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Evaluating the mitigation strategies of COVID-19 by the application of the CO₂ emission data through high-resolution agent-based computational experiments

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ABSTRACT

The negative consequences, such as healthy and environmental issues, brought by rapid urbanization and interactive human activities result in increasing social uncertainties, unreliable predictions, and poor management decisions. For instance, the Coronavirus Disease (COVID-19) occurred in 2019 has been plaguing many countries. Aiming at controlling the spread of COVID-19, countries around the world have adopted various mitigation and suppression strategies. However, how to comprehensively evaluate different mitigation strategies remains unexplored. To this end, based on the Artificial societies, Computational experiments, Parallel execution (ACP) approach, we proposed a system model, which clarifies the process to collect the necessary data and conduct large-scale computational experiments to evaluate the effectiveness of different mitigation strategies. Specifically, we established an artificial society of Wuhan city through geo-environment modeling, population modeling, contact behavior modeling, disease spread modeling and mitigation strategy modeling. Moreover, we established an evaluation model in terms of the control effects and economic costs of the mitigation strategy. With respect to the control effects, it is directly reflected by indicators such as the cumulative number of diseases and deaths, while the relationship between mitigation strategies and economic costs is built based on the CO₂ emission. Finally, large-scale simulation experiments are conducted to evaluate the mitigation strategies of six countries. The results reveal that the more strict mitigation strategies achieve better control effects and less economic costs.

1. Introduction

Brought by the rapid urbanization, various health and environmental issues, such as urban tuberculosis (Oppong et al., 2015) and pandemics (Bai et al., 2021), pose a significant risk to citizens and a great burden to city governors. To address these issues, city governors are deliberately implementing up-to-date socio-technological advancements in their healthy city strategies. However, city as a complex adaptive system creates complex interdependencies between humans, infrastructures, and network, which will inevitably result in increasing uncertainties and poor management decisions. Current healthy city strategies are not effective enough to deal with these issues. For instance, the Coronavirus Disease (COVID-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Tang et al., 2020), has generated 143,445,675 cumulative incidences and 3,051,736 deaths as of April 23, 2021 (WHO, 2021), which now still plagues most countries around the world. Therefore, studying the mitigation strategies of the COVID-19 epidemic is an effective supplement to the construction of healthy cities.

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To effectively control the spread of the COVID-19, many governments and scholars have devoted themselves to tackling this problem, and their studies can be mainly divided into the following three categories, data-based study, simulation-oriented study, pathology-related study. Some researchers analyzed the statistical data (Coccia, 2021; Gralinski and Menachery, 2020; Liu et al., 2020a; Liu et al., 2020b; WHO, 2020a; Xu, 2020) and they discovered the main characteristics of the COVID-19, such as the basic reproduction number ($R_0$) and the distribution of the incubation period. Moreover, data-driven methods were adopted in some studies (Bta et al., 2020; Peng et al., 2020; Roques et al., 2020). For instance, Roques et al. combined the SIR model with artificial intelligence methods to estimate early infection cases and mortality rates (Roques et al., 2020). Some researchers used simulation-oriented methods, such as multi-agent modeling, complex network modeling, and Monte Carlo simulation (Bock and Ortea, 2020; Niehus et al., 2020) to predict the development of the epidemic. For example, Broniec et al., (2020) explored the impact of social distance on the spread of the epidemic. As for pathology studies, some researchers focused on the pathology of the COVID-19 (Roujian et al., 2020; Veljkovic et al., 2019; Zhang et al., 2020; Zha et al., 2020). However, the evaluation of mitigation strategies on epidemic control is a field where current research is relatively inadequate.

Currently, the evaluation on mitigation strategies is mostly assessed through the indicator of the cumulative number of infections. Dunuwila et al. (Dunuwila and Rajapakse, 2020) established a disease spread simulation model based on the multi-agent method to study blockade and detection strategies under limited resource conditions, and the control effects were evaluated through a cumulative number of patients. Based on the multi-agent method, Chang et al., (2020) constructed an individual-level computational simulation model to study the control effects of various mitigation strategies in Australia, such as restricting international air travel, quarantining cases, and closing schools. Mukherjee et al., (2021) evaluated the different restart strategies of educational institutions based on the number of patients. The above-mentioned evaluations are all based on the infection status of population, which are simple to operate, but the impact of mitigation strategies on other aspects of society, such as environmental pollution, economic development, and public psychology, is ignored.

Studies reveal that strict mitigation strategies such as travel bans and blockades of most commercial and industrial activities would lead to a significant economic decline in the short term (Commission, 2020a). For example, the GDP of Wuhan City in the first quarter of 2020 decrease by 40.5% compared with the same period of the previous year (Commission, 2020b). To avoid short-term economic recession and unemployment tide, many countries (e.g., the United States and the United Kingdom) also take the impact of mitigation strategies on economic development into account (Danielli et al., 2020). It is noteworthy that there is currently no research studying the evaluation of the control effects and economic costs of mitigation strategies in the meantime. Therefore, our study aims to design effective mitigation strategies for different countries and cities by analyzing the control effects on the epidemic and the impact on economic development.

To evaluate the mitigation strategies of the COVID-19, this paper proposes a system model, in which an artificial society and an evaluation model are established. The construction of artificial society is based on the Artificial societies, Computational experiments, Parallel execution (ACP) approach (Wang, 2007). The key to the ACP approach is to construct an artificial society and generate diversified scenarios that are consistent with scenarios in real society. Based on the artificial society, various computational experiments can be carried out (Wang et al., 2015; Wang, 2007). Artificial society cooperates with real society in many ways, such as co-evolution, closed-loop feedback, and parallel control (Ma et al., 2020). Specifically, the artificial society in this paper includes five aspects: geographical environment, population, contact behavior, disease spread, and mitigation strategy. Other related work can be found in our previous study (Qiu et al., 2017; Song et al., 2014; Chen et al., 2015; Chen and Zhang, 2018; Zhang et al., 2015).

This paper innovatively evaluates mitigation strategies from two aspects: control effects and economic costs. Specifically, the control effect of mitigation strategies on the pandemic can be reflected by some metrics such as the cumulative number of patients and the cumulative number of deaths. However, it is challenging to directly establish a model of the impact of mitigation strategies on economic costs. Mitigation strategies restrict social production and living activities, thereby hindering the social-economic development. The reduction of commercial and industrial activities would undoubtedly lead to a reduction in the emission of pollutants such as CO$_2$, PM$_{2.5}$ (Ali et al., 2020; Bolano-Ortiz et al., 2020; WHO, 2020b; Zeng et al., 2020; Zhang, 2021). Wang et al., (2020) discovered that there is a linear relationship between the daily rate of new COVID-19 cases and the total reduction of CO$_2$ emission in various provinces of China. Moreover, Marjanovic et al., (2016) successfully predicted the GDP level through the CO$_2$ emission. Inspired by the above-mentioned studies, taking the reduction amount of CO$_2$ emission as a bridge, this paper establishes a model of the impact of mitigation strategies on economic costs. In particular, the impact of mitigation strategies on the economy cost consists of two parts, namely the GDP loss and medical expenditure. The GDP loss refers to the reduction of GDP caused by the implementation of mitigation strategies. Medical expenditure refers to the cost of treating patients. The sum of the two parts reflects the economic costs of mitigation strategies.

Based on the artificial society, we carry out the propagation simulations of COVID-19 and the evaluation of mitigation strategies in six countries, China (CHN), South Korea (KOR), Iran (IRN), Italy (ITA), the United Kingdom (GBR), the United States (USA). Wuhan is a typical city where the COVID-19 breaks out for the first time, so we choose Wuhan as the representative city of the real society. The artificial society of Wuhan is constructed based on statistical data such as Wuhan’s real population and geographic environment. In order to compare the control effect and economic costs of mitigation strategies adopted by different countries, we collect the statistics of pandemic and mitigation policies in six countries from January 1, 2020, to April 30, 2020, and model the strategies quantitatively. The results of large-scale simulation experiments reveal that mitigation strategies of strict patterns (CHN, KOR, and IRN) are more proactive than those of loose patterns (ITA, GBR, and USA). It is obviously that, in strict patterns, the epidemic is controlled and the economic costs are less.

In what follows, we introduce the system model, the artificial society modeling and the evaluation model in Section 2; in Section 3, we carry out the spread simulations of the COVID-19 and the evaluation experiments of different strategies; discussions are given in Section 4, and finally, we conclude our findings in Section 5.

2. Methodology

2.1. System model

Guided by the ACP approach, the system model can be established to help the prevention and control of the COVID-19 in real society. The workflow of the system model realizes the feedback control from artificial society to real society, via the iteration, interaction, and evolution of artificial society and real society. The general process of the system model proposed in this paper is described as follows:

Step 1: Construct the artificial society and the evaluation model. The construction of the artificial society consists of five elements, geographical environment, population, contact behavior, disease spread, and mitigation strategy. In addition, the evaluation model is two-fold, economic costs and control effects.

Step 2: Perceive and inject dynamic data into artificial society. In the simulation process, some static data, such as geographic information, can be injected into the artificial society at once, while some dynamic data, such as existing population information and pandemic-related
data, are injected into the artificial society constantly and dynamically.

**Step 3:** Conduct computational experiments. Since there are millions of persons in the artificial society, powerful computing power is needed in the experiments. Using a supercomputer, plenty of computational experiments are carried out to obtain the simulation data, based on the constructed artificial society.

**Step 4:** Implement the comprehensive evaluation. Based on the simulation data and the evaluation model, the effects and the costs of different mitigation strategies can be evaluated systematically.

**Step 5:** Optimize the mitigation strategies and carry out the strategies in reality. Based on the evaluation results of different strategies, decision-makers can choose a suitable strategy according to different situations of their country or city to guide the prevention and control of the epidemic in the real society.

The step 2 to 5 can be implemented circularly to achieve the iteration, interaction, evolution and feedback control between the artificial society and the real society. The diagram of the process is depicted in Fig. 1.

### 2.2. Artificial society modeling

In this paper, an artificial society based on the ACP approach is constructed as the experimental environment for the spread of COVID-19 in large cities, and the structure of the artificial society is shown in Fig. 2. In the construction, we mainly consider the four elements: population, contact behavior, disease spread model, and mitigation strategies. As shown in Fig. 2, the population modeling includes attributes such as age and gender, and all of this information is obtained through statistical data. The contact behavior in the crowd contains two types: regular and random contact. Both of these are characterized via complex network models. Based on the SEIR model (Nie et al., 2021), we formulate a disease course model and a spread model for COVID-19.
Fig. 2. Artificial society structure.

Fig. 3. The complex network of the artificial population.
Moreover, based on the policy data of relevant countries, an 8-tuple model is built for the mitigation strategy, which takes 8 elements into account, including contact quarantine, area traffic blockade, social contact restriction, etc.

### 2.2.1. Population modeling

Population modeling refers to the process of assigning attributes to individuals based on statistical data. According to the sixth national census data in 2010, the number of permanent residents in Wuhan is 9,785,392 and all of them belong to 172 subdistricts (Statistics, 2012). Using the detailed data, we generated virtual agents according to the real demographic information. In the artificial population, each individual has eight attributes, including ID, age, gender, subdistrict, housing location, social role, social relationship, and workplace as shown in Fig. 3.

The model proposed by Yuanzheng is employed to generate the artificial population (Ge, 2014), which relies on census data and annual data from the official statistics to define the role of each one in a family (Statistics, 2012; Statistics, 2011).

### 2.2.2. Contact behavior modeling

COVID-19 is spread through breath, cough, sneeze, and so on (Tang et al., 2020). Close contact behavior for a certain period is the necessary condition for spread. In this paper, we use the complex network to model contact behavior. In the network, the nodes represent individuals, and the edges represent the contact behavior between individuals, as shown in Fig. 3.

The contact behavior includes two types, regular contact behavior, and random contact behavior. The regular contact behaviors refer to the predictable contact behaviors that occur at homes, workplaces, schools, etc., as shown in Appendix 1. All other contact behaviors are random contact behaviors, such as shopping, leisure, and others that are not listed in Appendix 1. To model the regular contact behavior, the spatiotemporal contact behavior modeling method based on the weighted bimodal network is adopted (Duan, 2014). While for the random contact behavior, we propose the Scale Distance Degree (SSD) model, which is based on the gravity model and the preferential attachment. The details of the methods to model regular contact behavior and random contact behavior are shown in Appendix 1.

