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Quantitative evaluation of the role of Fangcang shelter hospitals in the control of Omicron transmission: A case study of the outbreak in Shanghai, China in 2022

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ABSTRACT

Since Omicron began to spread in China, Shanghai has become one of the cities with more severe outbreaks. Under the comprehensive consideration of the vaccine coverage rate, the number of Fangcang shelter hospital beds and the number of designated hospital beds in Shanghai, this paper established a deterministic compartmental model and used the Nelder-Mead Simplex Direct Search Algorithm and chi-square values to estimate the model parameters. we calculate $\mathcal{R}_0 = 3.6429$ when the number of beds in the Fangcang shelter hospital is relatively tight in the second stage and $\mathcal{R}_0 = 0.4974$ in the fifth stage when there are enough beds in both Fangcang shelter hospital and designated hospital. Then we perform a sensitivity analysis on $\mathcal{R}_0$ by using perturbation of fixed point estimation of model parameters in the fifth stage, and obtain three parameters that are more sensitive to $\mathcal{R}_0$, which are transmission rate (β_{1d}), proportion of the infectious (η) and the hospitalization rate of asymptomatic infected cases (δ_1). Through simulation, we obtain that if the hospitalization rate of asymptomatic infections $\delta_2 > 0.9373$ or the transmission rate $\beta_{1b} < 0.0467$, the second stage of Omicron transmission in Shanghai can be well controlled. Finally, we find the measure that converting the National Convention and Exhibition Center (NECC) into a Fangcang shelter hospital has played an important role in curbing the epidemic. Whether this temporary Fangcang shelter hospital is not built or delayed, the cumulative number of confirmed cases will both exceed 100,000, and the cumulative asymptomatic infections will both exceed 1 million. In addition, for a city of 10 million people, we obtain that if a permanent Fangcang shelter hospital with 17,784 beds is built ahead of epidemic, there will be no shortage of beds during the outbreak of Omicron. Our findings enrich the content of the impact of Fangcang shelter hospital beds on the spread of Omicron and confirm the correct policy adopted by the Chinese government.

1. Introduction

Since the outbreak of the COVID-19 in late 2019, the COVID-19 strain has also been iterated continuously, with the change of the environment and the passage of time [1,2]. On November 24, 2021, South Africa first reported the B.1.1.529 variant to the World Health Organization (WHO) [3]. After assessment, the WHO designated the SARS-CoV-2 variant: B.1.1.529 as a variant of concern, called Omicron [4]. Until now, there are five COVID-19 variant of concern defined by the WHO, which are Alpha, Beta, Gamma, Delta and Omicron [5]. Fig. 1 shows when and where the five COVID-19 variant of concern were first discovered.

Before Omicron was first discovered in South Africa, Delta strains were widely spread as the main popular strains of COVID-19 [6]. However, with the discovery of Omicron strains, Omicron began to replaced Delta strains as the main popular strain globally [7]. In addition, as of December 24, 2021, more than 110 countries and regions have reported cases of Omicron strain infection, including the United States, China, Denmark and other places [8]. Compared with the previous Delta strains, Omicron has stronger spreading ability [9,10] and

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immune escapeability [11,12]. Tom Wenselers, an evolutionary biologist at the Catholic University of Leuven in Belgium, believed that Omicron is likely to spread faster and infected more people than Delta [9]. In addition, based on the increasing COVID-19 cases and sequencing data, Wenselers also estimated that the number of people infected with Omicron in the same period is three to six times than Delta [9]. But, the severity of the clinical symptoms after the infection of Omicron is lighter than Delta, and the patient's hospitalization rate has also been reduced [13].

On December 9, 2021, two foreign passengers arrived in Tianjin, China, and were subsequently determined to be asymptomatic infections through nucleic acid testing. This is the first time that the Omicron strain has been detected in China [14]. With the spread of the Omicron in various provinces and cities, China's epidemic prevention and measures are facing unprecedented challenges. As a large city with a population of nearly 30 million people [15], Shanghai, China, has received widespread attention when the epidemic broke out. During this period, Shanghai adhered to its dynamic zero-COVID policy [16] and strategies to tackle both imported and domestic infections [17]. Besides, Shanghai has also adopted a series of non-pharmaceutical interventions (NPI) to curb the spread of the epidemic, including vaccination, the construction of Fangcang shelter hospitals and quarantine of asymptomatic infections and mild patients [18,19]. As a city with a population of ten of million, Shanghai has a high population density. Compared with the outbreak in Wuhan, China, the population of Shanghai is about 2.5 times that of Wuhan [20,21], it means that the spread of Omicron in Shanghai may be faster [10]. Meanwile, the Omicron strain will cause many asymptomatic infections and mild patients [22], if the asymptomatic infections and mild patients cannot be quarantined from the susceptible as soon as possible, the government will not be able to cut off the chain of transmission, which makes Shanghai even more difficult in epidemic prevention and control [23].

Since the global outbreak of Omicron, scholars around the world have done lots of research on parameter estimation, basic reproduction number, and forecasting trends. Among them, Cai et al. [24] reported that the cancellation of the dynamic zero-COVID policy would trigger a wave of infections in Omicron, causing about 1.55 million deaths. Schlickeiser et al. [25] predicted deaths in the UK, Switzerland and Germany using the SIR epidemic compartment model. Muniyappan et al. [26] dealt with the mathematical modeling of the second wave of COVID-19 and verified the current Omicron variant pandemic data in India. Based on the calculation of the $\mathcal{R}_0$ of Omicron in South Africa, Khan et al. [27] used PRCC to conduct a global sensitivity analysis. Li et al. [28] conducted a modeling study on the Wuhan area based on the beds of the Fangcang shelter hospital, and obtained that the increase of beds in Fangcang shelter hospitals is conducive to curbing the spread of the COVID-19 in Wuhan. However, there are still little work to investigate and analyze the epidemic of Shanghai from the Fangcang shelter hospitals, so in this paper we will discuss from the two aspects of the National Convention and Exhibition Center (NECC) Fangcang shelter hospital (Shanghai) and permanent Fangcang shelter hospital.

In this paper, we carry out a modeling study on the dynamics of COVID-19 in Shanghai epidemic taking into account vaccine coverage rate, the number of beds in Fangcang shelter hospitals, and the number of beds in designated hospitals. Then, we perform parameter estimation and calculate the basic reproduction number ($\mathcal{R}_0$) from February 24, 2022 to June 15, 2022 in Shanghai. In addition, we conduct a sensitivity analysis on the basic reproduction number to obtain sensitivity of parameters to $\mathcal{R}_0$, so as to reduce $\mathcal{R}_0$ by controlling the parameters to control the disease. Finally, we will show more details from the Fangcang shelter hospitals.

2. Method

2.1. Data

We collected data on reported COVID-19 human cases from February 24, 2022 to June 15, 2022, including cumulative cases, new daily cases, referral cases, recovered cases and deaths from the Shanghai Municipal Health Commission and the National Health Commission of the People's Republic of China [29,30]. Fig. 2 shows the number of asymptomatic infections under medical observation in Shanghai from February 24 to May 28. It was on an upward trend from the end of February to mid-April. At the peak, there were more than 255,000 cases of asymptomatic infections. At this time, the demand for Fangcang shelter hospital beds also reached the maximum. Subsequently, the number of existing asymptomatic infections gradually decreased, and began to slowly approach zero at the end of May.

In addition, we obtained the bed data of Fangcang shelter hospitals on April 5th, April 8th, April 9th, April 30th and May 6th and collected the bed data of designated hospitals on April 9th, April 30th and May 6th from the Shanghai Municipal Health Commission [31–35]. Because Shanghai is in the early stage of the epidemic on February 24, 2022, we assumed that on February 24, 2022, the number of beds in Fangcang shelter hospitals and the number of beds in designated hospitals are both 0. Due to the lack of bed data, we used Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) [36] to describe the change of the number of beds, which can make the change curve of bed data smoother and more realistic. The interpolation results of the number of beds are shown in Figs. 3,4 below and we marked the segmented time nodes in Fig. 3.

Fig. 3 shows that the number of beds in the Fangcang shelter hospital was relatively sufficient between the end of February and the end of March. The situation of Fangcang beds was relatively tight at the beginning of April, and then will remain tightly balanced (the number of Fangcang beds is close to the number of asymptomatic infections) between April 9 and April 17 [34]. Finally the number of beds was very sufficient by the end of April. From Fig. 4, we can see that the situation of beds in designated hospitals was relatively tight from mid-April to the end of April, and the number of beds in the rest of the period was far more than the number of inpatients, which means there will be no shortage of beds in designated hospitals.

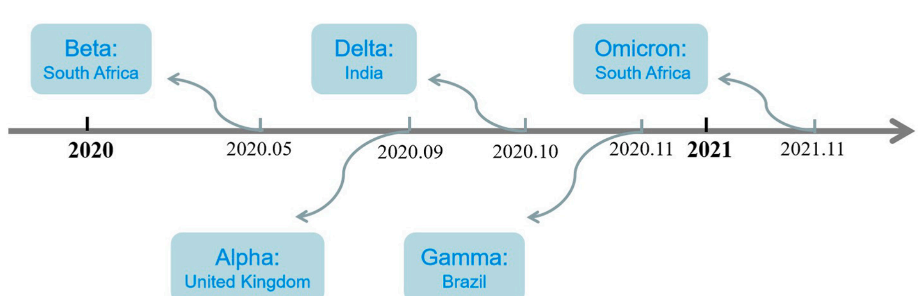

Fig. 1. COVID-19 concern strain timeline.

