Assessment of Human and Economic Costs from the Interaction of Pandemic Transmission and Government Policy

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Abstract—**This paper proposes a simple model of pandemic transmission. It examines several scenarios regarding two objectives: life loss and economic output loss. It explores the economic impact of medical resource constraints, vaccine distribution and lockdown policies in the event of the COVID-19 pandemic in 2020. Considering the objectives mentioned above, we can get the corresponding advantages and disadvantages of different policies. At the end of the paper, we also briefly discuss the possible reasons for the second wave of the pandemic in order to make further recommendations on policies.**

Index Terms—**COVID-19, pandemic scenario, policy making.**

I. Introduction

The start of the Covid-19 pandemic in the world quickly led to an unprecedented decline in economic activity. In 2020, real GDP fell by 31.4% in the second quarter. Even in a best-case scenario, GDP grew at an annual rate of 4.0% in the fourth quarter, still overall 2.5% below a year earlier [1]. Large gatherings were cancelled and people were forced to keep social distancing, which disrupted some businesses. As the pandemic continued, more businesses shut down and unemployment rose further. In 2021, more than 18 million people filed for unemployment insurance in the United States. The total number of continued weeks claimed for benefits in all programs for the week ending January 9 was 18 million, compared to 2 million in the same in 2021. In addition to the economic toll, the COVID-19 pandemic has also caused massive human loss. According to data released by the BBC on May 15 [2], the death toll was 581,900, and the official global death toll is 3.3 million, with the real numbers likely to be considerably higher. In the pandemic, many people died of the virus infection in their homes without being counted.

The government took some measures to control the spread of the pandemic and slow the economic decline. Under the pandemic situation, the lockdown policy directly led to the decline of consumption and economic slowdown. Although the virus spreading was controlled to a certain extent, the unemployment rate rose rapidly and then fell into the vicious circle of economic recession. On the contrary, loosening lockdown measures will affect economic development. At the same time, in the face of repeated pandemics, the virus becomes more widespread and more people will die. Different policy decisions relate to different economic outcomes.

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The contribution of this study is the comparative cost analysis of different policy choices in a pandemic. To the best of our knowledge, this is the first attempt in this area to measure the population loss against the economic loss to come up with relatively superior policies, also taking into account the interactions between several policies. We will attempt to capture and model the development of COVID-19 infection by studying the impact of COVID-19 infection on different agents in the economy, which will help develop policies, provide information, adequately respond to unexpected losses, and provide direct resources to those most affected by the pandemic.

II. Literature Review

During the COVID-19 pandemic, some governments adopted massive lockdown policies to contain the outbreak, which was an unprecedented response. At the same time, other countries have adopted other strategies, such as the construction of temporary medical stations and the roll-out of vaccinations. A systematic review of the pandemic policy is presented by Juneau *et al*. [3]. They compare interventions in historical epidemics and their benefits by collecting and comparing a large quantity of literature. Studies have shown that the health measures such as individual hand washing and wearing face masks are the most effective. Beyond that, some evidence also shows that the cost-effective interventions are rapid contact tracing and case isolation, protective equipment for health care workers and early vaccination, followed by home isolation and stockpiling of antiviral drugs, followed by social distancing measures. But the data collected by historical articles is not sufficient. To address this problem, we develop models based on these policies to simulate and compare the degree of intervention and economic cost of each policy under the COVID-19 pandemic. The most expensive policy in Juneau *et al*. [3] study was the lockdown. Despite its apparent unattractiveness, it was the policy of choice for a significant majority of countries.

Around the world, more than 90 countries, both developed and developing, have adopted lockdown policies. Ferguson *et al*. [4] evaluate the potential impact of public health measures in the absence of the COVID-19 vaccination. They look at two different levels of lockdown, mitigation and suppression. Mitigation policies are primarily aimed at slowing the spread of the pandemic and alleviating the shortage of medical needs. It is effective in reducing the strain on health resources, mainly by isolating people at higher risk, but a pandemic could still result in a large number of deaths. The suppressive policy is aimed at reversing the growth of the pandemic and reducing the number of cases to relatively low levels. It requires the entire population to maintain social distancing for long periods of time. The drawback of the suppressive policy is that if interventions are relaxed before the vaccination becomes universal, transmission can rebound quickly. Prior to the COVID-19 pandemic, no country had an experience with large-scale lockdown policies. This research provides a good reference for the countries to formulate policies. Therefore, we incorporate its conclusions into the consideration of our transmission model of the pandemic. We will study trends in the spread of the epidemic based on lax and strict control policies, and use modelling to assess the effectiveness of government interventions.

Non-pharmaceutical interventions are discussed in the literature above, and a model of vaccinations will be developed to discuss the dissemination trends and economic benefits of government interventions. In the study by Moore *et al*. [5], they estimate the effect of the vaccination in this COVID-19 pandemic by fitting existing epidemiological models. The result shows that vaccination can significantly reduce the total number of deaths but provides only partial protection to individuals. At the same time, there is a lot of uncertainty. When the vaccine is 60% effective, the number of deaths will be four times more than when the vaccine is 85% effective. This means that vaccination alone will not be enough to control the epidemic. How policies are selected and combined to maximise their effectiveness is crucial. Based on the above research, we will establish a comprehensive model of pharmaceutical and non-pharmaceutical interventions as well as further discuss the benefits of vaccination and other policy combinations.

III. Model

We analyse the interaction between the epidemiological evolution of COVID-19 and its implications for policy. We are defining the variable *t* as the time in months. *N* is the total population. Assuming that everyone is equally at risk of contracting the virus, the infection rate *i* is the proportion of new COVID-19 cases in a unit of time divided by population at the beginning of the period. The variable I_C represents the number of people who are newly infected, which is the number of people who may contract the illness, $I_{MC}(t)$, times the infection rate, $i(t)$. Because the more people are infected, the quicker the virus spreads, the infection rate will change as the number of newly infected people changes. We assume that the relationship between i and I_C is $i = \alpha * I_C + \beta$, where β is the initial value. In other words, upon the start of the pandemic, β would be the initial number of people to become infected and to initiate the spread of the virus. α is a constant that represents the transmission mechanism, which captures the speed of the virus spreading. We assume that the cured person will never be re-infected with the disease in the analysed timeframe, so we set I_{NC} to represent the number of people who have not been infected yet but can be infected. It is equal to the number of people who would not have been infected in the previous period minus the number of people who were infected in the previous period, which is $I_{NC}(t) = I_{NC}(t-1) - I_C(t-1)$.

With the assumption that the patients cannot go to work, we set $N_{AW} = N - I_C$ to represent the number of employees able to work. To observe the economic state of the world, we set Y as output. Assume that everyone can produce one unit of output each month, so the total output would be the sum of the output (or the number of living, healthy employees) every month. Then the economic loss, Loss, for one period is the expected economic output for that month minus the actual output in that period. The total economic loss can also be calculated by summing up the losses of all the periods.

