4: Quarantined Exposed Rates

and the total number of required swabs. The number of available swabs influences the SEQIR model:

$$\begin{tikzcd}
 & More\ people\ get\ quarantined \arrow[dr] & \\
More\ Swabs \arrow[ur] \arrow[dr, Leftrightarrow, "Equilibrium"'] & & Slower\ disease\ spread \arrow[dl] \\
 & Fewer\ Swabs\ needed &
\end{tikzcd} \tag{10}$$

As discussed in the methodology, the number of swabs can be calculated through the formula:

$$Required\ Swabs = \hat{S} = \sum_{d=0} round(\beta * S_d * I_d * N) \approx 324,000,000 \tag{11}$$

Using a sample total population $N = 328 million$ results in a total of around 324 million swabs required to test everyone who entered the Exposed compartment in the SEIR. From there, the relation between Testing Efficiency (percent of $\hat{S}$) and swabs required for the SEQIR model can be calculated:

It can be seen that the curves intersect at around 108 million swabs, roughly 33% of $\hat{S}$. Here are SEQIR models when T_E equals 0.33 and 0.66. When T_E equals 0, the resulting SEQIR is the as the SEIR model in Figure 1. Even at 33% Testing Efficiency (i.e. one in four cases are diagnosed), there is already a noticeable change in the model — namely, around 31.3% of the population remains susceptible after the Removed compartment reaches it equilibrium. In the time frame of the model, 208 days, not only does the intersection of the Susceptible and Removed population occur much later, neither has yet to reached its equilibrium. With a 66% Testing Efficiency, Figure 4 is almost completely flat.

The SQEQIR Model and Cost Reduction As evidenced by the push towards leaner supply chains, traditional inventories are expensive, and stockpiling swabs is no exception. In order to reduce the costs of

