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A System Dynamics Model for the Novel COVID-19 Pandemic

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Abstract. The novel coronavirus COVID-19 is a highly infectious disease with severe respiratory symptoms which may lead to death. According to the latest disease statistics, COVID-19 has been affecting 213 countries and territories around the world. So far, the statistics indicate that the disease led to about 367,000 deaths and 6 million infections worldwide between December 31st 2019 and May 30th 2020. In this paper, we propose a system dynamics model for the spread of COVID-19. The proposed model investigates possible mechanisms for the spread of infection among humans. The COVID-19 epidemiological parameters were estimated based on real pandemic data that covers a period of 110 days. The model was simulated and validated over 365 days for the cases of China, Italy, and USA. The model simulation outcomes predict a recession of the pandemic in China by August 2020 with a total of 85,832 COVID-19 infected cases. In Italy, the total number of infections is expected to reach 276,406. The model interestingly predicts another wave of the COVID-19 outbreak by early 2021. Finally, the large expected number of 3,394,754 infected people in the USA gives a clear warning of the possibility that the crisis can become out of control. Under such circumstances, quarantine procedures become ineffective, and a vaccine or a treatment becomes the only solution. The system dynamics model of COVID-19 provides a good estimation for the numbers of infected, recovered, and dead people, in addition to the pandemic timing and the peak time.

Keywords: Coronavirus, COVID-19, System Dynamics, Pandemic, Infectious Diseases.

1. Introduction

The outbreak of the novel coronavirus was discovered in Wuhan, China late December 2019. The virus was later named COVID-19 by the World Health Organization (WHO) [1], [2]. According to media reports on unpublished Chinese government data, the Chinese authorities had identified at least 266 people who contracted the virus and who came under medical surveillance. The earliest case was discovered on November 17th, 2019 – weeks before the authorities announced the emergence of the new virus [3], [4].

COVID-19 is associated with respiratory illness symptoms that are distinct from those of SARS, MERS, and influenza. Although the COVID-19 and influenza infections may have similar symptoms, COVID-19 has a higher degree of spread and severity [5]. Common symptoms include fever, cough, and shortness of breath. Other COVID-19 symptoms may include muscle pain, sputum production, diarrhea, sore throat, and abdominal pain [6], [7]. While the majority of COVID-19 cases result in mild symptoms, some may evolve into viral pneumonia and multi-organ failure [8]. The COVID-19 virus probably emerged from bats or some other animals [9]. However, while bats may be the ancestral hosts of COVID-19, the animal-to-human spill-over route remains unclear. Such route may involve other

intermediate hosts such as domesticated mammals, farm animals, or hunt wildlife animals. For example, civets and camels served as intermediate hosts for SARS-CoV and MERS CoV, respectively [10]. COVID-19 can spread among people who are in close proximity to each other (within about 6 feet) through respiratory droplets produced by coughing or sneezing of an infected person [11]. According to a letter written by Dr. Harvey Fineberg of the National Academy of Science to the White House, the results of available COVID-19 studies consistently point to aerosolization of the virus from normal breathing as the main infection mechanism [12]. Nevertheless, people may also get COVID-19 by touching a surface that has the virus and then touching their own mouths, noses, or eyes [7].

In order to understand the COVID-19 outbreak dynamics, it's necessary to trace the key milestones of the pandemic timeline. These milestones include the occurrence of the first confirmed case, the first patient recovery, the first pandemic-related death, and the quarantine start date. Here, we focus our investigation on three countries, namely China (where COVID-19 first emerged), Italy (the country with the largest death toll in Europe), and USA (the country with largest number of worldwide infections and deaths so far).

The COVID-19 timeline relative to the three countries has essentially the following key milestones:

1. (Dec. 31st 2019) The Wuhan Municipal Health Commission alerted WHO that 27 cases of pneumonia of an unknown cause were detected in Wuhan, China [13], [14].
2. (Jan. 7th 2020) The novel virus was identified as a new strain of the coronavirus and named 2019-nCoV by WHO. The source was still unknown, but animals were the most likely candidates [1].
3. (Jan. 9th 2020) The first pandemic-related death of a 61-year-old man was reported in Wuhan [15].
4. (Jan. 12th 2020) China shared the genetic sequence of the novel coronavirus for other countries to use in developing specific diagnostic kits [15].
5. (Jan. 13th 2020) The first infected case outside China was confirmed in Thailand [16].
6. (Jan. 20th 2020) Human-to-human transmission of infection was confirmed [1].
7. (Jan. 23rd 2020) WHO declared the outbreak an emergency in China, but stopped short of calling it a global health emergency [1].
8. (Jan. 23rd 2020) Quarantine procedures were enforced in Wuhan and neighboring cities to limit the spread of infection and help contain the outbreak [2], [6].
9. (Jan. 30th 2020) WHO has declared the coronavirus outbreak a Public Health Emergency of International Concern [17]. Also, the Centers for Disease Control and Prevention (CDC) confirmed the first case of human-to-human transmission in the USA [18].
10. (Jan. 31st 2020) The US government recommended a 14-day quarantine for US citizens returning from China (the quarantine was mandatory for travelers through the Hubei province) [19].
11. (Feb. 2nd 2020) The first death outside China is recorded in Philippines [20].
12. (Feb. 21st 2020) The COVID-19 outbreak erupted in Italy [21], [22].
13. (Feb. 29th 2020) The first death was reported in the USA [23].

14. (Mar. 8th 2020) Italy announced a lockdown to control the virus spread [24].
15. (Mar. 13th 2020) A state of National Emergency is declared in the USA under the Stafford Act [25].
16. (Apr. 3rd 2020) The total count of worldwide infections exceeds one million [26].
17. (Apr. 17th 2020) The total count of worldwide cases reported to WHO exceeds two million [26], [27].

At the time of publication, this timeline still evolves as different countries go through different stages of the pandemic.

In this paper, we develop a human-to-human transmission model for the COVID-19 pandemic. This model is used to simulate the coronavirus spread dynamics among people in three countries: 1) China where the pandemic initially started, 2) Italy which had one of the largest death records in Europe, and 3) USA which recorded the biggest worldwide numbers of infections and deaths at the time of writing this paper. Our model takes into consideration the factors of quarantine, isolation, age, and virus stability.

The rest of this paper is organized as follows. Section II gives the basic assumptions and details of the proposed system dynamics model for COVID-19. Section III demonstrates model validation and simulation outcomes for the three selected countries. As well, sensitivity analysis results are reported for key model parameters. The results are discussed in Section IV. Conclusions and future directions are given in Section IV.

2. Materials and Methods

The coronavirus (COVID-19) is a severe highly-infectious pandemic, which started from Wuhan in China and spread to 213 countries and territories all over the world in about five months. The COVID-19 pandemic resulted in quickly and widely spreading infections and deaths, in addition to the absence of vaccines or effective therapeutic procedures. Analyzing the COVID-19 transmission dynamics would help in understanding different aspects of the disease, identifying at-risk groups, pinpointing conditions that worsen the disease consequences, assess the effectiveness of certain public health intervention measures, and more importantly limit the spread of the pandemic.

In this work, we seek to design a system dynamics model for the COVID-19 transmission among humans. This model simulates the pandemic dynamics for a period of 12 months. The model is based on real data collected between Dec. 31st 2019 and Apr. 17th 2020 from reliable COVID-19 sources such as [15], [26], [27], [28], [29], and [30].

2.1 Parameters of the COVID-19 Model

Even though the pandemic is still evolving at the time of this writing, reliable estimates of the COVID-19 model parameters could be obtained based on early identified cases, and available statistics for about 110 days of pandemic data. These parameters can be grouped into four categories:

1) Transmission dynamics

Several parameters influence the transmission dynamics such as:

- The mean **incubation period** was estimated to be 5.2 days in Wuhan [11], and 6.4 days in other affected areas (with a range of 2.1 – 11.1 days) [31]. Also, based on 55924 laboratory confirmed cases, the mean incubation period was generally 5-6 days, with a range of 1-14 days [6]. This incubation period causes time delays between the infection and the onset of the illness. As well, laboratory confirmation of the infection typically takes 10 days on average from the onset of the illness [32].

