Research on Spatial Epidemic Dynamics Modelling of COVID-19 Outbreak: Take Nanjing as an Example

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Abstract: On 20 July 2021, Nanjing Lukou International Airport in JiangNing District, Nanjing, Jiangsu Province, China, reported six positive test results samples taken by airport staff. By 25 August, there were 235 COVID-19 cases confirmed in Nanjing and 596 cases in Yangzhou. Inspired by the models in Keeling and Rohani in 2002, we have built a model which introduced the commute parameters and commute sub-populations to simulate the spatial spread of the virus, including analyzed Nanjing and Yangzhou separately and combined the other two cities into consideration. We have discussed about two main situations about our spatial model, one about the isolated two cities Nanjing and Yangzhou interplay with the same R_0 or separated R_0, another about several cities in consideration interaction with their respective different R_0.

1 INTRODUCTION

It has been one and a half years since the COVID-19 pandemic outbreak began in Wuhan, Hubei Province, China, in December 2019. The COVID-19 pandemic main strain has evolved from the original SARS-CoV-2 to more transmissible and resistant strains. On 20 July 2021, Nanjing Lukou International Airport in JiangNing District, Nanjing, Jiangsu Province, China, reported six positive rRT-PCR (hereafter referred to PCR) test results in routine PCR test samples taken by airport staff. 21 July 2021, the government in Nanjing city (hereafter called Nanjing) began centralized isolation and sampling of airport-related personnel and areas. Also, the same day at 8 am, the analysis of PCR test samples at the airport was completed. Nanjing reported seven new locally confirmed cases of novel coronavirus infection and two new asymptomatic infections in Nanjing.

Moreover, seven days later, on 28, July Yangzhou city, Jiangsu Province, China (hereafter referred to Yangzhou) reported two new locally confirmed cases of COVID-19 linked to Nanjing this round outbreak. By sequencing the strains genes of the current outbreak in Nanjing, this round of epidemic situation is confirmed to be caused by the Delta variant strain (also known as lineage B.1.617.2), which was first detected in India in October 2020. By 25 August, there were 235 COVID-19 cases confirmed in Nanjing and 596 cases in Yangzhou; this outbreak in Yangzhou is 253.61% of the total in Nanjing.

In response to the latest outbreak caused by the mutant Delta variant, Nanjing and Yangzhou both have adopted district-level isolation and nucleic acid testing for all members. This study investigated the spatial epidemic dynamics of the COVID-19 virus between Nanjing and Yangzhou so far. Also, the spatial association of daily new cases in Nanjing and Yangzhou was measured and compared. The hypothesis of a spatial association of the epidemic between the two cities was considered based on the possibility of population movement between the two cities and different transmission routes.

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2 ANALYSIS

2.1 Data Sources

All the datasets of COVID-19 virus infection are collected from the official website of the National Health Commission of the People's Republic of China (National Health Commission of the People's of China, 2021). The website updates the latest infection situation, epidemic analysis, and prevention strategies. This study uses the data of 5 cities located in Jiangsu Province and 45 days of epidemic infection situation, in which the specific data source is obtained from the statistics bureau of each corresponding city, including the demographic data. All the real-time dynamic population movement data as the parameters e_{ij} and r_{ij} mentioned below are analyzed and discussed on the basis of the Baidu Qianxi data source (Baidu-qianxi, 2021).

2.2 Materials for Modelling

For how the virus spread from the population living in Nanjing to the population living in Yangzhou, we built a model to stimulate the epidemiological situation, which helps us estimate the cases in reality. In various examples, people calculated the commute cases would ignore the permanent relocation from one population to another because it may not generate a considerable influence as a significant epidemiological force, especially in a short-term case. Instead, the virus which spread by the commuters of two locations should be considered seriously.

2.2.1 Isolated-Cites Related Model

We now consider that the commuters live in Nanjing but occasionally travel to Yangzhou in this case. Inspired by the models in (Keeling, 2002) and (Das, 2020), We set S_{yn}, I_{yn}, and N_{yn} as the number of susceptibles, infections, and total hosts in Nanjing but currently located in Yangzhou.