### 2.2.3. Disease spread modeling

The disease model contains two aspects as the disease course and disease propagation. The disease course is the evolutionary process of health conditions experienced by patients (Duan, 2014), and disease propagation refers to the spread of the pathogen from patients to the susceptible. In this paper, we construct two models to characterize the two aspects of COVID-19, respectively.

Based on the SEIR model (Nie et al., 2021) and the course characteristics of the patients infected by COVID-19, the disease course model of COVID-19 is constructed, as shown in Fig. 4. In the model, there are 6 states of individuals, susceptible (S), incubation (E), symptomatic infection (I_s), asymptomatic infection (I_a), recovery (R), and death (D). If the susceptible contacts patients (E, I_s, or I_a), they will become E state with the probability of $P$. The duration of the incubation period is $T_E$. After the incubation period, with $\alpha$ probability, they will enter the asymptomatic infection state $I_a$. Otherwise, they will enter the symptomatic infection state $I_s$. Symptomatic patients may be dead with the probability of $\beta$. Otherwise, they will recover. Since the mortality rate of asymptomatic patients is 0, asymptomatic patients will inevitably enter the recovery state after a while. $T_{IR}$ represents the duration from the infected state to the recovery state. $T_{ID}$ represents the duration from the infected state to the dead state, and the infected state here includes symptomatic infection state and asymptomatic infection state.

In this paper, we take a reasonable value for the above parameters based on empirical data. $P$ changes according to different mitigation strategies. If no strategy works, $P$ is usually 0.05249 (Mossong et al., 2008; Yang et al., 2020). The proportion of asymptomatic infection is set as 31% according to the results of Nishiura et al., (2020) (i.e. $\alpha = 31\%$). As the average mortality rate of the patients is 2.01% (Yang et al., 2020), which contains asymptomatic patients, we set the mortality rate of symptomatic patients as 3.35% by calculation (i.e. $\beta = 3.35\%$). $T_E$, $T_{IR}$, $T_{ID}$ represent the period, these three variables follow a log-normal distribution. The mean value of $T_E$ is estimated as 5.1 days (95% CI, 4.5–5.8 days) (Lauer et al., 2020) (i.e. $lnT_E \sim Normal(3.25, 0.13)$). According to the work of Lewnard et al., (2020), the average time from infection to recovery is 9.3 days (95% CI, 0.8–32.9 days) (i.e. $lnT_{IR} \sim Normal(3.63, 1.81)$). The average time from infection to death is 12.7 days (95% CI, 1.6–37.7 days) (i.e. $lnT_{ID} \sim Normal(4.48, 1.53)$).

Fig. 5 demonstrates the spread of the disease from one person to another. The blue boxes in the figure represent the parameters of the quantified mitigation strategy. Their specific meanings are shown in Table 1. If a susceptible person is infected after contacting the patient and is not quarantined, this person may spread the disease to others. According to whether this person is symptomatic, multiple tests are performed. If the test result is positive, this person will not spread the virus to others, but if tested negative, this person will spread the virus to others according to a certain probability. The detail of how mitigation strategies affect the spread of disease will be introduced in the next section.

### 2.2.4. Mitigation strategy modeling

To model the different mitigation strategies adopted by different countries, we quantify the strategy from eight aspects, including social distancing, personal protection, throat swab detection capability, quarantine, traffic blocked, random test, test the suspected patient, and the time of executing the mitigation strategy. The symbols and detailed explanations of each element are shown in Table 1.

The social distance is reflected by the daily average number of contacts, expressed as $N'$ (Edmunds et al., 1997; Mossong et al., 2008). Personal protection is reflected in the probability of infection, expressed as $P'$ (Johnson et al., 2009; Lindsay et al., 2009). Time $T$ is a relative quantity, which is calculated from January 1, 2020. At time $t$, a mitigation strategy can be expressed as Equation (1).

![Fig. 4. The disease course model.](image-url)
The meanings and values of parameters.

| Parameter | Meaning | Value |
|-----------|---------|-------|
| $N'$    | The average number of contacted persons during the day | $[0, \infty]$ |
| $P'$    | Probability of infection | $[0, 1]$ |
| $C'$    | The capability of throat swab testing | $[0, \infty]$ |
| $Q'$    | Quarantine patients or suspected patients | [True or false] |
| $R'$    | Block the traffic between different subdistricts | [True or false] |
| $S'$    | Test the suspected patients | [True or false] |
| $T$     | The time of executing strategy | days |

$m^t = \langle N', P', C', Q', A', R', S', T \rangle$  \hspace{1cm} (1)

$m^t$ is the quantitative strategy from time $t$ to the next change in the mitigation strategy. All the mitigation strategies taken by a country over a period are called the mitigation strategy $M$. $M$ is a collection of multiple $m^t$. The details of the specific strategies of each strategy are presented in Appendix 2.

### 2.3. Evaluation model on economic costs

In this section, an evaluation model on economic costs is constructed, which mainly considers two aspects: the medical expenditure and the GDP loss. The medical expenditure is measured by the sum of medical expenses caused by cured cases and fatal cases during the epidemic. The evaluation model is based on the number of symptomatic patients which we obtain both in real society and artificial society. Since there is no direct relationship between the number of the symptomatic patient and the GDP loss, we establish a mapping relationship between new cases of the symptomatic patient and the GDP loss by using the CO$_2$ emission as the medium. The economic costs of mitigation strategies in different countries are formulated in Equation (2).

$$C_a = Tr_a + G_a$$  \hspace{1cm} (2)

where $Tr_a$ represents the medical expenditure, $G_a$ represents the GDP loss and $n$ indicates different strategies. The calculation methods of $Tr_a$ and $G_a$ will be described in detail later.

#### 2.3.1. Medical expenditure

We determine the medical expenditure by calculating the medical consumption of each cured patient and fatal patient. Since people in different ages cause different medical expenditure, we divide people into 9 classes according to age (1–9, 10–19, 20–29, 30–39, 40–49, 50–59, 60–69, 70–79, ≥80). Then Equation (3) is used to calculate the medical expenditure under different mitigation strategies.

$$Tr_a = \sum_{j=1}^{121} \left( N_{jn} \cdot \sum_{\lambda=1}^{9} \mu_\lambda \cdot \Psi_{c\lambda} + N_{fn} \cdot \sum_{\lambda=1}^{9} \nu_\lambda \cdot \Psi_{f\lambda} \right)$$  \hspace{1cm} (3)

where $n$ represents mitigation strategies, $j$ is a day, starting from the first day of the outbreak, and 121 represents the period from January 1, 2020, to April 30, 2020. On day $j$, the number of newly cured cases under the strategy $n$ is denoted as $N_{jn}$. Similarly, the number of newly fatal cases under the strategy $n$ is denoted as $N_{fn}$. $\mu_\lambda$ or $\nu_\lambda$ is the proportions of age groups $\lambda$ in cured and fatal cases respectively (Surveillance, 2020). The $\Psi_{c\lambda}$ or $\Psi_{f\lambda}$ are shown in Table 2.

#### 2.3.2. GDP loss

In this paper, we use the CO$_2$ emission as a bridge to establish a mapping relationship between the mitigation strategy and GDP loss. Wang et al. (2020) found that there is a linear relationship between the daily change rate of new cases and the cumulative reduction of CO$_2$ emission. This paper draws on and improves its fitting indicators to make the linear relationship more obvious. Besides, the CO$_2$ emission is directly related to social-economic activities, so there is also an obvious linear relationship between the CO$_2$ emission and GDP (Marjanović et al., 2016). The monthly gridded dataset of CO$_2$ emission used in this paper is obtained from the Open-source Data Inventory for Anthropogenic CO$_2$ (ODIAC) inventory developed by the Center for Global

### Table 2

| Age group | Fraction of age group in cured case (%) (Surveillance, 2020) | Fraction of age group in fatal case (%) (Surveillance, 2020) | Cost for a cured case (thousand ¥) (Bartsch et al., 2020) | Cost for a fatal case (million ¥) (Thunstrom et al., 2020) |
|-----------|-------------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| 0-9       | 0.90                                                        | 0.00                                                        | 101.4 (±3%)                                              | 699.6 (±3%)                                              |
| 10-19     | 1.20                                                        | 0.10                                                        | 101.4 (±3%)                                              | 105.6 (±3%)                                              |
| 20-29     | 8.10                                                        | 0.70                                                        | 117.3 (±3%)                                              | 111.1 (±3%)                                              |
| 30-39     | 17.00                                                       | 1.80                                                        | 117.3 (±3%)                                              | 109.0 (±3%)                                              |
| 40-49     | 19.20                                                       | 3.70                                                        | 142.1 (±3%)                                              | 95.2 (±3%)                                               |
| 50-59     | 22.40                                                       | 12.70                                                       | 142.1 (±3%)                                              | 71.1 (±3%)                                               |
| 60-69     | 19.20                                                       | 30.20                                                       | 152.5 (±3%)                                              | 46.2 (±3%)                                               |
| 70-79     | 8.80                                                        | 30.50                                                       | 152.5 (±3%)                                              | 25.5 (±3%)                                               |
| ≥80       | 3.20                                                        | 20.30                                                       | 106.3 (±3%)                                              | 10.3 (±3%)                                               |
Environmental Research (CGER, 2020). The geographical resolution of the dataset is 1° × 1°. The new case data in Wuhan from January 1, 2020, to April 30, 2020, are obtained from Wuhan Municipal Health Commission, (2020c). Wuhan’s GDP data from 2016 to 2020 are obtained from the Wuhan Municipal Bureau of Statistics (Bureau, 2020).

2.3.2.1. The relationship between the new case and CO₂ emission. The new cases of symptomatic patients are used to evaluate GDP loss, and in the following paragraphs, “new cases” represents the new cases of symptomatic patients. Based on the research of Wang et al., (2020), considering the influence of time and relative changes, we designed four pairs of indicators for CO₂ emission and new case, as shown in Table 3 and Table 4. W_j is the original daily new case data. W_j is the result of the logarithm of W_j. Relative changes is considered in W_j and W_j^4. The influence of time is considered in W_j, W_j^2 and W_j^4. The influence of COVID-19 is considered in Ω_2, Ω_3 and Ω_4. The influence of time is considered in Ω_2. Relative changes is considered in Ω_2 and Ω_4.

In the following, we focus on how W_j and Ω_2 are calculated, as they are the most complex indicators.

Random and volatile data of new cases show poor fitness if matched with CO₂ emission without preprocessing. Therefore, a 7-day moving window is firstly used in the new case data to weaken the influence of the random factors. The indicator W_j of the new case is designed as shown in Table 3, where j represents the jth day and N_j represents the number of new case in the jth day.

The next step is to deal with the CO₂ emission data. The CO₂ emission data are detrended by removing a temporal trend over 2016–2019 that best fit the data in the least-squares sense, as Equation (4) shows.

\[ E_{\text{trended}} = E_{\text{original}} + (2020 - t) \cdot \xi_m \]  

Where m is a month, t is a year and \( \xi_m \) is the linear regression slope of \( E_{\text{original}} \) against year in year. \( E_{\text{original}} \) is the daily average in month m, in the unit of (gram carbon/m²/day).

Then, the daily reduction of CO₂ emission is calculated from January to April 2020. We assume that COVID-19 do not contribute considerably to changes in CO₂ emission in December between 2015 and 2019, which serves as a reference change in the absence of COVID-19. The equation is shown as Equation (5). Where j is a day. \( E_{1} \) and \( E_{2} \) are the daily CO₂ emission with and without COVID-19, respectively. \( E_{1,2016–2019} \) is the daily detrended CO₂ emission in month m as an average for 2016–2019. \( E_{2,2015–2018} \) and \( E_{1,2015–2018} \) are the detrended CO₂ emission in December 2019 and the detrended average for December 2015–2018, respectively. CCF_j is the concentration confinement factor, which is proposed in Reference (Wang et al., 2020). CCF is obtained through NO₂ column concentrations and we directly use the CCF of Wuhan.

\[ \Delta E_j = E_j - E_{2,2015–2018} \cdot \frac{E_{2,2016–2019} - E_{1,2015–2018}}{E_{2,2016–2019} - E_{1,2016–2019}} \cdot (CCF_j - 1) \]

Then calculate the indicator Ω_2, the calculation formula is shown in Table 4. Where j is a day and 121 denotes the last day for Apr, 30, 2020 (j = 1 for Jan, 1, 2020). \( \Delta E_j \) is the total CO₂ emission reduction due to COVID-19. \( E_j \) is the total CO₂ emission in January–April without COVID-19. \( E_{2,2015–2018} \) and \( E_{1,2016–2019} \) are the daily CO₂ emissions with and without COVID-19, respectively (Equation (5)).

