METHODS

To determine the optimal order of opening various regions, a well-thought-out strategy should be developed after careful consideration of several important factors, such as the agricultural product supply between regions, manufacturing industry interdependency, medical resource reserved, and transportation networks, among others. However, the coupling of these data is very complicated. Considering that these factors are strongly correlated with the GDP, we simplify the problem to be based on the GDP as an illustrating example. We establish the following mathematical model to discuss the problem. First, a weighted directed network of economic interdependency between regions is constructed by using the GDP (the latest release in 2021) of each region. Specifically, let k_i be the GDP of region i, then the strength of interdependency between regions i and j can be expressed as

$$w_{ij} = \frac{k_j/d_{ji}^r}{\sum_{l=1}^{N} k_l/d_{li}^r}$$

where w_{ij} represents the supply that region i receives from region j, normalized by all regions (the total number of regions is denoted by N). In this setting, $\sum_{j=1}^{N} w_{ij} = 1$ and w_{ij} is proportional to k_j, weighted by the geographical distance d_{ji} between regions i and j whose strength is tuned by a parameter r, suggesting that the dependence of region i on region j is proportional to the GDP of region j, constrained by the supply distance.

Then we consider several regional opening sequences based on the network constructed above. The results are meant to illustrate the importance of the order of opening, and do not indicate that the final opening sequence should be determined merely based on the GDP and geographical locations. Note that in the process of opening regions according to a certain order, we assume that the communication of people and materials between regions is subject to the following restrictions to prevent epidemic transmission to unopened regions: opened regions can freely supply each other; unopened regions can freely supply each other; unopened regions can only unidirectionally supply opened regions i.e., opened regions cannot supply unopened regions (while the last restriction seems quite strict, the essential point is that the supply to unopened regions are inevitably affected and the degree of impact can be tuned by a threshold parameter w in our model as mentioned below). In this way, the restrictions might lead to insufficient supply or even cut-off to some regions, resulting in economic shutdown of these regions. The shutdown regions would fail to supply other regions, leading to a cascade shutdown of other regions until no more regions fail.

To evaluate the impact of different regional opening sequences, we define a loss function $F(S)$ for each ordered sequence of N regions $S = \{s_1, s_2, \ldots, s_N\}$. Since the shutdown of regions would induce not only economic loss but also serious inconvenience to people's work and life, we compute $F(S)$ as the sum of the shutdown duration of each region. Here we choose a threshold w (e.g.,$w = 0.5$), below which a region i is considered to be economically shut down, i.e., $\sum_j w_{ij} <$

w. Under the above model, we take provinces as regions and discuss six candidate opening sequences, i.e., four directional sequences (south to north, north to south, east to west, and west to east), a random sequence, and the optimal sequence by applying the simulated annealing algorithm, in three scenarios of regional supply networks: without distance constraint ($r = 0$), linear constraint ($r = 1$), and nonlinear constrain ($r = 2$). Note that the geographical location of each province is determined by the longitude and latitude of its capital city.

RESULTS

In Fig.1(A-C), the defined loss function $F(S)$ (shown as the area under each curve) of the six opening sequences are compared under $w = 0.5$. We find that opening provinces in different order results in quite different loss and the optimal sequence reduces the overall economic loss to a great extent in all three scenarios of regional supply networks. Specifically, the $F(S)$ of the optimal sequence is respectively 23%, 12%, 3% of the average $F(S)$ over the four directional sequences for $r = 0, 1, 2$.

After an opening sequence S is determined, regions will be opened one after the other, at the time when the daily new infections in the previously opened region reach its peak, i.e., when the daily increase is about to enter a recession period. With such a strategy, the peak of infections can be suppressed at a relatively low and stable level at the national scale. In Fig.1(D), we compare the curves of daily infections between two opening strategies, i.e., simultaneous opening of all provinces and sequentially opening provinces according to the optimal order, where the latter is obviously a superior solution (the peak is reduced by a factor of 10).

