Spread of COVID and Intervention Strategies in a Small Community

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Abstract

In this report, we simulate the spread of COVID in a small community with about one thousand people using the small-world model and Barabási-Albert model, then compares the outcome with the outbreak in Aosta, Italy. Then we simulate several intervention strategies to find out the best one, and give advice to the local government of this small community to lower the damage of COVID to this community. The main effort of building this project goes to the coding part. Therefore you may find it more interesting to read this report and try the code simultaneously.

1 Introduction

1.1 Inspiration

COVID has hugely impacted our daily life since December 2019. It has an "appropriate" spread rate and death rate, so it immediately spreads worldwide and damages society and the economy a lot.

And there is a small community with approximately 1000 people. One day, the local government suddenly found that there were $I0 = 5$ people showing symptoms of COVID. To reduce the effect of COVID on this small community, the government has several strategies to stop the spread of COVID, but they do not know which one is the best.

Therefore, in this report, we will figure out which strategy is the best for this small community, and advise the small community to use this strategy to stop the COVID, and give an approximate number of people being affected in this epidemic.

1.2 Basic Idea

The traditional SIR model assumes that all the people are "fully mixed," meaning that an infective individual has the same probability of infecting every person in the community. This assumption can help one write down the differential equation quickly, but as we can see in our daily lives, it is often not the case. [1] In the real world, each person will only contact a small group of people. And the number of people one will contact is also not equal.

There are also some improvements for the traditional SIR model, like the stochastic SIR model. But it also assumes that the people are fully mixed. Instead of considering people are fully mixed, we apply two network models to simulate the contact between individuals. They finally perform well on simulating the spread of COVID in Aosta, Italy.

1.3 Organization of this Report

The outline of the report is as follows. In section 2, we introduce the models we are going to use. In section 3, we simulate the spread of COVID and compare it with the real data in Aosta, Italy. In

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section 4, we introduce and apply several intervention methods to control the disease. In section 5, we compare the outcome of these methods and give our advice to control the spread of COVID, and give our conclusion.

2 Stochastic SIR and Network Models

2.1 Stochastic SIR

Suppose there are a population of N individuals in the community, and S is the number of susceptible, I is the number of infective, and R is the number of removal.

Stochastic SIR is a stochastic version of SIR model, instead of giving a confirmed number of people get infected each day, this model adds some probability of each people get infected in time interval t to $t + \delta t$: $p_{infection} = a(I/N) \cdot \delta t$, and the probability of removal $p_{removal} = b \cdot \delta t$, where a is average number of contacts per person per unit time, and $b = T_c^{-1}$ is the inverse average removal time. [2]

This is a good model that adds some randomness to the spread of disease. But it still assumes that people are fully mixed. Therefore, we will remove this assumption by using network models in the next few sections.

2.2 Network Models

2.2.1 Small-World Model

In real-world interactions, many individuals have a limited and, often at least, a fixed number of connections. [3]

Therefore, the small-world model assumes that people have the same number of neighbors, and also, they may connect to not neighbored people. So we also need to introduce a reconnection probability $p_{reconnect}$, which is the probability that one node drops the edge with its neighbor and connects to a random node. [3] And according to this paper, we choose $p_{reconnect} = 0.05$ to better simulate the real world.
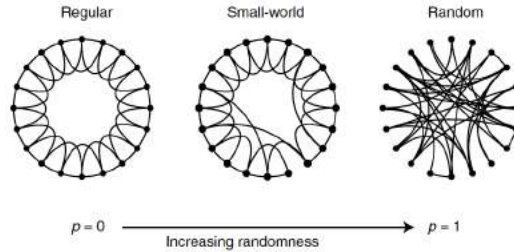

Figure 1: Small-world model

The small-world model is not a scale-free model. Still, since we need to imitate the spread of disease in a confined community, people are more likely to contact the people near to them, especially when the community is super large. But this model may have the problem that it does not consider the case of superspreader.

2.2.2 Barabási-Albert (BA) model

Many networks are highly right-skewed, most vertices have only a low degree, but there is a small number whose degree is very high.

BA-model is a scale-free model built from a small group of people and gradually adds new people to this group. And the new coming people are more likely to connect to the persons with a large degree. [4]

So sometimes BA model can better imitate the real world since it also considers the case of superspreader. But if the community is large enough, people can hardly contact those far from them; even

they are very famous. So, the BA model can better estimate the connection in a small community like in this case.

