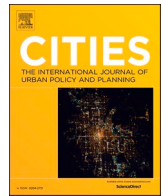




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Epidemic versus economic performances of the COVID-19 lockdown: A big data driven analysis

Haoran Zhang^{a,b}, Peiran Li^a, Zhiwen Zhang^a, Wenjing Li^a, Jinyu Chen^a, Xuan Song^{a,c,*}, Ryosuke Shibasaki^a, Jinyue Yan^b

^a Center for Spatial Information Science, The University of Tokyo 5-1-5 Kashiwanoha, 277-8568 Kashiwa-shi, Chiba, Japan

^b School of Business, Society & Engineering, Mälardalen University, SE-72123 Västerås, Sweden

^c Southern University of Science and Technology-University of Tokyo Joint Research Center for Super Smart Cities, Department of Computer and Engineering, Southern University of Science and Technology, 518055 Shenzhen, Guangdong, China

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ABSTRACT

Lockdown measures have been a “panacea” for pandemic control but also a violent “poison” for economies. Lockdown policies strongly restrict human mobility but mobility reduce does harm to economics. Governments meet a thorny problem in balancing the pros and cons of lockdown policies, but lack comprehensive and quantified guides. Based on millions of financial transaction records, and billions of mobility data, we tracked spatio-temporal business networks and human daily mobility, then proposed a high-resolution two-sided framework to assess the epidemiological performance and economic damage of different lockdown policies. We found that the pandemic duration under the strictest lockdown is less about two months than that under the lightest lockdown, which makes the strictest lockdown characterize both epidemiologically and economically efficient. Moreover, based on the two-sided model, we explored the spatial lockdown strategy. We argue that cutting off intercity commuting is significant in both epidemiological and economical aspects, and finally helped governments figure out the Pareto optimal solution set of lockdown strategy.

1. Introduction

The new coronavirus (COVID-19) pandemic has been spreading globally. According to the World Health Organization (WHO), the number of total confirmed cases had reached more than a hundred million, and the number of deaths has reached millions (WHO, 2020). Confronted with this severe pandemic, national governments have been compelled to respond with drastic measures, including lockdown to mitigate the coronavirus spread. However, lockdown policy has a dual character: although the policy has been widely proven to be a panacea for prevention and control of the new coronavirus (Fang, Wang, & Yang, 2020; Lau et al., 2020), it is also the most violent poison for economies (Fernandes, 2020; Nicola et al., 2020). Lockdown policy limits people's mobility such as leaving homes, and at the same time, mobility reduce highly restricts economic activities (Bonato et al., 2020), especially those of end-consumers (Barro, Ursúa, & Weng, 2020; Chen, Lerman, & Ferrara, 2020). Upstream industries will subsequently take a hit caused by economic chain reactions (Inoue & Todo, 2020). Due to this pandemic crisis, most major economies will lose at least 2.4% of the

value-gross domestic product (GDP) over 2020 (Duffin, 2020). In light of these problems, for national governments, the most decidedly thorny problem is how to balance the pros and cons of lockdown policy by adjusting the duration and intensity of implementation, but related studies remain limited.

Here, we explored the two-sidedness of lockdown policies in mitigating virus spread and economic damage, focusing mainly on three key questions: 1. What effect do different lockdown policies have on metropolitan activities; 2. What are the epidemiological performance and economic damage characteristics of different metropolitan lockdown policies; 3. How to optimize regional lockdown strategy with minimizing both life and economic losses. Based on billions of metropolitan trajectory data and millions of financial transaction data, we proposed a framework to trace the impacts of different lockdown policies on the epidemiological performance and economic damage in the Greater Tokyo Area - the most populous metropolitan area, the largest metropolitan area economy in the world. Compared with the existing optimal-solution-aiming studies, our work: 1. employed big and detailed data (including 1.3 billion metropolitan trajectory data and 1.2 million

* Corresponding author at: Center for Spatial Information Science, The University of Tokyo 5-1-5 Kashiwanoha, 277-8568 Kashiwa-shi, Chiba, Japan.
E-mail address: songxuan@csis.u-tokyo.ac.jp (X. Song).

financial transaction data, etc.) so that we can track individual-level activity, instead of a macro statistical number, which can afford detailed and spatialized simulation result; 2. took the human mobility as a bridge, precisely simulate both economic loss propagation and epidemical transmission. 3. can work out a Pareto optimal strategy, consisting of a series of policy-set, affording more flexibility than the past parameterized approaches. Our results found that the pandemic duration under the strictest lockdown is less about two months than that under the lightest lockdown, which makes the strictest lockdown characterize both epidemiologically and economically efficient. Moreover, based on the two-sided model, we explored the spatial lockdown strategy. We argue that cutting off intercity commuting is significant in epidemiological and economic aspects and finally helped governments

figure out the Pareto optimal solution set of Lockdown strategy. This study will offer fundamental support for guiding regional and national governments in designing health, social, and economic policies.