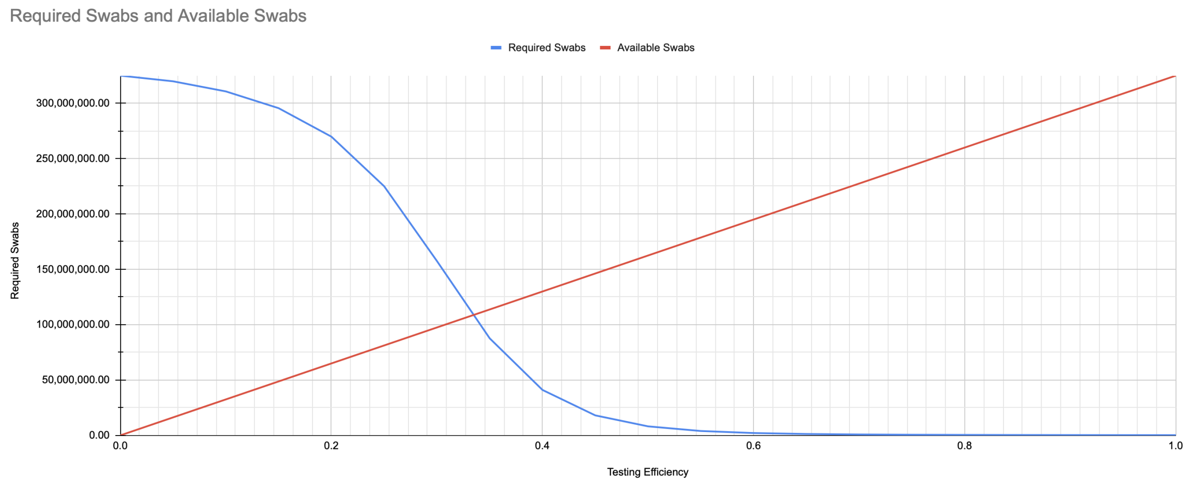


Figure 2: Required SEQIR Swabs

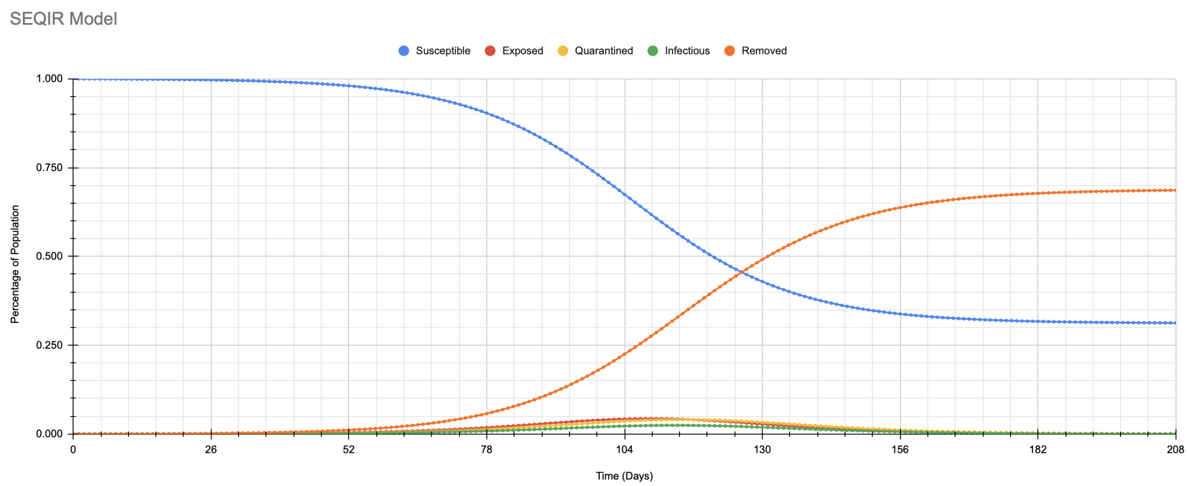


Figure 3: SEQIR model, with $T_E = .33$

a swab inventory, steps can be taken by the government. These include deals with suppliers and efficient inventory management strategies (such as selling swabs that have almost exhausted their shelf life at a reduced price to hospitals that can use them immediately and partially fund the replacements). However, another way to reduce costs is to reduce the number of required swabs by ensuring that there are quarantine, mask-wearing or shut-down procedures that slow the spread of the disease.

The SQEQIR model is used in this case. By mandating quarantines for susceptible individuals, the government can redistribute part of the burden of slowing the spread of the disease from testing and swabs to quarantining. Even with relatively low quarantining rates of the Susceptible population compared to the quarantining rates of exposed or infectious individuals, there can still be a drastic change in the course of the disease. The final two epidemiological rates are also introduced with the addition of the Q_U compartment:

Rate	Value	Notes
ρ	0.1	10% of the population quarantines
κ	.25	25 percent of people will break their quarantine

Table 5: Quarantined Unexposed Rates

Figure 5 uses the values mentioned in Table 5 as well as a T_E value of .20 to show the how quarantining