3 Simulate the Spread of COVID in the Network Models

In this part, we are trying to model the spread of COVID in a small community without any interfere.

We first use the small-world model and the BA model to model the daily contact between individuals, and then we suppose that people will only contact individuals that have a connection with them in the network graph. For example, the edges are shown in Figure 1.

Therefore, people can only be infected during contact with these infected people. In this way, we remove the assumption that people are fully mixed.

And we have make several assumptions:

1. We divide people into six categories: susceptible (S), infective and show symptom (I), Removed (R), the first day of infected and no symptom (I_1), the second day of infected and no symptom (I_2), vaccinated people (V).

2. $I1$ and $I2$ can also spread disease like I.

3. The average number of people one individual will contact with is $n_{contact} = 13$ (13.4 according to the paper)[5], and the rate of being infected during close contact is $a = 0.026$ [6].

4. Those who recovered from COVID have $Re\_S = 0.2$ probability of becoming S again [7].

3.1 Spread of COVID

To begin with, we choose five persons infected on day 1. And they are now without any symptoms.

Every day, people will contact several individuals that have connection with them in the network model graph. In the graph, the spread of COVID is generally divided into three stages.

1. Infection Stage. During the contact, infective (including I, I_1 and I_2) will spread the COVID to the susceptible (S) with probability $p_{infectS} = a \cdot \delta t$, and vaccinated people (V) with probability $p_{infectV} = a \cdot \delta t \cdot (1 - eff)$, where δt is the time slot, we choose it to be 1(day) here, and eff is the efficiency of vaccine. In this stage, we traverse all the connection in the network graph.

For each disease-causing contact, we generate a random number. If this number is smaller than p_{infect}, then we suppose the susceptible will be infected in this close contact. Then the S becomes I_1, $S - 1$, $I + 1$.

2. Recover Stage. Suppose the probability of recover each day is $b \cdot \delta t = T_c^{-1} \cdot \delta t = 0.1$, and the probability of infective becomes susceptible again is $Re\_S = 0.2$. In this stage, we traverse all infective, and change their state to susceptible ($I - 1$, $S + 1$), Removal ($I - 1$, $R + 1$), or unchanged.

3. Showing Symptom Stage. Besides the above two stages, we will change all I_1 to I_2, and all I_2 to I every day.

3.2 Plot the Spread of COVID on the Network

The result of the spread of COVID is shown on Figure 2 and Figure 3. (Green dots include "S, V", Red dots include "I, I_1, I_2", and Gray dots include "R")

According to the graph, for the small-world model, we can see that the COVID is consequently spread from one small group to another small group. The peak number of infected people is not so high since each individual's degree (number of contacts) is similar. Without the existence of super-spreaders, COVID is not likely to have a sudden outbreak. And this model is better to be used in simulating the spread of COVID between large groups.