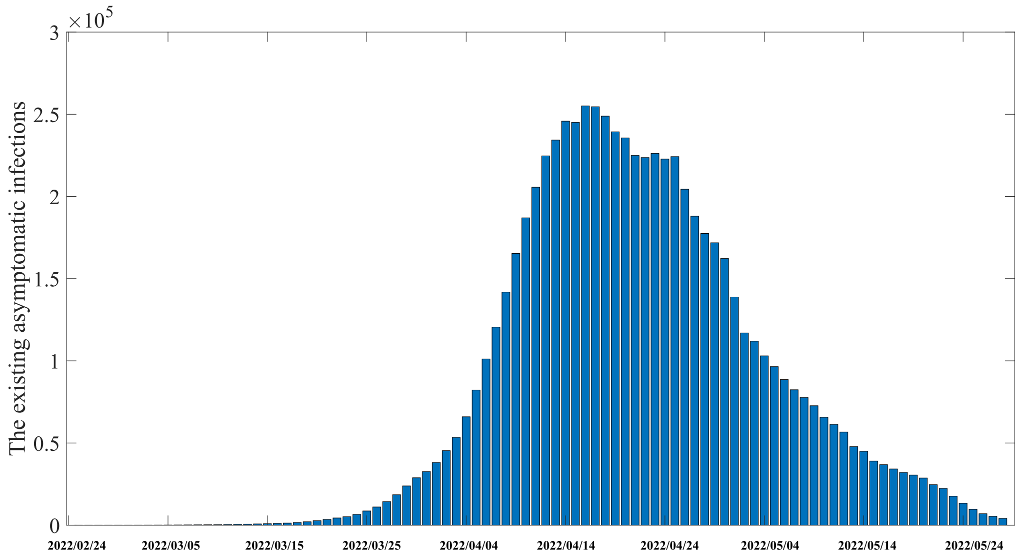

Fig. 2. Histogram of changes in existing asymptomatic infections.

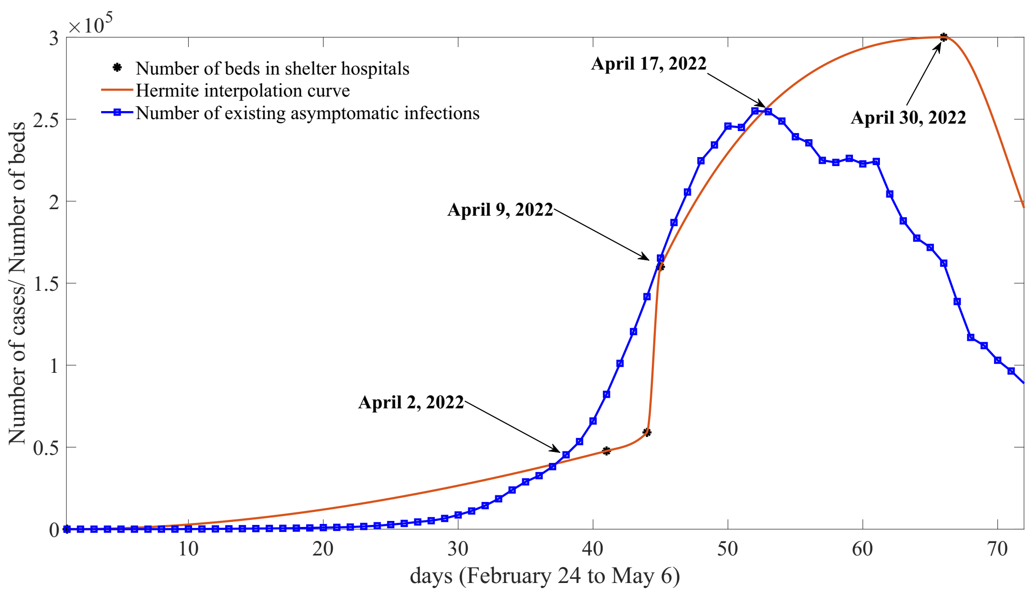

Fig. 3. Comparison of the number of beds in Fangcang shelter hospitals and existing asymptomatic infections.

2.2. Model

In this section, in order to better describe the actual situation of the spread of COVID-19 in Shanghai, we make the following assumptions:

1. Due to the short study period, the natural birth rate and natural death rate of the Shanghai population from February 24 to June 15, 2022 are ignored.
2. Assuming that patients with COVID-19 are not infectious and cannot be detected by nucleic acid testing during the latent period, in other words, susceptible contact with exposed will not cause the susceptible to infect COVID-19.
3. The model in this paper takes into account the vaccinated and unvaccinated susceptible (S), and accordingly considers two different transmission rates and two different infected populations. Among them, β_1 represents the transmission rate of susceptible who have been vaccinated against COVID-19 ($S\rho$), and β_2 represents the transmission rate of susceptible who have been not vaccinated against COVID-19 ($S(1-\rho)$). In addition, only healthcare workers will be exposed to H_1 and H_2. And we assume that healthcare workers are all vaccinated, so the unvaccinated susceptible people will not contact with H_1 and H_2 and get the COVID-19.
4. Due to limited medical resources, we assume that the time from a patient's nucleic acid test positive to isolation is constantly changing. When medical resources are sufficient, the patient transit time will be shortened.
5. When the number of hospital beds is insufficient (i.e., the number of beds is less than the number of cases), some patients cannot be transferred to the hospital for isolation, and we assume that these patients are in a state of home quarantine.
6. We assume that people in E have to pass the latent period ($1/\xi$) first, and then wait for a nucleic acid test time ($1/\sigma$) before they flow into A or I, so the transfer rate of E is $1/(1/\xi+1/\sigma)=\frac{\xi\sigma}{\xi+\sigma}$.

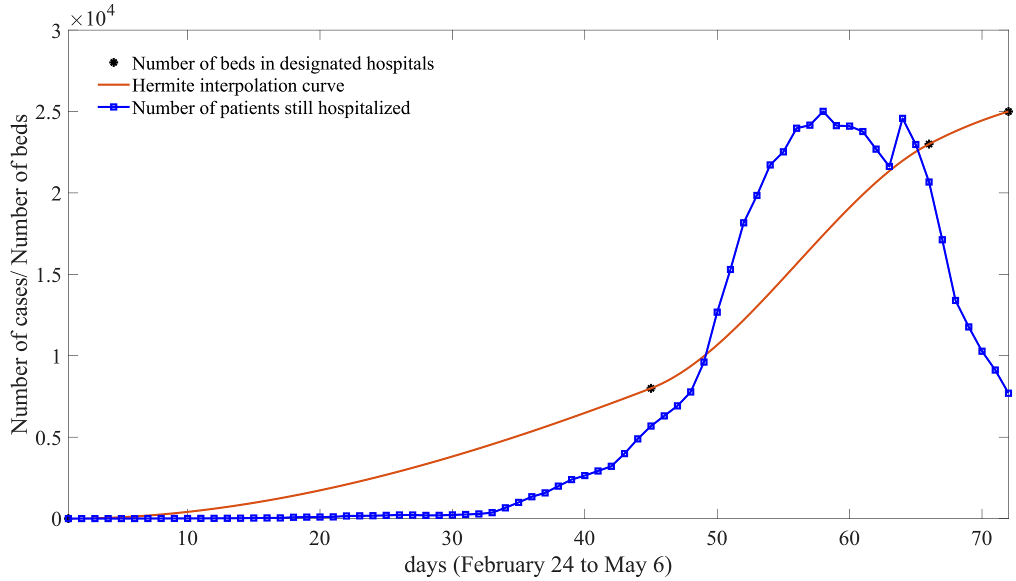

Fig. 4. Comparison of the number of beds in designated hospitals and the number of still hospitalized cases.

7. We don't take into account the differences in transmission to others between vaccinated patients and unvaccinated patients.
8. We ignore the different susceptibility of different ages, and do not consider the probability of symptoms, the probability of needing medical attention and the ability of self-healing for people of different ages after infection [37].

Based on the above assumptions, we propose a deterministic compartmental model based on vaccine coverage, the number of Fangcang shelter hospital beds, and the number of designated hospital beds (the flowchart is shown in Fig. 2.2). We divided the individuals into seven epidemiological subgroups, including susceptible (S), exposed (E), asymptomatic infections (A, H_1), symptomatic cases (I, H_2) and recovered (R). In particular, H_1 represents inpatients in Fangcang shelter hospitals; H_2 represents inpatients in designated hospitals, see Table 1 for details.

Fig. 5 shows the whole process of infection of susceptible individuals (S). Firstly, the susceptible S contacts the corresponding infected person to become exposed E, and secondly, when E passes the latent period, two situations will occur. When the patient has symptoms, it will flow into I, and then go to the designated hospital for treatment; when the patient has no symptoms, it will flow into A, and then enter the Fangcang shelter hospital for isolation and treatment. Eventually, the patient who recovers or dies will be removed.

Table 1
The definition of each compartment in the model.