Here we only use the standard SIR models as basics and expand the demographic and spatial parameters:

$$\frac{dS_{yy}}{dt} = \nu_{yy} - \beta_y S_{yy}\frac{I_{yn}}{N_{yn}} - \beta_y S_{yy}\frac{I_{yy}}{N_{yy}} - e_{ny}S_{yy} + r_{yn}S_{ny} - \mu_{yy}S_{yy} \quad (1)$$

$$\frac{dS_{yn}}{dt} = \nu_{yn} - \beta_y S_{yn}\frac{I_{yn}}{N_{yn}} - \beta_y S_{yn}\frac{I_{yy}}{N_{yy}} + e_{yn}S_{yy} - r_{ny}S_{ny} - \mu_{yn}S_{yn} \quad (2)$$

$$\frac{dS_{nn}}{dt} = \nu_{nn} - \beta_n S_{nn}\frac{I_{ny}}{N_{ny}} - \beta_n S_{nn}\frac{I_{nn}}{N_{nn}} - e_{yn}S_{yy} + r_{ny}S_{ny} - \mu_{nn}S_{nn} \quad (3)$$

$$\frac{dS_{nn}}{dt} = \nu_{ny} - \beta_n S_{ny}\frac{I_{ny}}{N_{ny}} - \beta_n S_{ny}\frac{I_{nn}}{N_{nn}} + e_{ny}S_{yy} - r_{yn}S_{ny} - \mu_{ny}S_{ny} \quad (4)$$

$$\frac{dI_{yy}}{dt} = \nu_{yy} + \beta_y S_{yy}\frac{I_{yn}}{N_{yn}} + \beta_y S_{yy}\frac{I_{yy}}{N_{yy}} - \gamma_y I_{yy} - e_{ny}I_{yy} + r_{yn}I_{ny} - \mu_{yy}I_{yy} \quad (5)$$

$$\frac{dI_{yn}}{dt} = \nu_{yy} + \beta_y S_{yn}\frac{I_{yn}}{N_{yn}} + \beta_y S_{yn}\frac{I_{yy}}{N_{yy}} - \gamma_y I_{yn} + e_{yn}I_{yy} - r_{yn}I_{yn} - \mu_{yn}I_{yn} \quad (6)$$

$$\frac{dI_{nn}}{dt} = \nu_{nn} + \beta_n S_{nn}\frac{I_{ny}}{N_{ny}} + \beta_n S_{nn}\frac{I_{nn}}{N_{nn}} - \gamma_n I_{nn} - e_{yn}I_{nn} + r_{ny}I_{yn} - \mu_{nn}I_{nn} \quad (7)$$

$$\frac{dI_{ny}}{dt} = \nu_{ny} + \beta_n S_{ny}\frac{I_{ny}}{N_{ny}} + \beta_n S_{ny}\frac{I_{nn}}{N_{nn}} - \gamma_n I_{ny} + e_{ny}I_{yy} - r_{yn}I_{ny} - \mu_{ny}I_{ny} \quad (8)$$

$$\frac{dN_{yy}}{dt} = \nu_{yy} - e_{ny}N_{yy} + r_{yn}N_{ny} - \mu_{yy}N_{yy} \quad (9)$$

$$\frac{dN_{yn}}{dt} = \nu_{yn} + e_{yn}N_{nn} - r_{ny}N_{yn} - \mu_{ny}N_{yn} \quad (10)$$

$$\frac{dN_{nn}}{dt} = \nu_{nn} - e_{yn}N_{yy} + r_{ny}N_{yn} - \mu_{nn}N_{nn} \quad (11)$$

$$\frac{dN_{ny}}{dt} = \nu_{ny} + e_{ny}N_{yy} - r_{yn}N_{ny} - \mu_{ny}N_{ny} \quad (12)$$

Where e_{yn} represents the rate of commuters located in Yangzhou currently but come from Nanjing, and r_{yn} represents the reverse commuters. The demographic parameters ν_{yn} and μ_{yn} measure the natality of individuals in Yangzhou but born in Nanjing and the mortality of the individuals who travel to Yangzhou from Nanjing. Other epidemic parameters were all depend on the people's commute directions.