For the BA model, with the existence of spread-spreaders, the spread of COVID has a higher peak here, and the disease has infected almost everyone in the center (people with large degrees). And most of the green points (healthy people) are located outside the center (people with small degrees), which coincides with our suppose.
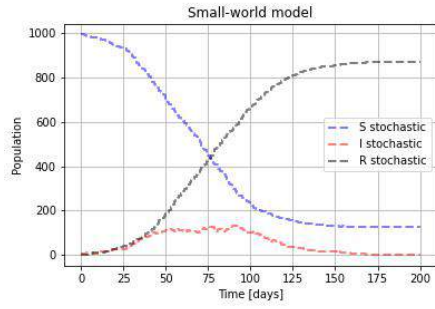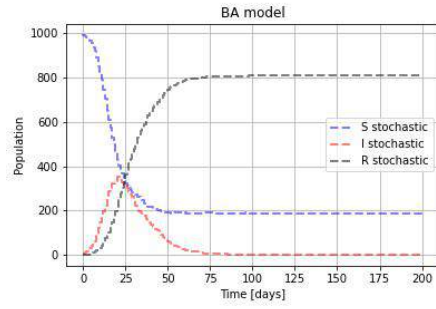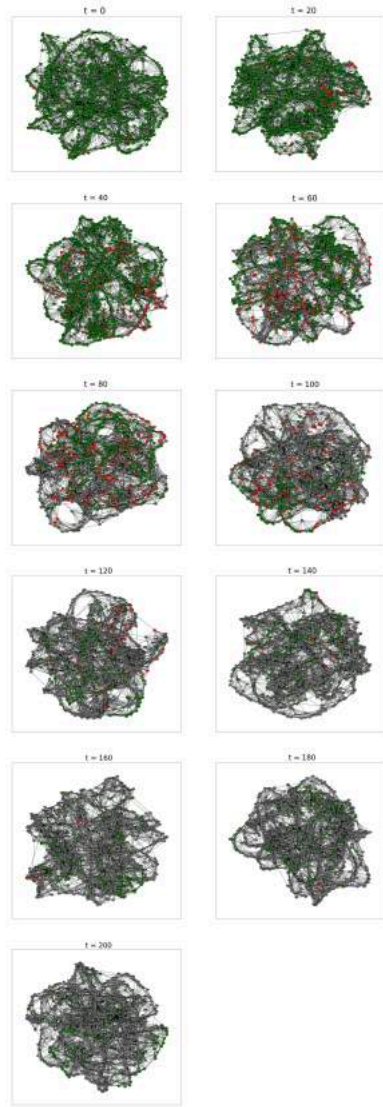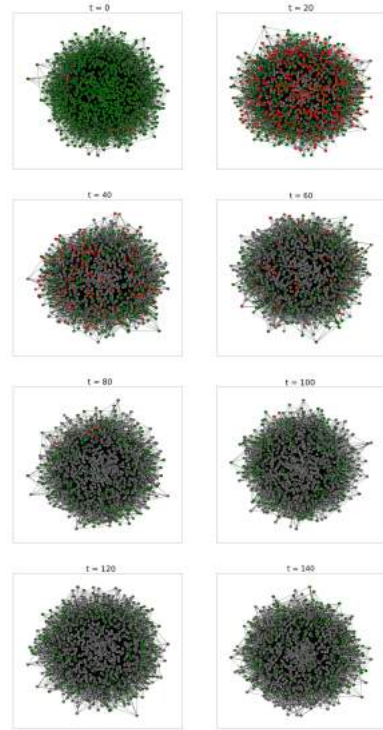
(a) COVID in small-world model   (b) COVID in BA model

Figure 2: Spread of COVID in network models

(a) COVID in small-world model   (b) COVID in BA model

Figure 3: Spread of COVID in network models through time

4

3.3 Compare with the Data in Aosta, Italy

Aosta is a small city with about 34,300 population in Italy. Since it is small enough that everyone is close enough to contact anyone in this city, it can apply the BA model to this city.

Since the first outbreak of COVID in this city was around October, people have already noticed that it is not a common disease, and people choose to cut down the frequency to go out. So the original model, which models the spread of COVID without intervening, may not be suitable for this data.

So, we introduce our first intervention strategy, lockdown, and try to model the spread of COVID under lockdown to fit the data in Aosta.

3.3.1 Lockdown

The main idea of lockdown is to reduce the contact between individuals. And this method can be achieved by shutting down bars, theaters and other places that often have a lot of people.

When a lockdown is applied, we suppose the daily contact between people will go down $skip\_rate = 78\%$. And we achieve this by randomly skipping the contact with probability $skip\_rate = 78\%$ between S, V and I, I_1, I_2 during the traverse. That is the reason why we call it $skip\_rate$ here.

3.3.2 Simulate

We use the data from September 25, 2020, and the following 130 days. The data comes from The Center for Systems Science and Engineering (CSSE) at JHU[8]. Since it is a small city, we applied the BA model to it.

Since our computer cannot support calculating a network with 30,000+ nodes, we scale the data of the toy BA model and compare it with the data in Aosta, Italy.
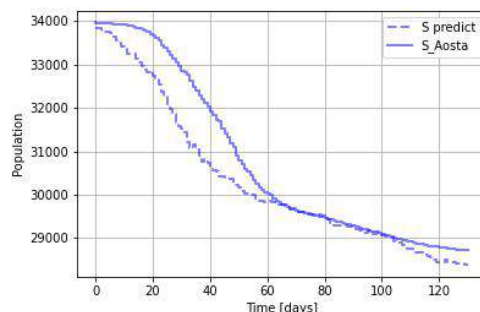

Figure 4: COVID Data in Aosta

When it starts appropriately, we can see in Figure 4 that the BA model will fit the data in Aosta, Italy, pretty well for most cases. And it shows the correctness of using the BA model to simulate the real-world connection.