Variables	Description (at initial moment t_0)	Value	Source
$S(t_0)$	Susceptible population	24,890,000	[15]
$E(t_0)$	Infected, asymptomatic, undetectable (latent period)	64	Estimated
$A(t_0)$	Asymptomatic infections who are not isolated	1	[29]
$I(t_0)$	Non-hospitalized confirmed cases	0	[29]
$H_1(t_0)$	Asymptomatic infections who are isolated in Fangcang shelter hospitals	4	[29]
$H_2(t_0)$	Confirmed cases who are isolated in designated hospitals	0	[29]
$R(t_0)$	Number of population who removed from infection	0	[29]
$H(t_0)$	Number of cumulative confirmed cases	0	[29]
$AH(t_0)$	Number of cumulative asymptomatic infections	1	[29]

The meaning of each parameter in equations is shown in Table 2 and the dynamical model is governed by the following system of differential equations:

$$\begin{cases} \dfrac{dS}{dt} = -\dfrac{S\rho\beta_1(A+qI+k(H_1+H_2))}{N} - \dfrac{S(1-\rho)\beta_2(A+qI)}{N}, \\ \dfrac{dE}{dt} = \dfrac{S\rho\beta_1(A+qI+k(H_1+H_2))}{N} + \dfrac{S(1-\rho)\beta_2(A+qI)}{N} - \dfrac{\xi\sigma}{\xi+\sigma}E, \\ \dfrac{dA}{dt} = \dfrac{\xi\sigma}{\xi+\sigma}\eta E - (\delta+\lambda+\omega)A, \\ \dfrac{dI}{dt} = \dfrac{\xi\sigma}{\xi+\sigma}(1-\eta)E + \omega A - (\gamma+\mu)I, \\ \dfrac{dH_1}{dt} = \delta A + \mu\theta I - (\alpha_1+\omega)H_1, \\ \dfrac{dH_2}{dt} = \omega H_1 + \gamma I - (\alpha_2+d)H_2, \\ \dfrac{dR}{dt} = \lambda A + \mu(1-\theta)I + \alpha_1 H_1 + \alpha_2 H_2, \\ \dfrac{dH}{dt} = \dfrac{\xi\sigma}{\xi+\sigma}(1-\eta)E + \omega A, \\ \dfrac{dAH}{dt} = \dfrac{\xi\sigma}{\xi+\sigma}\eta E. \end{cases}$$

2.3. The basic reproduction number

The basic reproduction number ($\mathcal{R}_0$) is the expected number of secondary cases from an infected individual in a fully susceptible population [39]. In other words, $\mathcal{R}_0$ refers to the number of susceptible people that a infected person can infect during the infection period. For non-threshold systems, we use $\mathcal{R}_0 = 1$ as the threshold to judge whether the disease disappear or persist [40]. When $\mathcal{R}_0 > 1$, the disease will not be well controlled and develop into an endemic disease; when $\mathcal{R}_0 < 1$, The disease will be controlled and gradually disappear [41].

From Driessche and Watmough [42], we can calculate the basic reproduction number as follows:

$$\mathcal{R}_0 = R_1 + R_2,$$
$$R_1 = R_{11} + R_{12} + R_{13} + R_{14} + R_{15},$$
$$R_2 = R_{21} + R_{22},$$

where

$$R_{11} = \frac{\beta_1 \eta \rho}{\delta + \lambda + \omega},$$
$$R_{12} = \frac{q\rho\beta_1(1-\rho)(\delta+\lambda+\omega-\delta\eta-\eta\lambda)}{(\gamma+\mu)(\delta+\lambda+\omega)},$$
$$R_{13} = \frac{\beta_1 k\rho(\delta\eta\gamma+\delta\eta\mu+\delta\mu\theta+\lambda\mu\theta+\mu\omega\theta-\delta\eta\mu\theta-\eta\lambda\mu\theta)}{(\alpha_1+\omega)(\gamma+\mu)(\delta+\lambda+\omega)},$$
$$R_{14} = \frac{\beta_1 k\rho\left(\gamma\omega^2+\mu\omega^2\theta+\alpha_1\delta\gamma+\alpha_1\gamma\lambda+\alpha_1\gamma\omega+\delta\gamma\omega+\gamma\lambda\omega+\delta\eta\mu\omega+\delta\mu\omega\theta+\lambda\mu\sigma\theta\right)}{(\alpha_1+d)(\alpha_1+\omega)(\gamma+\mu)(\delta+\lambda+\omega)},$$
$$R_{15} = \frac{-\beta_1 k\rho(\eta\gamma\lambda\omega+\alpha_1\delta\eta\gamma+\alpha_1\eta\gamma\lambda+\delta\eta\gamma\lambda+\delta\eta\mu\omega\theta+\eta\lambda\mu\sigma\theta)}{(\alpha_1+d)(\alpha_1+\omega)(\gamma+\mu)(\delta+\lambda+\omega)},$$
$$R_{21} = \frac{\beta_2\eta(1-\rho)}{\delta+\lambda+\omega},$$
$$R_{22} = \frac{q\beta_2(1-\rho)(\delta+\lambda+\omega-\delta\eta-\eta\lambda)}{(\gamma+\mu)(\delta+\lambda+\omega)}.$$

Among them, R_1 is the contribution of the population vaccinated with the COVID-19 to $\mathcal{R}_0$, R_2 stands for the contribution of the population not vaccinated against the COVID-19 vaccine to $\mathcal{R}_0$.

2.4. Parameter estimation

In this section, the model takes into account the relevant epidemic prevention policies and medical resources of Shanghai. From February 24, 2022 to June 15, 2022, Shanghai has different policies, measures and medical capacity in different periods. Therefore, we consider piecewise fitting for the above situation. In addition, we use the Nelder-Mead Simplex Direct Search Algorithm [43] and chi-square values [44] to estimate the model parameters, which are implemented by using fminsearch function in MATLAB (the Mathworks, Inc.). The fminsearch function uses the Nelder–Mead algorithm to compute the minimum of an unconstrained multivariate function using a derivative-free method. We use the built-in fminsearch function to continuously iteratively solve the optimal value of chi-square, so as to further obtain the fitting value of each parameter.

The formula for the chi-square value is as follows:

$$J = \sum_{i=1}^{112}\frac{\left(AH(t_i)-A\widehat{H}(t_i)\right)^2}{A\widehat{H}(t_i)} + \sum_{i=1}^{112}\frac{\left(H(t_i)-\widehat{H}(t_i)\right)^2}{\widehat{H}(t_i)} + \sum_{i=1}^{112}\frac{\left(H_2(t_i)-\widehat{H}_2(t_i)\right)^2}{\widehat{H}_2(t_i)}$$

$AH(t_i)$ stands for the daily cumulative asymptomatic infections, and $A\widehat{H}(t_i)$ stands for the corresponding fitted value of asymptomatic infections; $H(t_i)$ stands for the daily cumulative number of confirmed cases, and $\widehat{H}(t_i)$ stands for the corresponding fitted value of confirmed cases; $H_2(t_i)$ represents the daily number of hospitalized confirmed cases, and $\widehat{H}_2(t_i)$ represents the corresponding fitted value of hospitalized confirmed cases.

We divide the period from February 24, 2022 to June 15, 2022 into five stages for parameter estimation. The detailed description of each segment is as follows:

I. **February 24, 2022 to April 2, 2022: Before the bed situation in the Fangcang shelter hospital is tight.**

From February 24, 2022 to April 2, 2022, this was the early stage of the outbreak in Shanghai. The number of beds in Shanghai Fangcang shelter hospitals was relatively sufficient, and nucleic acid testing and antigen testing were not carried out in the city, but only in key areas of the city [45].

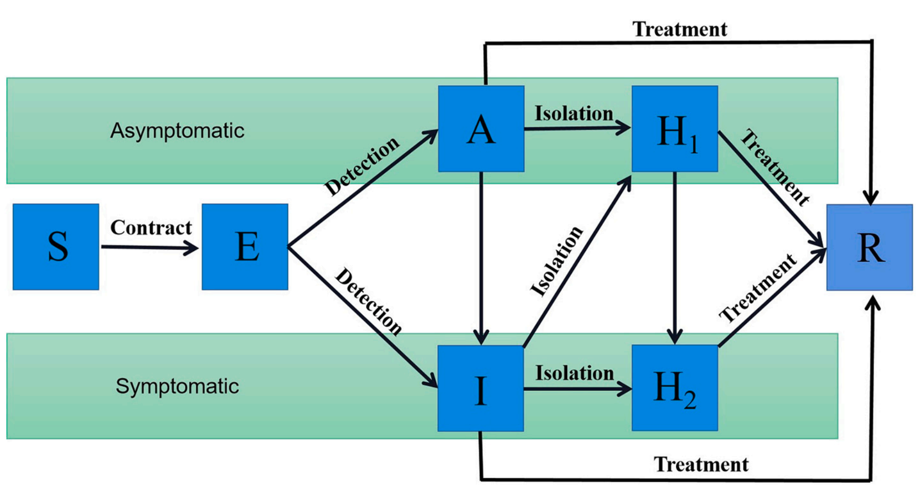

Fig. 5. The deterministic compartment model flowchart.

Table 2
The interpretation and fitting values of the parameters in the model.