We separated the population we would discuss into four sub-populations, people currently live in Yangzhou and also located in Yangzhou. People live in Yangzhou but currently locate in Nanjing, people live in Nanjing and currently located in Nanjing. People live in Nanjing but are currently located in Yangzhou (as the ***yy***, ***yn***, ***nn***, ***ny*** in the equations, respectively). Each sub-population group has its susceptibles, infections, and recovered groups. Among the four sub-populations, the two parts of the population currently located in a different city from their hometown represent the commute sections that cause the direct transmission of the virus in these two cities.

Also, we leave out the recovered groups and their corresponding equations in the above differential equations because this section has an independent system that would not impact the final result. Instead, we gave the region population equations as N_{yy}, N_{yn}, N_{nn}, and N_{ny} to illustrate the changing rate of population movement between Nanjing and

Yangzhou these four sub-population, which help us analyze such impacts in isolation.

2.2.2 Commuter Approximations

The differential equations we showed above provide an integrated description of the disease behavior and its spreading pattern. However, in some expanded situations with multiple areas related to the central city, a significant number of equations needed to be considered (details in Section Multiple-cites related model). Thus, we simplified the equations by assuming that all commuters have a fast movement. Under this assumption, the force of the infection of population Nanjing can be written as:

$$\lambda_y = \beta_y[(1-\rho)I_y + \rho I_n] \tag{13}$$

where the coupling parameter, ρ, can be defined as:

$$\rho = 2q(1-q) \tag{14}$$

where q represents the proportion of time which individuals spend away from their home population,

$$q = \frac{e_{yn}}{(r_{ny}+e_{yn})} = \frac{e_{yn}}{(r_{yn}+e_{ny})} \tag{15}$$

Among two main injected cities Nanjing and Yangzhou, a pathogen transfer occurs when either the susceptibles of one of these two populations or infections of another move, which gives us the equation of $\boldsymbol{\rho}$ from above. The maximum transmission of infections emerges when individuals spend equal amounts of time in both their home sub-population and away sub-populations as $\boldsymbol{q} = 1/2$.

2.2.3 Multiple-cites Related Model

In most realistic scenarios, we can not only consider the influences between two areas, and there can be several or dozens of cities impacted by the region where the epidemic outbreak. As the example of the outbreak of the COVID-19 virus in Nanjing, Yangzhou is not the only city that suffered a significant loss in economics and social environment, so in our model, we add a multiple regions equation pattern, which should give complete consideration to the situation for both the outbreak city and impacted cities. The index variable $\boldsymbol{i}$ represents the sub-population of the outbreak city, and $\boldsymbol{j}$ represents the sub-population in other impacted cities:

$$\frac{dS_{jj}}{dt} = \nu_{jj} - \beta_j S_{jj}\frac{I_{ji}}{N_{ji}} - \beta_j S_{jj}\frac{I_{jj}}{N_{jj}} - e_{ij}S_{jj} + r_{ji}S_{ij} - \mu_{jj}S_{jj} \tag{16}$$

$$\frac{dS_{ji}}{dt} = \nu_{ji} - \beta_j S_{ji}\frac{I_{ji}}{N_{ji}} - \beta_j S_{ji}\frac{I_{jj}}{N_{jj}} + e_{ji}S_{jj} - r_{ij}S_{ji} - \mu_{ji}S_{ji} \tag{17}$$

$$\frac{dS_{ii}}{dt} = \nu_{ii} - \beta_i S_{ii}\frac{\sum_j I_{ij}}{\sum_j N_{ij}} - \beta_i S_{ii}\frac{I_{ii}}{N_{ii}} - \sum_j e_{ji}S_{ii} + \sum_j r_{ij}S_{ji} - \mu_{ii}S_{ii} \tag{18}$$

$$\frac{dS_{ij_x}}{dt} = \nu_{ij_x} - \beta_i S_{ij_x}\frac{I_{ij_x}}{N_{ij_x}} - \beta_i S_{ij_x}\frac{\sum_{j_n} I_{j_n i}}{\sum_{j_n} N_{j_n i}} - \beta_i S_{ii}\frac{I_{ii}}{N_{ii}} + e_{ij_x}S_{j_x j_x} - r_{j_x i}S_{ij_x} - \mu_{ij_x}S_{ij_x} \tag{19}$$