4 Intervene Strategies

In this part, we are trying to lower the damage of this disease, that is, low down the number of infected people by COVID. And now have several ideas about how to control the disease, but we do not know which one will be best suited to this community.

The first one is lockdown, which has already shown in section 3.3.1.

The second one is vaccination. Using this method, we give the vaccine to those healthy people every day, protecting them from getting COVID.

The third is locking down. We control to cut down the number of close contact in this community by shutting down bars, schools, and other social places.

And the last one is to quarantine people who show symptoms, those who show symptoms are not allowed to contact anyone within ten days.

Therefore, in this part, we will find which method is the best for this community. And according to the research, we can guide the local government in this community can use this intervention method to stop the spread of COVID.

4.1 Lockdown

Since we have shown this method, we will just show the result of this strategy. And we choose $skip\_rate = 78\%$ here.

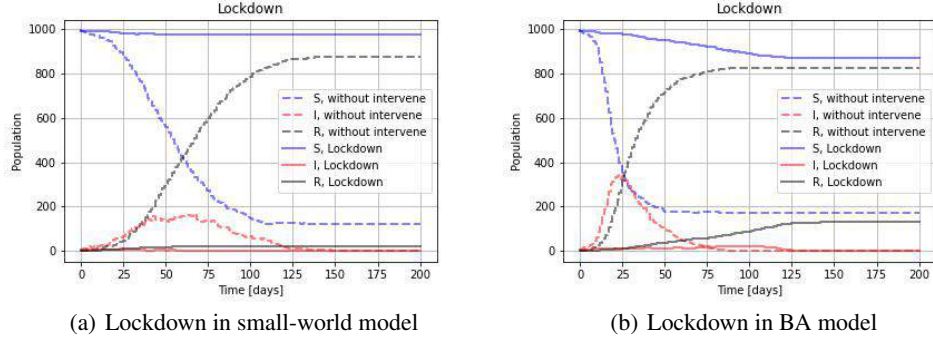(a) Lockdown in small-world model   (b) Lockdown in BA model

Figure 5: Lockdown in network models

Since with a lockdown rate of 78%, the daily contact one individual has is about three now. Therefore, it hugely suppresses the spread of disease. However, this is achieved by restricting the activities of people a lot. It will also have a significant impact on this community. So, it is not a long-time solution.

4.2 Vaccination

Using this method, we suppose $Vac\_rate = 80\%$ of the people in this community will get the vaccine, and due to the shortage of vaccines, there will only be $Vac\_daily = 20$ people get the vaccine each day.

The effectiveness of vaccine is $eff = 88\%$ (Pfizer against Delta variant). [9] So now, when infective contact with susceptible, the probability that the disease will be spread is $p_{infectedS} = a \cdot \delta t = 0.026$. When the susceptible has got the vaccine, the probability will drop to $p_{infectedV} = a \cdot (1 - eff) \cdot \delta t = 0.00312$.

We only give the vaccine to sensitive people, those who have already caught or recovered from the COVID will not be vaccinated. So the actual vaccinated rate may lower than 80%.

4.2.1 Randomly Vaccinate

In this part, we will randomly choose susceptible to give the vaccine, and this method is similar to the primary intervene method we are using now in the real world.

As shown in Figure 6, giving the vaccine to people will significantly reduce the number of infected people during the epidemic. In this simulation, it reduces about $7/9$ in the small-world model, and $1/2$ in the BA model. Also, the peak of disease is lower than before.

To make things better, vaccinating people will not affect people's daily lives. Therefore, this strategy can be used with any other strategy.
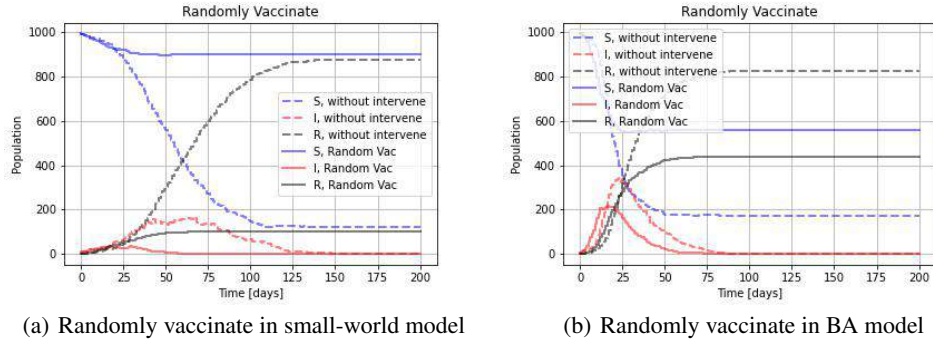
(a) Randomly vaccinate in small-world model   (b) Randomly vaccinate in BA model