-The **transmission rate R_o** is the number of newly infected people from a single case. For COVID-19, this number has been estimated to be 2.2 on average [11]. Other studies have estimated R_o to be between 3.6 and 4.0, and between 2.24 and 3.58 [33].

From the available data, we estimated the transmission rates in China, Italy, and USA to be 5.31, 5.399, and 4.522, respectively. For comparison, the transmission rates for the common flu and SARS are 1.3 and 2.0, respectively. Asymptomatic or pre-symptomatic transmission can still occur and impact the transmission dynamics.

-The **environmental conditions** associated with increased transmission (e.g. temperature, humidity, and seasonality) are still not fully understood and accounted for in pandemic models.

2) Disease severity

Severity of the coronavirus is typically affected by demographic factors (e.g. age, sex, and ethnicity), as well as pre-existing conditions. Earlier studies have demonstrated higher disease severity in male patients and also in patients with diabetes, hypertension and cardiovascular diseases [34], while very few cases have been reported in children. In addition, there is currently limited understanding of the COVID-19 severity and risk among different demographic groups [35], [36], and [37].

- The **fatality rate (FR)** is the percent of total infected cases that resulted in death. As of February 20th 2020, China witnessed 2114 deaths out of 55,924 laboratory-confirmed cases (with a fatality rate of 3.8%) [6]. Based on death counts as of April 17th 2020, we estimated the fatality rates in China, Italy, and the USA to be 5.60%, 7.45%, and 2.54%, respectively.

3) Susceptibility

Based on the epidemiological patterns observed so far in China, almost every person on Earth is assumed to be susceptible, although different risk factors can make some people more susceptible than others. Further studies are needed to investigate those susceptibility factors and decide whether survivors develop immunity to the disease [6].

4) Infection prevention and control

- Enhancing **quarantine and isolation procedures** (including travel restrictions, contact tracing, and reducing contact rates) may significantly lower the infection peak and reduce the cumulative predicted number of infected individuals [38]. Travel and mobility restrictions in China slowed down the COVID-19 spread from Wuhan to other cities in China by 2.9 days [39]. Another study indicated that the travel and quarantine procedures delayed the overall epidemic progression by 3-5 days [40].

-**Immunity and its diagnostics:** Cross-reactivity gives importance to pre-existing immunity against heterologous human coronaviruses [10]. Other important options for fighting the coronavirus include immunotherapy, and the use of convalescent sera or other agents (e.g. antiviral or non-antiviral products).

-**Treatment availability:** So far, there is no well-developed medicine to prevent or treat COVID-19.

-**Vaccination:** Several candidate vaccines are in preclinical development [41]. Given the current COVID-19 knowledge and vaccine development status, the Expert Group for COVID-19 Vaccine Prioritization recommended that vaccine development efforts targeting the novel coronavirus should be prioritized over efforts targeting other coronaviruses types [10].

-Virus stability: The COVID-19 physical and chemical stability characteristics haven't been adequately studied but are likely to be comparable to those of SARS. Doremalen

et al. [42] found that the coronavirus remains for several hours to days on surfaces and in aerosols. They also suggested that people may acquire the coronavirus through the air and after touching contaminated objects. They also showed that the coronavirus persists for hours in aerosols, copper, and cardboard. Even more, the virus survived for up to 3 days on plastic and stainless-steel surfaces.

- Age: Older people were found to be generally of a higher COVID-19 risk compared to younger people [43]. Thus, countries with higher populations of older people can expect more severe consequences than other countries, assuming all other factors are similar.

Table 1 summarizes all of the key variables in the COVID-19 model with definitions, units, stock, flow, and values.

2.2 COVID-19 Modeling with Causal Loop Diagrams

We consider a Susceptible–Exposed–Infected–Recovered-Death (SEIRD) pandemic model with quarantine and isolation schemes as shown in Fig. 1. This model is suitable for COVID-19 where the symptoms don't appear within the incubation period, and hence more people become exposed. After the incubation period, the symptoms emerge and then the exposed people become infected. Thus, the infected people are discharged through recovery or death after a period of time.

Quarantine procedures for susceptible people and isolation procedures for infected people represent key control strategies for COVID-19. The quarantine period must be longer than the period of the coronavirus incubation and stability. As well, the COVID-19 dynamics are highly affected by other factors such as the contact rate, transmission rate, disinfection, age, pre-existing conditions, immunity, recovery rate and fatality rate. While the effects of some of these factors can be reasonably estimated from available data, there are still high uncertainties of the effects of others such as the effect of the ambient temperature and humidity on virus stability, and also the effect of different treatment approaches on the recovery rate. Anyway, our model accounts for a wide range of these factors.

Figure 2 shows a causal loop diagram (CLD) of our COVID-19 model. This diagram represents the correlation between different model parameters.

There are four balancing loops (B1:B4) and two reinforcing loops (R1, R2) in this diagram:

B1 (total people – susceptibility rate): This balancing loop represents a negative correlation between the susceptibility rate and the total number of people.

B2 (infection rate – exposed people – infected people – isolation): This balancing loop signifies a negative correlation between isolation and the infection rate.

B3 (infected people – death rate - deaths): This balancing loop shows a negative correlation between deaths and infected people.

B4 (infected people – recovery rate – recovered people): This balancing loop exhibits a negative correlation between the numbers of recovered and infected people.

R1 (susceptible people – infection rate – exposed people- infected people): This reinforcing loop represents a positive correlation among its components.

R2 (susceptibility rate – susceptible people – infection rate – exposed people – infected people – recovery rate – recovered people): This is a reinforcing loop with positive correlation among its components. This loop is considered because of the re-infection possibility for recovered people.

The causal loop diagram has three-time delays. First, there is a delay between the

exposed and infected states. This delay is equal to the incubation period. Second, the transition from the infected to the recovered states is delayed by the average recovery time. Third, the transition from the infected to the death states is controlled by the average time from the infection confirmation to death. Using the available COVID-19 data, the median times from the disease onset to recovery for mild and severe cases are approximately 2 weeks and 3-6 weeks, respectively. Also, the available data suggests that the time period from the disease onset to the development of severe symptoms (including hypoxia) is one week. For the patients who have died, the time from the disease onset to death ranges from 2-8 weeks [6].

2.3 COVID-19 Modeling with the Stock and Flow Diagram

The COVID-19 causal loop diagram of Fig. 2 can be converted into the stock-and-flow diagram (SFD) in Fig. 3, which illustrates the system dynamics of the COVID-19 pandemic.

2.4 Equations of the COVID-19 Model

All people are generally susceptible to COVID-19, especially with no available vaccine for COVID-19 in the near future. Thus, the total input population P can be counted as susceptible people S,

$$\frac{\partial P}{\partial t} = \frac{\partial S}{\partial t} \tag{1}$$

However, preventive quarantine procedures and vaccine availability can control the number of quarantined and vaccinated people Q_p through the quarantine rate Q_r,

$$\frac{\partial Q_p}{\partial t} = S\, Q_r \tag{2}$$

The temporal variability of the number of susceptible people S is governed by

$$\frac{\partial S}{\partial t} = -S\, Q_r - SI_r + \frac{\partial R}{\partial t} \tag{3}$$

and

$$Q_r = \frac{Q_q + V}{2} \tag{4}$$

where Q_q and V represent the probabilities of quarantine and vaccine availability, respectively. The last term in (3), $\frac{\partial R}{\partial t}$, is the rate of change of the number of recovered people at time t. The infection rate I_r is given by

$$I_r = R_o\Big(b + \big(1 - Q_q\big) + (1 - Q_i)\Big)\,(1/(a + V_s)) \tag{5}$$

where R_o is the transmission rate (or the reproduction number), b is the contact probability, Q_i is the isolation probability, a is the incubation period, and V_s is the virus stability period.