2. Literature review

Interdisciplinary models are critical tools for anticipating, predicting, and responding to this pandemic crisis—including its biological and economic aspects—and also give governments theoretical support for coping with this thorny problem (Barton et al., 2020; Chen, Qian, & Wen, 2020; Dong, Du, & Gardner, 2020).

Most of the past related studies usually began with an in-depth interpretation of lockdown policies from a one-sided dedicated

Table 1
Studies on COVID-19 epidemics and economics.

Study case	Objects	Method	Data type	Data spatial scale	Economics	Epidemics	Fine-grained simulation ability
Chinazzi et al., 2020	To analysis the effect of government interventions (travel restrictions) on epidemical transmission	GLEAM (Global Epidemic and Mobility Model)	Macro statistical data	Province/City-level mobility data Province/City-level infected number	×	✓	×
Y. Fang et al. 2020b	To analysis the effect of government interventions (travel restrictions) on epidemical transmission	A parameterized SEIR model	Macro statistical data	Province/City-level mobility data Province/City-level infected number	×	✓	×
Jia et al., 2020	To analysis the effect of government interventions (travel restrictions) on epidemical transmission	A spatio-temporal ‘risk source’ model	Macro statistical data (Mobility data coming from mobile phone data)	Individual-level mobility data Province/City-level infected number	×	✓	✓
Jia et al., 2020	To analysis the effect of government interventions (travel restrictions) on epidemical transmission	A modified SEIR model	Macro statistical data	Province-level mobility data Province-level infected number	×	✓	×
Kucharski et al., 2020	To analysis the effect of government interventions (travel restrictions) on epidemical transmission	A modified SEIR model	Macro statistical data	Country-level mobility data Country-level infected number	×	✓	×
Wells et al., 2020	To analysis the effect of government interventions (travel restrictions) on epidemical transmission	Monte Carlo simulation	Macro statistical data	Country-level mobility data Country-level infected number	×	✓	×
Bonaccorsi et al., 2020	To analysis the effect of government interventions (travel restrictions) on economical loss	Linear Regressions	Macro statistical data (People's situation provided by Facebook)	Country-level mobility data Country-level infected number	✓	×	×
Huang et al., 2020	To analysis the effect of government interventions (travel restrictions) on economical loss	Linear Regressions	Macro statistical data (Mobility data coming from Internet map)	Country-level mobility data Country-level infected number	✓	×	×
Guan et al., 2020	To analysis the effect of COVID-19 pandemics on economical loss	Extended adaptive regional input-output (ARIO) model	Macro statistical data	Global supply chains data Country-level infected number	✓	×	×
McKibbin & Fernando, 2020	To analysis the effect of COVID-19 pandemics on economical loss	A global hybrid DSGE/CGE general equilibrium model	Macro statistical data	Country-level trade data (Global Trade Analysis Project (GTAP) database)	✓	×	×
Alvarez, 2020	Analysis, simulate the effect of government interventions on epidemical and economics	SIR epidemiology model and a linear economy to formalize the planner's dynamic control problem	Macro statistical data	Country-level economical data (GDP) Country-level infected number	✓	✓	×
Karin et al., 2020	Analysis, simulate the effect of government interventions on epidemical and economics	SEIR models and stochastic network-based models for epidemics. A constructed economical mechanism based on empirical studies	Macro statistical data	Statistical-level economical data Statistical-level infected number	✓	✓	×
This study	Analysis, simulate the effect of government interventions on epidemical and economics	Grided-based SEIR (a trajectory-based epidemic model) and Small-world model for epidemics. An agent-based input-output model for economics.	Micro record data	Individual-level mobility data Trade Transaction Data Statistical-level infected number	✓	✓	✓

perspective – merely from epidemics or economics (Table 1).