Figure 6: Randomly vaccinate in network models

4.2.2 Selective Vaccinate

In this part, we first give the vaccine to those who have more connections than other people, for example, the social service workers, teachers, etc. And as shown in the network graph, they have more degree (more edges connect to them) than other people.

And since these people are more likely to be infected, it is expected to be better than randomly giving the vaccine in BA model. As for the small-world model, since almost everyone has the same degree, there will almost no difference between randomly vaccinate and selective vaccinate.

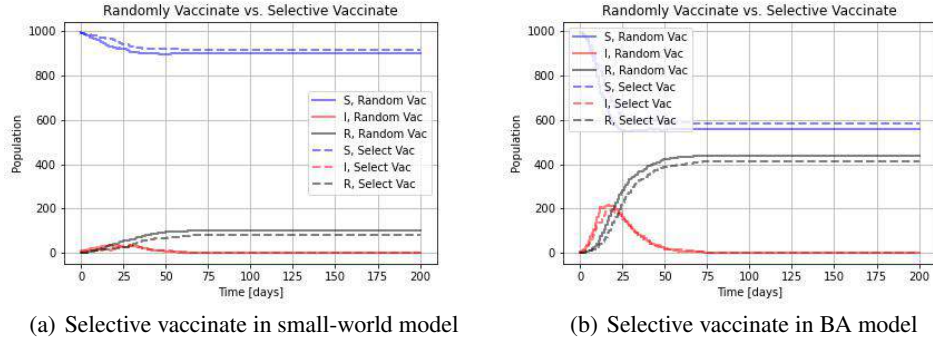(a) Selective vaccinate in small-world model   (b) Selective vaccinate in BA model

Figure 7: Randomly vaccinate in network models

This method outperforms the randomly vaccinate, but not as much as expected. The reason maybe be that although vaccines reduce the probability of people getting infected, those with large degrees still have a high risk of getting infected. Therefore, maybe it is not so beneficial to spend a lot of money investigating who has more connections and immune them.

4.3 Random Vaccine and Lockdown

In this part, we combine the method of randomly giving the vaccine to people and the lockdown strategy. But now we low down the lockdown rate to 50%.

The result is shown on Figure 8.

4.4 Quarantine

When people show symptoms of COVID, they are not allowed to contact anyone within ten days.

After ten days, if they are still showing symptoms, they cannot contact anyone for ten days more.

(a) Random vac & lockdown in small-world model   (b) Random vac & lockdown in BA model
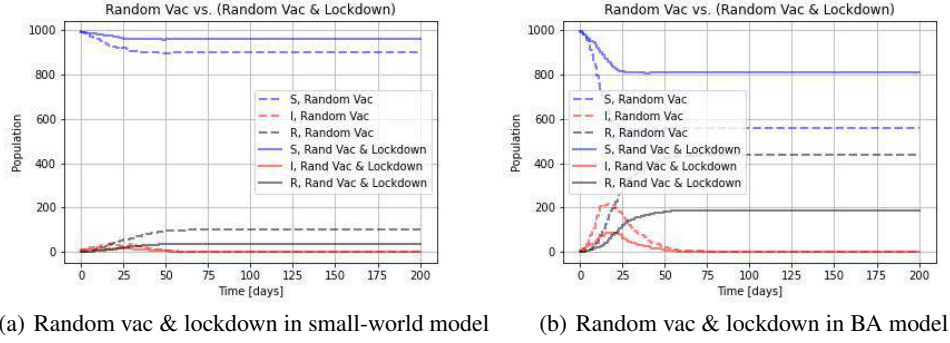
Figure 8: Random vac & lockdown in network models

Since if we still start the spread of disease with the point we chose before, the outcome of this intervention method will almost be one line. This means that the quarantine method will quickly stop the spread of disease by cutting down any connection to (I).