$$\frac{dI_{jj}}{dt} = \nu_{jj} + \beta_j S_{jj}\frac{I_{ji}}{N_{ji}} + \beta_j S_{jj}\frac{I_{jj}}{N_{jj}} - \gamma_j I_{jj} - e_{ij}I_{jj} + r_{ji}I_{ij} - \mu_{jj}I_{jj} \tag{20}$$

$$\frac{dI_{ji}}{dt} = \nu_{ji} + \beta_j S_{ji}\frac{I_{ji}}{N_{ji}} + \beta_j S_{ji}\frac{I_{jj}}{N_{jj}} - \gamma_j I_{ji} + e_{ji}I_{ii} - r_{ji}I_{ii} - \mu_{ji}I_{ji} \tag{21}$$

$$\frac{dI_{ii}}{dt} = \nu_{ii} + \beta_i S_{ii}\frac{\sum_j I_{ij}}{\sum_j N_{ij}} + \beta_i S_{ii}\frac{I_{ii}}{N_{ii}} - \gamma_i I_{ii} - \sum_j e_{ji}I_{jj} + \sum_j r_{ij}I_{ji} - \mu_{ii}I_{ii} \tag{22}$$

$$\frac{dI_{ij_x}}{dt} = \nu_{ij_x} + \beta_i S_{ij_x}\frac{I_{ij_x}}{N_{ij_x}} + \beta_i S_{ij_x}\frac{\sum_{j_n} I_{j_n i}}{\sum_{j_n} N_{j_n i}} + \beta_i S_{ij_x}\frac{I_{ii}}{N_{ii}} - \gamma_i I_{ij_x} + e_{ij_x}I_{j_x j_x} - r_{j_x i}I_{ij_x} - \mu_{ij_x}I_{ij_x} \tag{23}$$

$$\frac{dN_{jj}}{dt} = \nu_{jj} - e_{ij}N_{jj} + r_{ji}N_{ij} - \mu_{jj}N_{jj} \tag{24}$$

$$\frac{dN_{ji}}{dt} = \nu_{ji} + e_{ji}N_{ii} - r_{ij}N_{ji} - \mu_{ij}N_{ji} \tag{25}$$

$$\frac{dN_{ii}}{dt} = \nu_{ii} - \sum_j e_{ji}N_{jj} + \sum_j r_{ij}N_{ji} - \mu_{ii}N_{ii} \tag{26}$$

$$\frac{dN_{ij}}{dt} = \nu_{ij} + e_{ij}N_{jj} - r_{ij}N_{ij} - \mu_{ij}N_{jj} \tag{27}$$

Where $\boldsymbol{n}$ = 1, 2, 3, …, $\boldsymbol{x}$-1, $\boldsymbol{x}$+1, …, $\boldsymbol{n}$. and so $\boldsymbol{j_n}$ = $\boldsymbol{j_1}, \boldsymbol{j_2}, \boldsymbol{j_3}, \ldots, \boldsymbol{j_{x-1}}, \boldsymbol{j_{x+1}}, \ldots, \boldsymbol{j_n}$.

So we now obtain a new differential equation corresponding a one-multiple areas epidemic situations, where we have assumed the frequency of dependent transmission, as it is standard for human diseases. The pattern $\sum_{\boldsymbol{j}} \boldsymbol{X_{ij}}$ giving the number of summation of the individuals in group $\boldsymbol{X}$ (susceptibles, infected or total population) from outbreak region population $\boldsymbol{j}$ but currently located in spread region population $\boldsymbol{i}$, and similarly, $\sum_{\boldsymbol{j_n}} \boldsymbol{X_{ij_n}}$ represent the total number of individuals in the group of $\boldsymbol{X}$ from original outbreak city but now locate in surrounding cities $\boldsymbol{j_n}$ which are exclusive of the designated city $\boldsymbol{j_x}$.

The total equations have the same pattern as the isolated cities related model mentioned above, considering the multiple cities' mutual influences. It allows us to measure the situation with simulation in a higher degree of accuracy as we can consider the transmission of pathogen in the primary outbreak city with all sub-population that come from different cities blended.