From the perspective of epidemics, most of these studies employed macro-scale statistical data, province/city-level mobility data, and infected numbers to simulate/evaluate the effectiveness of government Interventions (travel restrictions) on epidemical transmission. For example, [Chinazzi et al. \(2020\)](#) applied a global metapopulation disease transmission model to epidemiological data from China and evaluated travel restrictions on the worldwide spread of the COVID-19 outbreak. Similarly, a series of studies based on macro-scale statistical data were conducted based on SEIR or modified SEIR models ([Jia, Lu, et al., 2020](#); [Kucharski et al., 2020](#); [Yang et al., 2020](#)). Unlike studies based on macro-scale data and the SEIR model, [Jia, Ding, et al. \(2020\)](#) constructed a spatio-temporal risk source model (with individual-level mobility data collected from mobile phones). [Wells et al. \(2020\)](#) employed a Monte Carlo model (also with macro-scale data) to achieve a similar goal. All of the above studies focused on one-side epidemical issues regardless of economic analysis.

From the perspective of economics, Some researchers focused more on the analysis of established facts. [Bonaccorsi et al. \(2020\)](#) analyzed the effect of government interventions (travel restrictions) on economic loss in Italy based on a linear regression method, and [Huang et al. \(2020\)](#) conducted a similar study on China. Some researchers focused on modeling the economic chain propagation. As the simulation of changes in transmission dynamics, [Guan et al. \(2020\)](#); [McKibbin and Fernando \(2020\)](#) analyzed the effect of COVID-19 pandemics on worldwide economics based on a dynamics method.

However, for the governments, the possibilities of pandemic scenarios are challenging to estimate, making it hard to extract academic support from one-sided analyses for policymaking directly. Therefore, it is essential to further reveal research gaps in our understanding of the dual character of lockdown policy to develop novel solutions to manage the spread of disease and lessen its impacts. Some researchers tried to solve this bi-sided complex by taking mobility as the bridge between pandemic scenarios and economic cost/loss. Aiming to find an optimal lockdown policy for a planner who wants to control the fatalities of a pandemic while minimizing the output costs of the lockdown, [Alvarez \(2020\)](#) employed a SIR epidemiology model and a linear economy model to formalize a simple optimal control model. Taking the entire country as a whole, they conclude with a parameterized optimal solution for lockdown measures. [Karin et al. \(2020\)](#) employed SEIR models and stochastic network-based models for epidemics, an experience-based analysis for economics, and concluded that a cyclic schedule of 4-day work and 10-day lockdown, or similar variants, can prevent a resurgence of the epidemic while providing part-time employment. Also, their study considered all populations as a whole to formalize the problem.

Despite the above efforts to solve the bi-sided epidemics-economics complex, gaps remain for detailer and more explainable solutions. First, most of the past studies focused on country-level issues based on macro statistical data instead of a detailed investigation of a metropolitan area. Second, for the current studies, which aim to understand the dual character of epidemics and economics, they only tried to find the relationship by regression fitting instead of simulation in physics. Lastly, although there have been studies trying to employ individual-level mobility data (mainly collected from part of mobile phone users), no attempt has been conducted to map the virtual data (part of population) to the real world (total population).

3. Mechanism of metropolitan lockdown modeling

Intensity and duration characterize the lockdown's impacts on epidemiological performance versus economic damage in metropolitan areas. On the one hand, lockdown limits people's movements, hence cutting the individual physical contact network and mitigating the virus. These effects are promoted by the strength and length of lockdown implementation. On the other hand, lockdown causes a mass of

mandatory business closures, especially in high-risk service industries. Due to the demand decline in these markets, economic impacts will occur and affect upstream industries. Consequently, residents gradually face the risk of suspension from work and decreased income. This risk, in turn, would cause a decline in spending power and negative feedback to the market. As lockdown intensity and duration increase, this economic damage would be devastating. Without any theoretical or experimental support, it would be hard for the government to formulate a wise policy with optimal intensity and duration. However, any small policy mistake on lockdown might cause huge losses of life and property.

