An Optimization of Shanghai's Lockdown Policy: Economy, Mental Health, and Severe Cases Considered

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1 Introduction

1.1 Background

The COVID-19 pandemic has haunted mankind for over 2 years and yet to be totally contained. Countries all over the world adopted multiple methods to combat the virus, where the two main branches are herd immunity (e.g. Britain, the USA, etc.) and zero-COVID policy (e.g. China, North Korea, etc.). This project will take Shanghai in 2022 as a case study example and focus on the lockdown policy of China's zero-COVID ambition.

Shanghai has been under city-wise lockdown since April 1, 2022 due to the Omicron Variant of COVID-19, and hasn't yet been totally lifted. Aside from being a public health crisis, this wave of pandemic has suspended Shanghai's economy for such a long time that according to Investor China and CNN, the lockdown has inflicted the world upon a multidimensional economic loss amounting to 11.78 billion RMB per day [4] [6]. Moreover, the strict lockdown policies such as "Maintain Indoors" and "Regularized PCR Test" have caused numerous trouble to citizens' lives and thus give rise to mental health issues, since lockdown policies are proven to significantly increase the depression, stress, and loneliness rate [8].

The reason why China is still sticking to the dynamic-zero ambition is that if they relax the policies, the huge population base would cause a significant number of severe cases and put many senior citizens at risk of their lives [13].

1.2 Our Focus

Based on the background knowledge stated below, we would like to develop an optimization model that captures the tradeoff among economic loss, public mental health, and number of severe cases. Given a period of time, we want to balance the economic loss, public mental health conditions, and severe cases by controlling the lockdown on-off state in the context of Shanghai 2022. Therefore, an optimal solution can be proposed and compared with the current lockdown policy in Shanghai.

1.3 Problem Description

To illustrate our interpretation and modeling of this problem, we should break the problem down into the following 4 parts:

1.3.1 Economic Loss

Lockdown suspends a lot of companies and factories and brings economic loss to the city day by day. Therefore, we model the economic loss from lockdown with a linear model to capture one of the largest negative impacts of the lockdown policies.

1.3.2 Public Mental Health

Public mental health issues, as another negative side of lockdown policies, can be modeled with sigmoid function. According to our observation, the residents in Shanghai were at first acceptable with the lockdown when it hasn't lasted so long, but as time goes by, depression, stress, and loneliness starts to grow and accelerate. Until recently, we found that citizens are more and more accustomed to the lockdown life and have overcome the lockdown difficulties. Therefore, the mental health concerns should follow a slow-fast-slow growing rate, which corresponds to the shape of the sigmoid curve.

1.3.3 Severe Cases

According to Chinese national conditions, the government places huge emphasis on controlling the severe cases and mortality of the pandemic. So, to simulate the Chinese circumstances better, we also adopted a large linear penalty on the number of severe cases.

1.3.4 Epidemic Simulation Model

Over the past two years after COVID-19 has emerged, many scholars have applied multiple epidemiological models to simulate and understand the propagation of the pandemic[1][3]. We referenced the SEIR model from Miguel Navascués' study, and adjusted it to better fit our data[10]. For instance, in their model, they categorized the infected people to be regular, hospitalized, and critical care, while we categorized them as regular cases and severe cases. The dynamic of this epidemic model can be better illustrated in Figure 1.

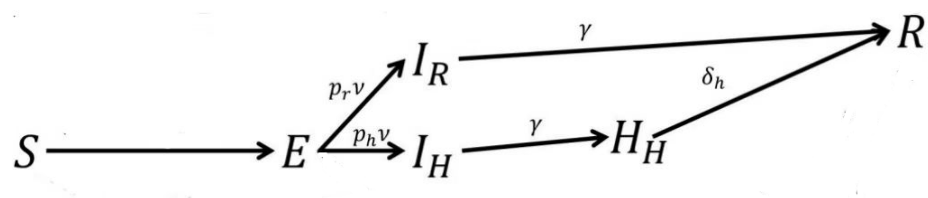

Figure 1: Our Adjusted SEIR Model

To compare the optimized results generated from our model with the current situation in Shanghai, we investigated the optimal lockdown policy in the timeframe of three months and one year. For three months, it's enough for places in China other than Shanghai to get fully vaccinated. It will then minimize the propagation in other cities and other cities would also be able to assist Shanghai afterwards. For one year, it's a long enough time for Shanghai to contain the pandemic wave by itself while considering the long-term cost brought by the lockdown.