Finally, the CO₂ emission indicator Ω_2 and the new cases indicator W_j are fitted by a regression model, which is shown in Equation (6).

\[ W_j = a_1 \cdot \Omega_2 + b_j \]

Through plenty of experiments, we compare the fitting results between four pairs of indicators in Tables 3 and 4 and the fitting results are shown in Fig. 6. To account for uncertainty, 95% confidence intervals of the model-averaged coefficients are also shown in the figure. In Fig. 6 (a), (b) and (c), the 95% confidence intervals range is large and \( R^2 \) is small, both of which means the linear relationship between the two indicators is not obvious. The results show that \( \Omega_2 \) and \( W_j \) fit best, which are adopted in the evaluation model.

2.3.2.2. The relationship between CO₂ emission and GDP. In this subsection, the linear relationship between CO₂ emission and GDP is obtained through data analysis. Since the GDP data are quarterly reported generally in China, we fit the relationship between the daily CO₂ emission and the average daily GDP in the first and second quarters from 2016 to 2019. Table 5 shows CO₂ emission data and GDP data in Wuhan.

We fit the CO₂ emission and GDP in different cities, such as Wuhan, Beijing, Guangzhou and Wenzhou. The fitting results are shown in Fig. 7. \( E_{\text{first}} \) and \( E_{\text{second}} \) represent the average daily CO₂ emission in the first quarter and the second quarter respectively. \( G_{\text{first}} \) and \( G_{\text{second}} \) represent the average daily GDP value in the first quarter and the second quarter, respectively. Among the three equations with the same color, the first one is the fitting formula; the second one and the third one show the value of \( R^2 \) and P respectively, which indicate the quality of the fitting results. According to the results, it is concluded that there exists a linear relationship between CO₂ emission and GDP to some extent.

The relationship between CO₂ emission and GDP in Wuhan is shown in Equation (7) and Equation (8).

\[ G_{\text{first}} = 2.28 \cdot E_{\text{first}} - 12.14 \quad (R^2 = 1.00) \]  
\[ G_{\text{second}} = 2.73 \cdot E_{\text{second}} - 15.31 \quad (R^2 = 0.95) \]

According to the above fitting results, the following two steps can be used to evaluate the impact of different mitigation strategies on GDP loss.

1. Based on the fitting results in Fig. 6, the CO₂ emission reduction can be obtained through the cases data.
2. Based on the fitting results in Equation (7) and CO₂ emission reduction data, GDP loss can be calculated.

3. Experiments

Based on the constructed artificial society, we conduct propagation simulations of COVID-19, and evaluate the control effects and the economic costs of mitigation strategies in six countries. Here, 7-group experiments are carried out, among which 6-group experiments are for mitigation strategies in six countries respectively and the last one is for no strategy.

The experiments of each strategy are run 1000 times to alleviate the influence of random factors, such as the infection probability and the length of the incubation period. To actuate an artificial society with millions of population, we carry out experiments based on the Tianhe supercomputer, which is a high-performance computer and ranked 6th in the world in 2020 (Top 500, 2020). All software and models are developed based on XSim-Studio, which is a simulation experiment platform.

3.1. Validation and sensitivity analysis

Firstly, validation experiments are designed to calibrate the input parameters of artificial society and validate the evaluation model respectively. Secondly, the sensitivity analysis is carried out to test the influence of input parameters on the selected output indicator (e.g., $R_0$, $T_{gen}$).

The main output of the artificial society is the incidence data of COVID-19, so we select three indicators that reflect the characteristics of disease propagation to verify the accuracy of the artificial society. These three indicators are reproductive number ($R_0$), generation period ($T_{gen}$) and growth rate of the cumulative case ($\dot{C}$) (Chang et al., 2020). Many studies estimated these indicators and published the values as shown in Table 6. In addition, we analyze the number of COVID-19 cases and the growth rate of the cumulative case $\dot{C}$ averages 0.216 per day during the first 3 weeks at the beginning of January 16, 2020 in China.

**Table 5**

| Year | CO₂ emission (gram carbon/m²/day) | GDP (billion ¥/day) | Carbon emission (gram carbon/m²/day) | GDP (billion ¥/day) |
|------|----------------------------------|---------------------|--------------------------------------|---------------------|
| 2016 | 6.48                             | 2.606               | 6.85                                 | 3.268               |
| 2017 | 6.63                             | 2.955               | 6.93                                 | 3.692               |
| 2018 | 6.77                             | 3.323               | 7.08                                 | 4.164               |
| 2019 | 6.98                             | 3.731               | 7.30                                 | 4.529               |

Fig. 6. Correlation between new case indicators and CO₂ emission indicators.
In the validation, the parameters of the disease spread model are shown in Table 7. Through numerous experiments (12,000 times), we obtain the value of the three indicators, including: 

\[ R_0 = 2.762, \, 95\% \, CI [2.725–2.802] \];
\[ T_{\text{gen}} = 8.804, \, 95\% \, CI [8.654–8.978] \];
\[ \dot{C} = 0.187, \, 95\% \, CI [0.185–0.189]. \]

Compared to the previous research, the value of three indicators are reasonable and the value of input parameters are determined.

Then, we validate the accuracy of the evaluation model by comparing the GDP loss based on the evaluation model with the GDP loss based on the trend forecast. Firstly, we obtain the GDP loss based on the evaluation model by evaluating the real epidemic data of COVID-19 in the first 4 months of 2020. Secondly, we obtain the GDP loss based on the trend forecast by using the historical GDP data from 2016 to 2019. The difference between the two kinds of GDP loss is about 9.14%, indicating that the evaluation model is reliable.

Finally, a sensitivity analysis is conducted to test the influence of input parameters on the selected indicators. We choose five parameters in the sensitivity analysis, including \( P_t \), \( \alpha \), \( \beta \), \( T_E \), and \( T_{IR} \). The sensitivity of the parameters is reflected by three indicators, including \( R_0 \), \( T_{\text{gen}} \), and \( \dot{C} \). We applied the elementary effects (EE) method proposed by Morris (1991) to obtain sensitivity measures \( \sigma_i \) and \( \mu_i^* \) (Canpolongo and Saltelli, 1997), and the results are concluded in Table 8. The smaller values of \( \sigma_i \) and \( \mu_i^* \) represent a lower sensitivity of the input parameters. Results reveal that our model is robust to the changes in the input parameters, with the highest sensitivity detected in \( R_0 \) and \( T_{\text{gen}} \) in response to the incubation period (\( T_E \)). Even for the most affected variables, the resulting variations are limited within their expected ranges. The details

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**Table 6**

| Indicators | study | estimates | 95% CI |
|------------|-------|-----------|--------|
| \( R_0 \) | (Kucharski et al., 2020; Liu et al., 2020c) | 2.35 | 1.15-4.77 |
| \( R_0 \) | Liu et al. (2020c) | 1.4-6.49 | / |
| \( T_{\text{gen}} \) | Huang et al. (2020) | 8.4-10.0 | / |
| \( \dot{C} \) | Chang et al. (2020) | 0.20 | / |

---

**Table 7**

Parameters in validation.

| Parameters | \( P \) | \( \alpha \) | \( \beta \) | \( T_F \) | \( T_M \) | \( T_D \) |
|------------|-------|---------|-------|-------|-------|-------|
| value | 0.05249 | 0.61 | 0.9665 | 4 day | 9.3 day | 12.1 day |

---

In the validation, the parameters of the disease spread model are shown in Table 7. Through numerous experiments (12,000 times), we obtain the value of the three indicators, including: \( R_0 = 2.762, \, 95\% \, CI [2.725–2.802] \); \( T_{\text{gen}} = 8.804, \, 95\% \, CI [8.654–8.978] \); \( \dot{C} = 0.187, \, 95\% \, CI [0.185–0.189]. \) Compared to the previous research, the value of three indicators are reasonable and the value of input parameters are determined.

Then, we validate the accuracy of the evaluation model by comparing the GDP loss based on the evaluation model with the GDP loss based on the trend forecast. Firstly, we obtain the GDP loss based on the evaluation model by evaluating the real epidemic data of COVID-19 in the first 4 months of 2020. Secondly, we obtain the GDP loss based on the trend forecast by using the historical GDP data from 2016 to 2019. The difference between the two kinds of GDP loss is about 9.14%, indicating that the evaluation model is reliable.

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of the sensitivity analysis are presented in Appendix 4.

### 3.2. Evaluation of control effects

Aiming at exploring the control effects of prevention strategies adopted by 6 countries, including CHN, KOR, IRN, ITA, GBR, and USA, we conduct 7 groups of experiments to simulate the spread of COVID-19, among which 6 groups are for mitigation strategies adopted by these countries respectively while the last group is simulated under no strategy condition. No strategy indicates that COVID-19 spreads freely in the artificial society without any mitigation strategies against the disease. In this paper, the mitigation strategies adopted by CHN, KOR and IRN are collectively called strict patterns. Correspondingly, the mitigation strategies of ITA, GBR, and USA are collectively called loose patterns. The experimental results are drawn in Fig. 8.

The figure mainly shows the data of daily increase in incubation, symptomatic patient, and death in artificial society under the different mitigation strategies of various countries (a) CHN. (b) KOR. (c) IRN. (d) ITA. (e) GBR. (f) USA. (g) No strategy. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

| Parameter | Range            | Parameter | \( R_0 \) |
|-----------|------------------|-----------|------------|-----------|-----------|-----------|-----------|-----------|-----------|
|           | \( \eta_1 \)    |           | \( \mu_i^* \) | \( T_{gen} \) |           | \( T_E \) |           | \( T_{IR} \) |           |
| \( p^\alpha \) | [0.05068–0.05429] | 0.703     | 0.545     | 1.378     | 0.875     | 0.008     | 0.008     |
| \( \alpha \)   | [0.50–0.95]      | 0.418     | 0.314     | 0.987     | 0.713     | 0.008     | 0.007     |
| \( \beta \)    | [0.950–0.991]    | 0.866     | 0.672     | 1.409     | 1.023     | 0.012     | 0.010     |
| \( T_E \)      | [3.0–7.0]        | 0.964     | 0.703     | 1.752     | 1.397     | 0.011     | 0.009     |
| \( T_{IR} \)   | [6.0–15.0]       | 0.708     | 0.528     | 1.821     | 1.258     | 0.012     | 0.014     |

**Table 8**

The results of sensitivity analysis.
Table 9
Accumulative cases under different mitigation strategies of 6 countries.

| Strategies   | Accumulative incubation | Accumulative symptom | Accumulative asymptom | Accumulative death |
|--------------|-------------------------|----------------------|-----------------------|--------------------|
| CHN strategy | 101,528                 | 55,832               | 45,696                | 1000               |
| KOR strategy | 84,272                  | 48,091               | 36,181                | 848                |
| IRN strategy | 146,261                 | 79,265               | 66,996                | 1460               |
| Loose patterns |                        |                      |                       |                    |
| ITA strategy | 187,130                 | 100,547              | 86,583                | 1860               |
| GBR strategy | 151,630                 | 80,820               | 70,810                | 1524               |
| USA strategy | 313,031                 | 166,392              | 146,639               | 3122               |
| No strategy  | 9,718,213               | 5,559,967            | 4,158,246             | 97,036             |

Note: The data in the table is the result after rounding.

Fig. 9. Economic costs of mitigation strategies in different countries. (a) The medical expenditure of strict patterns; (b) The GDP loss of strict patterns; (c) The economic costs of strict patterns; (d) The medical expenditure of loose patterns; (e) The GDP loss of strict patterns; (f) The economic costs of loose patterns; (g) The medical expenditure of no strategy; (h) The GDP loss of no strategy; (i) The economic costs of no strategy.
symptomatic patients, and deaths. Through the analysis of simulation under no strategy, as shown in Fig. 8(g), we obtain that the $R_0$ of COVID-19 in the artificial society is 2.1 by calculation, which is consistent with the results in (Yang et al., 2020). This finding indicates that the constructed artificial society and the disease model are reasonable enough to conduct computational experiments (see Table 9).

As shown in Fig. 8, the mitigation strategies of the six countries can greatly reduce the infection of people compared with no strategy. Therefore, a major reduction in the number of accumulative incubation, accumulative symptomatic, and accumulative deaths is observed. It can be seen in Fig. 8(a)–(f) that 100 days after the beginning of the epidemic, the number of new cases in the incubation state is almost zero with mitigation strategies, indicating that the spread of the epidemic has been effectively controlled. While the figure becomes zero only after 30 days without any strategies implemented. The phenomenon reveals that the spread of COVID-19 ends earlier under no strategy condition than that under mitigation strategies. This may be because 30 days after the beginning of the epidemic, almost everyone has entered the incubation state under no strategy condition, resulting in no susceptible case entering the incubation period. Among the mitigation strategies adopted by the six countries, the number of new cases in incubation reaches a peak between 33 days and 50 days. Among them, the largest number of new infections occurs in USA strategy, and the smallest is in the KOR strategy.