For later versions of the model, the vaccine rate is v, the number of people taking the vaccine at period t is V(t) and the cumulative number of vaccinated people is $CV(t)$. To lower the spreading of COVID, we assume that the vaccine is prioritising the people who had never contracted the virus before, so we will have $V(t) = v * I_{NC}(t)$. Then, the formula of the cumulative number of vaccinated people is $CV(t) = \sum_{i=1}^{t} V(i) = CV(t-1) + V(t)$. We can then calculate the number of people who may contract the illness I_{MC}, as the number of people who have not contracted the illness yet minus the cumulative number of people vaccinated in the last period, which is $I_{MC}(t) = I_{NC}(t) - V(t-1)$.

At the same time, there may be some people who cannot access the treatment due to the limitation of medical resources. In such cases, we assume people would die with certainty rather than the predefined mortality rate. Our model assumes that there is only one variant of the virus, so the death rate caused by the virus is constant and fixed at d, provided that people can access treatment. To represent the constraints of the medical resources, we set the hospital capacity constraint to *cst*, so that the number of people above this constraint will not be able to get treatment. We use pl to denote the number of people treated in hospitals and pd for the number of people left untreated. We calculate pl to be the minimum of I_C and *cst*, and pd to be I_C – pl. Since we cannot guarantee that all patients are treated, the chance of people who are treated in the hospital will die is d. Then the number of people who died at period t will be $D = pt * d + pd$.

To compare the trends of the death rate changing more clearly, we also calculate the cumulative number of people who die as $CD(t)$, which is equal to the sum of people who die until *t*, $CD = \sum_{i=1}^{t} D(t)$.

Table I is the summary of the notation:

TABLE I: Summary of the Notation

Notation	Meaning	Formula
t	Time	–
N	Total population	–
i	Infection rate	$i = \alpha * I_C + \beta$
α	Transmission mechanism	–
β	The initial infected	–
I_C	Newly infected number	$I_{MC}(t) * i(t)$
I_{NC}	Number of people who have not been infected	$I_{NC}(t) = I_{NC}(t-1) - I_C(t-1)$
N_{AW}	Number of people who are able to work	$N - I_C$
Y	Total output	$\sum_{1}^{24} N_{AW}$
Loss	Total economic loss	$10000 \times 24 - Y$
v	Vaccine rate	–
V(t)	the number of people taking the vaccine at period *t*	$I_{NC} * v$
CV(t)	cumulative number of vaccinated people	$CV(t) = CV(t-1) + V(t)$

$I_{MC}(t)$	The number of people who may contract the illness	$I_{MC}(t) = I_{NC}(t-1) - V(t-1)$
d	Death rate	–
cst	the constraints of the medical resources	–
pl	patients are treated in the hospitals	$min(I_C, cst)$
pd	number of patients excess the constraint	$I_C - pd$
D	The number of people who will die	$D = pt * d + pd$
CD(t)	cumulative number of people dead	$CD = \sum_{i=1}^{t} D(t)$

In the following part, we will discuss how the government's interventions will affect the economy. For example, President Biden's American Rescue Plan, announced in January 2021, highlighted policies including a national vaccination program. In this case, the main goal of the government is to minimise the damage caused by the outbreak and to sustain economic growth.

Governments' goals are often hard to achieve simultaneously. We assume that the government prioritises controlling the number of deaths, then the lockdown policy will be the best choice. Under such a policy, although the number of deaths has been ideally somewhat controlled, the financial losses caused by the stagnation of economic activity will be severe, and the country may enter a recession in extreme circumstances. On the contrary, if a country gives up on saving lives and prioritises keeping the economy going, many people will die, and in extreme cases, it may lead to a loss of trust in the government and social unrest. Furthermore, if the government prioritises the allocation of medical resources, vaccines and subsidies, the pandemic will undoubtedly be controlled to a certain extent, which will help the economy recover quickly. But at the same time, the government must pay to forbear the cost. Whereas we don't model this effect here, we know that this cost could increase the country's debt, which it would need to pay off through higher taxes or other ways in the future. For countries that are already overindebted, this would be a disaster since rising debt is likely to lead to hyperinflation and financial collapse.

We are focusing on how the capacity constraint, vaccination rate and lockdown policy affect the trend of the pandemic. At the same time, to be more realistic, we will also explain the main causes of the second wave. The same theory can be extended to the third wave, the fourth wave, and so on. To show the movement clearly, we set N=10000, d=0.15. We assume the total number of people(N) is 10000. Because 1000 is too small such that we cannot show the slight population changing clearly.10000 is big enough to show the details, and this also makes the comparison between scenarios easier. The death rate assumptions are established based on two factors. First, we looked at the highest mortality rate in Italy [6] to simulate the worst-case impact of the outbreak. At the same time, it might be difficult to extract the characteristics of the model if the mortality rate is too low. The low mortality rate could have little effect on population change. Due to those reasons, the death rate was assumed to be 15%. Then we could generate a few scenarios to see how the pandemic works. Following is the summary of the senarios.

TABLE II: SUMMARY OF SENARIOS

	Scenarios Name	Graph
Scenario 0	World without pandemic	–
Scenario 1	Pandemic Baseline	Fig. 1
Scenario 2	Pandemic with capacity limitation (a: loose constraint, b: strict constraint)	Fig. 2a
		Fig. 2b
Scenario 3	Pandemic with vaccination (a: vaccination plan starts from 1st month, b: vaccination plan starts from 7th month)	Fig. 3a
		Fig. 3b
Scenario 4	Pandemic with capacity limitation and vaccination (a: loose constraint, b: strict constraint)	Fig. 4a
		Fig. 4b
Scenario 5	Pandemic with lockdown policy (a: lockdown start from 1st month, b: lockdown start from 6th month, c: lockdown first then relax the policy)	Fig. 5a
		Fig. 5b
		Fig. 5c
Scenario 6	Pandemic with multiple lockdowns	Fig. 6a
	Pandemic with seasonality	Fig. 6b

A. Scenario 0

In Scenario 0, we have a world without the pandemic, so the vaccination rate is set to zero, v=0%, and no medical resources are used in pandemic, so there is no capacity constraint, cst=10000. In this case, no one would get infected, so i=0, I_{MC}=0 and I_{NC}=0, and no one died of the virus. There are no effects on output and economy, and the total output will be 240,000 units 24 months after.