The exposed people E have already been infected by COVID-19 but show no symptoms. The rate of change of this group is given by

$$\frac{\partial E}{\partial t} = SI_r \tag{6}$$

The exposed people E experience some delay (given by the incubation period) to show infection symptoms I. The rate of change of the symptomatic infections is given by

$$\frac{\partial I}{\partial t} = \frac{\partial E}{\partial t - a} - \frac{\partial R}{\partial t - T_R} - \frac{\partial D}{\partial t - T_D} \tag{7}$$

The patient discharge consists of recovered people R (whose recovery is delayed by the recovery time T_R), and dead people D (whose death is delayed by the time-to-death T_D). The rates of change of these two groups are respectively governed by

$$\frac{\partial R}{\partial t} = IR_r \quad (8)$$

and

$$\frac{\partial D}{\partial t} = ID_r \quad (9)$$

where R_r is the recovery rate, and D_r is the death rate.

With the general assumption that the births and deaths in the population are equal, the total number of people in the model is constant. Hence, the general rate equation for the model is

$$\frac{\partial P}{\partial t} = \frac{\partial Q}{\partial t} + \frac{\partial S}{\partial t} + \frac{\partial E}{\partial t} + \frac{\partial I}{\partial t} + \frac{\partial R}{\partial t} + \frac{\partial D}{\partial t} \quad (10)$$

3. Testing and Validation of the COVID-19 Simulation Model

3.1 Case Study 1: China

We used and analyzed COVID-19 data, collected between Dec. 31st 2019, and Apr. 17th 2020 from reliable sources [15], [26], [27], [28], [29], and [30]. Simulation results on infected, recovered, and dead people were validated against real data of China. Since the pandemic first emerged in China and this country is in the final stage of the pandemic, the data from China was used as the key benchmark for testing our model.

Some of the model parameters were estimated from data while others were set based on published research or WHO reports.

Figure 4 shows simulation results for the COVID-19 model with a 365-day period starting on Dec. 31st 2019 for the case of China (Table 1). The growth curve for the infected people is overlaid with that of the exposed people to show the delay between the onset of symptomatic and asymptomatic cases. The simulation expects a total of 85,832 infected people, and a total of 3,473 deaths at the day 221 (Aug. 7th). Also, the last recovery is expected by the day 248 (Sep. 3rd) with a total of 82,359 recovered people.

The simulation results on April 17th are close to the actual data from China on the same date. The simulated curve of the symptomatic active cases peaked with 62,643 cases on the day 61 (Feb. 29th), while the actual curve peaked at the day 49 (Feb. 17th) with 58016 cases [26]. Then, the simulated curve began to decline until it almost died out on the day 110. The simulated numbers compare well with the real data. In fact, the expected total numbers of infected, recovered, and dead people were 85,832, 79,329, and 3,345, respectively. The corresponding real numbers are 82,692, 77,944, and 4,632, respectively [26]. Note that the step increase in the number of deaths on the day 110 (Apr. 17th) is the result of the correction of the number of deaths in Wuhan. In fact, 1,290 additional deaths that had not been previously counted, were reported. This brought the total number of deaths in Wuhan from 2,579 to 3,869 [44], [45].

Figures 5, 6, and 7 compare the simulated and real curves for the active cases, recovered people, and deaths, respectively.

3.2 Case Study 2: Italy

Figure 8 shows simulation results for the COVID-19 model with a 365-day period starting on Feb. 15th 2020 for the case of Italy (Table 1). The growth curve for the infected people is overlaid with that of the exposed people to show the delay between the onset of symptomatic and asymptomatic cases. The simulated curve of the symptomatic active cases peaked at the day 60 (Apr. 14th 2020). The simulation expects the total numbers of infected, recovered, and dead people to be 276,406, 227,710, and 47,963 respectively, on

the day 365 (Feb 14th 2021). That means that there are still 733 active cases next year, and hence a second wave of the COVID-19 pandemic is possible.

3.3 Case Study 3: USA

Figure 9 shows simulation results of the COVID-19 model within 365 days starting on Feb. 15th 2020 for the case study of the USA (Table 1). The growth curve for the infected people is overlaid with that of the exposed people to show the delay between the onset of symptomatic and asymptomatic cases. The simulated curve of the symptomatic active cases peaked at the day 69 (Apr. 23rd 2020). The simulation expects the total numbers of infected, recovered, and dead people to be 3,394,754, 3,134,320, and 231,814, respectively, on the day 365 (Feb 14th 2021). That means that there are still 28,620 active cases next year, and hence a second wave of the COVID-19 pandemic is still likely. Indeed, a large number of exposed people exists in the USA case.

4. Sensitivity Analysis for the COVID-19 Model

We explore the effect of the quarantine procedures and their timing on the spread of COVID-19. In fact, delays in diagnosis and hospitalization, as well as lengthy incubation periods, can increase the disease spread and shorten the doubling time of the epidemic. Therefore, quarantine procedures play a key role in effective control and deceleration of the COVID-19 outbreak. In the following, we investigate the sensitivity of the simulation outcomes to changes in the quarantine start date. Specifically, for each of the three country case studies, we tried eight possible quarantine start dates that are uniformly spaced between the date of confirming the first COVID-19 case and the date of actually enforcing the quarantine procedures. We also analyzed the sensitivity of the simulation outcomes to changes in the effective quarantine percentage. In particular, we tried seven potential quarantine percentages through varying the default estimated quarantine percentage by ±2%, ±4%, and ±6%.

4.1 Sensitivity Analysis: China

In China, the quarantine started on the day 24 (Jan. 23rd 2020), and the average effective quarantine percentage is estimated to be 75% (Table 1). Sensitivity curves and statistics for variations in the quarantine start date are shown in Fig. 10 and Table 2, respectively. For each start date, Table 2 shows the peak day, and the numbers of the active and infected cases on the peak day. The bordered column in Table 2 and the green curve in Fig. 10 correspond to the actual quarantine start date. The eight simulated scenarios show that if the quarantine was started few days earlier, the numbers of active and infected cases would have been dramatically reduced. Indeed, an order-of-magnitude reduction in these numbers could have been made if the quarantine was started 18 days earlier.

The influence of the effectiveness of the quarantine procedures is analyzed through varying the quarantine percentage as shown in Fig. 11 and Table 3. While the peak day wouldn't have changed with varying the quarantine percentage, the numbers active and infected cases could have substantially increased (resp. decreased) if the quarantine percentage was slightly decreased (resp. increased).

4.2 Sensitivity Analysis: Italy

In Italy, the quarantine started on the day 23 (Mar. 8th 2020), and the average effective quarantine percentage is estimated to be 47% (Table 1).

Figure 12 and Table 4 show respectively the sensitivity curves and statistics for variations in the quarantine start date.

Quarantine start dates one and two weeks earlier than the actual date could have roughly reduced the active and infected cases by half and an order of magnitude, respectively.

Figure 13 and Table 5 show the impact of the effectiveness of the quarantine procedures. Decreasing (resp. increasing) the quarantine percentage by only 6% could have doubled (resp. halved) the numbers of active and infected cases.

4.3 Sensitivity Analysis: USA

In the USA, the quarantine started on the day 31 (Mar. 16th 2020), and the average effective quarantine percentage is estimated to be 40% (Table 1).

The effects of variations in the quarantine start date are shown by the sensitivity curves and statistics in Fig. 14 and Table 6, respectively. The impact of the quarantine delay is more pronounced in this case. Starting the quarantine just one week earlier could have helped the USA avoid 2 million infections.