Obviously, the control effects of strict patterns are generally better than that of loose patterns, which is mainly reflected in the ability to reduce the total number of new cases in incubation, and at the same time, people in all other states can be effectively reduced.

### 3.3. Evaluation of economic costs

We evaluate the economic costs of different countries’ mitigation strategies, and the results are shown in Fig. 9. In particular, the economic costs of different mitigation strategies are listed in Table 10.

From the changes in economic costs, it can be seen that the decline in GDP has the greatest impact on economic costs. The curves show that the figures of GDP loss decline rapidly in the early stage, but gradually flatten out in the later stage. At the beginning of the epidemic or the later end of the epidemic, the number of cases is often small, which may lead to relatively large changes in $V_t$ in the evaluation model. Therefore, slight fluctuations in the value of GDP loss are observed. Although there are minor fluctuations, the overall downward trend remains unchanged. It is noteworthy the figure on medical expenditure is not large at the beginning, while after a period of time it becomes large. This is because it takes a period of the incubation period for COVID-19-infected patients to enter the symptomatic state and then, they will consume medical resources. Moreover, the death cases also need to go through the symptomatic period, which causes the significant change in medical expenditure to be delayed even further. The decline in GDP loss continues until the end of the epidemic, that is, when the number of new cases reaches zero, the decline stop. The explosive spread of the epidemic ends in about 100 days. However, sporadic people are infected later, so the entire epidemic lasts until about 200 days at the latest.

Comparing the economic costs of the mitigation strategies of different countries in Table 10, it is found that the economic costs of the strict patterns are generally better than that of the loose patterns. The total economic costs of the CHN strategy are 669.697 billion (¥), which is observed a 27.30% drop compared to the economic costs caused by the American strategy. Compared with the ITA strategy which is relatively better among the loose patterns, the CHN strategy also reduces the economic costs by 16.00%. The average loss of the three mitigation strategies in the strict patterns is 735.59 billion (¥), while in the loose patterns the figure is 871.277 billion (¥). The economic costs caused by the strict patterns are 15.57% lower than that of the loose patterns. In the strategy model, the key difference between strict patterns and loose patterns lies in $N_t$ and $P_t$, that is, the average number of daily contacts and the probability of infection. The differences between the strict patterns and loose patterns can be reflected from two main aspects: the first is that people in CHN, KOR, and IRN are more likely to cooperate with the governments. Mitigation strategies, such as travel and contact restrictions, work better. While people in ITA, GBR and USA refuse to cooperate. For example, some politicians oppose restrictions and encourage people to resist the ban. Another aspect is the difference in etiquette culture in different countries. The etiquette between people in CHN et al. is relatively subtle, such as nodding, bowing, greeting, and shaking hands, while in ITA et al. face-to-face kisses and hugs are used usually. Such differences lead to different probabilities of infection.

In Table 10, compared with other strategies, the GDP loss caused by no strategy is the least, but it greatly increases the medical expenditure. The least decline in GDP may be due to reduced restrictions on social, industrial, and commercial production activities, and the short duration of the outbreak. Moreover, under the condition of no strategy, the number of symptomatic infections and deaths are significantly greater than that under mitigation strategies, and the medical cost is linearly related to the number of symptoms and deaths. Therefore, under this condition, the medical expenditure will be much higher than that under other strategies. In the loose patterns, the figures of medical expenditure and GDP loss are generally relatively large. The main reason is that the epidemic lasts for a long time since the restrictions of the loose patterns are loose, leading to an increment in GDP loss. The American strategy is the least effective of all strategies. Not only does the GDP decline the most, but also because of the large number of people suffering from the disease, its medical expenditure is also high.

### 4. Discussions

We switch the fixed mindset and evaluate the different mitigation strategies based on artificial society from two aspects: control effects and economic costs. Specifically, control effects are evaluated through indicators such as the cumulative number of cases in incubation and the cumulative number of death cases. Economic cost evaluated through medical expenditure and GDP loss refers to the impact of mitigation strategies on economic development. In this paper, three types of data are collected to establish the evaluation model of economic costs, including epidemic data of COVID-19, historical CO$_2$ emission data and GDP data. Both medical expenditure in the epidemic and the GDP loss are considered in economic costs. Therefore, we provide a more comprehensive evaluation of mitigation strategies from a perspective that is closer to the needs of social development. More importantly, the proposed system model is not only applicable to the COVID-19 pandemic but also applicable to other major pandemics.

From the perspective of control effects, under the strict patterns, the

### Table 10

| Strategies       | Medical expenditure (billion ¥) | GDP loss (billion ¥) | Economic costs (billion ¥) |
|------------------|--------------------------------|---------------------|--------------------------|
| **strict patterns** |                                |                     |                          |
| CHN strategy     | 63.47                          | 626.23              | 669.70                   |
| KOR strategy     | 29.39                          | 689.93              | 719.32                   |
| IRN strategy     | 63.31                          | 754.45              | 817.76                   |
| **loose patterns** |                                |                     |                          |
| ITA strategy     | 71.74                          | 725.56              | 797.30                   |
| GBR strategy     | 59.43                          | 835.30              | 894.74                   |
| USA strategy     | 105.56                         | 816.23              | 921.79                   |
| No strategy      | 4206.67                        | 243.18              | 4449.85                  |
number of new cases in incubation, the number of symptomatic patients, and the number of the deaths are generally lower than that in the loose patterns. Among the strict patterns, the KOR strategy has the lowest cumulative number of infections and is the most effective strategy to control the epidemic. From the perspective of economic costs, countries with strict patterns can reduce the damage to their economies. Among them, the CHN strategy keeps the economic costs of the city to a minimum, followed by the KOR strategy. It is noteworthy that GDP loss accounts for the vast majority of the economic costs (except no strategy condition). Therefore, when studying how to reduce economic costs, we should focus on the impact of mitigation strategies on GDP loss.

As the representatives of the loose patterns, GBR and USA have experienced repeated outbreaks of COVID-19, mainly due to the lack of strict control of the epidemic, which leads to the rapid spread of infections. Although the impact of mitigation strategies on economic activities in the loose patterns is relatively small, the long-term economic costs have been even greater because the epidemic has not been controlled. Some countries attach more importance to maintain the stability of economic activities, and the strict prohibition of economic activities may cause major problems in the loose patterns' countries, leading them to adopt the loose patterns' mitigation strategies. However, in the end, they would suffer more economic costs due to the decision. If the governments in these countries have conducted computational experiments supported by our system model and evaluation model, they may take different strategies and the outcome would be different.

In real society, the mortality rate is related to many factors. Through studying the results of daily new cases, we find that the number of deaths and the number of symptomatic patients are highly correlated, and it seems that the number of patients directly determines the number of deaths. However, in real society, many factors affect the number of deaths, such as hospital capacity, government disposal ability, social population age structure, and so on. Obviously, the larger the hospital capacity is, the lower the mortality rate will be. But if the government does not handle it well, the mortality rate may be high even with a large hospital capacity. For example, ITA and GBR have rich medical resources, but data show that the mortality rates in these two countries are much higher than those in other countries. Moreover, the mortality rate of the elderly is usually higher than the young. If a society has a higher proportion of the elderly, the overall mortality rate of the society will also be higher.

The proposed system model based on the ACP method can realize the evaluation of mitigation strategies, which is a good supplement to the healthy city strategy. This method relies on the parallel evolution of artificial society and real society, injects real society data into artificial society, and continuously simulates the control effects of different strategies, and finally selects suitable strategies for different cities and countries. Therefore, this system model can effectively formulate mitigation strategies for urban pandemic outbreaks in a timely and effective manner.

5. Conclusions

Based on the ACP method, this paper proposes a system model and constructs an artificial society for the evaluation of mitigation strategies of COVID-19. The artificial society of Wuhan is established through the modeling of five elements: geographical environment, population, contact behavior, disease model, and mitigation strategy. Based on the artificial society, large-scale computational experiments of the mitigation strategies of different countries are quickly carried out. Based on the evaluation model proposed in this paper, the mitigation strategies of the 6 countries are evaluated synthetically in terms of control effects and economic costs.

The contributions of this paper mainly include the following three aspects. First, a system model for the evaluation of mitigation strategies has been established. This system model can effectively respond to COVID-19 outbreaks in cities and help for computational experiments, predictions, evaluations, design, and optimization of mitigation strategies, which has a positive effect on urban healthcare development. Second, a comprehensive evaluation model of mitigation strategies has been established from the aspects of control effects and economic costs. In particular, we focus on the use of environmental data CO2 as a bridge to establish a mapping relationship between mitigation strategies and GDP loss. The model can effectively evaluate the spread of the epidemic under different mitigation strategies and the impact of different mitigation strategies on urban economic development. Third, experiments are carried out on three strategies in strict patterns (CHN strategy, KOR strategy, and IRN strategy) and three strategies in loose patterns (ITA strategy, GBR strategy, and USA strategy). Based on the simulation results, the different effects of the loose patterns and the strict patterns are analyzed and compared. Our work has a significant application prospect in the development of a healthy city, which helps to prevent and control urban epidemics.

Through the analysis of the mitigation strategies of the 6 countries, we found that the mitigation strategies of the strict patterns are superior to the loose patterns in terms of control effects and economic costs. The difference between the two types of patterns lies in the etiquette culture and the degree of implementation of the mitigation strategies, resulting in the different average number of daily contacts and the probability of infection. For example, strategies such as travel bans can effectively reduce the average number of daily contacts, and wearing a mask can effectively reduce the probability of infection. However, people in some countries conduct a weak implementation of strategies such as wearing masks, leading to an increase in the infection probability. These findings can guide the design of future mitigation strategies that starts from reducing the average number of daily contacts and the average probability of infection.

There are some remaining problems in this work that need further research. To enhance the authenticity of the experimental results, it is necessary to realize the interaction between the real society and the artificial society so that the artificial society can be closer to the real society. Therefore, in future works, the artificial society will be improved with more elaborate modeling, including the activities of individuals and the disease spread. Besides, the evaluation model in this paper only considers the control effects and economic costs, but more elements can be considered to make a more comprehensive evaluation. For example, the cognition of the people and the local culture are also important in judging the pros and cons of mitigation strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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1. Appendix 1

**Modeling of Regular Contact**

Generally, the contact behaviors show strong regularity spatially and temporally in the places of work, school, and family. In this paper, the spatiotemporal contact behavior modeling method based on the weighted bimodal network is taken to model the spatial and temporal correlated regular contact relationships. The bimodal network is a network integrated with individual space mobile networks and individual contact networks, the nodes of which include ‘agent’ nodes and ‘spatial’ nodes.

An individual schedule is used to describe the spatial movement of agents in an artificial society. Individuals will go to home, workplaces, or schools at different times, and they will have contact behaviors in these places. A contact network can be built based on these contacts.

In the artificial society, individuals (agents) transfer among various locations in the individual space mobile network with the advance of time, and individuals would contact each other when staying in the same region. Note that constrained by the nature of activities and other factors, the number of people that an individual can contact in a place is limited to \( N_{C} \).

Thus, we predefine the probability of an agent contacting another agent \( s \) in the same geographic space as \( p_{ij} \). It is assumed that an agent is \( a_{i} \), and the set of agents in the same geographic space is \( M_{i} \), then for any \( a_{j} \in M_{i} \), the contact probability for \( a_{i} \) to select \( a_{j} \) is:

\[
p_{ij} = \frac{w_{ij}}{\sum_{a_{q}\in M_{i}} w_{aq}}
\]

**Modeling of Stochastic Contact**

Different from regular contacts occurred in places such as family, work, and school, stochastic contacts refer to the behaviors that the schedule cannot accurately summarize and often includes commuting, shopping, leisure, and entertainment. Therefore, it is difficult to collect relevant data due to randomness. But we still can conclude some characteristics of this stochastic contact: (i) the probability of contact increases with the distance between two agents getting closer. For instance, people who live nearby or work together tend to contact at a higher probability; (ii) the contact number of a person obeys power-law distribution. In other words, in a half-day or a day, most people will have contact with very few people, and very few people will have much contact with many people.