B. Scenario 1

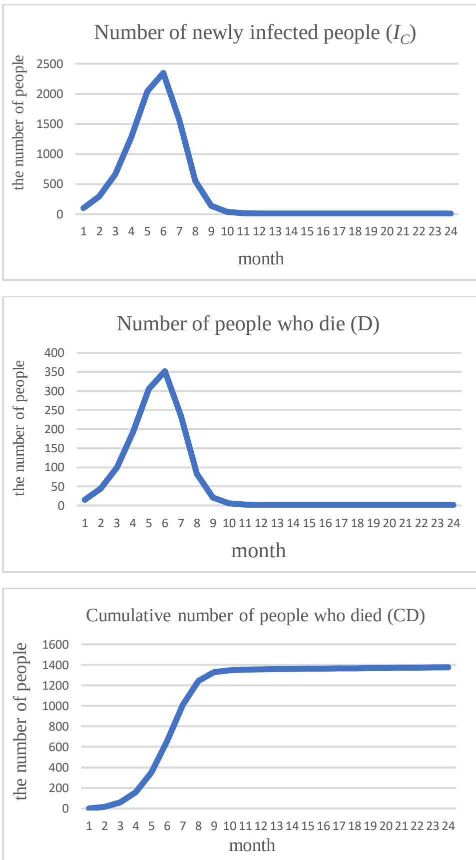


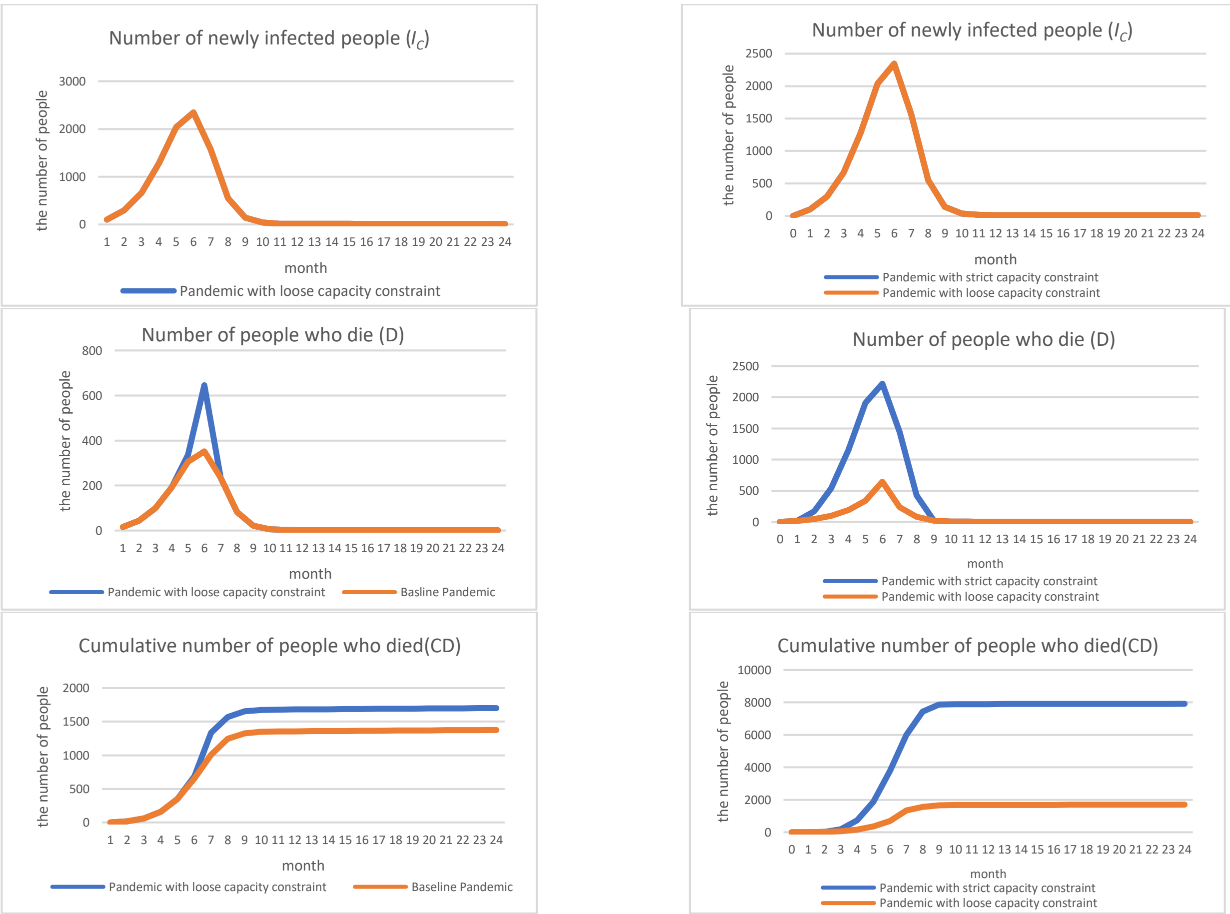
Fig. 1. Pandemic baseline graph.

In Scenario 1, called the pandemic baseline, we assume that the pandemic strikes and the government does not undertake any countermeasures. We set $\alpha=1/5000$ and $\beta=0.01$, which results in the following transmission dynamic:

At time 0, there is no disease, and no people are infected. As more people get infected, the infection rate *i* is increasing. The population is therefore decreasing because the deaths are increasing. As the pandemic continues, fewer people can still contract the virus, which implies that the infection rate will gradually peak and then start falling. The number of newly infected every month and the number of people who die would increase first then decreasing to zero eventually. From the Fig. 1, we can see that the number of newly infected people and the number of people who die have approximately the same trend. After 24 months, there are 1,376 deaths and 34,474 units of output lost compared with the world without the pandemic.

C. Scenario 2

In Scenario 2, we introduce the medical resource constraint. According to the data from United Nations, developing countries have an average of 113 beds per 100,000 people, which is 80% less than developed countries. The shortage of medical resources occurs not only in developing countries but also in developed countries. For example, in the USA, there were not enough N95 masks which necessitated the reuse of such single-use masks. In Italy, Ventilators and ICU beds were made available only for critically ill patients during the peak of the disease. Here, we consider two situations: one is the relative lack of medical resources; the other is the strict limitation of medical resources. The government can develop a set of measures that are more appropriate to the situation, based on the assessment of the tendency of pandemic and the level of medical resources. People who do not receive medical assistance have higher death rates than those who do. According to the *Delay-or Avoidance of Medical Care Because of Covid-19 -- Related Concern report released by CDC* [7], we can see the evidence of a rising death rate caused by insufficient medical resources. The shortage of medical resources may be caused by limited hospital capacity, insufficient medical equipment or insufficient medical staff. Here, we simplify it to the limit of hospital capacity. We consider two scenarios, the exists of medical constraints and a strict limitation of medical resources. We set the hospital constraints to 2000, *cst*=2000, called loose constraint, and to 150, *cst*=150, called strict constraint, respectively. In the loose constraint scenario, we observe the following transmission:



a) b)

Fig. 2. a) Pandemic with loose capacity limitation; b) Pandemic with the strict limitation.