2 Model Formulation

2.1 Model Explanation

2.1.1 Decision variable

We denote $T \in \{0,1\}^k$ as a plan of lockdown on-off state at each week. Since the government can't frequently change the state of lockdown, we restrict that each state decision whether on or off will last for 7 days. In our problem, we consider the plan for two different periods of time, 3 months and 12 months. For 3 months plan, T will be a 13 dimension binary vector where 1 denotes a 7-day lockdown and 0 denotes a 7-day non-lockdown phase. For 12 months plan, T will be a 52 dimension binary vector with the same 0,1 meaning. We have t_i denotes each element in T, meaning whether the lockdown is on or off at week i.

2.1.2 SEIR model

The ordinary differential equations for SEIR model are listed below, while r equals to r_0 during non-lockdown period and r equals to r_1 during lockdown period:

$$\frac{dS}{dt} = -r\beta S(I_R + I_H) \tag{1}$$

$$\frac{dE}{dt} = r\beta S(I_R + I_H) - vE, \tag{2}$$

$$\frac{dI_R}{dt} = p_R vE - \gamma I_R, \tag{3}$$

$$\frac{dI_H}{dt} = p_H vE - \gamma I_H, \tag{4}$$

$$\frac{dH_H}{dt} = \gamma I_H - \delta_H H_H, \tag{5}$$

$$\frac{dR}{dt} = \gamma I_R + \delta_H H_H. \tag{6}$$

Explanation of the parameters can be found in Table 1. The simulation graph of the SEIR model can be seen in Figure 2.