Based on these two characteristics, as well as relevant data limitations, the following two assumptions are made:

Assumptions 1: Take the subdistrict as the division basis. A network is formed by the stochastic contacts within the subdistrict, which is modeled according to the power-law characteristics. It can be regarded as a community in the contact network of the city.

Assumptions 2: The contact number across subdistricts obeys the ‘Gravity-law’. That is, there are more contacts between subdistricts that are closer. And a subdistrict with more population tends to have more contacts with other subdistricts.

Therefore, we propose the Scale Distance Degree (SSD) model to generate the stochastic contact network. In the following, we will explain three mechanisms involved in the algorithm:

1. **Community size and distance**

   That is to say, the larger the scale of the subdistrict is, or the smaller the distance between the subdistricts is, the higher the probability of selecting the subdistrict will be. The subdistrict selection probability \( P_{i} \) by a node in subdistrict \( u \) is

   \[
P_{i} = \frac{\alpha S_{i}d(u, v)^{\beta}}{\sum_{i=1}^{N_{C}} \alpha S_{i}d(u, i)^{\beta}} \quad \alpha > 0, \beta < 0
   \]

   where \( S_{i} \) is the size of the subdistrict \( v; d(u, v) \) is the distance between subdistrict \( u \) and \( v; \alpha \) is the impact index of subdistrict size; \( \beta \) is the impact index of distance; \( C \) is the set of all the subdistricts.

2. **Preferential attachment**

   If a new contact happens between two individuals in the same subdistrict or two different subdistricts, the probability that an individual is chosen is proportional to the contact number that the individual already has. The probability of an individual \( j \) in subdistrict \( v \) is \( P_{qv} \), it can be calculated as:

   \[
P_{ij} = \frac{D_{ij} + \alpha}{\sum_{k} (D_{ik} + \alpha)}
   \]

   \( D_{ij} \) is the degree of the individual \( j \) in subdistrict \( v \). \( \alpha \) is the offset, \( \alpha \in [-m, +\infty] \).

   The number of individuals in the artificial society is \( N = 9785388 \). Based on the work of Dong et al. (Dong et al., 2019; Edmunds et al., 1997; Mossong et al., 2008), the parameters are set as \( \alpha = 1.2, \beta = -1.5 \), and the average degree of this network is 13.4. There are 172 subdistricts, and the final contact number in this city is 24,463,470. The result is a network that consists of 9785388 nodes and 24,463,470 edges. As Fig. 1 shows, the degree distribution of this network follows the power-law.
Fig. 1. Network degree distribution and fitting results.

The degree distribution can be fitted with a line under the log-log scale as shown in Fig. 1. The coefficient of the line in the figure is -3.61. That is, the power-exponent of the power-law distribution is 3.61.

| Duration time | Activity         | Location     | Probability | Duration time | Activity         | Location     | Probability | Duration time | Activity         | Location     | Probability |
|---------------|------------------|--------------|-------------|---------------|------------------|--------------|-------------|---------------|------------------|--------------|-------------|
| Residents in community | Sleeping            | Home         | 100%        | Students in school | Go to bed       | Dormitory    | 100%        | Workers in the factory | Sleeping        | Home         | 100%        |
| 00:00–08:00   | Work              | Workplace    | 50%         | 08:00–12:00   | Self-Study      | Study Room   | 20%         |              | 08:00–12:00 | Work         | Workplace | 100%        |
| Rest          | Home              | 20%          |             | Self-Study    | Study Room      | Library      | 30%         |              | 08:00–12:00 | Work         | Workplace | 100%        |
| Lunch         | Park              | 20%          |             | Have a class  | Classroom       | 50%          |             |              | 12:00–13:00 | Lunch       | Canteen   | 70%         |
| 12:00–13:00   | Lunch Break       | Restaurant   | 50%         | 12:00–13:00   | Lunch           | Canteen      | 70%         |              | 13:00–17:30 | 30%         |
| Work          | Home              | 50%          |             | Restaurant    | Classroom       | 30%          |             |              | 13:00–17:30 | Work         | Workplace | 100%        |
| Rest          | Home              | 20%          |             | Have a class  | Classroom       | 50%          |             |              | 13:00–17:30 | Work         | Workplace | 100%        |
| Leisure       | Park              | 20%          |             | Self-study    | Study Room      | 20%          |             |              | 17:30–18:00 | Rest         | Home      | 50%         |
| 17:30–18:00   | Dinner            | Mall         | 45%         | 17:00–18:00   | Dinner          | Restaurant   | 40%         |              | 17:30–18:00 | Rest         | Home      | 50%         |
| Leisure       | Gym               | 5%           |             | Exercise      | Playground      | 60%          |             |              | 17:30–18:00 | Rest         | Home      | 50%         |
| 18:00–19:00   | Dinner            | Restaurant   | 50%         | 18:00–22:00   | Self-study      | Classroom    | 50%         |              | 18:00–19:00 | Dinner       | Canteen   | 70%         |
| Flight        | Restaurant        | 50%          |             | Restaurant    | Canteen        | 30%          |             |              | 18:00–19:00 | Dinner       | Restaurant | 30%         |
| 19:00–20:00   | Rest              | Home         | 50%         | Rest          | Dormitory       | 50%          |             |              | 19:00–20:00 | Rest         | Home      | 50%         |
| Leisure       | Stylistic Center  | 30%          |             | Rest          | Dormitory       | 50%          |             |              | 19:00–20:00 | Rest         | Home      | 50%         |
| 20:00–23:00   | Rest              | Home         | 100%        | 22:00–24:00   | Sleeping        | Dormitory    | 100%        |              | 20:00–23:00 | Rest         | Home      | 100%        |
| 23:00–24:00   | Sleeping          | Home         | 100%        |               |                 |              |             |              | 23:00–24:00 | Sleeping     | Home      | 100%        |

2. Appendix 2

Detailed measures and time of countries’ response to COVID-19 corresponding to the six strategies’ measures.

Policy in China.

| Time          | Measure Description                                                                 |
|---------------|--------------------------------------------------------------------------------------|
| 2019.12.30    | Wuhan Health Commission ‘Emergency Notice on Treating Pneumonia of Unknown Cause’ follow up statistics and report timely. |
| 2019.12.31    | The National Health Commission arrived in Wuhan to investigate and verify the situation. |
| 2020.1.1      | The South China seafood market was closed.                                           |
| 2020.1.2-1.8  | It was confirmed as a novel coronavirus.                                             |
| 2020.1.11     | 1. 41 cases were preliminarily diagnosed                                          |
| 2020.1.14     | 2. The National Health Commission requires daily updates on the epidemic situation. |
| 2020.1.19     | 1. The National Health Commission (NHC) dispatched working groups to the provinces to guide the prevention and control of the epidemic |
| 2020.1.20     | 2. Sharing new coronavirus gene sequences                                           |
| 2020.1.21     | 2. Experts judge that the epidemic is still preventable and controllable            |
| 2020.1.22     | 3. From January 20, information of new cases from each province will be released every day. |
| 2020.1.23     | Policy free refund related to Wuhan was announced                                   |
| 2020.1.24     | 1. Wuhan conducted epidemic screening for vehicles entering and leaving the city.   |
| 2020.1.25     | 2. Wuhan requires citizens to wear masks in public places.                          |

(continued on next page)
| Time       | Measure Description                                                                 |
|-----------|--------------------------------------------------------------------------------------|
| 2020.1.23 | 1. The city’s buses, subways, ferries and long-distance passenger transport will be suspended from 10 p.m., and the exit channel will be closed. |
|           | 2. Wuhan city decided to build Fire God Mountain-Hospital.                             |
|           | 3. Universities, middle schools, primary schools, kindergartens, etc. In Hubei delayed the opening of school. |
| 2020.1.24 | 1. China has carried out scientific research on the epidemic, with Zhong Nanshan as the team leader. |
|           | 2. Shanghai, Guangdong and other provinces as well as the PLA sent medical teams to support Wuhan. |
| 2020.1.25 | 1. Wuhan closed the tunnel across the river.                                            |
|           | 2. Decided to build the Thunder God Mountain-Hospital.                                 |
| 2020.1.26 | 1. Except for permitted vehicles, Wuhan urban area will be prohibited from vehicles.   |
|           | 2. National Health Commission: The epidemic has spread quickly and is at an early stage of spreading. |
|           | 3. The Central Leading Group on COVID-19 requires all localities to set up leading groups on COVID-19. |
|           | 4. National Health Commission: The average incubation period of the new virus is 10 days, the shortest is 1 day, and the longest is 14 days. The incubation period is infectious. |
| 2020.1.27 | 1. National Health Insurance Administration: Extend individual burden exemption policy to suspected cases |
|           | 2. The Spring Festival holiday was extended to February 2                              |
|           | 3. The Ministry of Finance and the National Health Commission allocated 60.33 billion yuan for epidemic prevention. |
| 2020.1.29 | 1. The Central Leading Group on COVID-19: allow personnel from non-high-epidemic areas to return to work after an appropriate delay. |
|           | 2. A total of 52 medical teams and 6097 medical workers have assisted Hubei.              |
|           | 3. The Central Working Group urged suspected patients to send for examination.           |
|           | 4. The central government emphasizes the unified management and allocation of key medical materials, and local governments must not withhold them under any name. |
| 2020.1.30 | 1. The General Office of the State Council has issued a circular requiring enterprises to quickly resume production of epidemic prevention equipment (protective suits, masks, goggles and negative pressure ambulances) |
|           | 2. The Ministry of Finance and the National Health Commission will grant 300 or 200 yuan per person per day for medical workers of epidemic prevention. |
| 2020.1.31 | The State Food and Drug Administration dispatched supervision groups to supervise enterprises of epidemic prevention equipment |
| 2020.2.1  | 1. Hubei province announced an extended holiday to start work on February 14             |
|           | 2. Public security and political work departments at all levels in Hubei implement the wartime reward mechanism. |
| 2020.2.2  | 1. Fire God Mountain-Hospital was completed and delivered.                             |
|           | 2. The jawbone troops undertook the distribution of living materials in Wuhan.          |
|           | 3. All suspected cases will be quarantined in Hubei.                                   |
| 2020.2.3  | 1. 1400 medical workers from the army were sent to Fire God Mountain-Hospital          |
|           | 2. Wuhan built three ‘makeshift hospitals’ overnight, namely Hongshan Gymnasium, with a total of 3800 beds, especially for the treatment of mild patients. |
| 2020.2.4  | 1. The first batch of patients were treated in the Fire God Mountain Hospital          |
|           | 2. The Central Leading Group on COVID-19: more than 2000 medical workers will be sent to Hubei. |
|           | 3. Wuhan has established 132 isolation places                                         |
|           | 4. The capacity of makeshift hospitals was expanded to 11, and the number of beds was increased to more than 10,000. |
| 2020.2.5  | 1. Hubei Province issued a notice to ensure that all suspected and confirmed cases should be received and treated, and allocated 200 million yuan for the construction of special treatment sites. |
|           | 2. Wuhan designated hospital only accepts and treats severe and critical patients.     |
| 2020.2.6  | 1. A comprehensive investigation mobilization meeting was held in Wuhan, requiring no one to be left out. |
|           | 2. Temperature monitoring for all people is carried out in Wuhan, which combines door-to-door test with self-test and report. Every person in each household is monitored once a day. |
|           | 3. For frontline staff for epidemic prevention, individual income tax shall be exempted. |
|           | 4. Vice Governor of Hubei province: There is a shortage of 2250 medical workers in the province. |
| 2020.2.7  | The capacity of makeshift hospitals has been expanded to 15, with more than 10,000 beds. |
| 2020.2.8  | 1. Thunder God Mountain-Hospital was delivered and began to treat patients             |
|           | 2. The Central Government adjusted the top leadership of Hubei province, and Wang Hesheng was appointed member and standing Committee member of Hubei Provincial Party Committee. |