This study mainly focused on dissecting epidemiological performances and economic impacts of different lockdown policies and devising the optimal policy mix for the government to balance lockdown's pros and cons. [Fig. 1a](#) displays the modeling mechanism. The framework has four essential parts: lockdown scenario setting, epidemiological performance assessment, economic damage evaluation, and policy mix suggestion. Concerning the lockdown scenario setting, we figured out three lockdown clusters according to the lockdown intensities of metropolitan areas worldwide. Moreover, to comprehensively illustrate the temporal impacts of different lockdown policies on metropolitan areas, we set two lockdown duration determination method scenarios: fixed schedule and dynamic adjusting. The main inputs of the model are individual mobility data and financial transaction data. Concerning the epidemiological performance assessment, from the individual mobility data, we can observe the individual daily trajectories and then detect their travel purposes by fusing trajectories data with the urban point of interest information (POI) data. Based on the real-world mobility changes in different travel purposes under different lockdown policies, we adopted a sampling method to generate individual mobility data and construct an individual physical contact network under different lockdown policy cases. Then, we utilized a compartmental model in epidemiology, a grid-based SEIR model ([Fan et al., 2020](#); [Yang et al., 2020](#)) to simulate the coronavirus spread process following human mobility. It also pointed out the case number curve, showing its increasing trend along the timeline. Concerning the economic damage evaluation, based on the financial transaction data, we tracked the capital flows on the end-consumer side and business networks in all industries. According to the firm information data and official lockdown measure information, we separately reconstructed the business networks, shutting down the specified industries mandatorily closed during the different-intensity lockdowns. Then, we took the new business networks as input for the proposed agent-based input-output model to track the propagation of the economic impacts of different lockdown policies. Concerning the policy mix suggestion, we coupled the above analysis results, made a comprehensive comparative analysis of the different lockdown policies, and computed the Pareto optimal solution set of the policy options, which could further support fundamental support related to policy suggestions for the government.

4. Data and methods

4.1. Data description

This study employed various datasets: big GPS record data for human mobility tracing, metropolitan POI data for travel purpose labeling, financial transaction records and firm information data for economic modeling, and some other data helping analysis:

4.1.1. Human mobility data

To model real-world human mobility used for epidemic simulation, we employed following dataset: "Konzatsu-Tokei (R)" Data refers to people flows data collected by individual location data sent from mobile phone under users' consent, through Applications provided by NTT DOCOMO, INC. Those data is processed collectively and statistically in order to conceal the private information. Original location data is GPS data (latitude, longitude) sent in about every a minimum period of 5