Also, Fig. 15 and Table 7 show large-scale effects of varying the quarantine percentage in the USA case. In fact, a 6-percent decrease (resp. increase) in the quarantine percentage could have increased (resp. decreased) the numbers of active and infected cases by about 2 million.

Table 1. Attributes of the key variables in the COVID-19 model: definition, unit, stock-and-flow type, and values in each of the three country case studies.

No	Parameter	Variable	Definition	Stock & Flow	Unit	Initial & Value	China	Italy	USA
1	Total People	P	The total number of people in a country or region	Converter	People	Population	(1,438,103,848)[1]	(60,482,424)[1]	(330,575,633)[1]
2	Susceptible People	S	The number of people easily influenced by COVID-19	Stock	People	Population	1,438,103,848	60,482,424	330,575,633
3	Exposed People	E	The number of people who have COVID-19 but no symptoms	Stock	People	NA*	0	0	0
4	Quarantined & Vaccinated People	Q_p	The number of people who are quarantined or vaccinated for COVID-19	Stock	People	NA*	0	0	0
5	Infected People	I	The number of people with symptomatic COVID-19	Stock	People	1 ≤	27	3	15
6	Recovered People	R	The number of COVID-19 survivors	Stock	People	0 ≤	0	0	0
7	Deaths	D	The people who died because of COVID-19	Stock	People	0 ≤	0	0	0
8	Quarantined Inflow Rate	Q_r	The number of people quarantined daily due to COVID-19	Flow	People/ Day	Cal.**	--	--	--
9	Expose Inflow Rate	E_r	The number of susceptible people exposed daily due to COVID-19	Flow	People/ Day	Cal. **	--	--	--
10	Infection Inflow Rate	I_r	The number of exposed people infected daily with COVID-19	Flow	People/ Day	Cal. **	--	--	--
11	Recovered Inflow	R_i	The number of infected people recovering daily from COVID-19	Flow	People/ Day	Cal. **	--	--	--
12	Deaths Inflow	D_i	The number of infected people who die daily because of COVID-19	Flow	People/ Day	Cal. **	--	--	--
13	Transmission Rate	R_0	The number of cases directly infected by one case in a population where all individuals are susceptible to infection with COVID-19	Converter	--	0 ≤	5.31	5.399	4.522
14	Preventive Quarantine	Q_q	The average percentage of separating and restricting the movement of people to see if they become infected with COVID-19. These people may have the disease but do not show symptoms	Converter	%		75 %	47 %	40 %
15	Start Quarantine	Q_s	The day when the quarantine started after the first confirmed infected case	Converter	Day	1 ≤	24	23	31

16	Incubation Period	a	The time from the moment of exposure to COVID-19 until symptoms of the disease appear	Converter	Day	2 - 14	6	6	6
17	Virus Stability	V_s	The period that the virus can remain viable and infectious	Converter	Day	0 ≤	4	4	4
18	Contact Possibility	b	The possibility of interaction between infected and susceptible people	Converter	%	0 – 100	25 %	25 %	25 %
19	Isolation	Q_i	The percentage of the separated sick people with COVID-19 from the people who are not sick	Converter	%	0 – 100	85 %	85 %	85 %
20	Time to Death	T_D	The average period between the time of infection with COVID-19 until death because of the infection	Converter	Day	1 – 56	28	28	28
21	Time to Recover	T_R	The average period between the time of infection with COVID-19 until recovery	Converter	Day	1 – 28	14	14	14
22	Mortality Rate		The ratio of the number of deaths due to COVID-19 and the number of infected people	Converter	%	0 ≤	0.056	0.0745	0.0254
23	Recovery Rate	R_r	The percentage of infected people who recovered from COVID-19	Converter	%	0 ≤	0.437	0.121	0.113
24	Immunity	Im	The ability to resist COVID-19 infection due to the presence of specific antibodies or sensitized white blood cells	Converter	%	0 – 100	90 %	90 %	90 %
25	Medicine Efficacy	M_e	A percentage of a drug's beneficial effect on COVID-19 as proved by substantial evidence from clinical trials	Converter	%	0 – 100	0	0	0
26	Vaccine Availability	V	The availability percentage of COVID-19 vaccines	Converter	%	0 – 100	0	0	0
27	Age Factor	A	The percentage that causes an increase in the mortality rate because of age (calculated relative to the median age)	Converter	%	0 ≤	0.196	0.244	0.196
28	Median Age	M_a	The age midpoint for a population	Converter	Year	0 ≤	38.4	47.3	38.4
29	Pre-existing Conditions	C	Medical conditions that existed before the COVID-19 infection, and that increase the mortality rate	Converter	%	ND****	NU***	NU***	NU***
30	Temperature	t	The ambient temperature at which the coronavirus can survive	Converter	C^0	ND****	NU***	NU***	NU***
31	Humidity	H	The ambient humidity at which the coronavirus can survive	Converter	%	ND****	NU***	NU***	NU***
32	Disinfection	D	The percentage of coronavirus-free rooms, wounds, clothing, etc.	Converter	%	0 - 100	90 %	90 %	90 %

[1] The current populations of China, Italy, and USA as of Sunday, April 5, 2020, based on Worldometer and the latest United Nations data [26].
* Not Available. ** Calculated Variable. *** Not Used. **** Not Determined Yet.

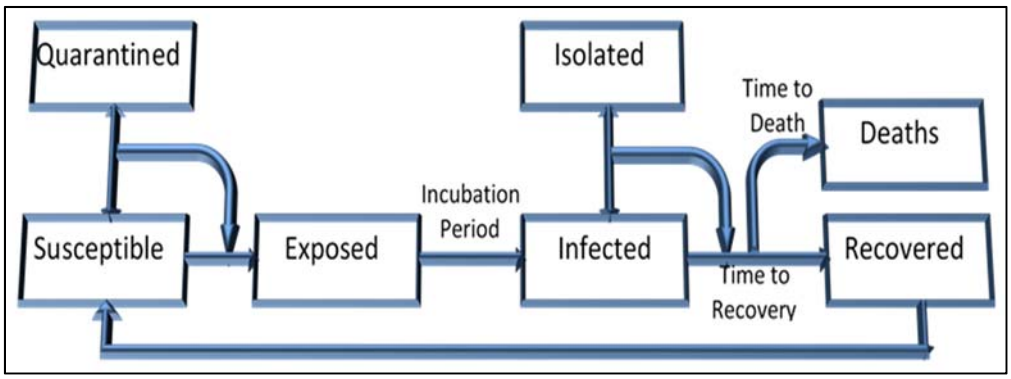

Fig. 1. A block diagram of the SEIRD epidemic model for COVID-19.

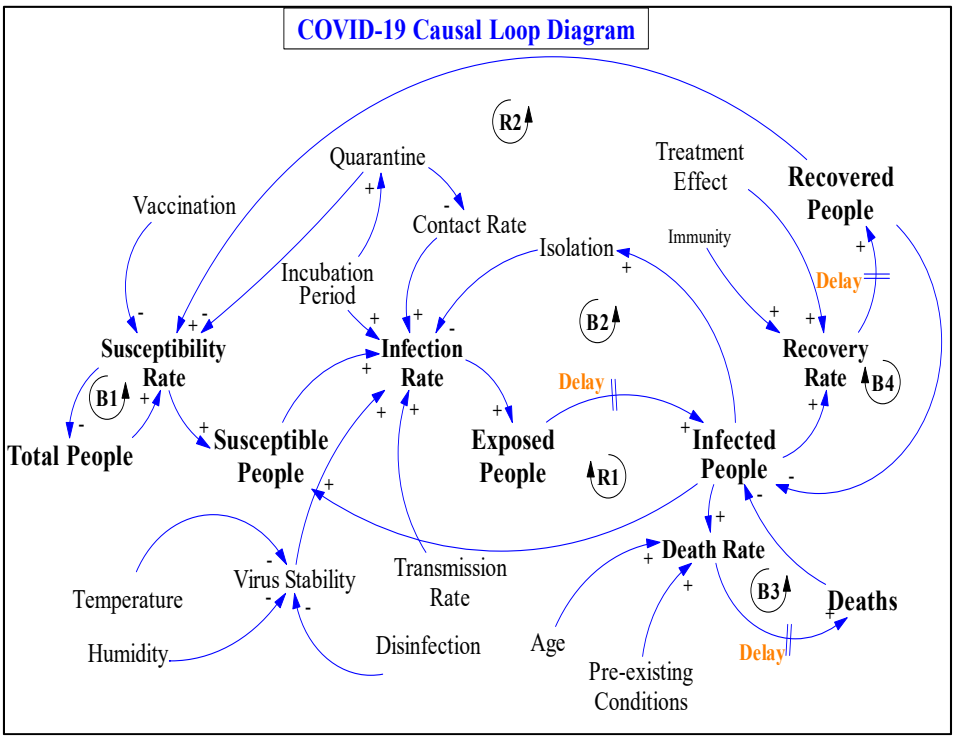

Fig. 2. A causal loop diagram of the COVID-19 model.