Variables	Description	Value	Source
ρ	The COVID-19 vaccine coverage rate of Shanghai	0.9091	[38]
$/\sigma$	Average duration of COVID-19 latent period	1.52	[24]
d	The mortality rate of confirmed cases	2.3142×10^{-5}	Calculated
ξ_1	The rate of nucleic acid detection (stage 3,4,5)	0.6	Fixed
ξ_2	The rate of nucleic acid detection (stage 2)	1	Fixed
λ	The self-healing rate of asymptomatic infections	0.1	Fixed
ξ_3	The rate of nucleic acid detection (stage 1)	0.4428	Estimated
α_1	The recovery rate of asymptomatic infections	0.1651	Estimated
α_{2a}	Recovery rate of confirmed cases (stage 1,2,3,4)	0.0946	Estimated
α_{2b}	Recovery rate of confirmed cases (stage 5)	0.1292	Estimated
ω	The rate of asymptomatic infections turned into confirmed cases	0.0039	Estimated
β_{1a}	Transmission rate of vaccinated susceptible individuals (stage 1)	1.8137	Estimated
β_{1b}	Transmission rate of vaccinated susceptible individuals (stage 2)	0.9500	Estimated
β_{1c}	Transmission rate of vaccinated susceptible individuals (stage 3)	0.7542	Estimated
β_{1d}	Transmission rate of vaccinated susceptible individuals (stage 4)	0.5829	Estimated
β_{1e}	Transmission rate of vaccinated susceptible individuals (stage 5)	0.4713	Estimated
β_{2a}	Transmission rate of unvaccinated susceptible individuals (stage 1,2)	2.9502	Estimated
β_{2b}	Transmission rate of unvaccinated susceptible individuals (stage 3,4,5)	0.8514	Estimated
k	Infectivity reduction factor	4.0013×10^{-5}	Estimated
q	Infectivity reduction factor	0.0367	Estimated
η	The proportion of asymptomatic infections	0.9159	Estimated
δ_1	The hospitalization rate of asymptomatic infections (stage 1,4,5)	0.8312	Estimated
δ_2	The hospitalization rate of asymptomatic infections (stage 2)	0.1810	Estimated
δ_3	The hospitalization rate of asymptomatic infections (stage 3)	0.6636	Estimated
θ	The proportion of the infectious	0.8187	Estimated
γ_1	The hospitalization rate of confirmed case (stage 1,2,3,5)	0.8621	Estimated
γ_2	The hospitalization rate of confirmed case (stage 4)	0.7485	Estimated
μ	The transfer rate of comfirmed cases	0.0072	Estimated

II. **April 2, 2022 to April 9, 2022: The situation of beds in Shanghai Fangcang shelter hospitals is relatively tight.**

From April 2, 2022 to April 9, 2022, the number of beds in Shanghai Fangcang shelter hospitals is less than the number of existing asymptomatic infections, and the transit time for asymptomatic infections will be prolonged. In addition, Shanghai also started city-wide antigen testing on April 3 [46], city-wide nucleic acid testing on April 4 [47], and continued antigen testing or nucleic acid testing on April 6 and April 8 [48,49], so the screening rate of COVID-19 cases will increase dramatically.

III. **April 9, 2022 to April 17, 2022: The bed situation of Shanghai Fangcang shelter hospital has improved compared to before, and it is in a state of tight balance.**

During this period, the number of beds in Fangcang shelter hospitals was very close to the number of asymptomatic infections, and the transit time of asymptomatic infections was relatively relieved compared with the previous period (April 2, 2022 to April 9, 2022).

IV. **April 17, 2022 to April 30, 2022: The situation of beds in designated hospitals is relatively tight.**

The number of beds in designated hospitals will be less than the number of existing confirmed cases, and the transit time for confirmed cases will be longer than the other four stages. Besides, with the introduction of zoning and differentiated management [50], the transmission rate will be reduced.

V. **April 30, 2022 to June 15, 2022: The number of beds in Fangcang shelter and designated hospitals are both sufficient.**

In the last stage, the number of beds in Fangcang shelter hospitals and designated hospitals are both far more than the number of existing cases. With Shanghai's zero community transmission policy on May 16 [51], the transmission rate will be further reduced, and the transfer time of COVID-19 cases will be greatly shortened. Besides, under the condition that the hospital beds are sufficient, the relevant policies issued by Shanghai to improve the treatment rate [52] have also greatly accelerated the recovery rate of confirmed cases in the diagnosed hospital.

In the process of parameter estimation, on the basis of considering the number of beds and related policies and measures, we fitted three sets of data of cumulative confirmed cases, cumulative asymptomatic infections and real-time hospitalized confirmed cases at the same time. The fitting results of the model are shown in Fig. 6. It can be seen from the figure that the fitting results and the actual results are well fitted, but there is still a certain deviation between the curve and actual value in the middle part. On the one hand, we fit three sets of data at the same time, and it is difficult to make a set of parameter values perfectly fit the three sets of data; on the other hand, because the number of hospital beds is too discrete, there will be unavoidable errors in segmental fitting by using the bed number curve obtained by interpolation.

3. Main results

3.1. Estimated results and $\mathcal{R}_0$

A total of 28 parameters and 9 compartmental initial values were considered in the model due to piecewise fitting. Among them, 22 parameters and 1 compartmental initial values need to be estimated, and the rest of the parameters and the initial value of the compartmental can be obtained through the announcement issued by the Shanghai Municipal Health Commission and calculations.

In detail, Table 1 shows that the initial values of $S(t_0)$, $A(t_0)$, $I(t_0)$, $H_1(t_0)$, $H_2(t_0)$, $R(t_0)$ and $AH(t_0)$ can be obtained from Shanghai Municipal Health Commission [29], only $E(t_0)$ need to be estimated. Besides, among the 6 fixed parameters, we fixed the vaccine coverage in Shanghai (ρ) by referring to the results of Wu et al. [38]. The latent period of the Omicron ($1/\sigma$) is 1.52 days [24]. Then, by calculation, we can get the mortality rate of confirmed cases (d). We also assumed the nucleic acid detection time ($1/\xi_1$,$1/\xi_2$) and the self-healing time of asymptomatic infections ($1/\lambda$) and fixed them. Table 1 and Table 2 shows the details of all parameters and compartmental initial values.

Then, we calculate the results of $\mathcal{R}_0$ at the five stages. Before the situation of beds in the Fangcang shelter hospital is tight in Shanghai (February 24, 2022 to April 2, 2022), $\mathcal{R}_0 = 1.8851$; when the situation of beds in Shanghai Fangcang shelter hospitals is relatively tight (April 2, 2022 to April 9, 2022), $\mathcal{R}_0 = 3.6429$; $\mathcal{R}_0 = 0.9135$ between April 9, 2022 and April 17, 2022 in the third stage; $\mathcal{R}_0 = 0.5975$ in the fourth stage (April 17, 2022 to April 30, 2022) and $\mathcal{R}_0 = 0.4974$ in the fifth stage (April 30, 2022 to June 15, 2022). It can be clearly seen from Table 3 that the basic reproduction numbers of these five stages show a trend of first increasing and then decreasing. Because of the shortage of beds, some patients cannot be hospitalized for isolation in time, which will

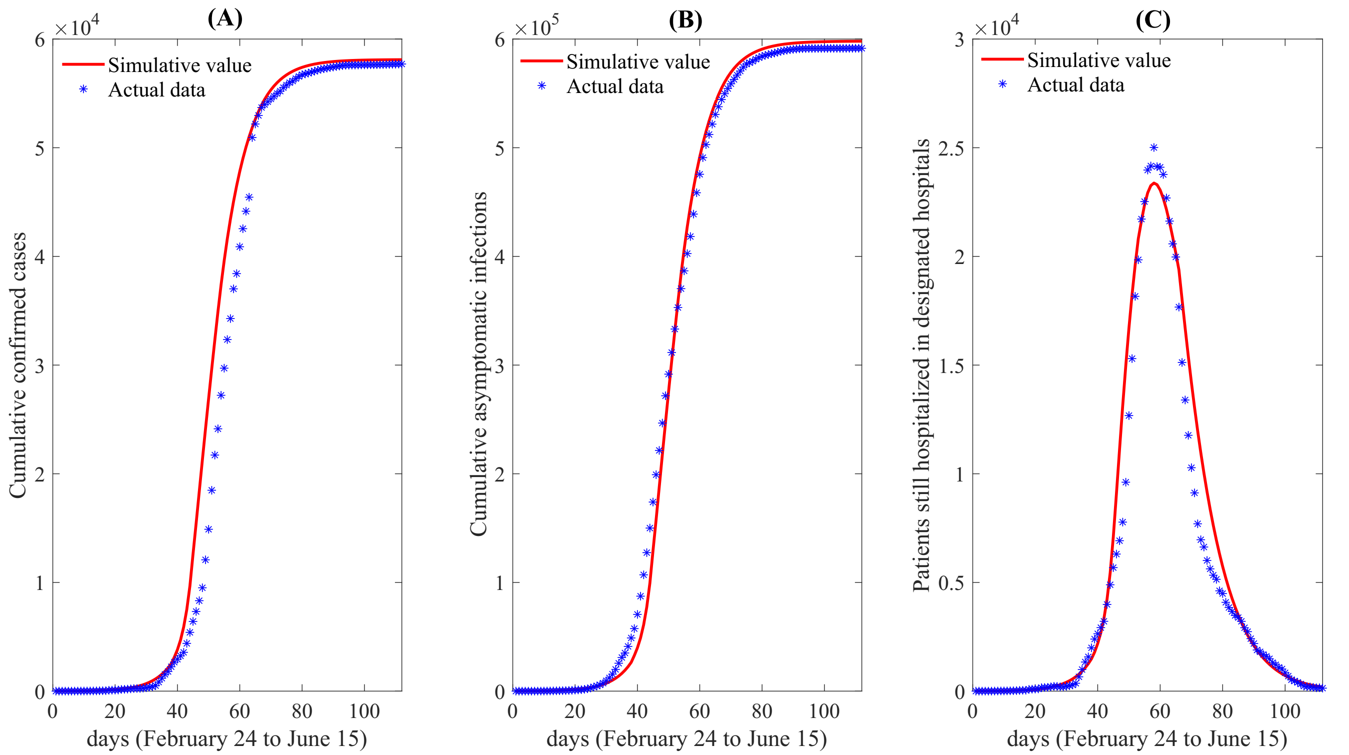

Fig. 6. The fitting chart of model and actual data. (A) Fitting results of cumulative confirmed cases. **(B)** Fitting results of cumulative asymptomatic infections. **(C)** Fitting results of real-time hospitalized confirmed cases.

lead to cross infection and further increase $\mathcal{R}_0$. However, with the increase of hospital beds and the implementation of various epidemic prevention measures, the value of $\mathcal{R}_0$ continued to decline, and finally less than 1.