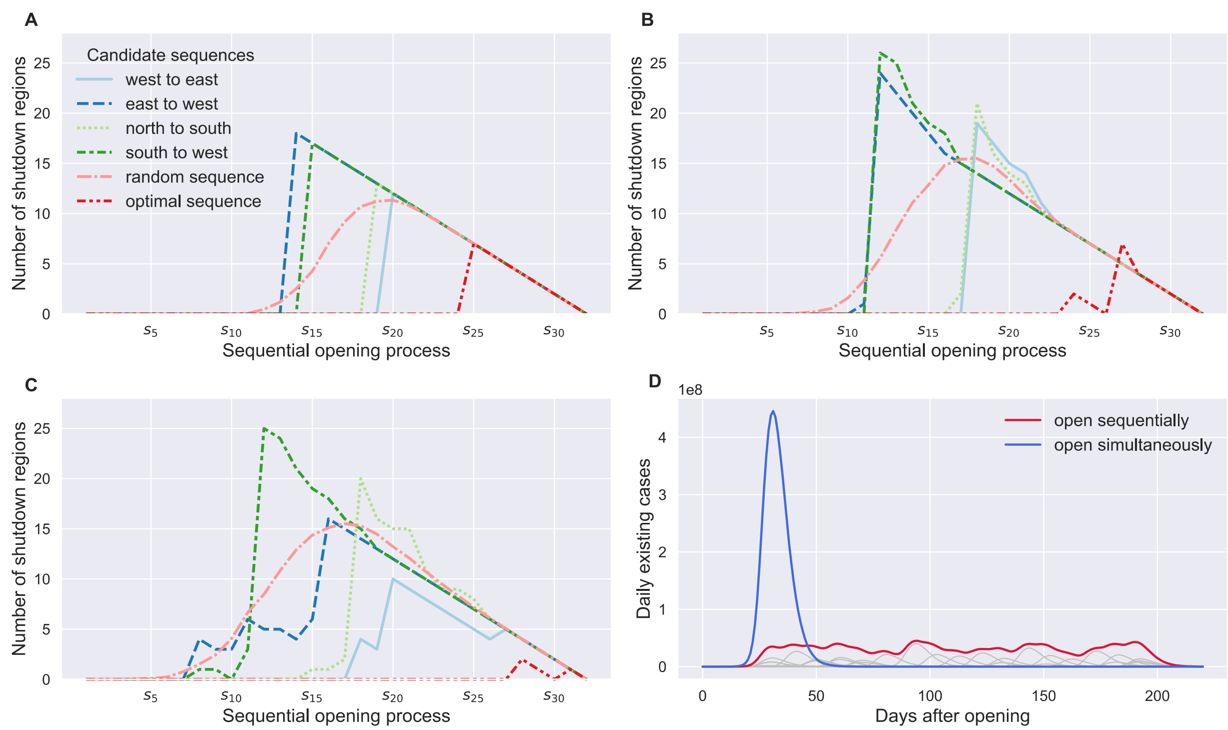

Figure 1: Loss function and daily infections when sequentially opening provinces ($\boldsymbol{w = 0.5}$). Each of (A-C) shows the curves describing the opening processes of six candidate sequences, the corresponding loss $F(S)$ is the area under each curve. (A-C) represent the three scenarios with $r = 0, 1, 2$, respectively. (D) shows the daily infections under the transmission rate of Omicron [1]. The red line shows the daily existing cases when provinces are sequentially opened according to the optimal order determined by the simulated annealing algorithm. The blue line displays the daily existing cases when all provinces are opened simultaneously.

REFERENCES

[1]. Ito, K., Piantham, C., & Nishiura, H. Estimating relative generation times and relative reproduction numbers of Omicron BA. 1 and BA. 2 with respect to Delta in Denmark. medRxiv, 2022.