Fig. 2a) shows a trend like the baseline world, where deaths and new infections tend to rise increasingly fast, reach the peak, and start to decrease gradually. With the medical resource constraint, there is a sharp increase in the number of deaths in the seventh month, which nearly doubles compared to the baseline world. The cumulative deaths are almost twice higher than in the baseline scenario at the end of 24 months. The pandemic causes 1,702 deaths and a loss of 40,362 units of output after 24 months. We can see that there are 383 people who could not get the treatment in months 6 and 7, those people died. This scenario has 326 more deaths and 5,888 units of output loss compared with no resources limitation. Interestingly, the final deaths increase is less than 383. This is because after the population plunged in June and

July, the number of infections and deaths has been lower than in the baseline model since then.

We can consider that the government may reduce deaths by making up for the shortage of medical resources. If 5,000 units of revenue were just enough to make up for the lack of medical resources, there would be fewer deaths. This means that the government would probably achieve the same or better condition as the baseline scenario by redistributing resources to healthcare. In the United States, the need for additional beds has led to the rapid construction of medical facilities in response to the pandemic. For example, University of Pennsylvania's Medical Department in Philadelphia was rushing to open part of a new hospital building in College Town to help with the influx of new coronavirus patients. The facility opened 119 beds on March 21 and expected to open 500 rooms by mid-April.

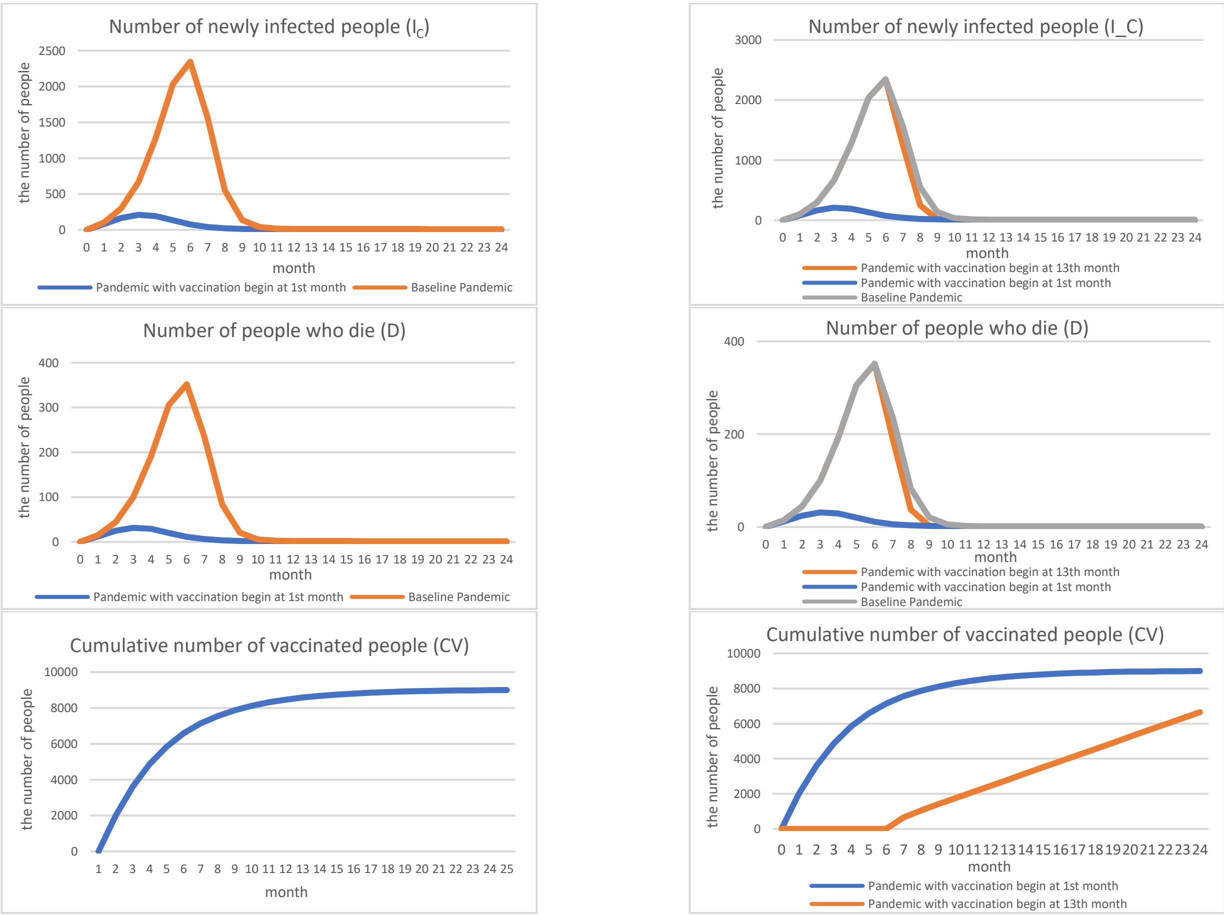
However, there is considerable uncertainty when making such decisions. For example, if the 5,000 units cannot be exchanged for sufficient medical resources, people will still die because they do not get medical treatment. There is also a time lag between the government's awareness of the need to invest in medical resources and the actual investment of medical resources. Furthermore, the increase of medical resources usually takes time. It is often difficult for governments to predict the trend of the pandemic, so it is very likely that medical resources are not being deployed when they are most needed. Therefore, it is possible to end up in the worst of both worlds: plenty of resources wasted on unused medical equipment and, nevertheless, significant life loss.

In the strict resource constraint, *cst*=150, scenario, we have the following transmission as shown in Fig. 2b).

We can see that this trend is the same as in the relaxed constraint scenario, but the number of deaths increases sharply. This is understandable because more people will die without treatment because of limited medical resources. Under this scenario, we have 7,918 death and 155,689 units of economic loss, which is significantly more than in any of the previous scenarios. As the medical resources constraint increased to 13 times, the death number increased to 20 times compared with the loose constraint scenario. It can be observed that the number of deaths caused by the lack of medical resources does not increase at the same rate. The more scarce medical resources are, the higher the real death rate it is.

D. Scenario 3

In Scenario 3, we model the vaccination distribution based on the baseline scenario. Getting vaccination can keep people from getting COVID-19 and would be a safer way to help build protection. On an individual level, vaccination reduces the risk of infection, the pain of illness and even death. More broadly, vaccinations can save lives, slow outbreaks, and reduce the likelihood of economic shutdowns. Here we assume that the vaccine is completely safe and will work as soon as people are vaccinated. To study the effect of distributing vaccination, we set the vaccination rate to 20%, and there is no constraint on medical resources. The pandemic dynamics are shown in Fig. 3a):



a) b)

Fig. 3. a) Pandemic with vaccination start from 1st month; b) Pandemic with vaccination start from 7th month.