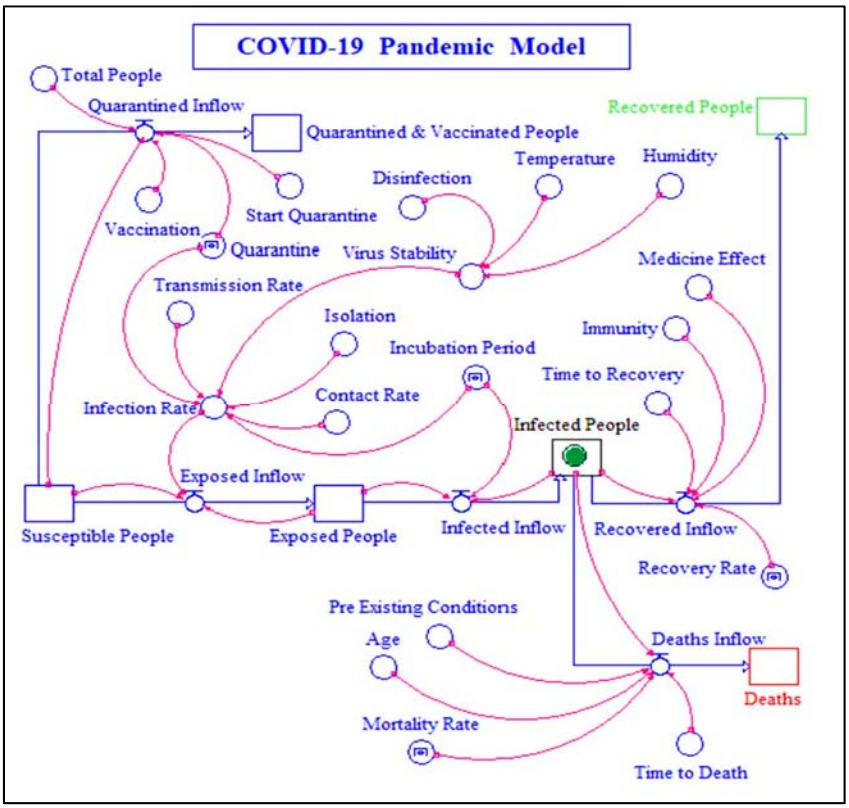

Fig. 3. A stock-and-flow diagram for the COVID-19 model.

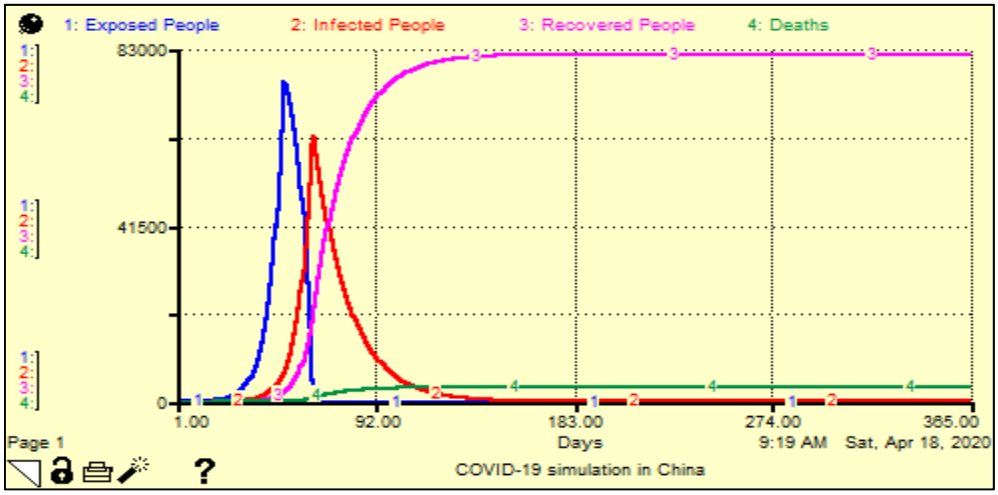

Fig. 4. COVID-19 simulation results for China.

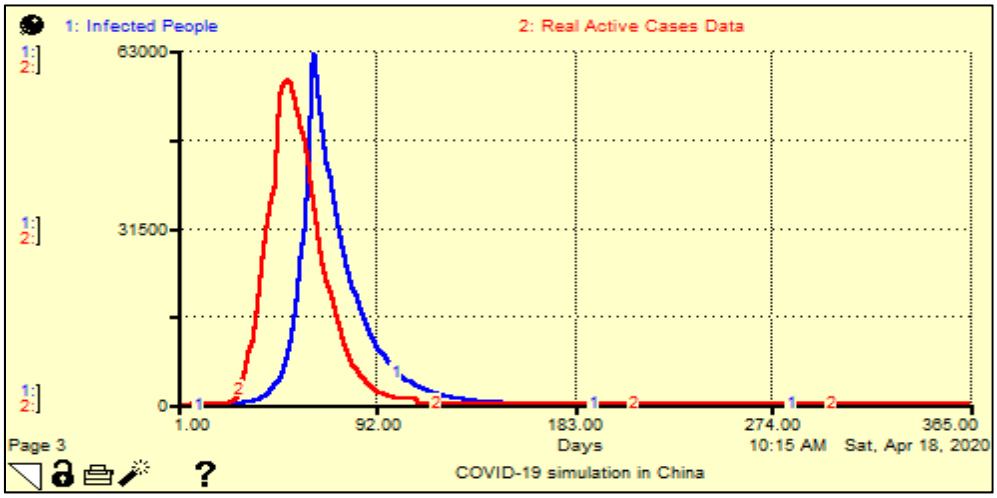

Fig. 5. Comparison of the simulated and real curves of active cases in China.

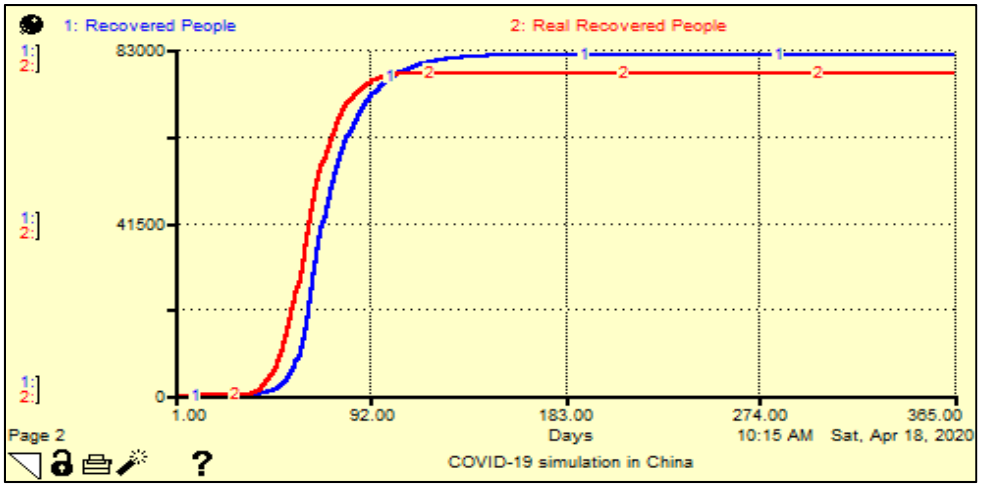

Fig. 6. Comparison of the simulated and real curves of recovered cases in China.