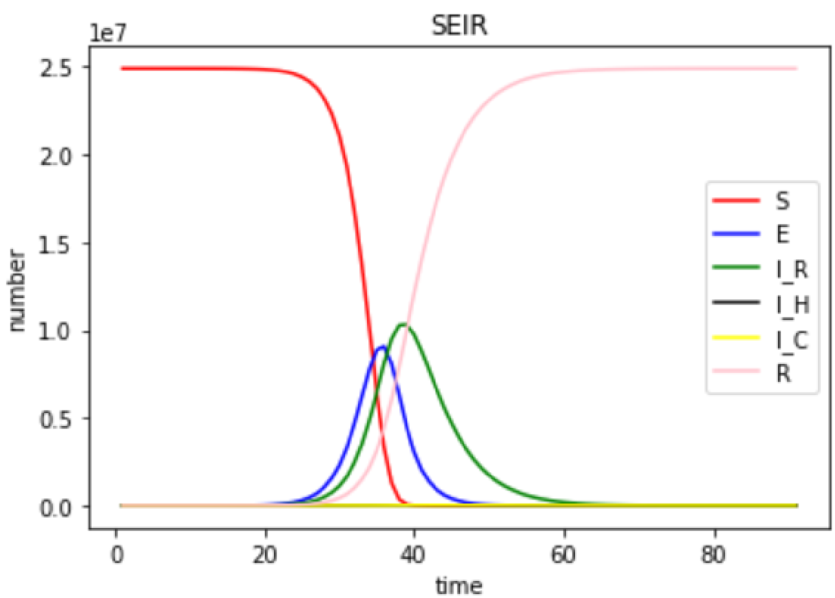

Figure 2: SEIR Disease Simulation Graph

Parameter	Meaning
$S(t)$	Number of susceptible people at time t
$E(t)$	Number of exposed people at time t
$I_R(t)$	Number of infected People going to become an non-severe case at time t.
$I_H(t)$	Number of infected People going to become severe cases(H) at time t.
$H_H(t)$	Number of severe patients at time t.
$R(t)$	Number of removed people who are recovered, immune, or dead.
r_0	Average number of people of an infected person would contact per day divided by the total population number when lockdown is off
r_1	Average number of people of an infected person would contact per day divided by the total population number when lockdown is on
β	Probability of a susceptible person get infected after contact with a infected person
v	The inverse of average days an exposed person turn to be infected
p_R	Probability of an exposed person will eventually be a non-severe case
p_H	Probability of an exposed person will eventually be a severe case(H)
γ	The inverse of average days an infected person turn to be a non-severe case or severe case(H)
δ_H	The inverse of how many days it takes for a severe case to be removed(H)

Table 1: Parameter Explanation Table

We take the integral of equation(1)-(6) on interval [n-1,n] and apply left Riemann sum (See Appendix B). Then we get corresponding recursive formula as:

$$S_n - S_{n-1} = -r\beta S_{n-1}(I_{R_{n-1}} + I_{H_{n-1}}) \tag{7}$$

$$E_n - E_{n-1} = r\beta S_{n-1}(I_{R_{n-1}} + I_{H_{n-1}}) - vE_{n-1}, \tag{8}$$

$$I_{R_n} - I_{R_{n-1}} = p_R vE_{n-1} - \gamma I_{R_{n-1}}, \tag{9}$$

$$I_{H_n} - I_{H_{n-1}} = p_H vE_{n-1} - \gamma I_{H_{n-1}}, \tag{10}$$

$$H_{H_n} - H_{H_{n-1}} = \gamma I_{H_{n-1}} - \delta_H H_{H_{n-1}}, \tag{11}$$

$$R_n - R_{n-1} = \gamma I_{R_{n-1}} + \delta_H H_{H_{n-1}}. \tag{12}$$

Note that the subscription n denotes the n^{th} day. Therefore, with a lockdown plan $T \in \{0,1\}^k$, we can get the dynamic changes of severe cases recursively. We can also obtain the total sum of severe cases N by summing up $\gamma \mathrm{I}_H$. We can then define a function $F : \{0,1\}^k \to \mathbb{Z}$ that takes the lockdown plan as input and outputs the total sum of severe cases:

$$F(T) = N \tag{13}$$

2.1.3 Economic Loss

C_1 denotes the importance factor of economic loss. The overall date for lockdown is $7 \times \sum_i t_i$. Since we model economic loss linearly, the economic loss is $7C_1 \times \sum_i t_i$. Since $C1$ is a parameter, we can simplify the economic loss term as $C_1 \sum_i t_i$.

2.1.4 Public Mental Health Loss

C_2 denotes the important factor of public mental health loss. m_j denotes the length for each continuous lockdown period. (e.g. [1 1 1 0 0 1 1 0 0 0 1 1] has $m_1 = 3, m_2 = 2, m_3 = 2$) As we observed in Shanghai, residents' mood is relatively stable during the lockdown in the first week, and the negative moods rise rapidly in the second and third weeks. After that, the mood of residents tends to mild down again. We apply a sigmoid function $f(x) = \frac{1}{1+e^{-(wx+b)}}$ to measure the overall mental problems residents may face during each continuous on lockdown state. With tuning, we find sigmoid function with w=1.7, b=-7 best fit our observations. The sigmoid function f is shown in Figure 3. The public mental health loss for each continuous on lockdown state is $C_2 \times f(m_j)$. Then the overall public mental health loss is $C_2 \times \sum_j f(m_j)$. We also define function $\phi : \{0,1\}^k \to \mathbb{Z}^d$, which takes the lockdown plan as input and outputs the corresponding m_j's denoting length of the j-th continuous lockdown period. The function is given by

$$\phi(T) = M$$

such that

$$M = [\, \text{---}\ m_j\ \text{---}\,] \in \mathbb{Z}^d$$

where d is the number of continuous lockdonw periods in a certain lockdown plan.