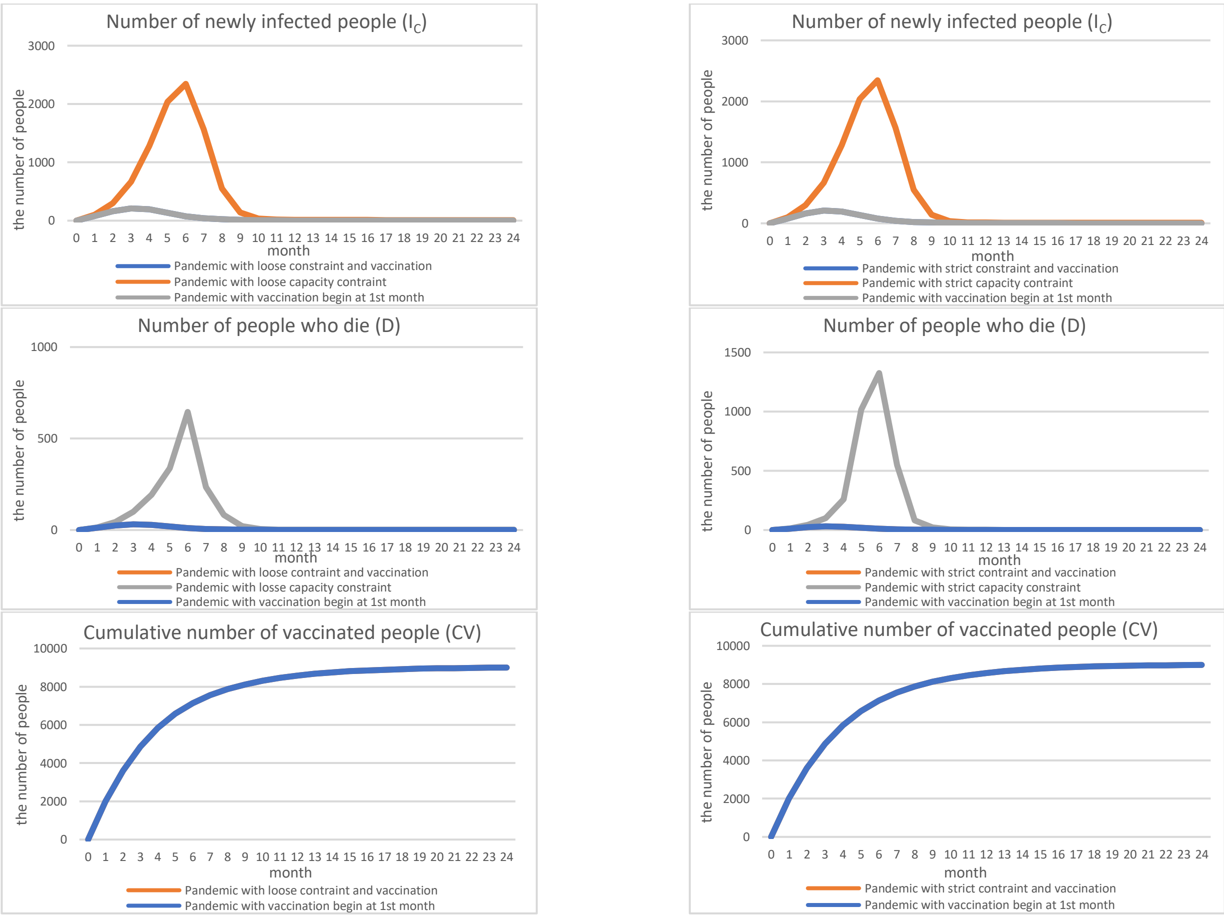
From the Fig. 3a), we can see that this scenario has a similar trend as the baseline but with a lower peak. From the data, we can see that there are fewer people who get infected and die. There are 146 death and 3,872 units of output loss after 24 months, which means 1,230 fewer deaths and 30,601 fewer units lost compared with the baseline scenario. Clearly, if spending 30,000 units of economic output could be spent to better develop the vaccinations, this could be a worthwhile investment for the government. But research and development are often costly, and ultimately the effectiveness of vaccines cannot be fully guaranteed. This means that the economic benefits of vaccines may be lower than expected. Also, it is almost impossible to start distributing vaccines at the beginning of the pandemic. This means there is a time lag between development and distribution. It is possible that the vaccine will be distributed after most people are already immune to the virus. The vaccine would have little effect on the containment of the pandemic.

As mentioned, in the real world, vaccines are not normally distributed at the start of an outbreak, and it takes time to develop a vaccine against such a new virus. We simulate a world where the vaccines cannot be distributed in a timely manner. We assume that it takes 6 months to develop the vaccinations, so distribution starts from 7th month. We obtain the following dynamics:

From Fig. 3b), we can see that the trend of delayed vaccine distribution is between the immediate distribution scenario and the baseline (where the curves overlap). In the delayed distribution scenario, there were 1,238 deaths and 31,507 units of output lost after 24 months, which is 138 fewer deaths and 2,966 fewer units of output less than the baseline. The scenario is approaching the baseline because the government started the vaccine plan at the peak of the pandemic when vaccines were less effective in preventing disease and controlling the infection. In the worst case, if the vaccinations are distributed after the natural ending of the pandemic, in which case they would be a waste of resources and would not help to control the pandemic.

E. Scenario 4

In Scenario 4, we combine Scenarios 2 and 3. In China, they build the emergency hospital to increase the ability to take in and isolate patients [8]. After the vaccine was developed, China starting distributing it immediately. We are trying to look at the payoff of doing this by combining theory two and three. As before, we approximate the scarce medical resources as hospital capacity constraints. We set the hospital constraints to 2000, *cst=2000*, and 150, *cst=150*, respectively, and let the vaccination rate be 20%. Then we have:



a) b)

Fig. 4. a) Pandemic with loose capacity limitation and vaccination; b) Pandemic with strict capacity limitation and vaccination.

From Fig. 4a), we can draw a conclusion that the outcomes are almost identical to Scenario 3a. A closer look at the data shows that the lack of medical resources is no longer affecting the evolution of the pandemic because of the reduced number of cases due to vaccine distribution. This makes sense because by vaccinating, fewer patients enter hospitals, so hospitals are less likely to be overloaded. But the disadvantage of this model is that we assume that the vaccine is quick enough to be distributed in a timely manner. If changes are made, such as a delay in vaccination schedules, medical resources may again become scarce, and there may exist some people who will not obtain the treatment. In this case, the result of this scenario will be worse than Scenario 3a, i.e. more deaths and more economic losses, but it will still be better than Scenario 3b.