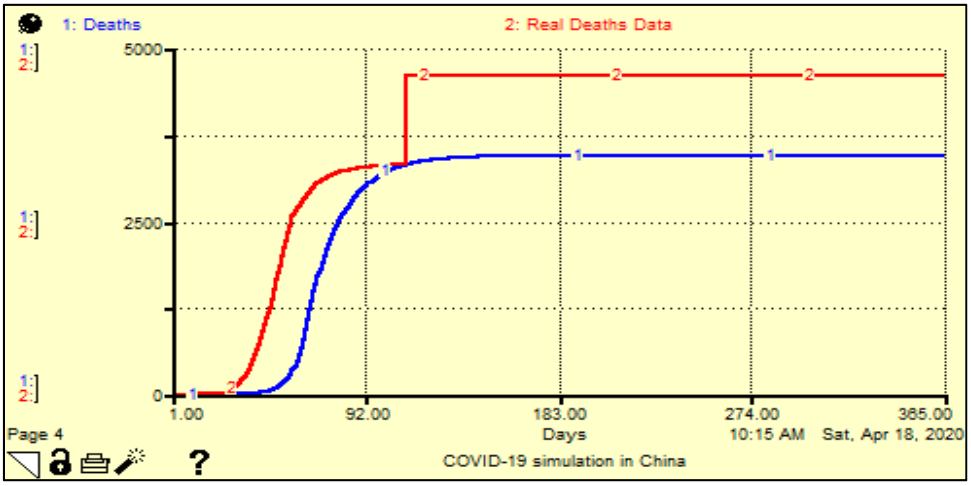

Fig. 7. Comparison of the simulated and real curves of death cases in China.

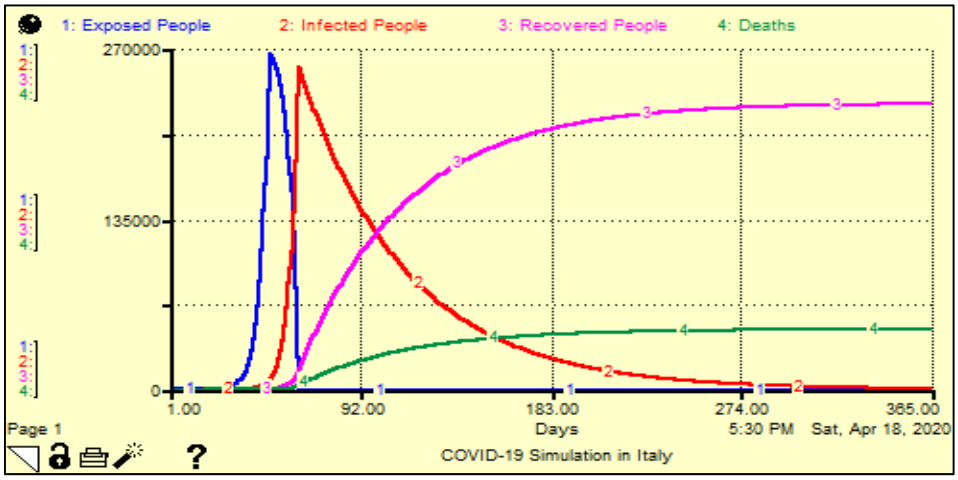

Fig. 8. COVID-19 simulation results for Italy.

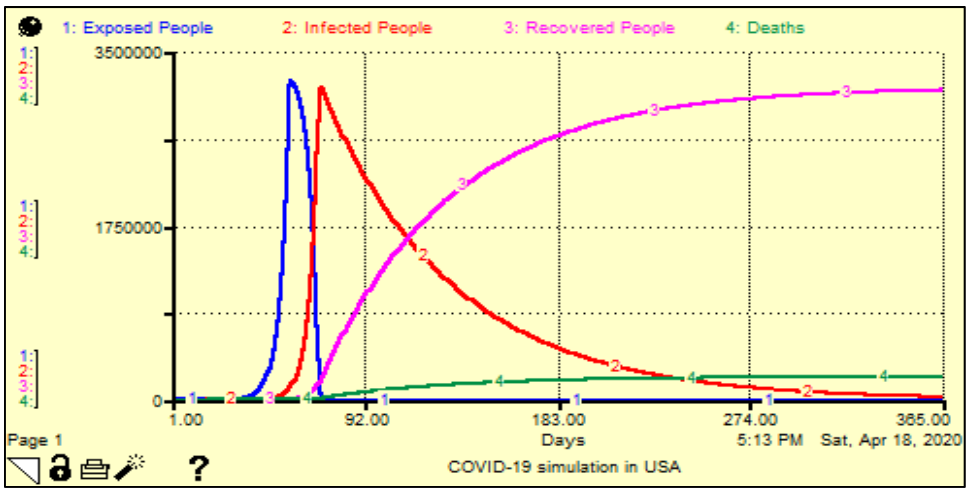

Fig. 9 COVID-19 simulation results for USA.

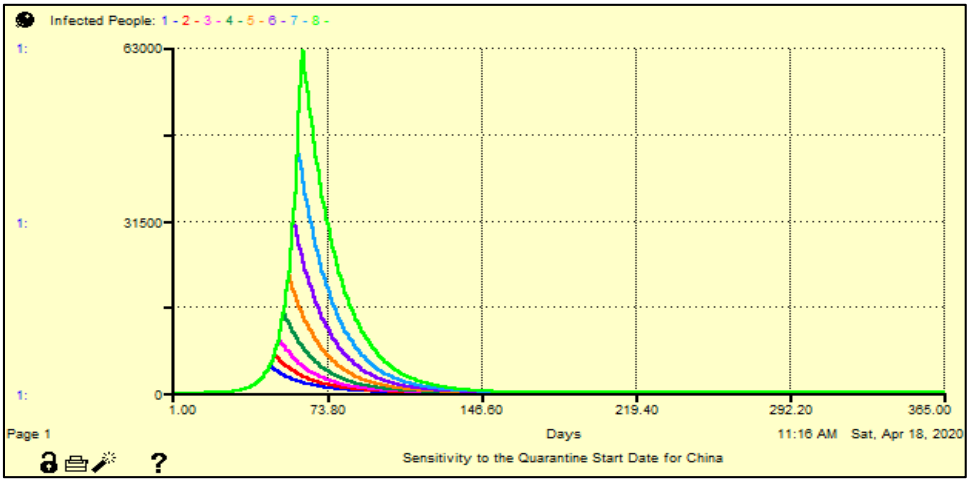

Fig. 10. Curves of sensitivity to the quarantine start date for China.

Table 2. Statistics of sensitivity to the quarantine start date for China.