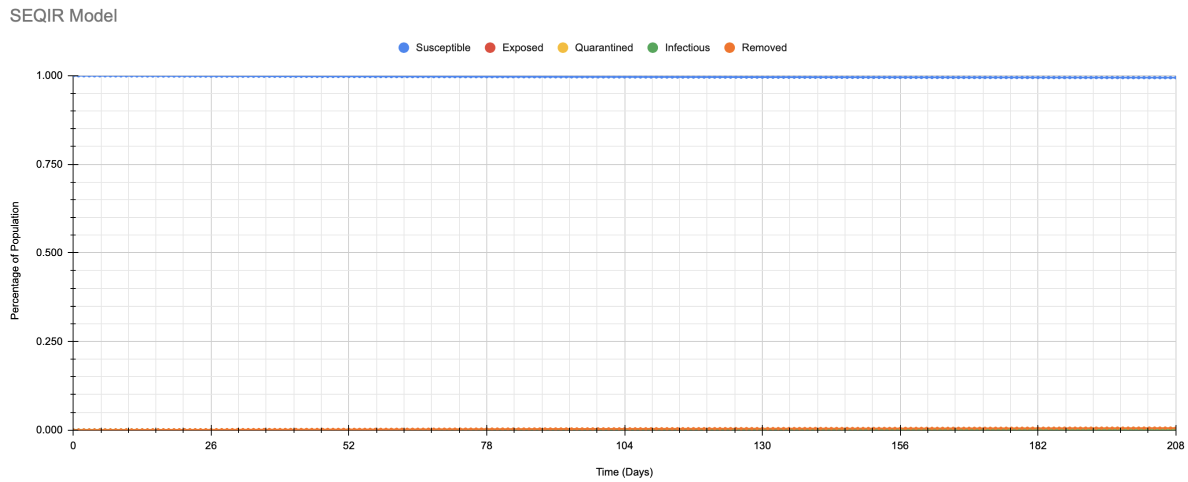


Figure 4: SEQIR model, with $T_E = .66$

susceptible individuals affects the transmission of the disease.

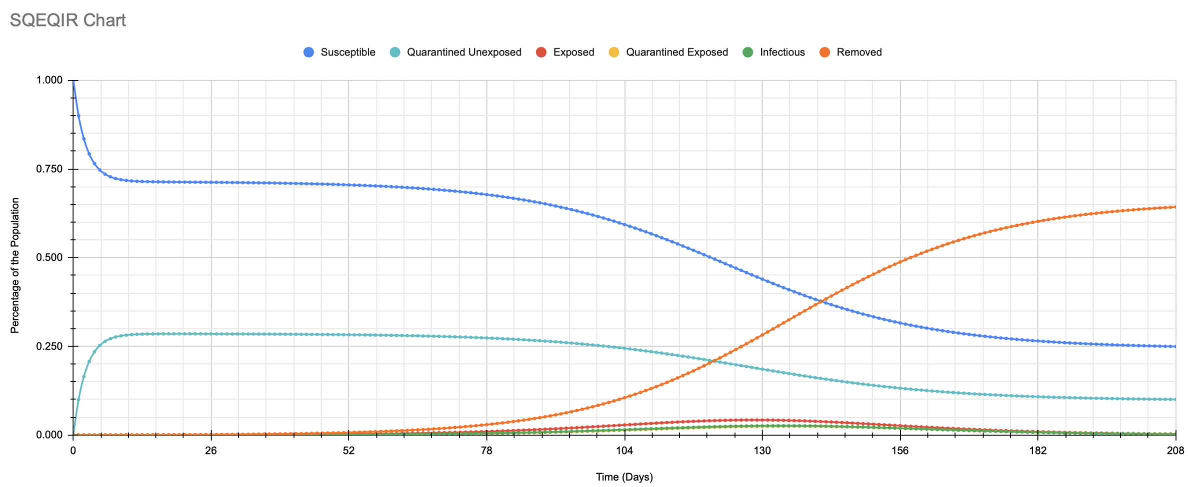


Figure 5: SQEQIR model, T_E=.33

Even with very conservative estimates of quarantining (only one in ten people obeying the mandatory quarantine, and one in four who do end up leaving quarantine), the intersection of Susceptible and Removed curves occurs close to 20 days later than in Figure 3, and only 65% of the population enters the Removed compartment.

6 Results

In Section 5.4, it was shown how the different models, SEIR, SEQIR, and SQEQIR, operate under certain initial conditions.

These initial conditions (specifically T_E and ρ) can be expanded to the full range of values to show how some of the important data points change. Within the SEQIR model, the number of days until the Susceptible and Removed population curves intersect (cut off at 208 days, Figure 6) and the Maximum Removed population and Minimum Susceptible population (Figure 7) can be graphed as a function of T_E.

As a comparison, the same figures can be reproduced for the SQEQIR while keeping ρ and κ constant at 0.1 and 0.25, respectively.