From the Fig. 4b), we can see that the trend of the pandemic transmission mechanism is similar to the world with vaccination. There is 245 death which is 99 more than scenario 4a, the world with relatively adequate medical resources (*cst=2000*), and 5925 units of output loss, which is 2053 more than scenario 4a after 24 months. When we compared the pandemic world with strict capacity constraints, the number of deaths and economic losses was reduced by more than 30 times due to the introduction of the vaccine. So the vaccination could be the best choice regardless of the cost and the development period.

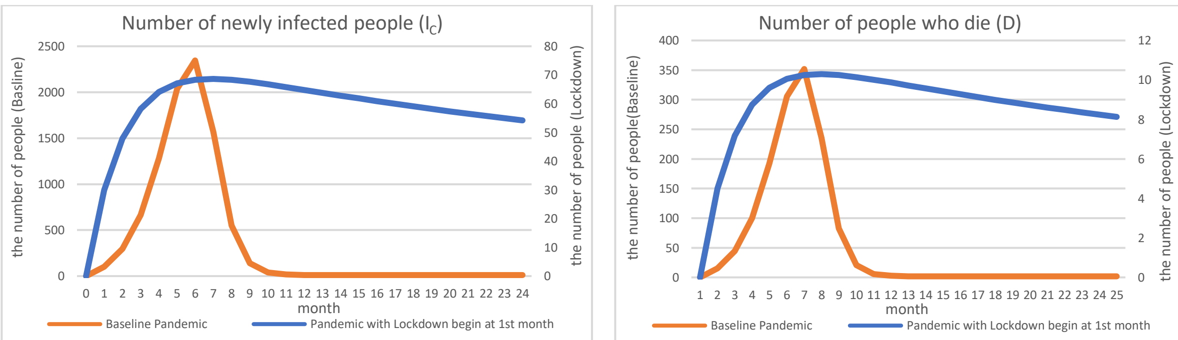
F. Scenario 5

In the 5th scenario, we develop a model of a lockdown. On January 23, 2020, the Chinese government had not only has blocked Wuhan, but it has also imposed a restricted access agreement on the city of Huanggang, 30 miles to the east. That means up to 18 million people were under strict lockdown. Subsequently, India, Iran, Israel, and England imposed a lockdown. To represent the lockdown policy, we set the percentage of people who are locked down as *LD*. Under no lockdown, we have *LD=0%*. If the lockdown is strictly enforced, which means no one can go out, it becomes *LD=100%*. We are assuming that all the people who are not in lockdown and not infected are working. Then the number of people who are able to work at the beginning of the month will change to the total number of people at the beginning of this month times 1 minus *LD*, or $N_{AW} = (1 - LD) * N$. The amount of output by the end of the month(y) will be the number of people who are able to work at the beginning of this month minus the people who get infected this month, which is $y = N_{AW} - I_C$. The total output (Y) would be the sum of the outputs at the end of each month.

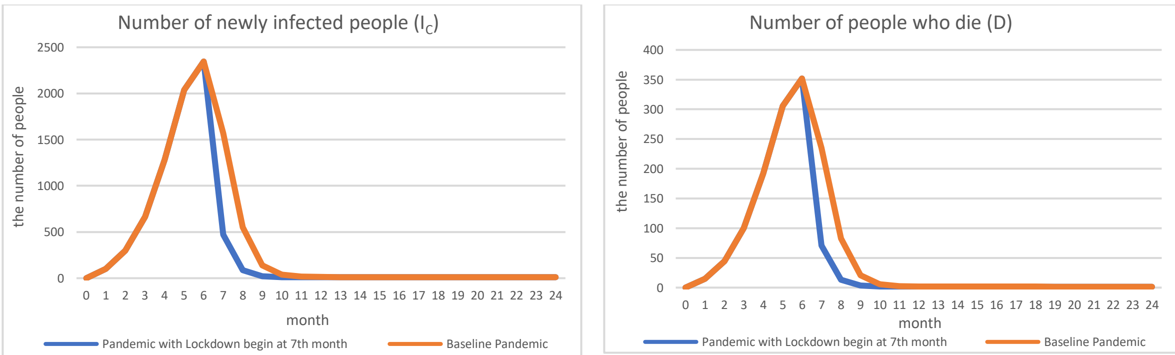
When we measure the number of people who may contract the illness, it is hard to tell how many of them will go out to work. But we do know that, on average, the number of people who may contract illness whereas working outside will change with the spread of the pandemic. In other words, as more people become immune to the virus, the number of people who will not be infected when working outside will increase. Consequently, we assume that the proportion of people working outside at risk of being infected is the same as the proportion of people at risk of being infected in the whole society, I_{MC}/N. We use I_{MCW} to denote the number of people who will work and may contract the illness, where $I_{MCW} = (I_{MC}/N) * N_{AW}$.

Different countries have applied different lockdown policies, and the main criteria to be measured are the degree of the lockdown policies, the duration of implementation and the timing of relaxing the lockdown. Here, we discuss three conditions. The first is a strict lockdown that starts from the beginning of the pandemic and continues throughout; the second is a strict lockdown that is implemented after the outbreak begins but only for a certain period of time; the third is the strict lockdown policy that is being gradually relaxed after the outbreak lasts for a certain period of time. We set the overall lockdown rate to 70%. These degrees of lockdown prevented people from gathering but still allowed them to have some outdoor activities. And the loose lockdown rate is set to 10%, people are still required social distance and they are limited to the large gathering. But most of the activities are back to normal.

In the first case, we have the following pandemic transmission mechanism:



a)



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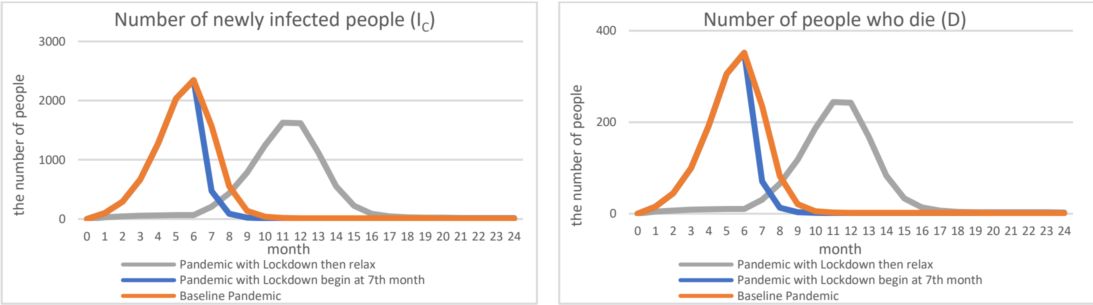


c)

Fig. 5. a) Pandemic with lockdown start from 1st month; b) Pandemic with lockdown start from 7th month; c) Pandemic with lockdown then easing the restrictions.