**Policy in South Korea.**

| Time       | Description                                                                                       |
|-----------|---------------------------------------------------------------------------------------------------|
| 2020.1.20 | 1. The Department of Disease Control and Prevention of the Republic of Korea raised the alert level of infectious disease disaster crisis from ‘concern’ to ‘attention’. |
|           | 2. Passengers with temperature over 37.5 °C or symptoms of respiratory diseases will be separately confirmed in their health status and whether they have been in contact with the cases, and quarantined after taking into account epidemiological information such as residence and place of visit. |
| 2020.1.27 | The South Korean government’s alert registration for COVID-19 has been raised.                    |
| 2020.2.2  | It announced that foreigners who have visited or stayed in Hubei province for within 14 days will be denied entry from February 4. |
| 2020.2.4  | The 11th Century Hospital in Gwangju, South Korea, has been closed with 121 patients and medical staff locked inside. |
|           | Inpatients and medical staff on some floors are classified as high risk groups.                     |
|           | On that day, 84 people were classified as low-risk and transferred to the dormitory group of Gwangju Fire Fighting School, an isolation facility. |
| 2020.2.19 | Seven hospitals in South Korea have suspended or closed their emergency rooms due to the outbreak, the Ministry said. |
| 2020.2.20 | 1. Close contact tracing of confirmed patients.                                                    |
|           | 2. The mayor urged Daegu residents to stay at home.                                                 |
| 2020.2.21 | The Prime Minister has designated Daegu city and Qingbei Ching-tao County, which have seen a large increase in confirmed COVID-19 cases, as key epidemic management areas. Special epidemic prevention measures have been taken to provide hospital beds and human and material support. |
| 2020.2.22 | Speaking to the people, the prime minister urged them to suspend religious activities held indoors or outdoors in crowded areas, and urged them to cooperate with the government’s epidemic prevention efforts |
| 2020.2.23 | 1. President Moon Jae-in of the Republic of Korea presided over the Novel Coronavirus epidemic response meeting in the Office building in Seoul, indicating that the government decided to elevate the epidemic alert to the highest level and strengthen the response measures |
|           | 2. The Ministry of Education of the Republic of Korea has announced that all schools nationwide will be postponed until March 9. |

(continued on next page)
Continued from previous page:

| Time               | Description                                                                                                                                 |
|--------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| 2020.2.25          | 1. The central government of the Republic of Korea (ROK) has decided to impose maximum lockdown measures on Daegu and Gyeongsang North Province       |
|                    | 2. The Kingston Corona-19 Special Committee on Countermeasures was established.                                                              |
| 2020.3.5           | South Korean Prime Minister Hyeon-seok announced that the city of Gyeongsan would be designated as a special infectious disease control zone, banning the export of masks and restricting the purchase of masks from Monday. |
| 2020.3.15          | Moon Jae-in declared Daegu and Gyeongsan, North Gyeongsang province, Qingdao county and Fenhua County, which have been hit hard by the epidemic, as special disaster areas |
| 2020.3.19          | 1. The scope of South Korea's immigration control is extended to all countries and regions in the world.                                       |
|                    | 2. Moon promised 50 trillion won in emergency economic measures for small businesses.                                                          |
| 2020.4.4           | The South Korean government decided to extend the "social distance restriction period" by two weeks until the 19th.                             |

Policy in Iran.

| Time               | Measure description                                                                                                                                                                                                 |
|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2020.2.19          | 1. The Health authorities of Iran have traced the source of infection to two patients who died of coVID-19. Those who had close contact with the two patients have been quarantined                                                  |
|                    | 2. Besides, some suspected cases have been detected in Qom. Relevant personnel have been isolated, and testing is underway                                                                                           |
| 2020.2.20          | 1. Schools in Qom have been closed                                                                                                                                                                                     |
|                    | 2. Iran has three new confirmed cases of COVID-19. The Ministry of Health recommended the suspension of religious activities in Qom                                                                                      |
| 2020.2.24          | 1. More than 250 people have been quarantined                                                                                                                                                                          |
|                    | 2. The closure of Tehran may be considered                                                                                                                                                                              |
| 2020.2.27          | The Iranian government has announced a ban on Chinese citizens entering Iran                                                                                                                                              |
| 2020.2.28          | 1. Iran’s Health minister Saeed Namaki has announced that all schools in the country will be closed for three days                                                                                                       |
|                    | 2. The Iranian Football Association has decided to continue all football matches                                                                                                                                 |
| 2020.2.29          | 1. A team of five volunteers from the Red Cross Society of China arrived in Tehran, the capital, to provide assistance to Iran, and took with them some medical supplies provided by The Chinese side |
| 2020.3.3           | 1. To prevent novel Coronavirus from spreading through the prison, the Iranian government temporarily released more than 54,000 prisoners                                                                          |
|                    | 2. The First deputy speaker of Iran’s Islamic Parliament, Massoud Pezeshkian, claimed that the health ministry had provided false case data                                                                       |
| 2020.3.7           | Iran’s Minister of Information and Communications Technology, Mohammad Javad Azari Jahromi, said on Twitter that everyone would be given 100 GB of free Internet traffic to encourage them to stay at home                               |
| 2020.3.13          | 1. The General Staff of the Army of the Islamic Republic of Iran has announced that the army will take to the streets in the next 24 h to ensure the closure of all commercial centers, streets and markets throughout the country |
|                    | 2. Iran will close most of its petrol stations from The 14th to prevent people from driving out 3. All entrances and exits from Tehran to the field are equipped with checkpoints                                               |

End of March in 2020

1. Iran announced a “social distancing” program until April 8, after which some people will be allowed to return to work and some academic, cultural and religious sites will be opened.

Policy in Italy.

| Time               | Description                                                                                                                                                                                                 |
|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2020.1.31          | Italy has declared a state of emergency, suspending all flights between the Chinese mainland, Hong Kong, Macao and Taipei from today                                                                                   |
| 2020.2.22          | 1. Travelers who have visited the territory of the People’s Republic of China, including Hong Kong and Macao, within 14 days of entering Italy must report to the Italian Ministry of Health and must be quarantined at home or in hotels |
|                    | 2. People who have been in contact with a confirmed patient will be placed under mandatory quarantine for 14 days                                                                                                 |
|                    | 3. Italian Prime Minister Giuseppe Conte announced that all access to the affected areas would be closed, and that work and sports would be suspended                                                           |
|                    | 4. Health Minister Roberto Speranza said the local health ministry would follow a trustee home quarantine system to monitor quarantines closely and would apply the same measures to those in isolation conditions                        |
|                    | 5. The Italian army and law enforcement are responsible for enforcing the blockade                                                                                                                             |
|                    | 6. Schools in ten cities in Lombardy, in Veneto and in Emilia Romagna were closed                                                                                                                            |
|                    | 7. All public events will be canceled, and commercial activities will be suspended or terminated before 6 o’clock                                                                                               |
|                    | 8. Train services were suspended in the worst-affected areas, with no stops at Codonio, Maleo and Cana Pustoleogo stations                                                                                  |
|                    | 9. Patients with symptoms are advised to dial emergency number 112 instead of going directly to hospital to reduce the spread of the disease                                                                 |
|                    | 10. The Italian Ministry of Health has set up a website and a hotline of 1500 to provide the public with the latest information on the outbreak and reports of suspected cases                                           |
|                    | 11. The Italian Cabinet announced new measures to control the spread of the disease, including quarantine for more than 50,000 people in 11 northern cities                                                 |
|                    | 12. Public gatherings were banned, all sports and religious activities were cancelled, and schools, bars and other places were closed                                                                              |
|                    | 13. Food, medicine and other essential supplies will be distributed to residential areas to reduce people’s travel                                                                                        |
| 2020.2.23          | 1. Serie A football has cancelled four matches between Inter Milan and Sampdoria, Atalanta against Sassuolo, Verona against Cagliari and Torino against Parma |
|                    | 2. Veneto cancels Venice Carnival                                                                                                                                                                           |
|                    | 3. Popular attractions such as the Grand Theatre Milan-kara, Milan’s Cathedral, the Cathedral of the Basilica of Saint-Marc and the Milan Theater were closed |
|                    | 4. HSR Italy and New Passenger transport requires all trains to be equipped with hand sanitizers and all attendants to be given face masks, disposable gloves and disinfectant                                  |
| 2020.2.24          | 1.500 police are patrolling the exclusion zone of Lodi and Veneto                                                                                                                                               |

(continued on next page)
2.  The head of Basilicata region Vito Badi has imposed a 14-day quarantine on all people from affected areas in northern Italy.
3.  The Ministry of Health announced the deployment of 31 laboratories across the country to analyze swab samples from suspected cases of coronavirus.
4.  The company continues to allow employees to work from home.
5.  Install thermal scanners to measure the temperature of visitors and staff.

| Time          | Measure Description |
|---------------|---------------------|
| 2020.2.25     | Announced that online education will be provided to students in the affected areas from March 2 |
|               | Students in Palermo and Naples are closed until February 29 |
|               | Classes at Basilicata University continued, but with a thermal scanner |
| 2020.2.26     | The Italian authorities announced the closure of all levels of schools, including universities, for 2 weeks as the number of deaths rose to 100 nationwide |
|               | All schools in Taranto and Puglia will be closed until the 29th |
|               | A number of schools were closed in Rossettolgia Bruzzi |
| 2020.2.27     | The Italian government has issued a new decree to seal off all the provinces of the Lombardy region and 14 provinces in the Four regions of Veneto, Emilia Romagna, and Piedmont, and Marche until April 3, affecting 16 million inhabitants. The decree bans access to the exclusion zone for all persons and punishes violators with up to three months in prison |
|               | All schools in Messina will be closed from February 29 until March 3 |

2020.3.1
The Council of Ministers adopted a new law on epidemic prevention and control.

The decree divides Italy into three regions: the red zone, the yellow zone, and the safe zone. The Yellow zone consists of Lombardy, Veneto, and Amelia Romagna, three of which have suspended social and sporting activities and closed schools, theatres, clubs, and cinemas.

The rest of the safe areas need to publicize prevention and control measures in public places and carry out special disinfection on public transport.

| Time          | Measure Description |
|---------------|---------------------|
| 2020.3.4      | All schools in Italy would be empty until April 3 and that the Serie a Derby would be postponed. |
| 2020.3.7-8    | The Italian government has issued a new decree to seal off all the provinces of the Lombardy region and 14 provinces in the Four regions of Veneto, Emilia Romagna, and Piedmont, and Marche until April 3, affecting 16 million inhabitants. The decree bans access to the exclusion zone for all persons and punishes violators with up to three months in prison |
|               | All sports grounds, swimming pools, spas, and health centers in the exclusion zone will be closed, outdoor sports events will be held behind closed doors, and shopping centers will be open only on weekends. Other commercial activities can be carried out regularly, but the requirement is to keep customers within 1 m of each other. |
|               | Entertainment venues are closed. |
| 2020.3.9      | The government announced the suspension of all sporting activities in the country until April 3, with the exception of Italian clubs or national teams required to participate in international competitions. |
|               | Prime Minister Conte announced that the blockade would be extended to cover 60 million people throughout the country. |
|               | The school closing period has been extended from March 15 to April 3, banning public gatherings in outdoor bars, restaurants and other places. |
| 2020.3.11     | The government allocated 25 billion euros in emergency funds. That night, Conte announced the tightening of the blockade and the closure of all commercial and retail businesses except those providing basic services, such as grocery stores and pharmacies. |
|               | Strengthen the distribution of intensive care units. |
| 2020.3.15     | The Italian Winter sports Federation decided to go ahead with the women’s World Cup alpine skiing competition in Latiler on Monday. |
|               | The AIM of the U.K. should be to immunize society as a whole, not to suppress the epidemic completely. |
|               | A group of 501 local and 40 international scientists and university professors in the U.K. have signed an open letter arguing that the government should divide the country into three regions: red, yellow, and safe. |
|               | More than 280,000 people on the Joint British website are demanding that the government learn from the blockade imposed in Italy. |
| 2020.3.21     | The government announced that school closures would not be included in the measures, but more than 600,000 people on the JOINT UK website asked the government to suspend classes. |
| 2020.3.24     | The Italian Council of Ministers (Cabinet of Government) adopted the newly revised epidemic prevention and control decree, which, on the basis of integrating the previous prevention and control decree, significantly increased the penalties for violations of prevention and control measures. |
|               | Regional governments can take more stringent prevention and control measures based on laws and regulations. |
| 2020.4.9      | Italy’s Senate has approved a 25bn euro economic rescue package. |