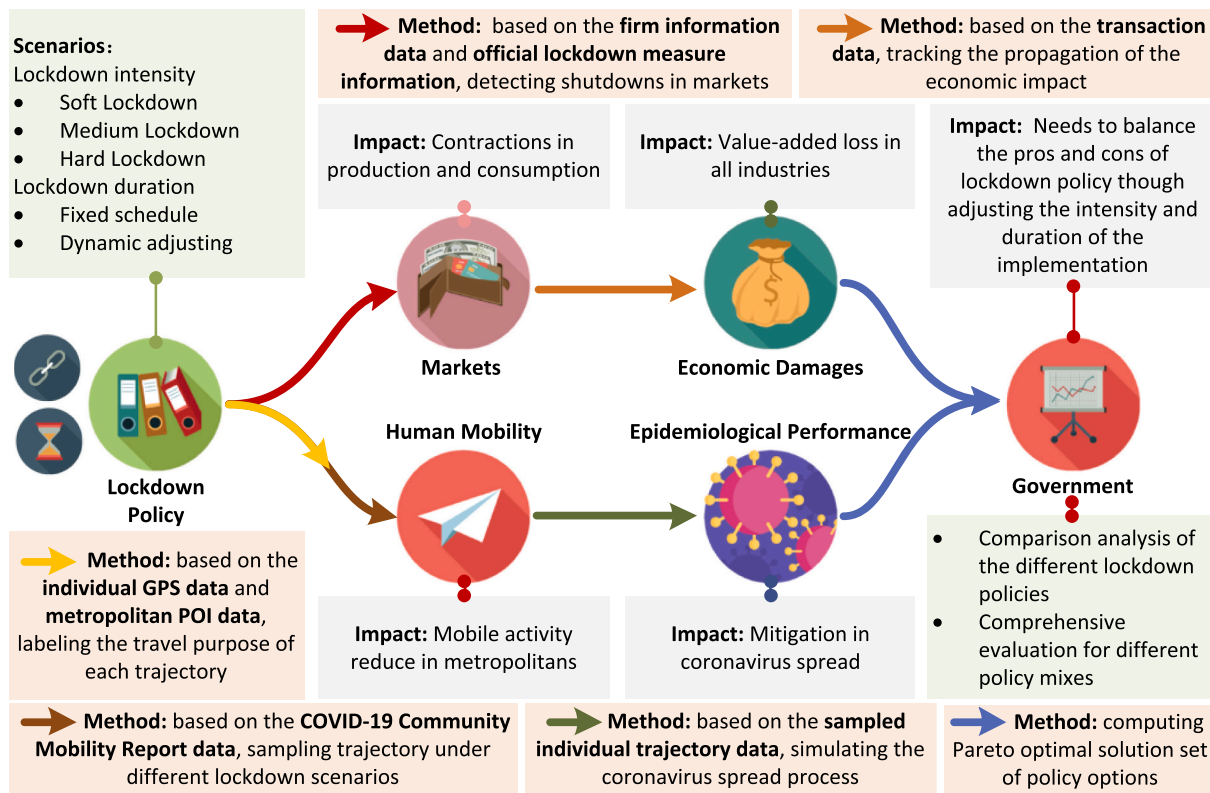


Fig. 1. Mechanism of the two-sided metropolitan lockdown modeling for analyzing epidemiological performance and economic damage. The colors of the arrows vary according to different data sources and methods. The orange panes illustrate the data sources and how the data were utilized in this research. The grey panes show the specific impacts on each component under the COVID-19 lockdown policy. The green panes represent the scenarios we set to give a comprehensive analysis of different situations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

minutes and does not include the information to specify individual. *Some applications such as “docomo map navi” service (map navi • local guide).

4.1.2. *Financial transaction records and firm information data*

Over 1.66 million transaction records from across Japan were used in this study. Each transaction record includes both sides of the transaction, transaction item category, transaction time, and transaction amount. The company information dataset includes 302,845 firms, and all of them could be matched with the transaction record data. For each company, the dataset also includes their location, industry category, capital, number of employees, etc. These firms are classified into 89 industries.

4.1.3. *Other data sets*

The average wage information of each industry is open data from a career research company, Mynavi Corporation. The consumption structure information of different demographic groups is from the Survey of Family Statistics and Consumption by the Statistics Bureau of the Ministry of Public Affairs, Japan. The survey results are from about 30,000 households. COVID-19 Community Mobility Reports is an open dataset from Google.

4.2. *Mobility-based epidemic simulation*

4.2.1. *Sampling trajectory under different lockdown scenarios*

To simulate mobility change under possible three situations during Covid-19, we simulated the human mobility data to fit the mobility before April 8th, after April 8th, and under a fully restricted situation. In every scenario, we used the Google community mobility report dataset of COVID-19 in Japan to acquire the reduction rate of each type of

activity (home places, workplaces, park places, and other activities). Moreover, we randomly selected different ratios of mobile users and every mobile user's different workdays and replaced them with home places to simulate more approximated situations with these three scenarios by Gibbs sampling.

4.2.2. *Mobility-based epidemic model*

The Greater Tokyo Metropolis contains four prefectures. Under a specific lockdown strategy, people's mobility behavior changes correspondingly. Two aspects could simulate this change: On one hand, we employed an existing grid-based epidemic model (Fan et al., 2020; Yang et al., 2020) to capture the epidemic transmission and to scale it up by ‘small-world’ model (Lin, Li, Zhao, Zhang, & Song, 2021), on the other hand, a propagation-tracking model captures the economic loss. Combining these two results (in epidemics and economics), we can evaluate the strategy and finally find the Pareto optimal solution.

4.3. *Market and economic damage simulation*

Here, based on our previous work (Zhang et al., 2021), we employed an agent-based input-output model to track the propagation of the economic impact of lockdown, as shown in Fig. 2. We took each firm as an agent of this model (we also regard the resident customers of each firm as a “firm”). The input of the model includes the closure measures and initial consumption reduction of all industries. The model has a two-step iterative procedure as follows:

4.3.1. *Transaction volume shrinkage*

According to the model input, we computed the change of scale for each firm and estimated the shrinkage in transactions between firms and customers, which is formulated as

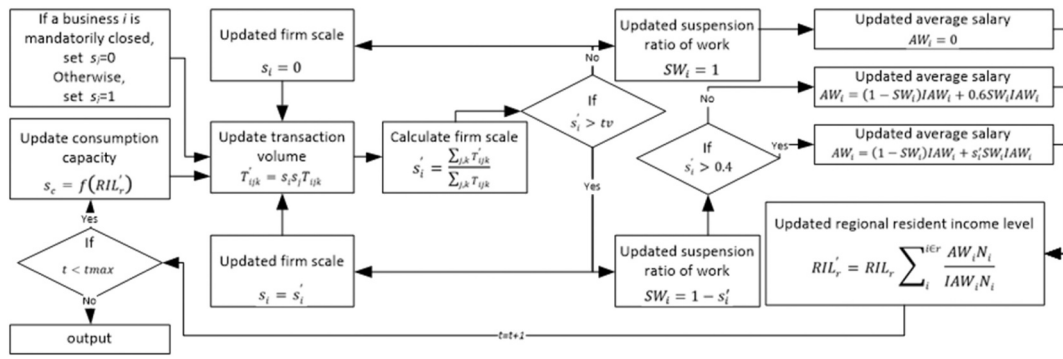


Fig. 2. Framework for Tracking propagation of the economic impact of lockdown (Zhang et al., 2021).