Simulation No.	1	2	3	4	5	6	7	8
Qua. day	3	6	9	12	15	18	21	24
Peak day	45	48	50	52	54	56	59	61
Active cases	4,856	6,865	9,694	14,462	21,671	31,012	43,836	62,643
Infected cases	6,589	9,448	13,317	19,541	28,789	42,592	60,386	85,832

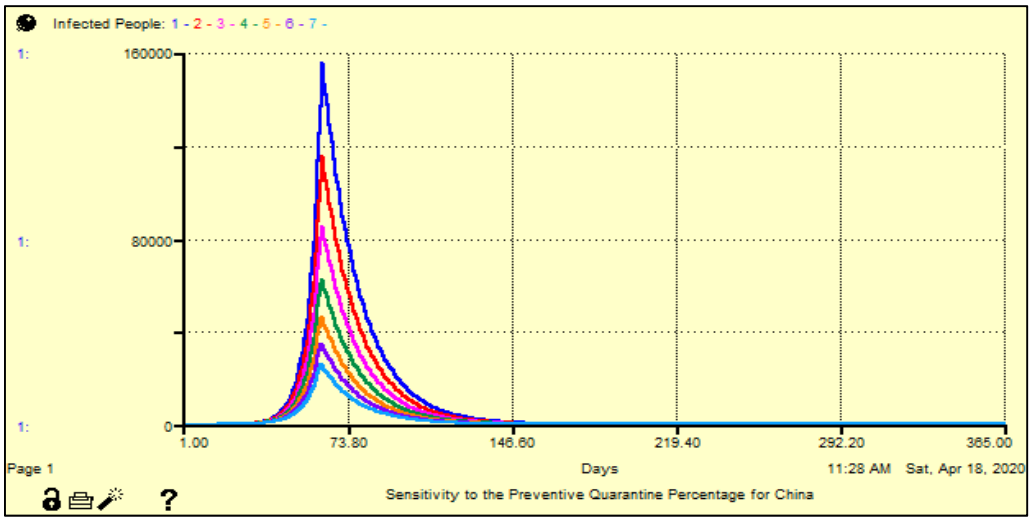

Fig. 11. Curves of sensitivity to the quarantine percentage for China.

Table 3. Statistics of sensitivity to the quarantine percentage for China.

Simulation No.	1	2	3	4	5	6	7
Qua. percent	69%	71%	73%	75%	77%	79%	81%
Peak day	61	61	61	61	61	60	60
Active cases	156,547	115,615	85,198	62,643	46,053	34,532	25,826
Infected cases	204,243	153,204	114,756	85,832	64,202	48,557	36,595

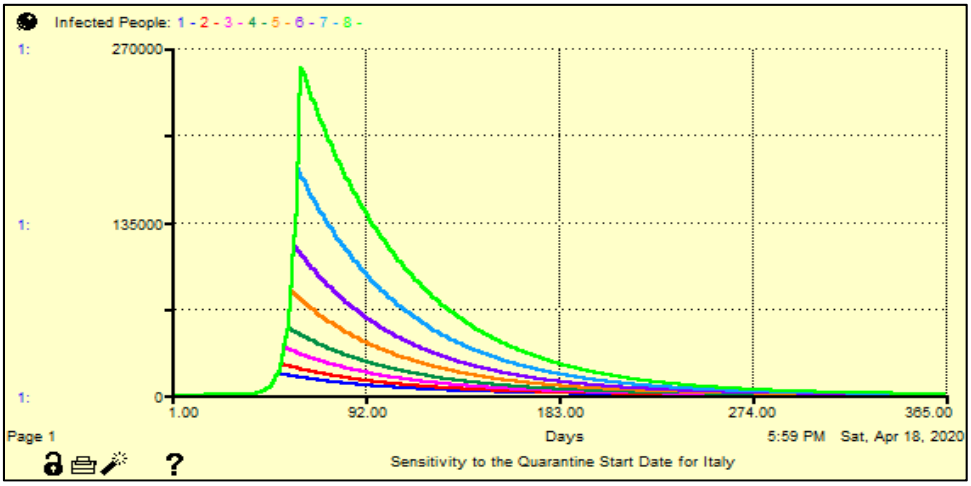

Fig. 12. Curves of sensitivity to the quarantine start date for Italy.

Table 4. Statistics of the sensitivity to the quarantine start date for Italy.

Simulation No.	1	2	3	4	5	6	7	8
Qua. day	2	5	8	11	14	17	20	23
Peak day	49	51	52	54	55	57	58	60
Active cases	16,891	24,026	37,263	52,889	82,232	116,470	177,977	224,418
Infected cases	18,093	26,026	42,543	57,187	87,776	125,702	189,887	276,406

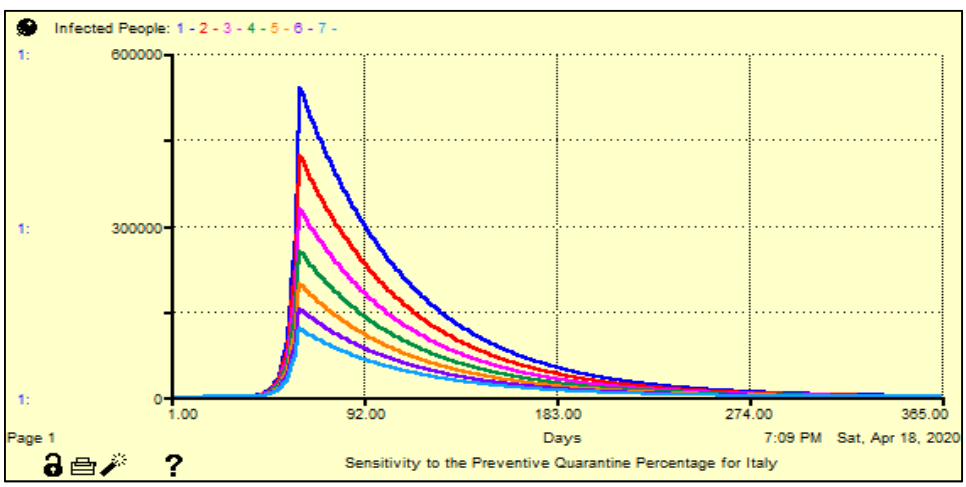

Fig. 13. Curves of sensitivity to the quarantine percentage for Italy.

Table 5. Statistics of sensitivity to the quarantine percentage for Italy.

Simulation No.	1	2	3	4	5	6	7
Qua. percent	41%	43%	45%	47%	49%	51%	53%
Peak day	60	60	60	60	60	60	60
Active cases	476,934	371,573	289,005	224,418	173,991	134,687	104,107
Infected cases	580,769	454,136	354,563	276,406	215,162	167,252	129,833

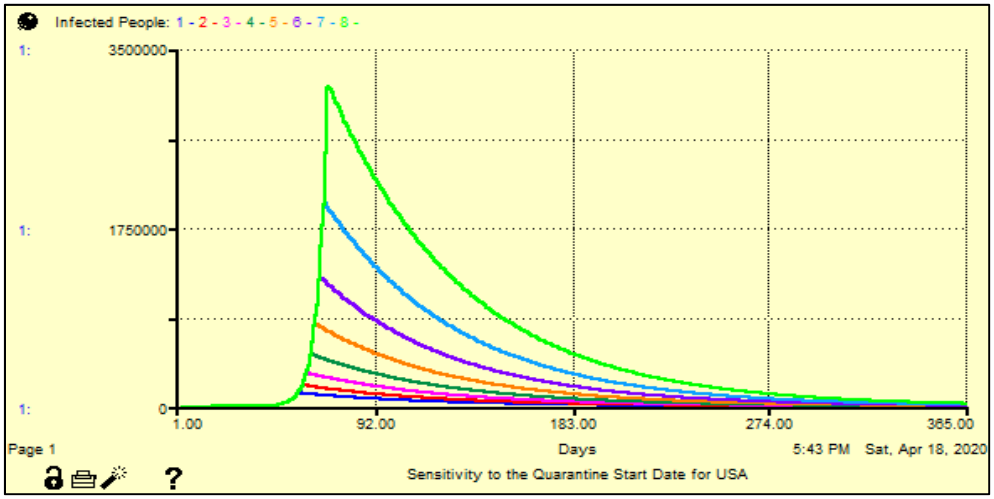

Fig. 14. Curves of sensitivity to the quarantine start date for USA.

Table 6. Statistics of the sensitivity to the quarantine start date for USA.