3.2. Sensitivity analysis of $\mathcal{R}_0$

Sensitivity analysis is used to determine the sensitivity of predictor parameters to input parameters [53]. Therefore, sensitivity analysis on $\mathcal{R}_0$ allows us to know which parameters have a greater impact on the epidemic, and then we can take measures to control the high sensitive parameters to reduce the basic reproduction numbers, so as to control the spread of infectious diseases.

There are generally two approaches for sensitivity analysis, one is based on the fixed point estimation of model parameters [54] and the other is based on the uncertainty in the estimation of model parameters [55]. Here we refer to the practice in the article of Chitnis et al. [54], and select the method of perturbation of fixed point estimations. Because the case data in the fifth stage is more and more stable, so the parameter values obtained by fitting in this stage (the fifth stage, i.e., April 30, 2022 to June 15, 2022) were selected to conduct sensitivity analysis on $\mathcal{R}_0$. If a small perturbation of the parameter can make a large change in $\mathcal{R}_0$, then this parameter is very sensitive; otherwise, the parameter is considered to be insensitive. Table 4 shows the sensitivity index of each parameter to $\mathcal{R}_0$.

Table 3
The value of $\mathcal{R}_0$ at different stages.

Stages	Time	The value of $\mathcal{R}_0$
The first stage	February 24, 2022 to April 2, 2022	1.8851
The second stage	April 2, 2022 to April 9, 2022	3.6429
The third stage	April 9, 2022 to April 17, 2022	0.9135
The fourth stage	April 17, 2022 to April 30, 2022	0.5975
The fifth stage	April 30, 2022 to June 15, 2022	0.4974

From Table 4, parameters η, β_{1d}, β_{2b}, q, k and θ have a positive effect on $\mathcal{R}_0$; δ_1, ω, γ, α_1, μ and α_{2b} have a negative effect on $\mathcal{R}_0$. Among them, the three parameters η, β_{1d} and δ_1 are very sensitive to $\mathcal{R}_0$, so lower proportion of the infectious (η), lower transmission rate (β_{1d}) and higher hospitalization rate of asymptomatic infections (δ_1) can effectively reduce the $\mathcal{R}_0$.

Next, we conduct a sensitivity analysis on the second stage according to the above method, and study what value of the parameters can curb the epidemic by adjusting the changes of some parameter values. From the sensitivity analysis, we obtained three parameters that are more sensitive to the second stage, including β_{1b}, η, and δ_2; excluding the scale coefficient η, we choose δ_2 and β_{1b} to analyze it. The analysis results are shown in Fig. 7, when $\delta_2 > 0.9373$ or $\beta_{1b} < 0.0467$, $\mathcal{R}_0$ is smaller than 1. Therefore, increasing the hospitalization rate of asymptomatic infections δ_2 and decreasing the transmission rate β_{1b} are more effective in controlling the disease when it begins to spread.

Table 4
Sensitivity index of different parameters to $\mathcal{R}_0$.

The parameter	Sensitivity index to $\mathcal{R}_0$	The corresponding percentage change (%)
η	0.9568	-1.0451
β_{1d}	0.8470	-1.1806
β_{2b}	0.1530	-6.5375
q	0.0038	-2.6493×10^2
k	0.0002	-5.1452×10^3
θ	1.25217×10^3	-7.9867×10^6
δ_1	-0.8855	1.1293
ω	-0.0040	2.5066×10^2
γ	-0.0037	2.6715×10^2
α_1	-1.6716×10^{-4}	5.9823×10^3
μ	-3.1331×10^{-5}	3.1917×10^4
α_{2b}	-2.8255×10^{-5}	3.5392×10^4

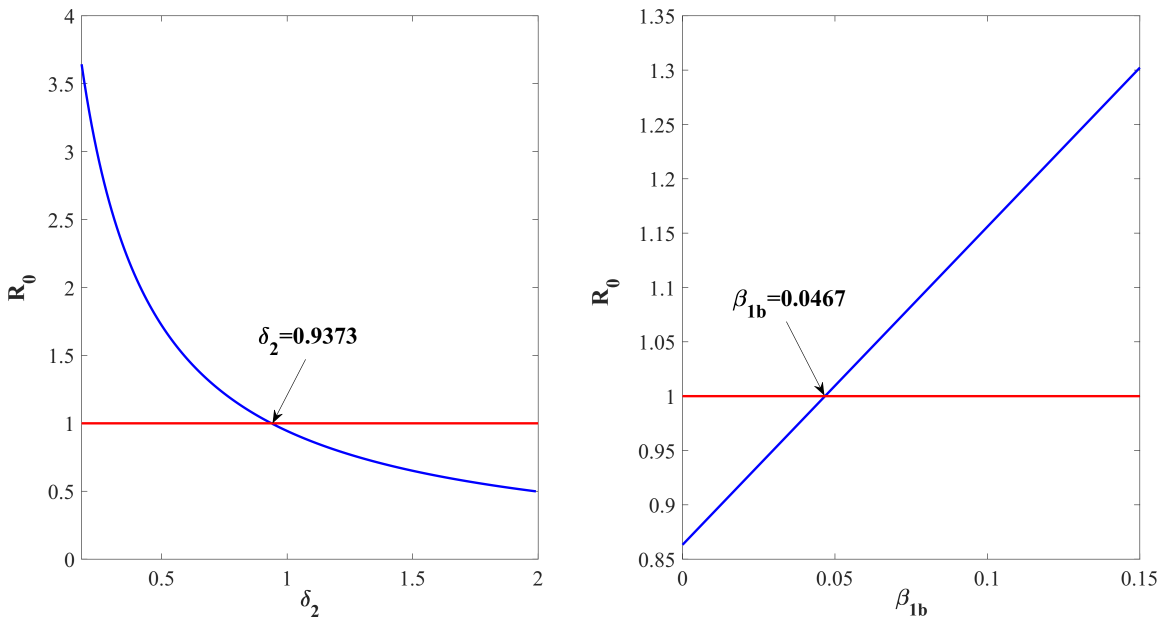

Fig. 7. The variation of $\mathcal{R}_0$ with respect to the hospitalization rate of asymptomatic infections δ_2 and transmission rate β_{1b}.

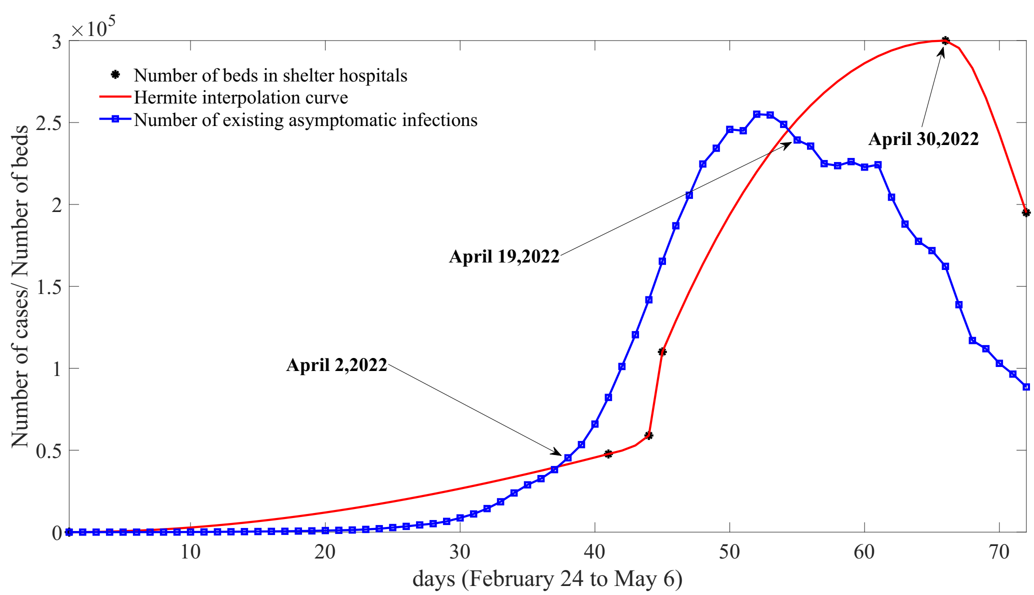

Fig. 8. Fangcang shelter hospital beds interpolation curve (if not reconstruction the NECC).