$$T'_{ijk} = s_i s_j T_{ijk} \quad (5)$$

where s_i, s_j are the 0 to 1 values representing the scale of firm i and j (we use s_c to represent the resident customers of each firm); T_{ijk} is the amount of transactions k between them before the iteration, and T'_{ijk} is the decreased transaction volume.

Firm scale shrinkage. In return, the scale of a firm is recalculated according to the decreased revenue, which is formulated as

$$s'_i = \frac{\sum_{j,k} T'_{ijk}}{\sum_{j,k} T_{ijk}} \quad (6)$$

where s'_i is the shrunken scale of firm i . When the firm-scale is lower than a certain threshold tv (a value with a mean of 0.2 and a variance of 0.05, this value is estimated based on macroeconomic statistics) in each simulation, it will be regarded as facing the risk of bankruptcy, and all the transactions involved will no longer be included in the next iteration. After each iteration, the model will output the changes of firm scale and gross revenue and expenditure of each industry.

4.3.2. Tracking shrinkage of resident consumption

Based on the propagation of the economic impact of lockdown, we detected the scale shrinkage of each firm. With the scale shrinkage rate of each firm, we assumed the same ratio of employees would face the risk of suspension of work, SW_i , and with the same ratio reduction in their salary (however, according to the labor law, the salary reduction rate cannot be higher than 40%). Based on the average wage of each industry, IAW_i , we calculated the average salary of the employee of firm i , AW_i :

$$AW_i = (1 - SW_i)IAW_i + s'_i SW_i IAW_i \text{ When } s'_i > 0.4 \quad (7)$$

$$AW_i = (1 - SW_i)IAW_i + 0.6SW_i IAW_i \text{ When } tv < s'_i \leq 0.4 \quad (8)$$

$$AW_i = 0 \text{ When } s'_i \leq tv \quad (9)$$

Then we could update the income level of each administrative region r , RIL_r . Based on the survey results of consumption structure in different income-level groups, we reconstructed the consumption structure of each region. We figured out the resident consumption reduction on each industry's product. Finally, we could estimate out the s_c of the residential customers, and take this into the iteration process of tracking the propagation of the economic impact of lockdown. When the iteration time exceeds the time threshold $tmax$, we output the result.

$$RIL'_r = RIL_r \sum_i \frac{AW_i N_i}{IAW_i N_i} \quad (10)$$

$$s_c = f(RIL'_r) \quad (11)$$

4.4. Pareto optimal solution

For each prefecture of Greater Tokyo Metropolis, including Tokyo, Chiba, Saitama, Kanagawa, we assigned a lockdown policy from 'S', 'M', and 'H'. S represents soft, M is for medium lockdown, and H is for hard lockdown. Thus, we have a total of 81 policy-set combinations and we simulated both the economic impact and epidemic result in each situation. Then, for each policy-set P_i , we have two dimensions' results, including economic loss EL_{i_s} and infected number IN_i . If a situation P_i is preferred to (strictly dominates) another situation P_j , written as $P_i \succ P_j$. The Pareto frontier is thus written as:

$$Pareto(P) = \{ \hat{p} \in P : \{ \bar{p} \in P : \bar{p} \succ \hat{p}, \hat{p} \neq \bar{p} \} = \emptyset \} \quad (12)$$

5. Results

5.1. Metropolitan activity clustering under different lockdown policies

The measures—compulsory or recommended confinement, curfews, and quarantines—have been in place in about 100 countries and territories. We focused on 48 major global metropolitan areas (defined by GPCI) and collected authoritative information on their lockdown policies from official government websites. We found three typical lockdown policies characterized by soft to hard degrees of lockdown (Fig. 3a). In soft-lockdown regions, governments have either light restrictions or no restrictions on their citizens. However, they have appealed to people to reduce their daily mobility and take some necessary precautions. Out of publicity impact and self-concern, people consciously control their movement, leading to a decrease in end-consumer activities. At the medium-lockdown level, governments have restricted the movement of only some citizens or for only part of the day and mandatorily closed partial sectors of high-risk service industries. In some severe pandemic regions, governments implemented the highest-level lockdown policy, announcing restrictions on the movement of all or most of their citizens around the clock in response to the virus, and only allowed necessary industries to remain open, thereby maintaining people's necessities for life. In this case, the degrees of urban mobility and economic activities sharply drop.