Simulation No.	1	2	3	4	5	6	7	8
Qua. day	3	7	11	15	19	23	27	31
Peak day	55	57	59	61	63	65	67	69
Active cases	134,030	210,426	330,383	518,744	814,529	1,279,021	2,008,472	3,154,059
Infected cases	143,675	225,700	354,567	557,038	875,164	1,375,028	2,160,487	3,394,754

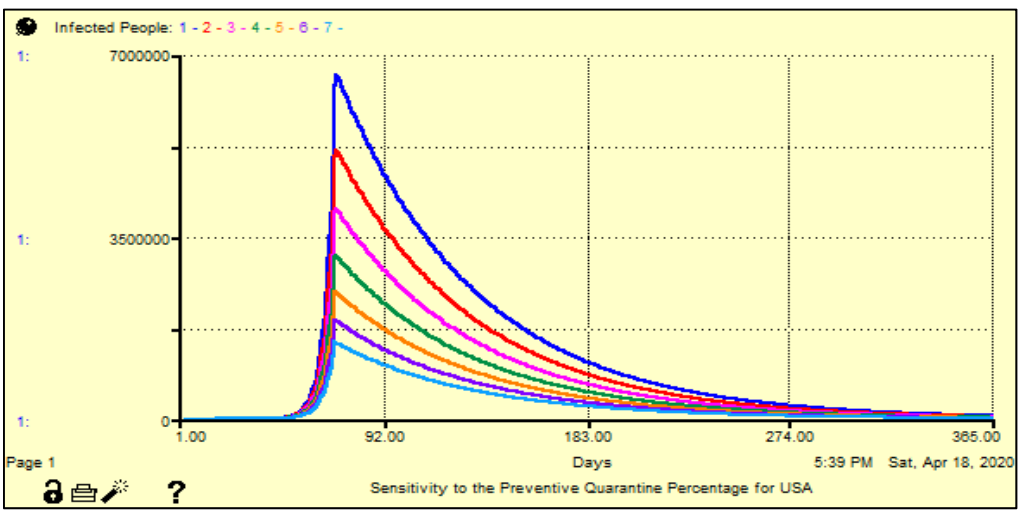

Fig. 15. Curves of sensitivity to the quarantine percentage for USA.

Table 7. Statistics of sensitivity to the quarantine percentage for USA.

Simulation No.	1	2	3	4	5	6	7
Qua. percent	34%	36%	38%	40%	42%	44%	46%
Peak day	69	69	69	69	68	68	68
Active cases	6,656,138	5,199,921	4,053,919	3,154,059	2,455,833	1,919,941	1,496,854
Infected cases	6,639,774	5,576,573	4,355,212	3,394,754	2,641,054	2,050,828	1,594,959

5. Discussion

Comparison of real COVID-19 data from China and the results produced by simulating our model show a good accuracy for our model. Nevertheless, further research is needed to more accurately characterize the epidemiological parameters underlying the transmission dynamics of COVID-19 and identify effective control and mitigation measures. The time lag between the simulated and the real curves may be ascribed to the incubation period, time-to-recovery, and time-to-death model parameters.

First of all, the simulation results for the COVID-19 data of China show S-shaped growth of the pandemic curve with a growth factor > 1 until a peak is reached in day 61. Then, the growth factor becomes approximately equal to 1 and the pandemic curve saturates. Next, the growth factor becomes <1 and the curve begins to collapse until the COVID-19 pandemic essentially ends in the day 248 with expected total cases of 85,832 people.

Secondly, the simulation results for Italy indicate expected total cases of 276,406 people. More importantly, the simulations show that the pandemic may continue until early 2021, as a number of exposed people may be present after a year of the pandemic outbreak.

Thirdly, the simulation results for the USA are somewhat different from those of China and Italy. The total cases are expected to reach 3,394,754 people by the end of the simulation period. This large number of confirmed cases and the large number of exposed people indicate that the pandemic in the USA can be quite difficult to control. So, medications and vaccinations for COVID-19 can be the best solution in the USA case.

Finally, sensitivity analysis of the quarantine timing and effectiveness for the three country case studies (China, Italy, and USA) indicate that the peak infection time is sensitive to time of declaring and executing quarantine measures, while the change in the quarantine effective percentage affects the infection peak height. The sensitivity simulation results show a positive correlation between the quarantine time and the infection peak time and a negative correlation with the infection peak height. The simulations also show a negative correlation between the quarantine quality and the infection peak height.

6. Conclusions

The system dynamics model of COVID-19 provides a good estimation for the numbers of infected, recovered, and dead people, in addition to the pandemic timing and the peak time. The model also allows the manipulation of some epidemiological parameters in order to slow and stop transmission, prevent outbreaks, and delay pandemic spread. The ultimate solution for the COVID-19 pandemic is of course to find effective medical treatment methods or vaccinations. Anyway, early and strict quarantine procedures represent the best available solution right now. Indeed, in order to reduce COVID-19 illness and death rates, adopted measures must fully incorporate quick diagnosis and isolation, rigorous contact tracing, monitoring, quarantine enforcement, and direct community engagement.

Declaration

The authors report no conflict of interest.

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نظام ديناميكي لجائحة الفيروس التاجي الجديد (كوفيد–19)

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المستخلص. الفيروس التاجي الجديد (كوفيد–19) هو مرضٌ شديدُ العدوى يصاحبُه أحيانًا أعراضٌ تنفسيةٌ شديدةٌ قد تؤدي إلى الوفاة. وفقًا لأحدثِ الإحصائيات فإنَّ كوفيد–19 يؤثر على 213 دولة وإقليمًا حول العالم. تشيرُ الإحصائياتُ إلى أنَّ المرضَ أدى إلى حوالي 367,000 حالةِ وفاةٍ و6 ملايين إصابة في جميع أنحاء العالم بين 31 ديسمبر 2019 و30 مايو 2020. في هذه الورقة البحثية، نقترحُ نموذجَ نظامٍ ديناميكي لانتشارِ كوفيد–19. يبحثُ النموذجُ المقترحُ في الآلياتِ المحتملةِ لانتشارِ العدوى بين البشرِ. تمَّ تقديرُ المعلماتِ الوبائيةِ على أساسِ بياناتِ الجائحةِ الحقيقيةِ التي تغطي فترة 110 أيامٍ. تمَّ مُحاكاةُ النموذجِ والتحققُ مِنْ صحتِهِ لحالاتِ الصين وإيطاليا والولايات المتحدة الأمريكية على مدى 365 يومًا. تتنبأُ نتائجُ المحاكاةِ النموذجيةِ بحدوثِ ركودٍ للوباءِ في الصين بحلولِ أغسطس 2020 بإجمالي 85,832 حالة إصابة بكوفيد–19. في إيطاليا، مِن المتوقعِ أنْ يصلَ العددُ الإجمالي للمصابين بالعدوى إلى 276,406. يتنبأُ النموذجُ أيضًا بموجةٍ أخرى من تفشي كوفيد–19 بحلول أوائل عام 2021. وأخيرًا، فإنَّ العددَ الكبيرَ المتوقعَ البالغ 3,394,754 مصابًا في الولايات المتحدة يُعطي تحذيرًا واضحًا من إمكانية خروج الأزمة عن نطاق السيطرة. في ظل هذه الظروف، تصبحُ إجراءاتُ الحجرِ الصحي غيرَ فعَّالة، ويُصبحُ اللقاحُ أو العلاجُ هو الحلُ الفعَّالُ. يُوفرُ النموذجُ الديناميكي لكوفيد–19 تقديرًا جيدًا لأعداد المصابين والمتعافين والوفيات، بالإضافةِ إلى توقيتِ الجائحةِ ووقتِ الذروةِ.

الكلمات المفتاحية: الفيروس التاجي الجديد، كوفيد–19، نظام ديناميكي، جائحة، الأمراض المعدية.