3 DISCUSSION

In the early stage of this new outbreak of the COVID-19 virus in Nanjing, Jiangsu Province, the first three infected persons were diagnosed on 20 July in Lukou International Airport station. Then, the pathogen spread to the center area of Nanjing with extremely high transmission speed, which caused more than a hundred people to be infected in just a week. Moreover, on the second day of the government of Jiangsu Province announced that there were 100 persons had been infected by the new variant, Yangzhou's public health authorities detected the first infected individuals who were assuredly traveled from Nanjing. Also, on the same day, Yangzhou had diagnosed two infected people. After that, the virus spread faster than expected. The number of infections in Yangzhou surpassed the counterpart in Nanjing in 6 days and exceeded 300 after another day.

Although the government of Yangzhou had token emergency measures immediately after the first virus carrier was discovered, the explosive growth of infected people still caused severe damage to Yangzhou. In these cases, we are going to stimulate the spread situation without any artificial intervention.

3.1 Isolated-cities Related Estimate

Figure 1 and Figure 2 show the number of infections and susceptibles in the outbreak city Nanjing and the impacted city Yangzhou within a hundred days, the data of total population in Nanjing (Nanjing Bureau of Statistics, 2021) and Yangzhou (Yangzhou People's Government, 2021) was collected from the seventh national census of China in May 2020, and the parameters related to the epidemic outbreak were determined by setting the $\boldsymbol{R_0} = 5$ for all location and sub-population.

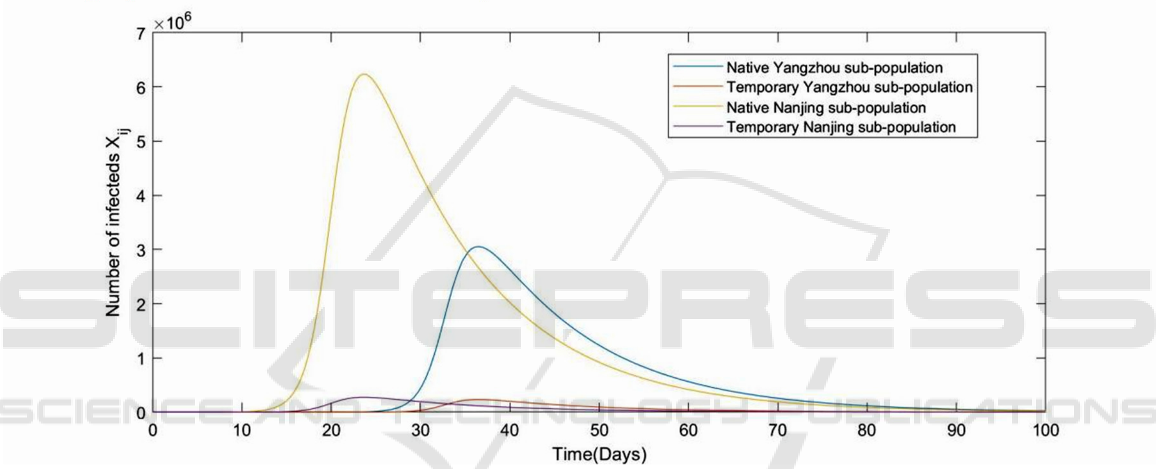

Figure 1. The change of number of infections in Nanjing and Yangzhou with same R_0.