3.3. The impact of the NECC Fangcang shelter hospital

In this section, we will discuss how much Shanghai's measure of converting the NECC into a Fangcang shelter hospital has played a role in curbing the spread of the epidemic, so we assume that Shanghai will not put the NECC into use during this epidemic. Because the NECC Fangcang shelter hospital provided 50,000 beds [33] for asymptomatic infections to use, we change the bed data on April 9, 2022 from the original 160,000 to 110,000. We still use PCHIP to deal the number of beds, the interpolation result is shown in Fig. 8.

Fig. 8 shows that the situation of beds in Fangcang shelter hospitals is relatively tight from April 2, 2022 to April 19, 2022 and there will be no tight balance of beds under this simulation. Therefore, we divided the period from February 24, 2022 to June 15, 2022 into four stages for simulation, the first stage: February 24, 2022 to April 2, 2022; the second stage: April 2, 2022 to April 19, 2022; the third stage: April 19, 2022 to April 30, 2022; the fourth stage: April 30, 2022 to June 15, 2022. The new segment node has been marked in Fig. 8. so we select the parameter δ_2 to describe the hospitalization rate of asymptomatic infections in the second stage, and we select the parameter δ_1 in the rest of stages. Therefore, on the basis of re-segmenting the time, we use the parameter values obtained by parameter estimation to estimate the values of cumulative confirmed cases and cumulative asymptomatic infections.

From Fig. 9, if there were no 50,000 beds provided by the NECC, the cumulative confirmed cases would reach 575,438, which is 9.97 times than the actual cumulative confirmed cases; the cumulative asymptomatic infections would reach 5.88 million, which is 9.95 times than the actual cumulative asymptomatic infections. Therefore, the measure of converting the NECC into a temporary Fangcang shelter hospital has largely curbed the spread of the epidemic in Shanghai and cut off the transmission chain of the Omicron.

Besides, we discuss the importance of the NECC from another

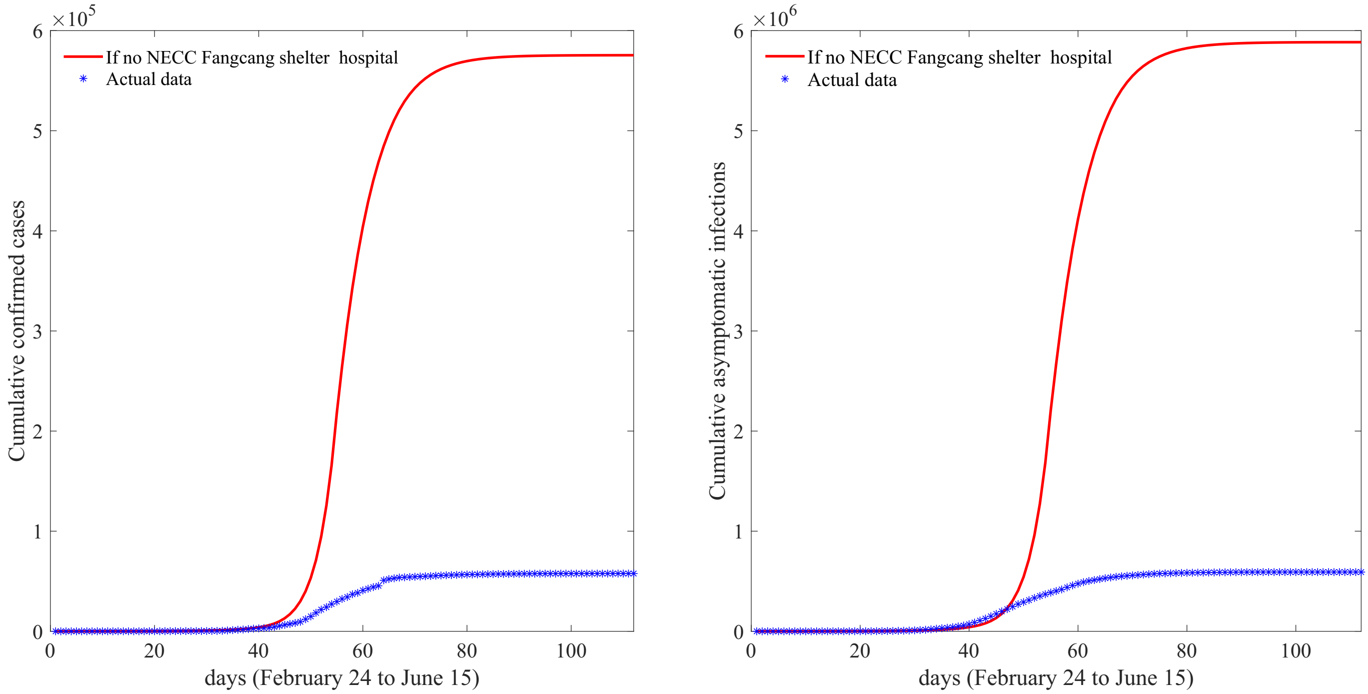

Fig. 9. The comparison chart of patients under no NECC Fangcang shelter hospital.

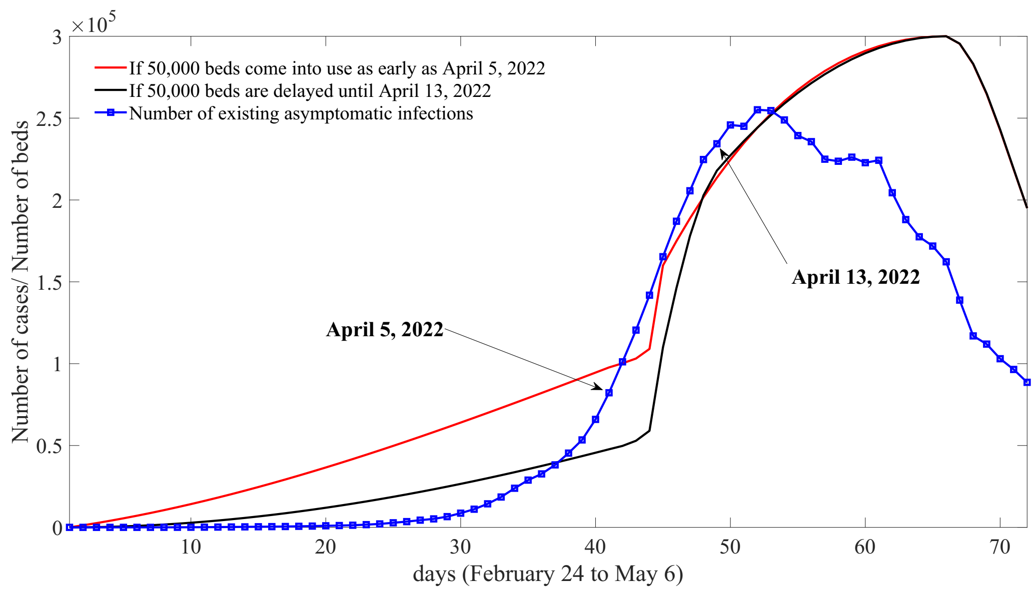

Fig. 10. Fangcang shelter hospital beds interpolation curve (if the reconstruction time of NECC is advanced or delayed).

perspective. On April 9, 2022, Shanghai was at a time when the epidemic was more serious. The construction of the temporary shelter of the NECC greatly curbed the spread of the epidemic. Next, we discuss the construction time of the temporary shelter that provides 50,000 beds. From Fig. 10, we can see that if the temporary shelter is put into use on April 5, 2022, there will only be a slight shortage of shelter beds in Shanghai from April 6, 2022 to April 17, 2022 (Tight balance); If the temporary shelter is delayed until April 13, 2022, the shortage of shelter beds will continue from April 2, 2022 to April 17, 2022. Among them, there is a severe shortage of beds before April 13, 2022, and a slight shortage of beds after April 13, 2022. For the detailed segmentation time and parameter selection in the above two cases, see Table 5.

The simulation results of the above two cases are shown in Fig. 11. We can obtain that if the temporary shelter with 50,000 beds is built on April 5, 2022, the final cumulative asymptomatic infections will be controlled at about 140,000, and the cumulative confirmed cases will not exceed 13,600. On the contrary, if the temporary shelter is built on April 13, 2022, the final cumulative asymptomatic infections will exceed 1,620,000, and the cumulative confirmed cases will exceed 158,000.

3.4. The impact of permanent Fangcang shelter hospitals

In the event of a new highly contagious strain or an emerging infectious disease, permanent Fangcang shelter hospitals can effectively and quickly isolate patients. Otherwise, it will easily lead to a shortage of medical resources such as hospital beds. Therefore, building permanent

Table 5
Advance or delay the reconstruction time of NECC.