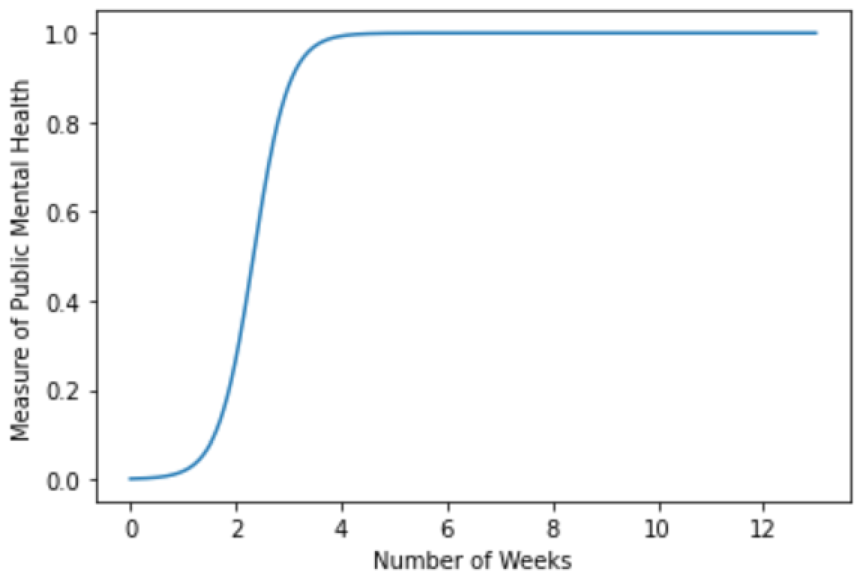

Figure 3: Sigmoid Curve

2.1.5 Severe Case Loss

Let N denote the overall severe cases. We wish to restrict N under a certain number, that is $N <= C$ for some C. We transform such constraint into objective function, making it as an severe case loss. Let C_3 denote the important factor of severe case loss. Then the severe case loss is $C_3 \cdot N$

2.2 Objective Function

The objective function is the total loss which combines economic loss, public mental health loss, and severe case loss together. The function $F(T)$ is defined in section 2.1.2 and $M = [— m_j —]$ follows section 2.1.4. Let L denote the total loss, k is 13 or 52 in the corresponding time period cases. The objective function is as follows:

$$\min_T L = C_1 \sum_i t_i + C_2 \sum_j f(m_j) + C_3 \cdot N$$

s.t.

$$f(m_j) = \frac{1}{1 + e^{-(1.7m_j - 7)}}$$

$$N = F(T)$$

$$M = \phi(T)$$

$$T = [\text{---}\ t_i\ \text{---}] \in \{0,1\}^k \quad \text{where } i \in [1,k]$$

$$M = [\text{---}\ m_j\ \text{---}]$$

All parameter values can be found in Appendix A.

3 Data Description

The data we utilize in our project involves both ground truths and inferred information. Ground truths include epidemiological facts about COVID-19 Omicron variant, demographic data in Shanghai, and daily pandemic report in Shanghai. Inferred information are those inaccessible parameter values that we tuned in our model.

3.1 Ground Truth

3.1.1 Shanghai Population

According to Shanghai Bureau of Statistics, Shanghai has a relatively stable population of 24.8932 million[12]. We take this number as the initial population in our model.

3.1.2 Pandemic-Related

According to Jørgensen et al. in March 2022, the secondary attack rate of the Omicron variant is 25.1%[7]. This is so far the most recent investigation on the transmission pattern of the Omicron variant. We use this number as the transmission rate β in our model, indicating that the close contacts have a 25.1% probability of catching the disease.

For the incubation period, the average duration is 3 days[5]. This number corresponds to the v in the SEIR model. For the severe case rate, we use the data that chief epidemiologist Zunyou Wu from the Chinese Center for Disease Control and Prevention revealed at the press conference. Among all cases in China from January to March 2022, 0.2% of the positive cases turned out to be severe cases[14].

As for the daily cases report in Shanghai, we gathered the data from Shanghai Municipal Health Commission[11].