The trend shown in Fig. 5a) of the pandemic varies considerably from the baseline world. Both the number of new infections and the number of deaths in the initial period increased and then gradually began to decline. The quantities in the two scenarios are so different that they are represented in different units in Fig. 5a). The biggest difference from previous scenarios is that the rate of decline is so slow that it produces a giant fat tail. After 24 months, the total number of deaths was only 208, but the total output lost amounted to 170,190 units. Total deaths showed a substantial decrease, almost 1/4 to 1/6 compared to the previous scenarios, but economic losses also increased significantly, almost 5 to 8 times. This means that if the government chooses to impose a strict lockdown policy, it risks causing an economic contraction and sustaining huge economic losses. We also noticed that, after 24 months, there were still 8,611 people who were not immune to the virus. This means that the government will need to continue the lockdown and other policies to slow down the pandemic. That could mean that 24 months later, the government is still facing a pandemic situation.

We now consider another variant under this scenario, which is that the government starts the lockdown policy when the pandemic is about to reach its peak. For example, On April 17, 2020, as the outbreak was nearing its peak in New York, Governor Andrew Cuomo of New York announced the New York State high-level action to combat the pandemic. By law, 100% of the nonessential labour force in New York State is obligated to stay at home or work from home. We will see the theoretical effect of this in the following part. We set the percentage of people in lockdown set 70%. The transmission mechanism looks as follows:

In this scenario, the trend of the entire pandemic is very close to that of the baseline world as shown in Fig. 5b). Twenty-four months later, there were 1,116 deaths and 140,626 units of output lost. When we compared with the baseline world, there are 260 more death and almost 5 times larger damage to the economy. When the government imposes the lockdown at the peak of the pandemic, this results in a huge cost and ends up ineffective in saving people's lives. The relatively loose constraint resulted in 908 more deaths and 38,564 more economic losses than a completely strict lockdown (i.e. 70% lockdown through 24 months). This means that if the government is to impose a lockdown, it should do so as soon as possible, or else it will end up with huge economic losses and less than satisfactory results. But we cannot completely deny the effectiveness of the lockdown. As can be seen from the charts, after the month of the implementation of the lockdown policy, there was a rapid decline in the number of deaths, which may be the primary objective of the government.

Finally, we look at what happens if the government choose to lockdown quickly first and then begin to lift the restrictions. We will set the timing of relaxation to happen after the 6 months. This is reasonable because in the lockdown period, there are not too many infected people, so there is social pressure to relax the lockdown rules. As seen in scenario 5a, a continued lockdown would have a substantially negative impact on the economy, so there might be pressure on the government to avoid this. In the coronavirus pandemic, many countries are opening up after periods of lockdown. Prime minister Narendra Modi announced on April 14 that some of the curbs would be lifted in places outside "containment zones" and in areas where the possibility of the pathogen spreading was low to revive economic activity. In our analysis, we model a strict lockdown for the first 6 months, and then reduce it to 10%. The pandemic has the following transmission mechanism:

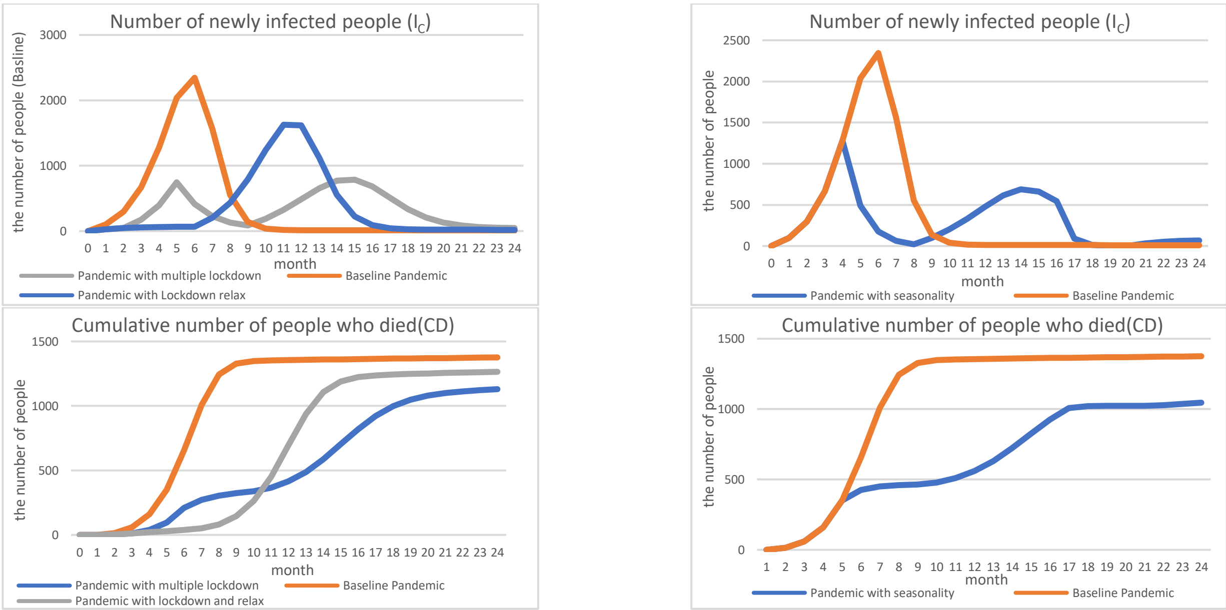
From Fig. 5c), we can see that after the lockdown was relaxed, the pandemic began to spread continuously. And the trend of spread after policy easing was very similar to that of the baseline world. After 24 months, there would be 1,265 death and 83,038 units of output loss. Interestingly, compared to the baseline world, the number of deaths is very close, but the economic losses are nearly twice as high. In other words, the pandemic under this scenario will end up with death similar to those in the baseline world but much higher economic loss. In this scenario, it is reasonable to believe that keeping people from going out would slow down the process of the outbreak. But if just the policy of lockdown were implemented, the pandemic would be postponed rather than end. When the countries back to normal, the pandemic will continue to develop rapidly, eventually approaching the baseline world. At the same time, society will suffer significant economic losses.

G. Scenario 6

Until now, we've talked about unimodal problems, but that's not the case in real life. In India, the number of infections has been falling steadily since a peak of more than 93,000 cases per day in mid-September 2020. By mid-February, India was averaging 11,000 cases a day. After that, India quickly loosened its lockdown policy and carried out many gathering activities, such as elections and watching two international cricket games. In less than a month, things began to unravel. India is being hit by a devastating second wave of the coronavirus and cities are facing a new lockdown. By mid-April 2021, the country was averaging more than 100,000 cases a day. On April 18, India recorded more than 270,000 cases and more than 1,600 deaths, both new single-day records.