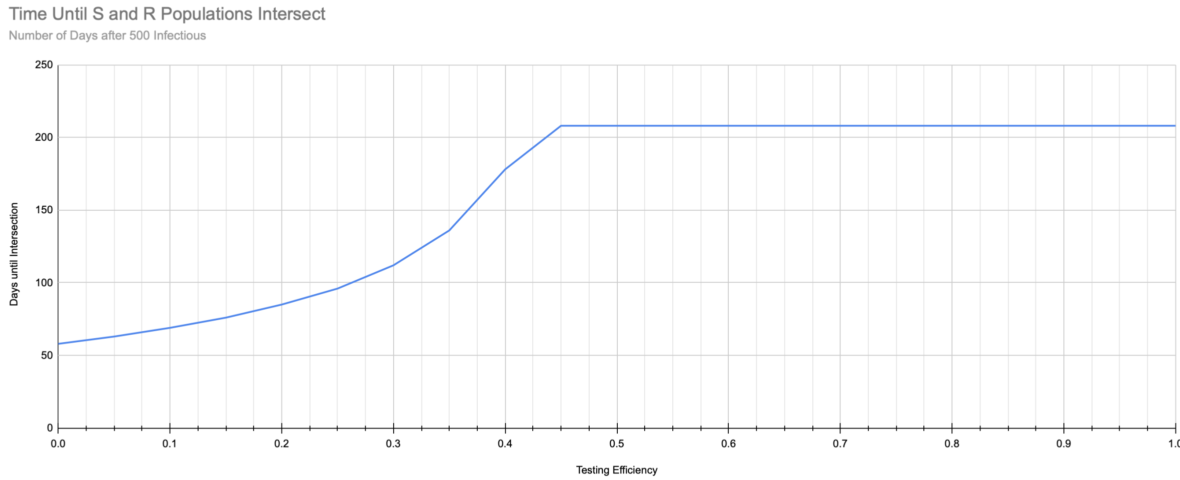


Figure 6: Intersection S and R curves in the SEQIR model

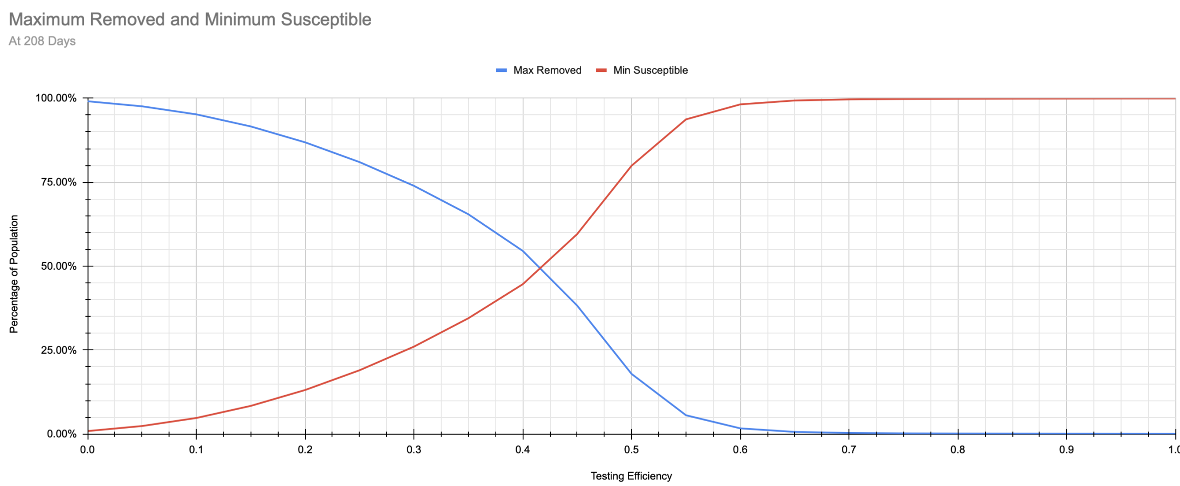


Figure 7: Maximum Removed and Minimum Susceptible Population

Lastly, we can compare SQEQIR models at different ρ values while keeping the Testing Efficiency constant. This is pertinent because many Testing Efficiency values are unrealistic when compared to the budget of the SNS. Swabs cost roughly \$0.75 (Daklapack). The cost of purchasing 108 million swabs (the equilibrium of required and available swabs in the SEQIR model) is \$83.7 million, or 24% of the SNS procurement budget. This does not include the additional warehousing costs, and, since swabs have a shelf life of approximately 1 year, this would be a recurring cost each year. Obviously, this is a realistic spending plan. A more realistic value is 20 million swabs, or 4.43% of the procurement budget.