Reconstruction time	Corresponding time of different stages	Parameters
Advance	The first stage: February 24, 2022 to April 2, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1a}, β_{2a}, k, q, η, δ_1, λ, θ, γ_1, μ, ξ_3
	The second stage: April 2, 2022 to April 6, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1b}, β_{2a}, k, q, η, δ_1, λ, θ, γ_1, μ, ξ_2
	The third stage: April 6, 2022 to April 17, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1c}, β_{2b}, k, q, η, δ_3, λ, θ, γ_1, μ, ξ_1
	The fourth stage: April 17, 2022 to April 30, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1d}, β_{2b}, k, q, η, δ_1, λ, θ, γ_2, μ, ξ_1
	The fifth stage: April 30, 2022 to June 15, 2022	ρ, σ, α_1, α_{2b}, ω, d, β_{1e}, β_{2b}, k, q, η, δ_1, λ, θ, γ_1, μ, ξ_1
Reconstruction time	Corresponding time of different stages	Parameters
Delay	The first stage: February 24, 2022 to April 2, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1a}, β_{2a}, k, q, η, δ_1, λ, θ, γ_1, μ, ξ_3
	The second stage: April 2, 2022 to April 13, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1b}, β_{2a}, k, q, η, δ_2, λ, θ, γ_1, μ, ξ_2
	The third stage: April 13, 2022 to April 17, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1c}, β_{2b}, k, q, η, δ_3, λ, θ, γ_1, μ, ξ_1
	The fourth stage: April 17, 2022 to April 30, 2022	ρ, σ, α_1, α_{2a}, ω, d, β_{1d}, β_{2b}, k, q, η, δ_1, λ, θ, γ_2, μ, ξ_1
	The fifth stage: April 30, 2022 to June 15, 2022	ρ, σ, α_1, α_{2b}, ω, d, β_{1e}, β_{2b}, k, q, η, δ_1, λ, θ, γ_1, μ, ξ_1

Fangcang shelter hospitals in various cities in advance [56], and responding quickly when the epidemic breaks out, which will better curb the spread of the epidemic.

Firstly, we consider it in terms of segments and number of beds. Assuming that Shanghai has the permanent Fangcang shelter hospital in this epidemic, we will discuss the change of the cumulative cases in this epidemic under the conditions of 10,000, 30,000 and 50,000 beds respectively. We add these initial bed numbers to each of the original data points and use PCHIP to interpolate the bed data. Fig. 12 shows the interpolation curves under different beds. By comparing different curves, we find that the more permanent Fangcang shelter beds, the less the time of bed shortage during the epidemic. If there is a permanent Fangcang shelter hospital with 50,000 beds, the bed situation will be under strain only two days and there will be sufficient beds for the rest of the time.

In addition, we also simulate the cumulative confirmed cases and cumulative asymptomatic infections in permanent Fangcang shelter hospitals with different beds. Fig. 13 shows that the construction of permanent Fangcang shelter hospitals has played an important role in curbing epidemic. No matter how many beds are set up in permanent Fangcang shelter hospitals, the final estimated cases will be lower than the actual cases. If there is a 50,000-bed Fangcang shelter hospital in Shanghai ahead of schedule during this epidemic, the final cumulative confirmed cases will drop to 3.26×10^4, and the cumulative asymptomatic infections will drop to 3.37×10^5, both are close to the half of actual data.

Secondly, we do not consider re-segmenting the stages, but consider it from the perspective of parameters. we change the hospitalization rate of asymptomatic infections (δ) under the assumption that the number of Fangcang shelter beds is sufficient. So we assume that the hospitalization rate of asymptomatic infections from the beginning to the end of the epidemic (February 24, 2022 to June 15, 2022) is δ_1, the rest of the parameters remain unchanged. At this time, the change curve of the number of existing asymptomatic infections and cumulative asymptomatic infections are shown in Fig. 14.

It is shown that if there is no shortage of Fangcang shelter hospital beds during the pandemic, the peak of existing asymptomatic infections will be controlled at 33,565, so Shanghai only needs a permanent Fangcang shelter hospital with 33,565 beds to control the epidemic to a certain extent without bed shortage, and the cumulative asymptomatic infections will controlled within 142,000.

Finally, we discuss permanent Fangcang shelter hospitals in cities of different scales and also consider it from the perspective of parameters. On this basis, we modify the initial values of the susceptible compartment (S') and the exposed compartment (E') according to the ratio of S to E in Shanghai. We assume that the ratio of S' to E' in cities with different population sizes is equal to the ratio of S to E in Shanghai (we assume $u = S/E$). In addition, we also assume that all populations in different cities are susceptible (S'), so the initial number of exposed ($E' = S'/u$) of these cities can be obtained. The simulation results are shown in Table 6. From the table, for a city of 10 million people, a permanent Fangcang shelter hospital with 14,016 beds can control the epidemic to a certain extent without a shortage of beds, and the final cumulative asymptomatic infections will be controlled below 60,000.

4. Conclusion and discussion

As Omicron begins to spread in China, we need to show greater determination to contain the outbreak. The measures and decisions Shanghai has taken in response to the epidemic have provided a good

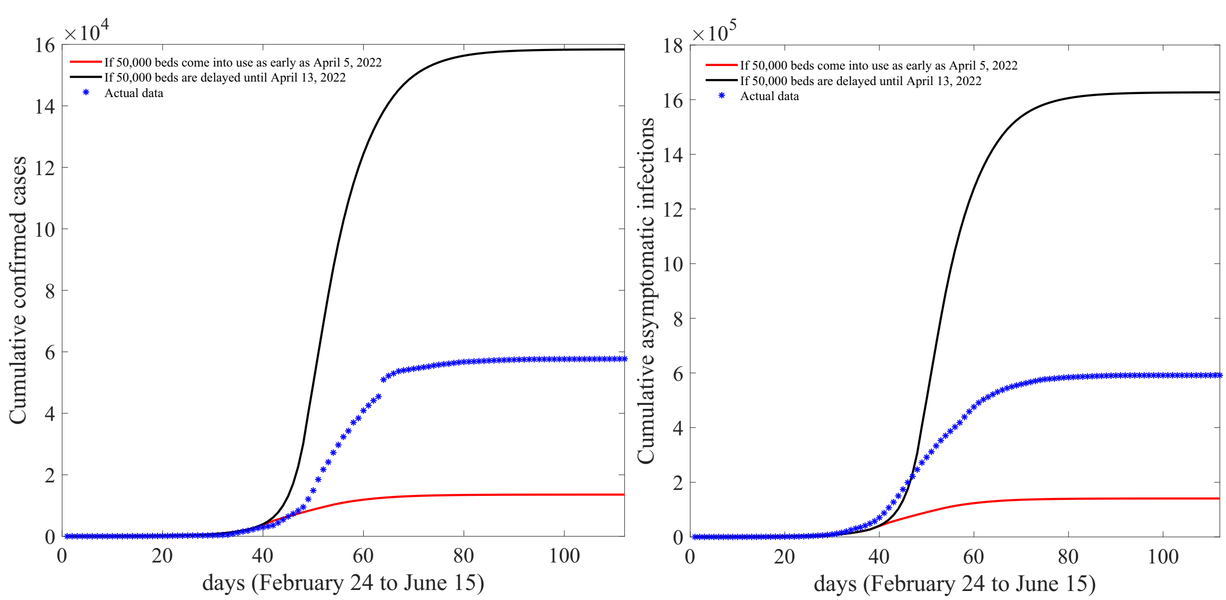

Fig. 11. The comparison chart of patients under different reconstruction time of the NECC Fangcang shelter hospital.

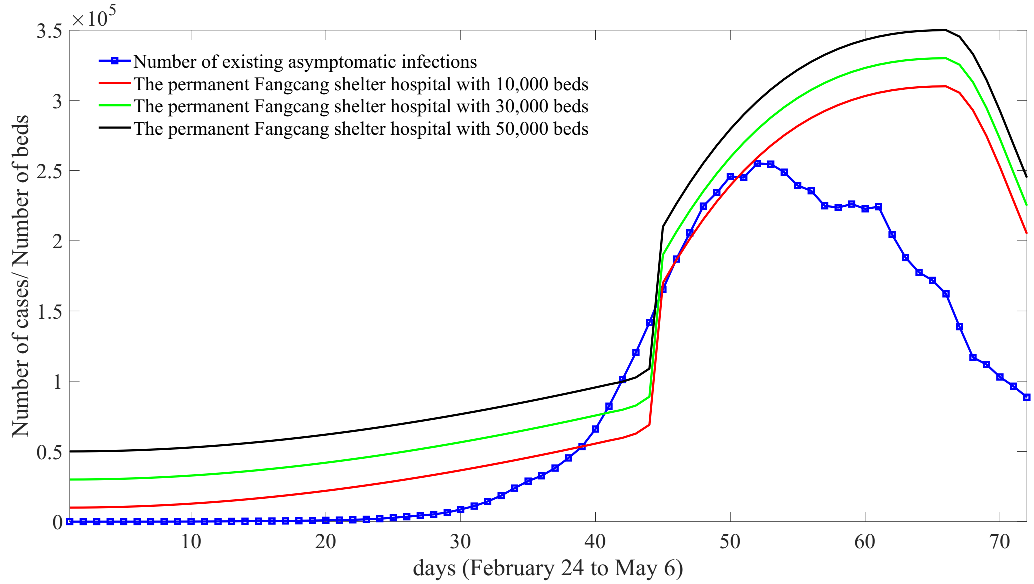

Fig. 12. The interpolation curves under different Fangcang shelter beds.