We found that metropolitan activity characteristics are quite different under different lockdown policies. Based on the COVID-19 Community Mobility Reports from Google, we observed the mobility changes of different travel purposes in 48 metropolitan areas (Fig. 3b). We found the significant difference between the medium and hard lockdowns is that hard lockdown more significantly limits activity in the grocery category, implying worse economic damage and a more significant decrease in mobility. Additionally, we pointed out the highly similar activity change characteristics in different metropolitan areas when local governments implement medium or hard lockdown policies. The results show that we can confidently utilize the mean value of mobility changes in medium or hard lockdown to approximately

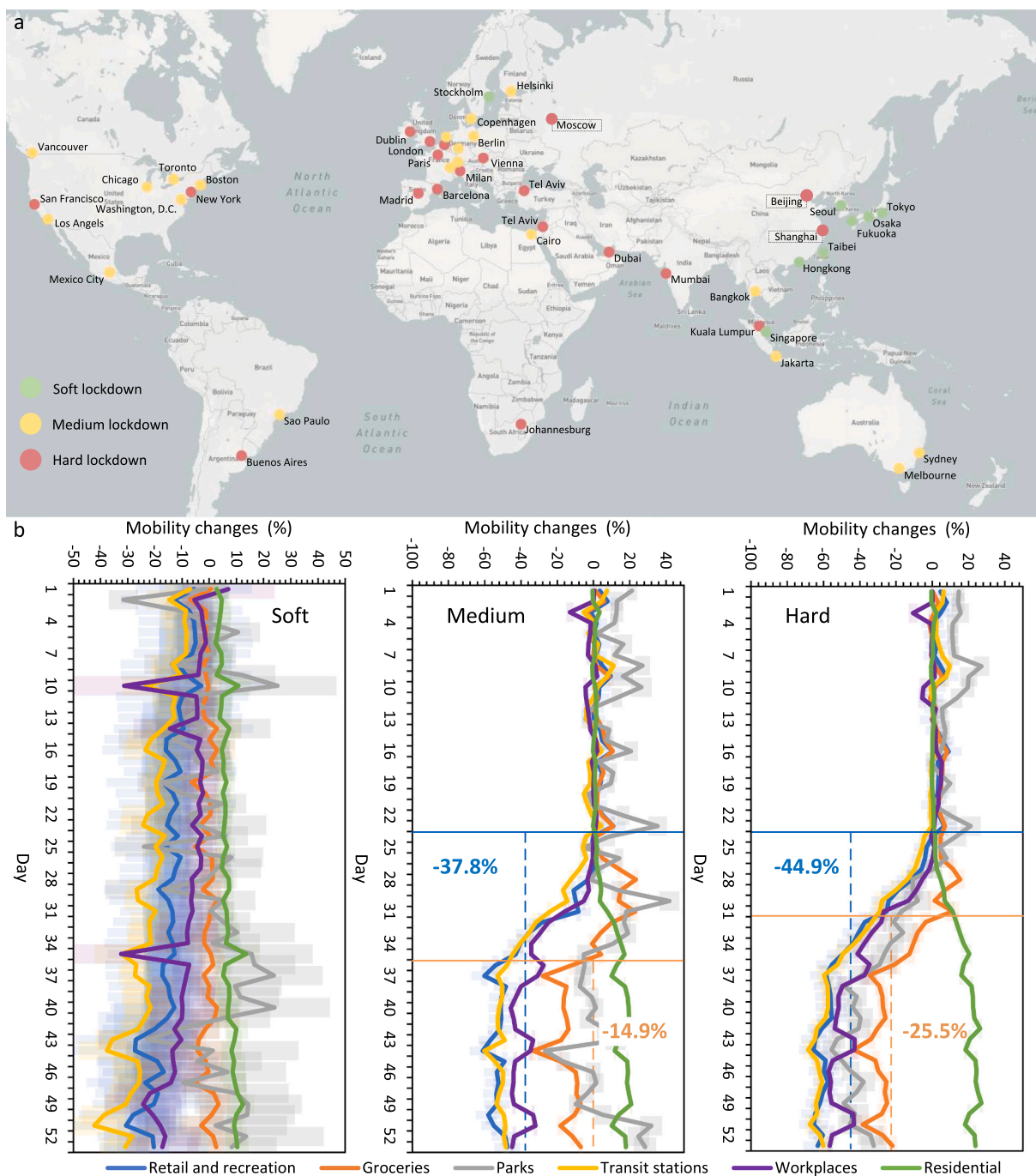


Fig. 3. Metropolitan activity characteristics under different lockdown policies before April 7th 2020. a. Classification of lockdown pattern of the 48 global major metropolitan areas. The authoritative information on their lockdown policies is from the official government websites. The metropolitan areas in red are under hard lockdown. Those in yellow are under medium lockdown, and those in green are under soft lockdown. The metropolitan areas whose names are highlighted by a dashed box represent no data on their mobility changes. b. Mobility changes of different travel purposes and under different lockdown policies. The retail & recreation line represents mobility trends for places like restaurants, cafes, shopping centers, theme parks, museums, libraries, and movie theaters. Groceries line represents mobility trends for places like grocery markets, food warehouses, farmers markets, specialty food shops, drug stores, and pharmacies. The Parks line represents mobility trends for places like national parks, public beaches, marinas, dog parks, plazas, and public gardens. The transit stations line represents mobility trends for places like public transport hubs such as subway, bus, and train stations. Workplaces line represents changes in mobility trends for places of work. Furthermore, the Residential line represents changes in mobility trends for places of residence. The transparent squares represent the confidence intervals. The blue and orange light lines represent the time when the retail and groceries mobilities reduce. The dotted lines represent the average decreased values. The transparent boxes represent the confidence intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

simulate the same situation of a metropolitan area that hard or medium policies have never controlled. However, when it comes to soft-lockdown policy, there are huge differences between different metropolitan areas. Since soft-lockdown policies do not adopt many