3.2 Inferred Information

Regarding the average number of people one would contact per day divided by the total population number(r_1), the current literature gives various answers. Kwok et al. in 2018 reported that in Hong Kong, one would on average meet 12.9 people in 2.9 geographical locations[9]. By estimation, since Shanghai's population density is approximately half as high as Hong Kong's, we infer that a Shanghai citizen would meet 6-7 people per day. However, Del Valle et al. in 2007 found that on average in Portland, one person aged 20-50 would meet 22 people per day[2]. We then take $[\frac{6}{24894320}, \frac{22}{24894320}]$ as a range for the r_1.

For the initial number of people who are actually infected and exposed to the virus, it's impossible to know since we only know the number of people who are tested positive every day. Also, since what the Shanghai government did is not totally transparent to us, we can't know the day when Shanghai started to take measures. We denote the day as t_s. Therefore, we decided to use grid search to find the r_1, E_0, and I_{R_0} that fits the daily cases reports the best. We adopted the mean squared percentage error(MSPE) to measure the fitness since it can reflect the magnitude of the error compared with the actual value, which is given by

$$MSPE = \frac{\sum_{j=1}^{V}(\frac{E_j}{A_j})^2}{V}$$

We plotted the error in relation to the number of days we consider that Shanghai hasn't started to take measures. According to Figure 4, we see that starting from day 5, the error starts to grow sharply, which is the elbow point. Thus, we conclude that possibly Shanghai's pandemic prevention starts to take effect on day 5 so that it can't be simulated with the basic SEIR model that assumes natural transmission. We also acquire that $r_1 = \frac{7.5}{24894320}, E_0 = 23, I_{R_0} = 2$ simulates the first 5 days' situation very well.

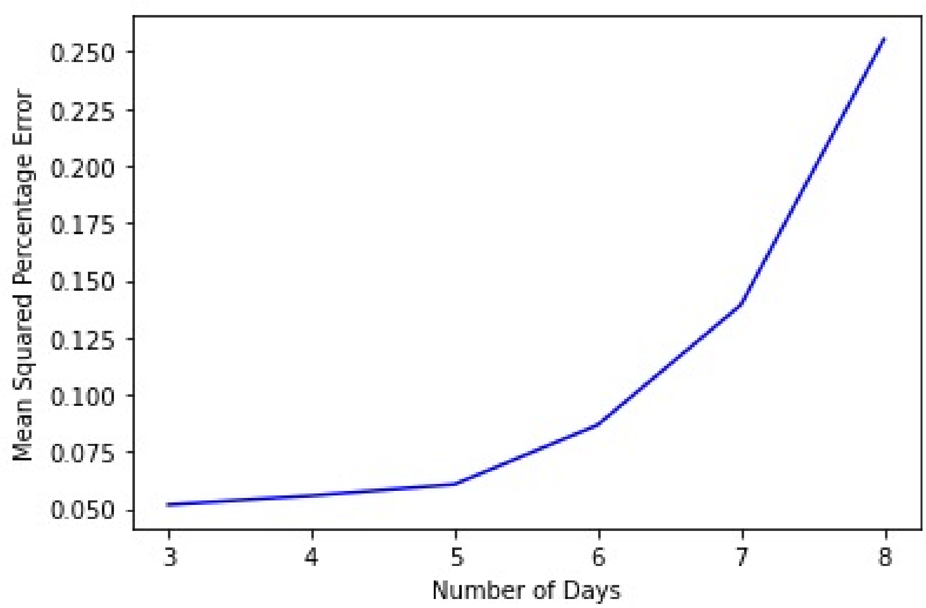

Figure 4: MSPE in relation to the number of days we consider that Shanghai hasn't started to take measures

3.3 Solution Algorithm

First of all, the SEIR model is captured by a series of ordinary differential equations with high dimensions. Due to the complex nature of the system, we are unable to derive a set of explicit functions that describe the SEIR model using analytical methods. However, it's relatively easy to use numerical methods to generate numbers of people of a certain state in the SEIR model at time t. Namely, given a plan $T \in \{0, 1\}^k$ and the initial parameter, it's handy to generate the number of susceptible, exposed, infected, severe populations. So, we can then compute the objective function value. With these considered, enumeration and Genetic Algorithm are very suitable for solving the optimization problem.