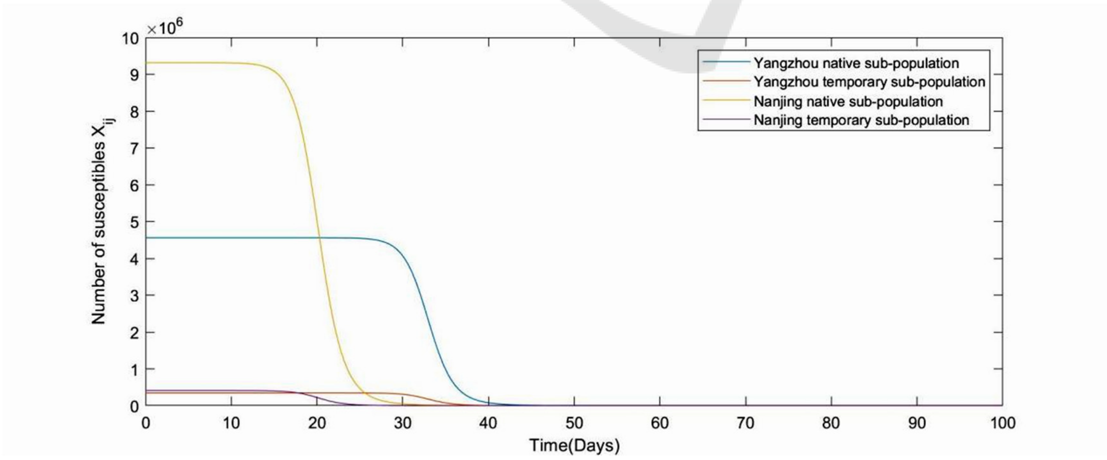

Figure 2. The change of number of susceptibles in Nanjing and Yangzhou with same R_0.

However, the primary reproduction number of the COVID-19 virus in Jiangsu was not the same anywhere. Cause it was associated with medical and social resources like hospital in-patient condition, service facilities, medical equipment, population base, and government executive ability. Nanjing is the capital of the Jiangsu Province, so we have reason to believe that all these living environments and facilities in Nanjing are better than the counterpart in Yangzhou, so we reduce the value of $\boldsymbol{R_0}$ to 3.3 in Nanjing without changing the value of Yangzhou's.

As shown in Figure 3 and Figure 4, the number of infected individuals decreased for all sub-population after we changed $\boldsymbol{R_0}$, since the average $\boldsymbol{R_0}$ for both two regions decreased, the proportions of infections for both Nanjing and Yangzhou were getting smaller, and falling rates of the number of the susceptibles in these two cities were becoming flat also.

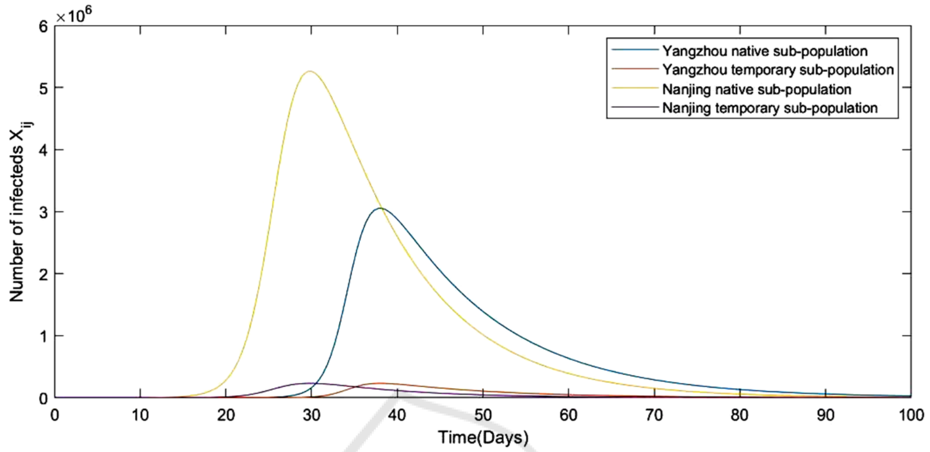

Figure 3. The change of number of infections in Nanjing and Yangzhou with separated R_0.