**Policy in Britain.**

| Time          | Measure Description |
|---------------|---------------------|
| 2020.2.24     | Central London Community Healthcare NHS Trust has established a COVID-19 Drive-through test center in Parsons Green Health. |
| 2020.2.28     | The NHS has set up a COVID-19 drive-through screening center at the Western General Hospital in Edinburgh. |
| 2020.3.12     | After an emergency cabinet meeting, the British government announced that the epidemic prevention work had moved from “containment” to the second phase of “delay”. |
| 2020.3.13     | The U.K. authorities announced that school closures would not be included in the measures, but more than 600,000 people on the JOINT UK website asked the government to suspend classes. |
|               | The AIM of the U.K. should be to immunize society as a whole, not to suppress the epidemic completely. |
| 2020.3.16     | All theatres in the West End were closed and performances suspended. |
|               | Downing Street has decided to switch to the daily news on the epidemic. |
|               | A group of 501 local and 40 international scientists and university professors in the U.K. have signed an open letter arguing that the government’s herd immunity strategy is not working and that community isolation or even stronger measures should be taken to contain the outbreak. |
| 2020.3.17     | More than 280,000 people on the Joint British website are demanding that the government learn from The Blockade imposed in Italy. |
| 2020.3.18     | The U.K. announced that classes would be suspended and resumed until further notice. |
| 2020.3.19     | All exams will be cancelled. |
| 2020.3.20     | The U.K. military will deploy up to 20,000 standby forces to the U.K.’s streets, hospitals and other key locations to help with the response. |
| 2020.3.22     | The Cabinet office announced that the government will pay 80% of employees unable to work due to the virus, up to a maximum of £ 2500 a month. |
| 2020.4.16     | The U.K. announced an extension its blockade for at least three weeks. |
### Table 1: Policy in America.

| Time         | Measure Description                                                                                  |
|--------------|------------------------------------------------------------------------------------------------------|
| 2020.1.16    | 1. The U.S. Department of State, citing the “Watch Level 1 Alert” of the US Centers for Disease Control and Prevention, issued an update to its health Alert |
|              | 2. Urge U.S. citizens traveling to Wuhan, China, to avoid contact with, animal markets and livestock products, and propose a series of preventive measures |
| 2020.1.17    | The CENTERS for Disease Control and Prevention (CDC) announced that starting from today, JFK International Airport, San Francisco International Airport and Los Angeles International Airport will conduct entry screening for passengers flying directly from Wuhan, China or connecting flights to the United States to detect whether they have symptoms related to novel Coronavirus. Among them Kennedy international airport check from the evening of 17th, San Francisco and Los Angeles airport from 18th |
| 2020.1.22    | 1. The Centers for Disease Control and Prevention announced that it is raising its travel health recommendation to level 2 and expanding airport screening. In addition to the original San Francisco, Los Angeles, and New York Kennedy International Airports, Atlanta and Chicago international Airports are also screening direct and indirect flights through Wuhan. All eligible people were rescheduled for inspection at the above five airports. In addition, 14 airports have been notified and put on alert. |
| 2020.1.30    | 1. The State Council has issued its highest level 4 travel alert, warning U.S. citizens not to travel to the Chinese mainland because of the spread of COVID-19. The proposal to send a CDC team has preliminary approval. |
| 2020.1.31    | 1. The United States declares that novel Coronavirus is a national public health emergency and that from February 2 foreign nationals other than United States citizens or green card holders or their relatives will be refused entry if they visit mainland China within two weeks. On the same day, three major US airlines announced they would stop flying to the Chinese mainland |
| 2020.2.11    | American Airlines announced that it would suspend flights to Mainland China and Hong Kong until April, a month longer than other U.S. airlines |
| 2020.2.26    | President Trump has appointed Vice President Mike Pence to lead the national response to the outbreak. Pence will oversee the entire response, including working with government health agencies and an earlier Virus task force appointed by Trump. |
| 2020.3.1    | 1. After the Federal Reserve announced to cut the benchmark interest rate by 50 basis points, the epidemic situation in the U.S. began to enter into a state of tension |
| 2020.3.2    | 1. Trump held meetings with key members of his federal emergency response team and pharmaceutical companies |
| 2020.3.3    | 1. The United States is in a state of emergency |
| 2020.3.4    | 1. Robert Redfield, director of the Centers for Disease Control and Prevention, says it will offer free coronavirus testing across the United States |
| 2020.3.12   | 1. Nevada has issued a home quarantine |
| 2020.3.13   | 1. Mr Trump suggested that “tens of thousands of people” could get better while continuing to work without any treatment or rest |
| 2020.3.14   | House passes Coronavirus Relief Plan. |
| 2020.3.18   | Nevada’s governor has announced a month-long moratorium on non-essential business activities during which all casinos, amenities bars, cinemas and stadiums in the state will be closed |
| 2020.3.19   | The State Department said it would suspend all regular visa services and issue a level 4 travel alert to the world, urging AMERICANS not to travel abroad. In addition to advising all U.S. citizens who do not plan to stay abroad indefinitely to return to the United States immediately, americans who do not stay abroad are also advised to avoid international travel |
| 2020.3.25   | The U.S. Senate approved a $2.2 trillion Novel Coronavirus bailout |
| 2020.3.27   | US President Donald Trump has approved 15 states and two territories (Guam and Puerto Rico) into a “state of disaster” over the outbreak. |
| 2020.3.30   | 1. Washington, D.C., has issued a home stay order that will impose fines on those who leave without permission |
| 2020.3.31   | 1. Virginia issues a home stay order, and people who leave without authorization face a fine |
| 2020.4.1    | 1. President Trump has announced a “disaster state” for the outbreak |
| 2020.4.2    | 2. Georgia, Mississippi and Pennsylvania issued home quarantine orders |
| 2020.4.3    | 3. Nevada has issued a home quarantine |
| 2020.4.4    | 4. President Trump has announced that he will use the Defense Production Act to ban the export of scarce medical supplies |
| 2020.4.9    | 5. The Federal Reserve announced that it will provide a total of 2.3 trillion dollars in loans to all sectors of the United States |
| 2020.4.11   | 6. President Trump has approved a “state of major disaster” in Wyoming, the first time in history that 50 states and four OVERSEAS U.S. territories have been declared “states of major disaster.” |

3. Appendix 3

The strategy of the six countries are denoted as \( M_1(China), M_2(South Korea), M_3(Iran), M_4(Italy), M_5(Britain), M_6(America) \). Each strategy includes several \( m^2 \) and \( m^4 \) is consisted of 8 different elements, as shown in Equation (4).

\[
m^2 = < N^0, P^0, C_1, Q_1, A_1, B_1, S_1, T >
\]

\[(4)\]

In the normal condition, \( N^0 \) and \( P^0 \) are set as 13.4 and 0.05 according to the work of Mossong et al. (Edmunds et al., 1997; Mossong et al., 2008). \( N^0 \) is the average number of contacted persons during the day, which is corresponded to the actual measure. Let \( N^0 \) be the actual number of social contacts of an individual. \( N^0 \) is assumed to be a discrete variable and obeys Normal distribution, with a mean value of \( N^0 \).

The method of box-Muller (Banks et al., 2007) is used to generate \( N^0 \), as shown in Equation (5):

\[
N^0 = N^0 + \sigma ( -2 \ln r_1 )^{1/2} \cos(2\pi r_2)
\]

\[(5)\]

In which \( N^0 \) is the mean value, \( \sigma \) is the standard deviation, \( r_1 \) and \( r_2 \) are uniformly distributed random numbers between \([0,1]\). According to the work of Edmunds et al. (1997), \( \sigma \) is estimated as 8.5.

\( C^1 \) quantifies the capability of throat swab testing. It is limited by the technical capacity, financial support, and quarantine policy of each country.

For the population of the artificial society is about 10 million, we mainly focused on the maximum test number per 10 million people until April 30. Therefore, according to the statistical data from the work ofRichied et al. (Ritchie et al., 2020), the test capability per 10 million people on April 30 for each country were estimated in Table 1.
When the disease began to spread, the testing capacity gradually increased over time to meet the demand. Among them, the testing capability of Iran improved a lot after April 30. However, before that time, the number of tests \( (C^r) \) is clearly at a relatively low level. So \( C^r \) from Iran was the lowest among all countries in the period considered in this paper (from the end of December 2019 to the end of April 2020).

As for \( C^s \), according to the data disclosed by the countries, it could be assumed that the daily testing capacity increased over this period of observation. In this paper, we assume that \( C^s \) increased linearly during this period:

\[
C^s = \frac{C^{s_1} \times T}{T_s}
\]

Let \( t_0 \) be the time when the first case is diagnosed. \( T_s \) is the duration from \( t_0 \) to the end of observation, \( T \) is the duration from \( t_0 \) to \( t \). \( C^s \) denotes the test capability on time \( t \). \( C^{s_1} \) represents the test capability at the end of observation. \( C^{s_1} \) is set according to Table 1. Maximum of the test capability per 10 million people of six countries.

\( Q^s \) quantifies the measure states that the persons who have contacts with a diagnosed person would be quarantined. \( B^s \) quantifies the measure of area blockade that the spreading across subdistricts is invalid. By adopting such a measure, it is possible to effectively stop the spread of large areas in the early stage.

\( R^s \) means random sampling tests for areas with severe epidemics. The measure was implemented by South Korea initially. Here we only consider the implementation of this measure two from South Korea.

\( S^s \) quantifies the measure of throat swab testing for suspects. The measure is entirely determined by the government’s policy and medical resources. It is also influenced by the limitation of test capability.

\( T \) is the time delay from the occurrence of the first patient to the implementation of the current measure.

As time goes on, the mitigation strategies of different countries would change according to the specific domestic situation. Assuming that the strategy changes at times \( t_0, t_1, t_2 \) and so on, and the mitigation strategy of a country for a long period of time can be denoted as:

\[
M = <m^0, m^1, m^2, \ldots, m^k> \tag{7}
\]

In which \( m^k \) indicates quantified strategy for a period of time. The project of Oxford COVID-19 Government Response Tracker initiated by Hale et al., (2020) has collected the government response to COVID-19 from 180 countries. We analyzed the measures from the end of December 2019 to the end of April 2020 taken by six countries (China, South Korea, Iran, the United Kingdom, Italy, and the United States), and extracted one strategy for each country. The six countries are selected for their typical and different strategies.

The measures of strategies from six countries were introduced and quantified based on the statistics of governments’ responses (Lewnard et al., 2020). \( M_0 \) represents the quantified result of no strategy and it is shown in Table 2. The details of the quantified strategies are explained in the following.

### Table 1

| Country     | Test Capability per 10 Million People |
|-------------|--------------------------------------|
| China       | 13,895                               |
| South Korea | 3900                                 |
| Iran        | 1180                                 |
| Italy       | 11,320                               |
| Britain     | 12,250                               |
| America     | 7030                                 |

Strategy China (\( M_1 \))

Wuhan is the first city in China to suffer from the epidemic and the strategies in Wuhan is representative. Fig. 2 shows the strategy of Wuhan. On January 20, the Chinese Health Commission released the information that the disease could be transmitted by human beings. Then the strict measure of city lockdown was carried out, which attracted great attention from the public, resulting in the rapid decrease of the average number of contacts and infection probability. So starting on January 20, \( N^s \) and \( P^s \) decreased rapidly. The minimum of \( N^s \) after the closure of the city on January 24 is estimated to be about 4 according to the average household population in the statistical data and daily purchase of necessities per person. From January 20 to January 24, \( N^s \) was considered as the average number of contacts under normal conditions and closed city results. The minimum of \( P^s \) is set as the minimum value in Eastern strategies, which is estimated as 0.0005.

\( P^s \) is set to drop linearly from January 20 to February 2, considering that the information about the pandemic would need some days to spread to all the public. The quantitative results of all measures of China’s epidemic mitigation strategy from December 30 to April 30 are shown in Table 3.
Table 3
Quantitative results of $M_1$

| $N$  | $P$   | $C$  | $Q$  | $B$ | $R$ | $S$  | $T$  | Realtime |
|------|-------|------|------|-----|-----|------|------|----------|
| 13.4 | 0.0500| 0    | 0    | 0   | 0   | 0    | 0    | 19.12.25 |
| 12.2 | 0.0437| 547  | 0    | 0   | 0   | 0    | 0    | 19.12.30 |
| 7.1  | 0.0170| 2845 | 1    | 0   | 0   | 0    | 26   | 20.01.20 |
| 6.2  | 0.0119| 3282 | 1    | 1   | 0   | 1    | 30   | 20.01.24 |
| 4.0  | 0.0005| 4267 | 1    | 1   | 0   | 1    | 39   | 20.02.02 |
| 4.0  | 0.0005| 4814 | 1    | 1   | 0   | 1    | 44   | 20.02.07 |
| 4.0  | 0.0005| 9081 | 1    | 0   | 0   | 1    | 83   | 20.03.17 |
| 4.0  | 0.0005| 13,895| 1   | 0   | 0   | 1    | 127  | 20.04.30 |

**Strategy South Korea ($M_2$)**

The strategy of South Korea is shown in Fig. 3. On January 20, South Korea raised its alert level and introduced timely and rigorous testing, quarantine, and patient isolation measures, which attracted great attention from the public, resulting in the rapid decrease of the average number of contacts and infection probability. So starting on January 20, $N$ and $P$ decreased rapidly.