For optimization in a three month period, we adopted the enumeration method since the input T is a 13-dimensional vector with binary values. The total number of possibilities for T is 2^{13}, which is still within the computers' capability. Therefore, we enumerated all the possible T's, computed the corresponding objective function values, and found the optimal solution.

However, when we extend our timeframe to 12 months, the input T becomes a 52-dimensional vector. It's then significantly inefficient to enumerate, so we applied the Genetic Algorithm to solve the problem. The solution flow can be described as follows:

1. Randomly generate a pool of 8 chromosomes, each of which represents a feasible solution $T \in \{0, 1\}^k$ (k is contingent on the timeframe of the problem). This pool of chromosomes represents the initial generation.

2. Compute the objective function value for each of the chromosomes(i.e. feasible solutions).

3. Compare the objective function values, and keep $m = 4$ chromosomes that obtained better objective function values.

4. Use one-point crossover to generate the next generation of 8 chromosomes.

5. Perform random mutation on each of the chromosomes with 2 elements being mutated.

6. Result in a new generation of 8 chromosomes, and loop back to step 2.

7. Terminate the algorithm after 500 iterations.

8. Select the optimal solution from all the generations of chromosomes.

4 Results and Discussion

To make economic loss, public mental health loss, severe case loss comparable, we set $C_1 = 137.36, C_2 = 50000, C_3 = 1$ such that these three losses are balanced in the most extreme situations where we don't turn on lockdown throughout the whole period of time or we continously turn on the lockdown. The results generated from this configuration of parameters is [0 0 0 0 0 0 0 0 0 0 0 0 0], meaning that we don't apply lockdown at all. We notice that the result is sensitive to the parameter setting, so we conduct a sensitivity analysis on parameters to see how they influence the result. We set k_1, k_2, k_3 be the ratio among C_1, C_2, C_3, so the parameters $C_1 = 137.36 \cdot k_1, C_2 = 50000 \cdot k_2, C_3 = k_3$ in sensitivity analysis.

4.1 Sensitivity Analysis of Three-month Period

When k_1,k_2 is big while k_3 is small, the result is [0 0 0 0 0 0 0 0 0 0 0 0 0] which means not applying lockdown at all; When k_1,k_2 is small while k_3 is big, the result is [1 1 1 1 0 0 0 0 0 0 0 0 0] which means applying lockdown in the first four weeks and release it afterwards;When k_1,k_2,k_3 has a similar ratio, the result could be [1 1 0 1 1 0 1 1 0 1 0 1 0] which implies a regular schedule for applying and releasing lockdown.

When k_1,k_2 are big, the model cares more about economic loss and public mental health loss. The way to reduce both economic loss and public mental health loss is not to lockdown. Thus, the result is not using lockdown at all; When k_3 is big, the model cares more about severe case loss. The model wants the overall severe cases be low. The best way to reduce overall severe case is to apply lockdown at the very beginning until the virus is totally contained. So, the result is [1 1 1 1 0 0 0 0 0 0 0 0 0] where after 4 weeks of lockdown, the virus has disappeared already, so it can release from lockdown afterward. When k_1,k_2,k_3 have similar ratio, this ratio asks the objective function to balance economic loss, public mental health loss, and severe case loss together. The result [1 1 0 1 1 0 1 1 0 1 0 1 0] shows that the optimal solution is to apply lockdown not exceeding two weeks at each time. This is because the weight of public mental health loss is relatively high. And public mental health loss increases dramatically after 2 weeks. Thus, to balance severe case loss, the best way is to apply lockdown discretely but not last too long each time.

A sample result of setting $k_1 = 1$ can be found in Appendix C.