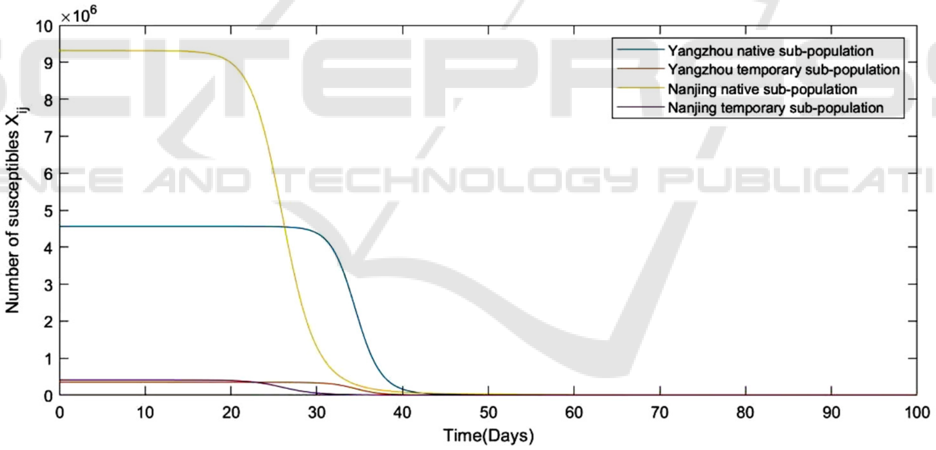

Figure 4. The change of number of susceptibles in Nanjing and Yangzhou with separated R_0.

3.2 Multiple-cities Related Estimate

In the epidemic outbreak at Nanjing, Jiangsu, in July, the virus not merely attack Yangzhou, it still spread to other cities in Jiangsu Province, there are dozens of cities like Suqian, Huaian, Suzhou, Xuzhou, Wuxi, Changzhou, etc., were impacted by the pathogen that first discovered in Nanjing. The spread of the new variant type of COVID-19 virus is complicated and changeable, especially in spatial spread modeling. We need to be more careful in consideration of several cities 'interaction effects.

Figure 5 and Figure 6 showed that the numbers of infections and susceptibles in these four cities, Nanjing, Yangzhou, Suqian, and Huaian, in 120 days and 100 days, respectively. We added the other two cities Suqian (Suqian Municipal Bureau of Statistics, 2021) and Huaian, into consideration based on original unchanged conditions, with ten original cases in the native Nanjing sub-population. All the commuters from the other three cities were assumed to have freedom of movement or actions in Nanjing.

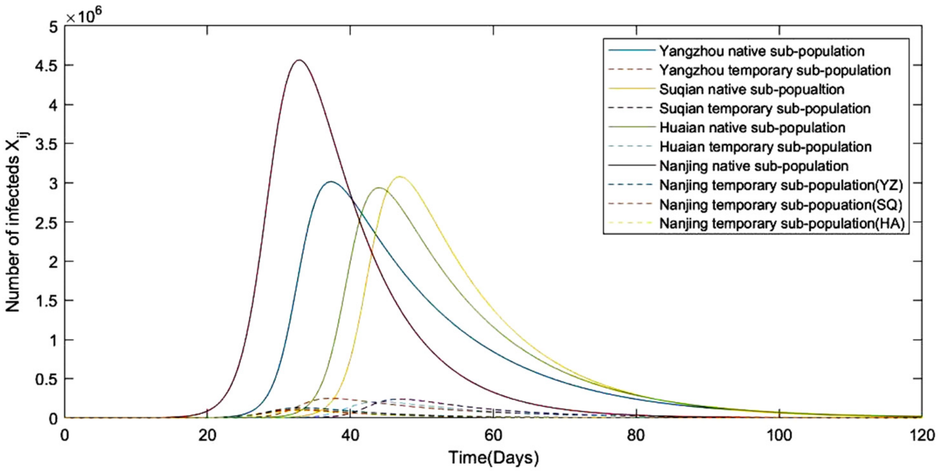

Figure 5. The change of number of infections in four cities.