On January 27, the alert level was raised again, so $N$ and $P$ decreased again. By February 23, the most stringent quarantine measures were in place, and the measure of random testing to the public was carried out.

The alert level was upgraded on February 23, and the most stringent lockdown measures were adopted on February 25. The minimum $N$ after the closure of the city was estimated as 4 according to the average household population in the statistical data and daily purchase of necessities. From January 9 to February 25, it was considered as a linear decline process.

It was considered that $P$ reached the minimum value on February 23, which was set as 0.0005 according to the estimated minimum value of Eastern strategies. The public would have a few days to respond to the information, the $P$ was set to decline from January 9 to 23 gradually.

Table 4 shows the quantified results of all measures of strategy South Korea from January 9 to April 30.
Fig. 3. The pandemic statistics and responses of government in South Korea.

Table 4
Quantitative results of $M_2$

| $N^*$ | $P^*$ | $C$ | $Q^*$ | $B^*$ | $R^*$ | $S^*$ | $T$       | Realtime |
|-------|-------|-----|-------|-------|-------|-------|-----------|----------|
| 13.4  | 0.0500| 0   | 0     | 0     | 0     | 0     | 20.01.15  | 13.4     |
| 12.2  | 0.0437| 164 | 1     | 0     | 0     | 0     | 20.01.20  | 12.2     |
| 10.5  | 0.0348| 442 | 1     | 0     | 0     | 1     | 20.01.27  | 10.5     |
| 4     | 0.0005| 1435| 1     | 1     | 1     | 0     | 20.02.23  | 4        |
| 4     | 0.0005| 1508| 1     | 1     | 1     | 1     | 20.02.25  | 4        |
| 4     | 0.0005| 2208| 1     | 1     | 1     | 1     | 20.03.15  | 4        |

Strategy Iran ($M_3$)

Strategy of Iran is shown in Fig. 4. $N^*$ and $P^*$ were reduced due to the outbreak in Iran on February 19, which attracted public attention. International traffic control began around February 27, and all schools were closed, so $N^*$ and $P^*$ were reduced again. By March 13, when the most stringent quarantine measures were in place, $N^*$ and $P^*$ reached the lowest.

The minimum $N^*$ after the closure of the city was estimated as 4 according to the average household population in the statistical data and daily purchase of necessities.

Note that $P^*$ reached its minimum value on March 13, which was set as 0.0005 according to the estimated minimum value of Eastern strategy. The general public needs a few days to respond to the information, so the $P^*$ was set to decrease from February 19 to March 13 gradually.

Table 5 shows the quantified results of all measures of strategy Iran from February 19 to April 30.
Table 5
Quantitative results of $M_3$

| $N^c$ | $P^c$ | $C^c$ | $Q^c$ | $B^c$ | $R^c$ | $S^c$ | $T$   | Realtime  |
|-------|-------|-------|-------|-------|-------|-------|-------|-----------|
| 13.4  | 0.0500| 0     | 0     | 0     | 0     | 0     | 0     | 20.02.14  |
| 11.7  | 0.0412| 78    | 0     | 0     | 0     | 0     | 0     | 20.02.19  |
| 9.0   | 0.0270| 202   | 1     | 0     | 0     | 1     | 13    | 20.02.27  |
| 8.4   | 0.0235| 233   | 1     | 1     | 0     | 1     | 15    | 20.02.29  |
| 6.0   | 0.0111| 342   | 1     | 1     | 0     | 1     | 22    | 20.03.07  |
| 4     | 0.0005| 435   | 1     | 1     | 0     | 1     | 28    | 20.03.13  |
| 4     | 0.0005| 699   | 1     | 1     | 0     | 1     | 45    | 20.03.30  |
| 4     | 0.0005| 1180  | 1     | 1     | 0     | 1     | 76    | 20.04.30  |

**Strategy Italy ($M_4$)**

Strategy of Italy is shown in Fig. 5. $N^c$ and $P^c$ started to reduce slightly for the outbreak in Italy on January 31. Many measures about quarantines and blockages began around February 22, so $N^c$ and $P^c$ rapidly decreased starting from February 22.

By March 7, when the most stringent lockdown measures were in place, $N^c$ and $P^c$ reached their lowest levels. The minimum of $N^c$ after the closure was calculated as 6 according to the average household population in the statistical data and daily purchase of necessities.

It was considered that the $P^c$ reached the minimum on March 7, which was set as 0.001 according to the estimated minimum value of western strategy. Set $P^c$ gradually decreased from January 31 to March 7.

Table 6 shows the quantified results of all measures of the strategy Italy from January 31 to April 30.
Strategy Britain \((M_5)\)

Strategy of Britain is shown in Fig. 6. \(N^t\) and \(P^t\) started to reduce as a result of the outbreak in the United Kingdom on January 31. They dropped rapidly after the school closures and public closures began around March 18. By March 23, when the most stringent lockdown measures were in place, \(N^t\) and \(P^t\) reached their lowest levels.

The strictest isolation measures were taken on March 23. The minimum of \(N^t\) after the closure of the city was calculated as 6 people according to the average household population in the statistical data and daily purchase of necessities. From January 31 to March 23, \(N^t\) was considered to linearly decreased.

Note that \(P^t\) reached its minimum value on March 23, which was set as 0.0001 according to the estimated minimum value of western strategies. \(P^t\) was set to decrease from January 31 to March 23 gradually.

Table 7 shows the quantified results of all measures of the UK vaccination strategy from January 31 to April 30.
Fig. 6. The pandemic statistics and responses of government in the United Kingdom.

Table 7
Quantitative results of $M_5$

| $N$  | $P$  | $Q'$ | $Q''$ | $R'$ | $R''$ | $S'$ | $T$   | Realtime |
|------|------|------|-------|------|-------|------|-------|---------|
| 13.4 | 0.05 | 0    | 0     | 0    | 0     | 0    | 0     | 20.01.26 |
| 12.8 | 0.046| 596  | 0     | 0    | 0     | 0    | 5     | 20.01.31 |
| 9.6  | 0.025| 3456 | 0     | 0    | 0     | 0    | 29    | 20.02.24 |
| 6.9  | 0.007| 5958 | 1     | 1    | 0     | 1    | 50    | 20.03.16 |
| 6.6  | 0.005| 6196 | 1     | 1    | 0     | 1    | 52    | 20.03.18 |
| 6.0  | 0.001| 6792 | 1     | 1    | 0     | 1    | 57    | 20.03.23 |
| 6.0  | 0.001| 11,320|1     | 1    | 0     | 1    | 95    | 20.04.30 |

Strategy America ($M_6$)

Strategy of America is shown in Fig. 7. $N'$ and $P'$ were reduced slightly for the emergence of the epidemic in the United States on January 21. By March 4, when the CDC began to advertise people to avoid gathering contacts, $N'$ and $P'$ were further reduced. On March 30, when the most stringent lockdown measures were carried out, $N'$ and $P'$, reached the lowest levels.

The minimum daily contact number after the closure of the city was estimated to be 6 according to the average household population in the statistical data and daily purchase of necessities. From January 21 to March 30, $N'$ decreased linearly.

It was considered that $P'$ reached the minimum on March 30, which is set as 0.001 according to the estimated minimum value of western strategy. $P'$ was set to gradually decrease from January 31 to March 7.

Table 8 shows the quantified results of all measures of the strategy America from January 31 to April 30.
Table 8
Quantitative results of $M_6$

| $N$  | $P$  | $C$ | $Q$ | $R$ | $S$ | $T$ | Realtime |
|------|------|-----|-----|-----|-----|-----|----------|
| 13.4 | 0.050| 0   | 0   | 0   | 0   | 0   | 20.01.16 |
| 12.9 | 0.047| 341 | 1   | 0   | 0   | 1   | 20.01.21 |
| 10.7 | 0.032| 1775| 1   | 0   | 0   | 1   | 20.02.11 |
| 8.5  | 0.017| 3276| 1   | 1   | 0   | 1   | 20.03.04 |
| 7.7  | 0.013| 3754| 1   | 1   | 0   | 1   | 20.03.13 |
| 6.0  | 0.001| 4914| 1   | 1   | 0   | 1   | 20.03.30 |
| 6.0  | 0.001| 7030| 1   | 1   | 0   | 1   | 20.04.30 |

4. Appendix 4

The elementary effects (EE) method proposed by Morris are used in our sensitivity analysis. It focuses on identifying a few significant input parameters from numerous input parameters in a model using very few calculations. For a given value $x$ of $X$, the EE of the $i$th input parameter can be defined as Equation (8).

$$EE_i = \frac{g(x + e_i \Delta_i) - g(x)}{\Delta_i}$$

where $x$ is one sample of input parameter vector $X$ and $g(x)$ is the corresponding model output, $e_i$ denotes a vector of zeros while its $i$th component is equal to 1, $\Delta_i$ is a step length of $x_i$ moving along the $X_i$ axis, $x + e_i \Delta_i$ is another sample by changing the $i$th input parameter from $x_i$ to $x_i + e_i \Delta_i$ and $g(x + e_i \Delta_i)$ is the corresponding model output. Two sensitivity measures, $\mu'_i$ and $\sigma_i$ (Canpolongo and Saltelli, 1997), are used to assessing sensitivity and they are defined in Equations (9) and (10).

$$\mu'_i = \frac{\sum_{r=1}^{R} |EE_r|}{r}$$

(9)

$$\sigma_i = \sqrt{\frac{\sum_{r=1}^{R} (EE_r - \sum_{r=1}^{R} EE_r)^2}{r-1}}$$

(10)

$\mu'_i$ and $\sigma_i$ are the mean of the $|EE|$ distribution and the standard deviation of the $EE$ distribution respectively. Since $EE_i$ measures the influence of $X_i$ on the model output at a local point, the mean $\mu'_i$ can be employed to measure the overall influence of the $X_i$ on the model output. The standard deviation $\sigma_i$ measures the ensemble of the input parameter’s effects including nonlinear effect or interactions with other input parameters.
We choose five input parameters, including $P_t$, $\alpha$, $\beta$, $T_E$, and $T_{IR}$, and three output indicators, including $R_0$, $T_{gen}$, and $\dot{C}$ in the sensitivity analysis. By consulting the literature, we obtain the range of these input parameters (Lewnard et al., 2020; Nishiura et al., 2020; Yang et al., 2020) as shown in Table 9. The distribution of the parameters is shown in Fig. 8 (d).

Table 9
The results of sensitivity analysis

| Parameter | Range       | $R_0$ | $\mu^*$ | $\sigma$ | $\mu^*$ | $\sigma$ | $\mu^*$ | $\sigma$ |
|-----------|-------------|-------|---------|----------|---------|----------|---------|----------|
| $P_t$ (x1) | [0.05068-0.05429] | 0.703 | 0.545   | 1.378    | 0.875   | 0.008    | 0.008   |
| $\alpha$ (x2) | [0.50-0.95] | 0.418 | 0.314   | 0.987    | 0.713   | 0.008    | 0.007   |
| $\beta$ (x3) | [0.950-0.991] | 0.866 | 0.672   | 1.409    | 1.023   | 0.012    | 0.010   |
| $T_E$ (x4) | [3.0-7.0] | 0.964 | 0.703   | 1.752    | 1.397   | 0.011    | 0.009   |
| $T_{IR}$ (x5) | [6.0-15.0] | 0.708 | 0.528   | 1.821    | 1.258   | 0.012    | 0.014   |

Table 9 summarises the results of the global sensitivity analysis using the Morris method, with $r = 20$ repeats and $k = 5$ input parameters, resulting in 120 parameter combinations i.e., $r(k+1)$. When estimating $R_0$ and $T_{gen}$ for each parameter combination, we run simulations $n = 12,000$ times. For another output indicator $\dot{C}$, we run simulations $n = 500$ times for each parameter combination, averaging the results over these runs before the computations of the sensitivity effects.

The results in Table 9 are visualized in Fig. 8. The small values of $\sigma$ and $\mu^*$ indicate the low sensitivity of the parameters. From Fig. 8, we know that $R_0$ and $T_{gen}$ are most sensitive to the changes in the incubation period ($T_E$), but these two parameters still stay within the expected ranges (e.g., $R_0$ varies between 1.921 and 4.054, and $T_{gen}$ varies between 8.283 and 11.902). $\dot{C}$ shows the small global sensitivity to all input parameters.

In summary, the analysis shows that the model is robust to the changes in the input parameters, with the highest sensitivity detected in $R_0$ and $T_{gen}$, in response to the incubation period ($T_E$). Even for the most affected variables, the resulting variations are limited within their expected ranges.
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