4.2 Sensitivity Analysis of One-year Period

There are only two possible results. When k_1,k_2 is big while C3 is small, the result is [0 0 0 0 0 0 0...]; When k_1,k_2 is small while k_3 is big, the result is [1 1 1 1 0 0 0 0...]; The reason for only having two choices is that the time period exceeds to 12 months. The third method in three-month periods is not valid because applying lockdown discretely but not lasting too long can't thoroughly contain the virus but delay its outbreak. However, the delay for outbreak has a limit as well. When the time period rises from 3 months to 12 months, the breakout will eventually happen during the time period which causes large severe cases. In this way, the best solution is either applying lockdown determinedly until the virus disappears or not applying lockdown at all based on how important C_3 is.

4.3 Significance

One of the takeaway from this study is that the optimal plan for lockdown is highly dependent upon how the government weigh economic loss, public mental health, and severe cases over each other, since these three factors exhibits high sensitivity in our sensitivity analysis. If the Shanghai government cares more about the public mental health and economy, the optimal solution is to intermittently turn on and off the lockdown or even not applying lockdown at all. On the other side, if the government emphasize reducing the number of severe cases, the best solution is to apply the lockdown till the virus disappear.

Moreover, intermittent lockdown is a temporary way to delay the outbreak of the pandemic and reduce public mental health issues as well as economic loss. If Shanghai can gather enough support and vaccine immunity from other cities within a 3-month period, intermittent lockdown is applicable. However, if we extend the scope to a one-year period, the outbreak is doomed to happen so that the optimal lockdown plan is either continuous lockdown or not applying lockdown at all.

Due to the super infectious nature of the Omicron variant, a thorough lockdown is the only optimal solution to contain the virus and limit the number of severe cases since China strongly cares about reducing the number of severe cases. Therefore, through our modeling of the lockdown policy in Shanghai, we acknowledge that the current policy in Shanghai is reasonable and effective.

Appendix A: Parameter Value Table

Parameter	**Value**
S_0	24894295
E_0	23
I_{R_0}	2
I_{H_0}	0
H_{H_0}	0
R_0	0
r_0	0.25/24894320
r_1	7.5/24894320
β	0.251
v	1/3
p_R	0.998
p_H	0.002
γ	1/5
δ_H	1/8

Table 2: Parameter Value Table

Appendix B

$$\frac{dS}{dt} = -r\beta S(I_R + I_H)$$

Take integration of [n-1,n], we get:

$$\int_{n-1}^{n} \frac{dS}{dt} dt = \int_{n-1}^{n} -r\beta S(I_R + I_H) dt$$

The left side is:

$$\int_{n-1}^{n} \frac{dS}{dt} dt = S_n - S_{n-1}$$

We apply left Riemann sum $\int_a^b f(x)dx \approx (b-a)f(a)$ to right side, we get:

$$\int_{n-1}^{n} -r\beta S(I_R + I_H) dt \approx [n-(n-1)][-r\beta S_{n-1}(I_{R_{n-1}} + I_{H_{n-1}})] = -r\beta S_{n-1}(I_{R_{n-1}} + I_{H_{n-1}})$$

Combine the equations above together, we retrieve:

$$S_n - S_{n-1} = -r\beta S_{n-1}(I_{R_{n-1}} + I_{H_{n-1}})$$

Appendix C: Sample Result

Ratio	Plan
1:1:1	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:1:2	$T = [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:1:3	$T = [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:1:4	$T = [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:1:5	$T = [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:2:1	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:2:2	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:2:3	$T = [1\ 1\ 0\ 1\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0]$
1:2:4	$T = [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:2:5	$T = [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:3:1	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:3:2	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:3:3	$T = [1\ 1\ 0\ 1\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0]$
1:3:4	$T = [1\ 1\ 0\ 1\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0]$
1:3:5	$T = [1\ 1\ 0\ 1\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0]$
1:4:1	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:4:2	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:4:3	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:4:4	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:4:5	$T = [1\ 1\ 0\ 1\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0]$
1:5:1	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:5:2	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:5:3	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:5:4	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$
1:5:5	$T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$

Table 3: Optimal Plans under Different Configuration of $k_1 : k_2 : k_3$ Ratio

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