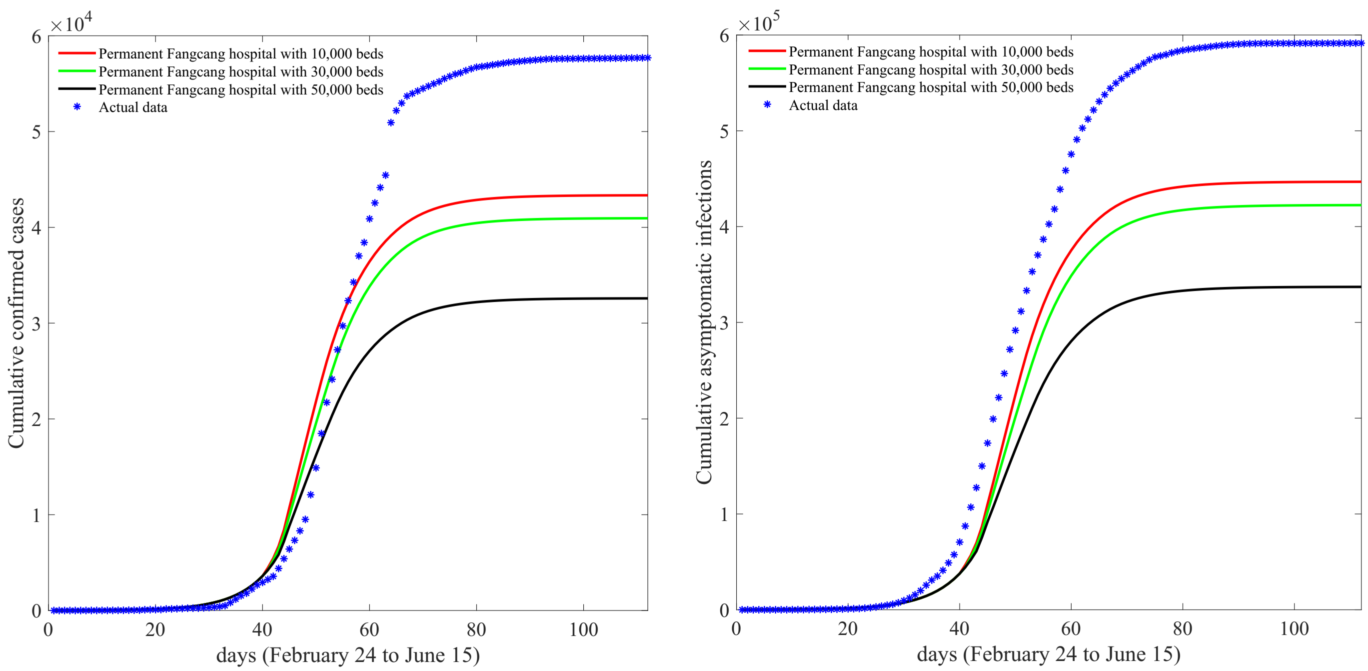

Fig. 13. The comparison chart of cases under different number of permanent Fangcang shelter beds.

experience for other cities, which have more than 10 million people. Through the dynamic modeling analysis of Shanghai from February 24, 2022 to June 15, 2022, $\mathcal{R}_0 = 1.8851$ in the first stage; $\mathcal{R}_0 = 3.6429$ in the second stage; $\mathcal{R}_0 = 0.9135$ in the third stage; $\mathcal{R}_0 = 0.5975$ in the fourth stage and $\mathcal{R}_0 = 0.4974$ in the fifth stage. Besides, we find that if the hospitalization rate of asymptomatic infections $\delta_2 > 0.9373$ or the transmission rate $\beta_{1b} < 0.0467$, the transmission of Omicron in Shanghai will be well controlled in the second stage.

In the last section, we get the idea that the measure of converting the NECC into a temporary Fangcang shelter hospital filled the shortage of beds in Shanghai at that time. If Shanghai not put the NECC into use during this epidemic, the cumulative number of asymptomatic infections in Shanghai will reach 4.15 million, the cumulative number of confirmed cases will exceed 400,000. If this temporary shelter with 50,000 beds is built four days ahead of schedule, the final cumulative asymptomatic infections will be controlled at around 140,000, and the cumulative confirmed cases will not exceed 13,600.

In addition, building permanent Fangcang shelter hospitals can also reduce COVID-19 cases and curb the spread of the epidemic. Taking Shanghai, a city with a population of 24.89 million, as an example, building a permanent Fangcang shelter hospital with 33,565 beds will curb the infectious disease and avoid shortage of hospital beds. We hope that our paper can give some references to other cities and regions where the epidemic is still very serious.

This paper starts with the number of hospital beds and constructs a compartmental model based on the consideration of vaccine coverage. Although different contact rates and different transfer rates are considered according to the segmentation, there are still some shortcomings in

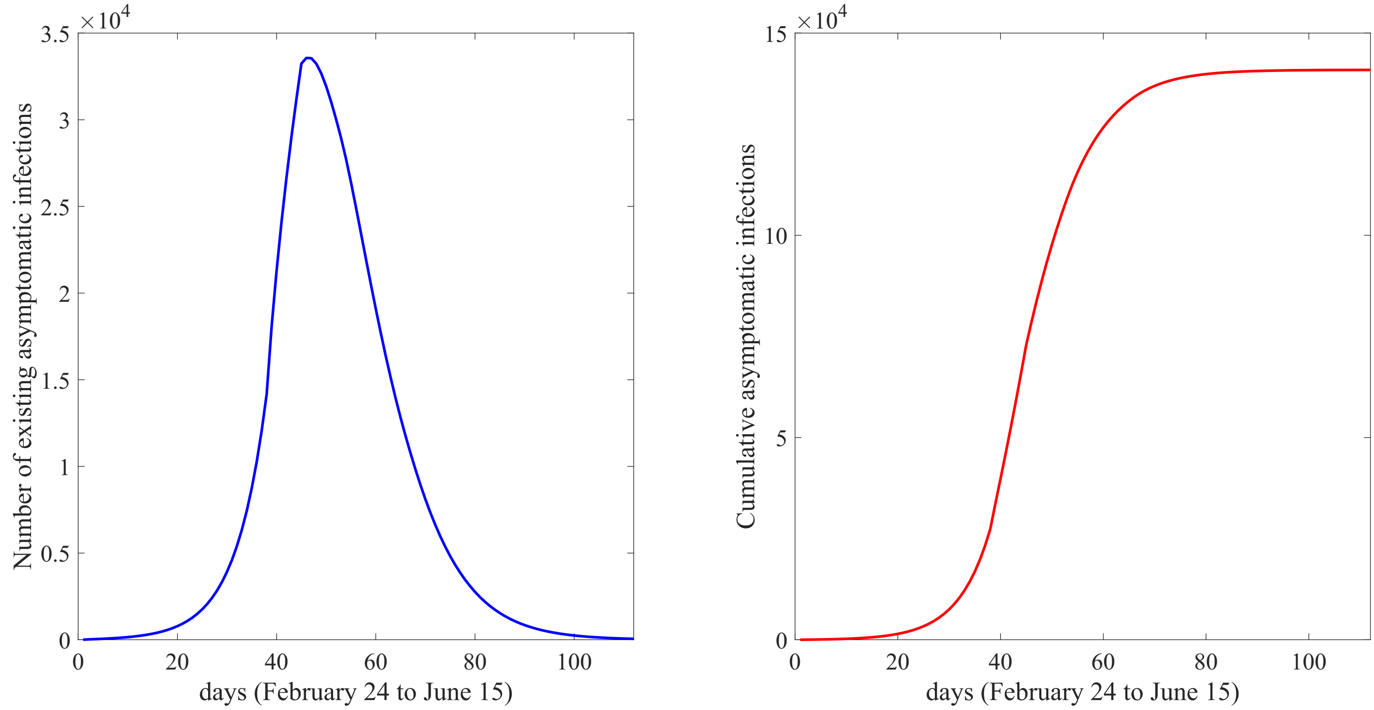

Fig. 14. The chart of cases when the number of beds in the Fangcang shelter hospital is sufficient.

Table 6
The number of permanent Fangcang shelter hospital beds corresponding to the city population of different scales.

City size	Permanent Fangcang shelter hospital beds	Cumulative asymptomatic infections
1×10^6	2196	9194
5×10^6	7451	31,264
1×10^7	14,016	58,825
2×10^7	27,145	113,943
5×10^7	66,532	279,295
7×10^7	92,790	389,529
9×10^7	119,048	499,763

this paper. First, antigens and nucleic acids are not considered in more detail, including the optimal cycle of antigen detection and nucleic acid detection. Second, only two groups of people who are vaccinated and unvaccinated are considered, and then in the vaccinated population, different doses of vaccination can be considered more deeply. Third, the COVID-19 vaccine has the ability to reduce the risk of infection in susceptible people, reduce the risk of infected patients spreading to others and reduce the symptoms of patients. In this paper, we only considered reducing the risk of infection in susceptible individuals. Fourth, there are many directions could be expanded, a natural extension is to consider contact heterogeneity using complex networks approach [57–59]. In addition, people of different ages have different susceptibility and different self-healing abilities, which are also issues worthy further study. In the future, we can conduct further research in the direction of vaccination doses, age structure and antigen detection. In addition, due to the uncertainty of the outbreak of the epidemic, this paper determines the number of permanent Fangcang shelter hospital beds in different cities based on the peak of the epidemic, but the construction of permanent Fangcang shelter hospitals also needs to consider human, material and financial resources, these all are required a more comprehensive consideration.

CRediT authorship contribution statement

Sheng-Tao Wang: Methodology, Formal analysis, Data curation, Writing – original draft. **Li Li:** Conceptualization, Methodology, Writing – review & editing. **Juan Zhang:** Visualization, Writing – review & editing. **Yong Li:** Conceptualization, Methodology, Writing – review & editing. **Xiao-Feng Luo:** Methodology, Writing – review & editing. **Gui-Quan Sun:** Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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