We introduce a pandemic with the second wave as Scenario 6. What we can observe from Indian policy is that the second wave is likely to be related to repeated lockdowns. In scenario 6a we will study the effects of multiple lockdowns on the spread of the pandemic. In addition, we also consider the impact of seasonal changes on the spreading. The article 'Will summer slow the spread of COVID-19?' [9] introduces how the virus behaves seasonally: it is more prevalent in winter and less prevalent in summer. This could be because human behaviour is seasonal, with people spending more time outdoors in the summer, leading to lower infection rates, or it could be that people benefit from increased exposure to sunlight and thus have a stronger immune system. So we take into account seasonal factors in scenario 6b to see if they would affect the development of a second wave.

We first look at the effects of multiple government lockdowns. We assume that the government will enforce a strict lockdown for the first two months, followed by an easing of restrictions from March to May. It is followed by another lockdown from June to September and then another relaxation. It is six months of strict lockdown and 18 months of loose policy. The lockdown lasts for the same time as in scenario 5b. Similar to scenario 5, a strict lockdown will keep 70% of the people at home, and a loose policy will keep 10%. We will see the following changes:



a) b)

Fig. 6. a) Pandemic with multiple lockdowns; b) Pandemic with seasonality.

As we can see from the Fig. 6a) above, after two lockdowns, the pandemic developed a second wave trend compared to the baseline benchmark. This proves that the government's lockdown policy has a direct impact on the second or even multiple waves of the pandemic. In this scenario, the number of deaths is reduced relative to the baseline world. Interestingly, the same strict lockdown for a total of six months resulted in fewer deaths and fewer losses than in the world where lockdown then relaxed. The human and economic costs of repeated lockdown are lower than lockdown from the beginning. This could happen due to the strict limitation when the trend is reaching its peak. But it's still hard to say if the short-term high-frequency lockdown policy is better off than the long-term low-frequency lockdown policy. Imposing lockdown when reaching the peak can have some effect on saving lives. But the trend of the pandemic is also hard to predict.

In scenario 6b, we will discuss how seasonality affects the transmission of the epidemic. We know that the pandemic slows in the summer and accelerates in the winter. Thus we are going to come up with two sets of α's and β's. β's role is to increase the initial number of infected people in the epidemic from zero, whereas α's governs the dynamics of the transmission. Therefore, in summer, we set α to 1/20000 and β to 0%. In winter, we set α to 1/5000 and β to 1%. Then we have the following transmission mechanism of the pandemic:

Fig. 6b) above shows the trend of the second wave of the pandemic. The pandemic peaked in April of the first year and February of the following year and showed a trend of the third wave in September of the second year. Thus, seasonal changes can also lead to repeated changes in the pandemic. Therefore, the government can make lockdown policies in line with this observation, such as strengthening the lockdowns in the season when the virus is more active and relaxing the restrictions for the rest of the time.

H. Summary Table

Table III is the death toll and economic output loss summary of all the scenarios:

TABLE III: SUMMARY OF THE DEATH TOLL AND OUTPUT LOSS

Scenario	Description	Total number of deaths	Total output loss
0	No Pandemic	0	0
1	Pandemic Baseline	1,376	34,473
2a	Pandemic with Loose Capacity Constraints	1,702	40,362
2b	Pandemic with Strict Capacity Constraints	7,918	155,689

3a	Pandemic with Vaccination begin at 1st month	146	3,872
3b	Pandemic with Vaccination begin at 7th month	1,238	3,150
4a	Pandemic with Loose Capacity Constraints & Vaccination	146	3,872
4b	Pandemic with Strict Capacity Constraints & Vaccination	245	5,925
5a	Pandemic with Lockdown constant	208	170,190
5b	Pandemic with Lockdown begin at 7th month	1,116	140,626
5c	Pandemic with Lockdown relax	1,265	83,038
6a	Pandemic with multiple lockdown	1,130	79,055
6b	Pandemic with seasonality	1,046	22,293

IV. Conclusion

The key lesson from this paper is that when the pandemic strikes, we can see that government assistance in medical resources could save many lives, which is less costly and more effective than other policies. Emergency measures such as increased medical equipment and protective gear should be therefore considered first. In addition to replenishing medical resources, the government may be able to alleviate medical pressure through lockdown policies and vaccine distribution. The lockdown could be effective in reducing the number of deaths in the short term, but it may cause significant economic losses. It basically slows the spread of the pandemic and delays the arrival of the pandemic wave. If not used in conjunction with other policies, the cost of this policy could be enormous, and the impact on reversing the pandemic negligible. As for vaccines, the earlier and faster they are distributed, the fewer lives and economic damage the pandemic will cause. If the government cannot distribute the vaccine before the first wave peaks, it will not have a considerable dampening effect on the first wave. But that does not mean the distribution of vaccines is pointless. Vaccines distributed in the first wave would help to slow the spread of a second wave.

We also looked at what might trigger the second wave of the pandemic. The first possible reason is the repeated lockdown imposed by the government. The second one is the natural factor of seasonality. In previous cases, the vaccination may not have had an immediate effect, but its role in preventing a second wave is significant. If the government's focus is on saving lives, it should be tightening the lockdown sooner rather than later. Excessive hesitation may undermine the effectiveness of the policy. If governments are more focused on reducing economic losses, the early development and distribution of vaccines seem to be crucial. Although we have not predicted this in the model, we can speculate that the government can adjust the degree of lockdown policy appropriately according to the season, so as not only to ensure that the population will not suffer a large loss, but also to not stifle the economy too much.

This paper suffers from several limitations that are worth pointing out. In our model, we set the infections to increase linearly. However, the rate of infection might be different. For example, it may increase exponentially, or it may change as the season changes. At the same time, the mutation of the virus may also lead to a change in infection rate and death rate. So the real pandemic could be more uncertain than our models predict. In future studies, the prediction could be enhanced by modifying the infection rate equation if needed.

Moreover, we try to present a single scenario for each policy in this paper. In real life, there may be more combinations. However, we do not want the model to become too large or contain too many free parameters. Therefore we have decided against including these combinations. In future studies, different countries can build models based on their characteristics to achieve more accurate predictions.

Finally, our theories mainly explore the situation of a single-wave pandemic, and we only mentioned the possible causes of a larger number of waves towards the end of this paper. This is because we want that the model can start from a simpler perspective and compare the characteristic of different policies more clearly. If the topic shifts from policy optimality to forecasting in future, we could try to develop models of multi-wave pandemics based on these theories to fit the real world.

Conflict of Interest

The author declares no conflict of interest.

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