Figure 10 shows the various reduced SQEQIR models (graphing the sum of the Susceptible and Quarantining Unexposed population and the Removed population) for a range of ρ values from 0.1 (the conservative estimate used earlier) to 0.4 (the probability of entering exposed quarantine P_{QE} mentioned earlier). (Although this range could of course be wider with stricter enforcement of the quarantine, it shows that even conservative estimates have a powerful impact on the model).

7 Conclusion

In times of pandemic, especially one that disrupts international supply chains, national governments may be thrust into the position of supporting hospitals and local governments who are trying to battle

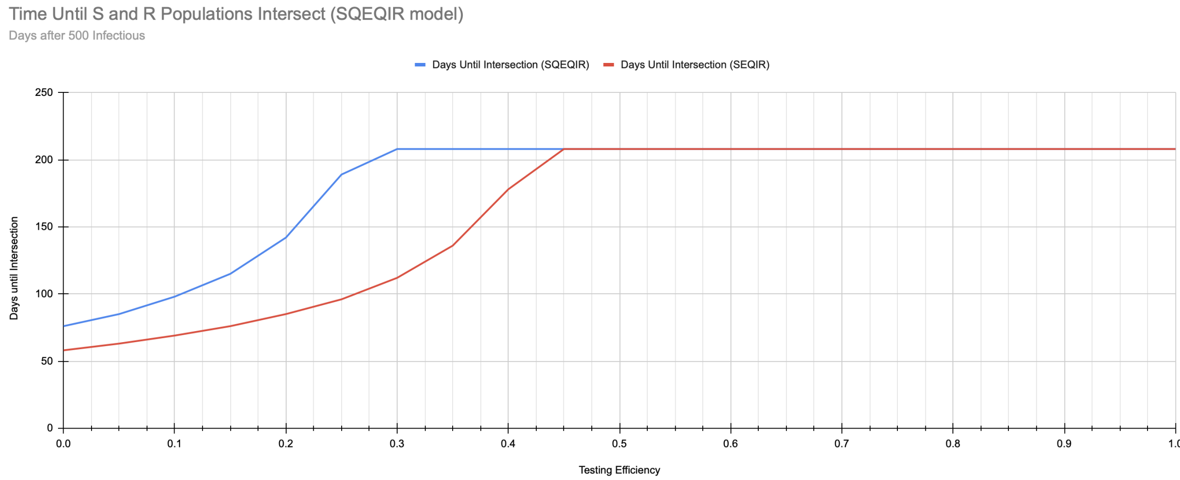


Figure 8: Intersection of S and R curves in the SQEQIR model

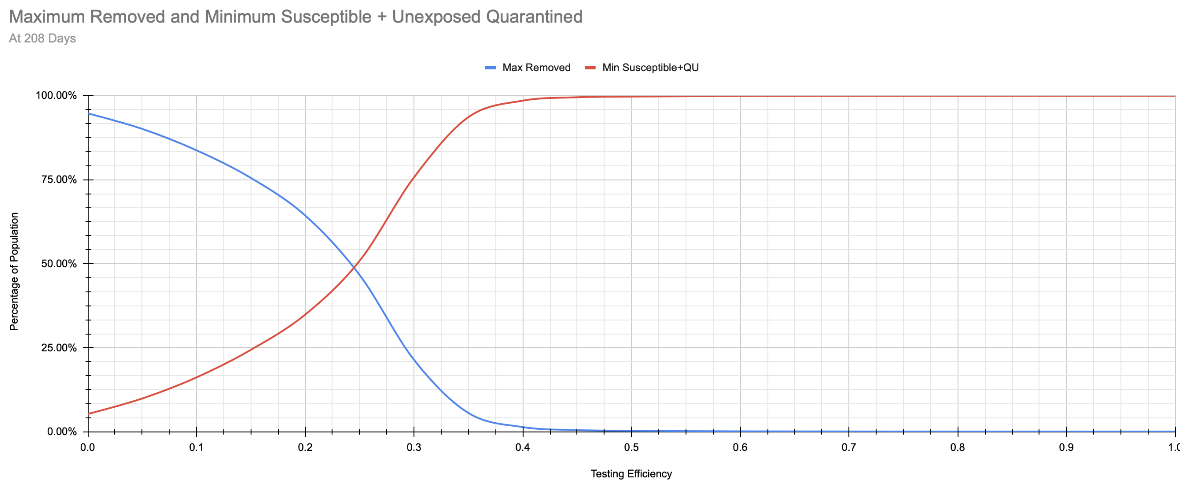


Figure 9: Maximum Removed and Minimum Susceptible in the SQEQIR model

the pandemic. This support may come in two ways: supply chain actions and policy actions. Supply chain actions, specifically a federal stockpile, will help ease medical supply