The COVID will start spreading even people have not shown any symptoms (I_1 and I_2), so it will still have some chances to spread before people are quarantined. However, it is still such a powerful strategy.

Therefore, to show the performance of quarantine, we start with points 0 - 4 (those with large degrees) here.

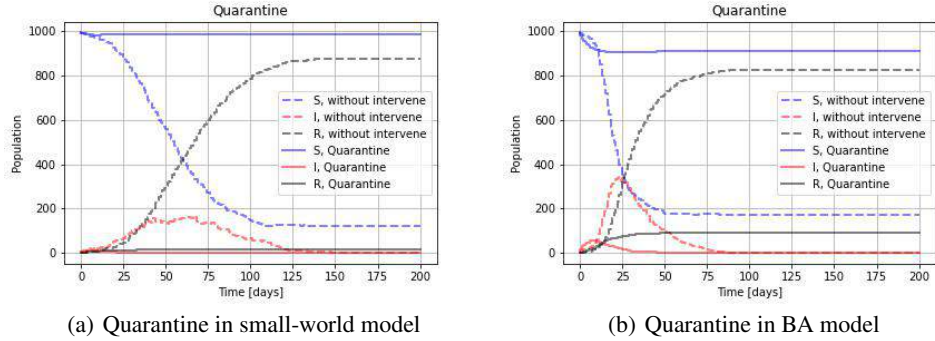(a) Quarantine in small-world model   (b) Quarantine in BA model

Figure 9: Quarantine in network models

For the small-world model, since almost everyone has the same degree, COVID quickly disappeared in this kind of network.

For the BA model, since we start with those with larger degrees, and there are two days before the quarantine. So they can spread the disease in these two days. But since quarantine can significantly reduce the days they can infect other people, both the peak and the total number of infected people is reduced dramatically.

4.5 Randomly Vaccinate and Quarantine

In this strategy, we combine the method of randomly giving the vaccine to people and quarantine infected people.

This method outperforms any other strategies, but since the quarantine method is already good enough, we can hardly see improvement on the plot. Therefore, we will show the result in the next section.

5   Conclusion

5.1   Result of Different Strategies

By modeling the spread of COVID in this small community, we get the result of using different strategies. To sum up, we show the result in the table 1 below.

The infected rate is the estimate percentage of people got infected during the outbreak of COVID. $I_r = (N - S)/N$. And peak is the highest percentage of people is infective at one day.

Table 1: Result of different strategies**

Model	Strategy	Peak (%)	Infected Rate (%)
Small-world	No intervention	16.6	87.8
	Lockdown (78%)	1.1	2.2
	Randomly Vaccinate	3.4	10.0
	Selective Vaccinate	3.4	8.1
	Random Vac & Lockdown (50%)	1.9	3.8
	Quarantine*	1.1	1.4
	Random Vac & Quarantine*	0.8	1.3
BA	No intervention	34.3	82.6
	Lockdown (78%)	2.3	12.9
	Randomly Vaccinate	21.6	44.0
	Selective Vaccinate	19.4	41.5
	Random Vac & Lockdown (50%)	8.6	18.9
	Quarantine*	5.6	9.0
	Random Vac & Quarantine*	4.4	6.5

(*All strategies containing quarantine start with nodes 0 - 4. So if we start with the same five nodes, the performance will be even better.)

(**Result maybe slightly different each time.)

5.2   Suggestion

By comparing different interference methods, we notice that vaccine is helpful, especially when you and your friends do not have large contact with other individuals. But suppose everyone still keeps the social behavior like before. In that case, the vaccine will not be as helpful as before, especially when the new variant of COVID appears, making the vaccine's efficiency drops. For example the Omicron variant these days.

Combining vaccination and reducing the amount of close contact with other people will dramatically reduce the number of infected people. But above all of that, the most useful interfere way is still quarantine people when they show symptoms.

Since this is a small community with 1000 population, the best model to fit the contact of this community is the BA model, we will give suggestion according to the result in BA model.

So if the community wants to reduce the number of people being infected and the effect of COVID on society, the best intervention strategy is to quarantine those who show the symptoms of COVID, and at the same time, give the vaccine to those sensitive people.

Code

The main part of this project is the coding part. Therefore, all the code written in a jupyter notebook file used for writing this report and generating the plot is attached to the folder. And there are also some instructions on the jupyter notebook.

References

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