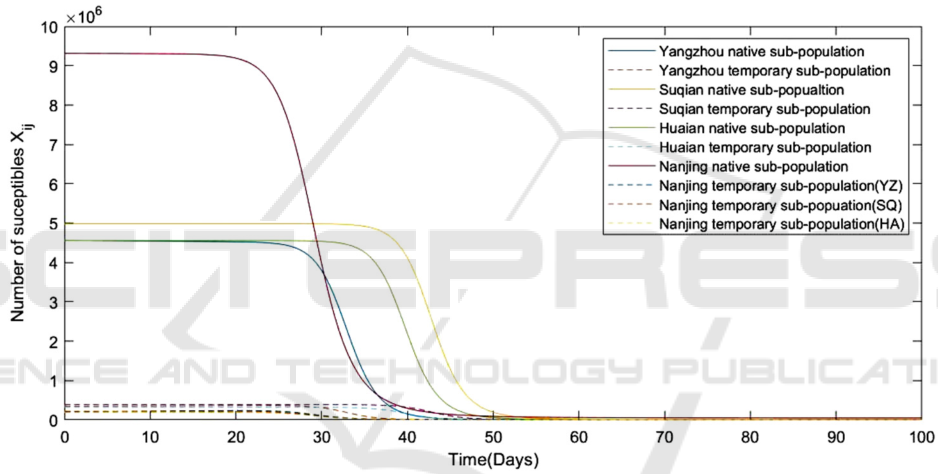

Figure 6. The change of number of susceptibles in four cities.

As we see in the Figures above, Nanjing was going through a significant epidemic, which is the source of initial infection from 10 cases in LuKou International Airport. Its number of infections peaked the headmost and experienced the most severe epidemic due to its hosts having the most significant population in Jiangsu. Moreover, for the other objects in the graph: Yangzhou, which is the second large city except for Nanjing in the chosen four cities, has reached its peak just next to Nanjing's, the population size is similar to other impacted cities. Since Yangzhou is the closest city to the origin city, the commuting rates between Nanjing and Yangzhou are higher, which might be caused that Yangzhou is the earliest outbreak of the infection city among the others. Suqian and Huaian have a similar population and city size (Suqian Municipal Bureau of Statistics, 2021), which causes a mirrored image in the graph. Moreover, two sub-populations in the same region have a similar trend or are said differently. Their corresponding curves have the same sign of their first differential coefficients.

4 CONCLUSION

We ensure now that this new variant virus of COVID-19 is spread to China from other countries and the Delta strain (B.1.617.2) has a transmission rate 1.4 times that of the original SARS-COV-2 strain. The commutative number of infections in Jiangsu Province has reached 500 in less than 20 days, and at peak in less than 30 days.

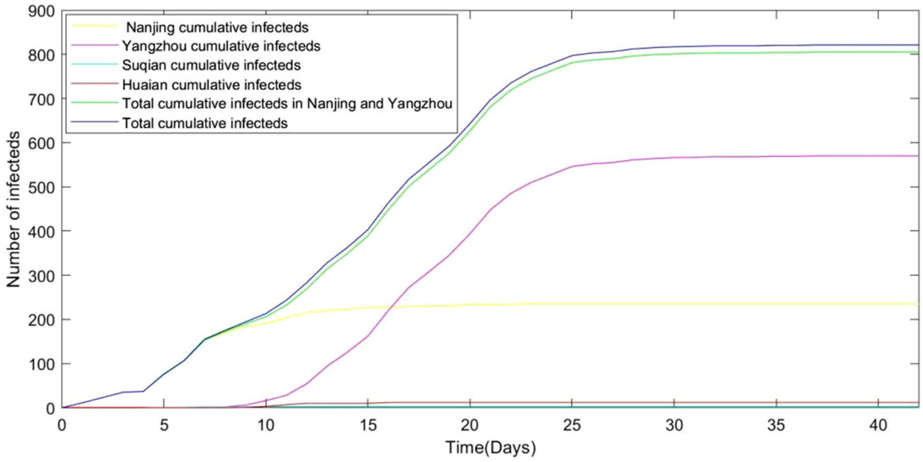

Figure 7. The change of cumulative number of infections in Jiangsu Province in 45 days.

This study shows the spatial spread of the epidemic the public health policy's advantage in controlling the predicting outbreak of the epidemic in Nanjing, Yangzhou, and whole Jiangsu Province, as we see in the model which gave the consequence that the virus was spread without any precautionary measure like quarantine policies and medical treatment, millions of people would be infected. However, the virus population would become extinct in about 200 days in simulations, the damage it would cause we can never imagine.

The primary defect of our modelling research is that in an ideal modeling spread environment, our model only considers the commute associativity between the original outbreak city and surrounding impacted cities but not the cross-infection among the surrounding cities themselves. Such a situation may result in a neglected extreme spread tendency, happening among the urban agglomerations.

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