demand that hospitals can't meet themselves due to a steady trend to leaner inventories in hospitals for competitive profit margins. Stockpiles are expensive and federal budgets are not infinite, so to reduce the number of swabs in the stockpile federal governments can implement policy actions in conjunction with the supply chain actions. Mandating quarantine, mask-wearing or other measures that will slow spread of the pandemic constitute such policy actions.

Each of the tiers of government involvement can be modeled with epidemiological models. SEIR models are used for no involvement, SEQIR models are used for supply chain involvement only, and SQEQIR models are used for the balance of policy and supply chain involvement. Throughout any emergency response, it is imperative to keep channels of communication open between all parties participating in the response to maximize the efficiency of the supply chain and policy actions.

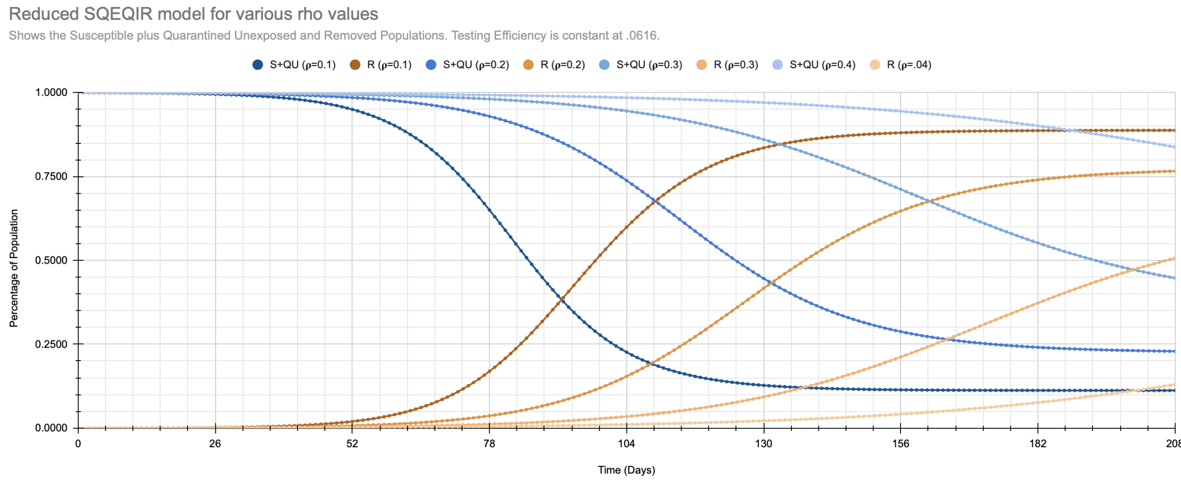


Figure 10: Reduced SQEQIR at various ρ values

8 Sources

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