mandatory constraints, the mobility change will be affected more by different cultures, residents' habits, etc., compared with medium and hard-lockdown policies. The evidence behind this statement is our finding that the metropolitan areas which adopt soft-lockdown policies

in the same country show highly correspondence with human mobility changes. In contrast, metropolitan areas in different countries show much more difference in human mobility behavior.

5.2. Epidemiological performances of different lockdown policies

Here, we quantified huge gaps in epidemiological performances of different lockdown policies. We mainly focused on a representative metropolitan case—the Greater Tokyo Area, the most populous metropolitan area and the largest metropolitan economy globally—to dissect the relationship among lockdown implementation, mobility reduction, and epidemiological performance. Based on COVID-19 Community Mobility Reports from Google, POI data, and 1.3 billion metropolitan trajectory data, we simulated human mobile behaviors under different lockdown policies, as shown in Fig. 4a. It can be seen that the stricter the lockdown policy, the less the human mobility, especially in the metropolitan center area and the main commuting channel areas. The results show that a lockdown policy can effectively reduce mobility intensity, cut people's physical contact network, and theoretically mitigate the virus spread rate.

Based on the simulated mobility results and SEIR model, we tracked the spatio-temporal virus spread process and figured out the total case

number (TCN) under different lockdown policies. We took the simulated TCN based on original urban mobility data (indicating the most difficult situation) as the baseline regarding epidemiological performance. We took the decrease rate of the simulated TCN under a specific lockdown policy with the baseline's TCN as the indicator to show the epidemiological performance of the policy. From the results (Fig. 4b), the baseline's TCN is 68,627 cases. Under the soft lockdown policy, the TCN drops about 35.29% compared with the baseline. The epidemiological performance of the medium lockdown policy is about 87.35%. Additionally, the pandemic duration shortens by about 33.59% compared with the soft lockdown policy. The hard lockdown policy shows a powerful effect on preventing the virus spread, with an epidemiological performance value of 98.60%. It takes a mere 52 days to terminate the virus spread, which is a shortening effect of about 66.89%, 60.30%, and 40.23% compared with the baseline, soft, and medium lockdown policies, respectively.

5.3. Economic damage characteristics of different lockdown policies

Here, we analyzed the economic damage of one-month lockdown scenarios at different policy intensity levels (Fig. 5a). We found an approximate arithmetic progression relationship among the degrees of

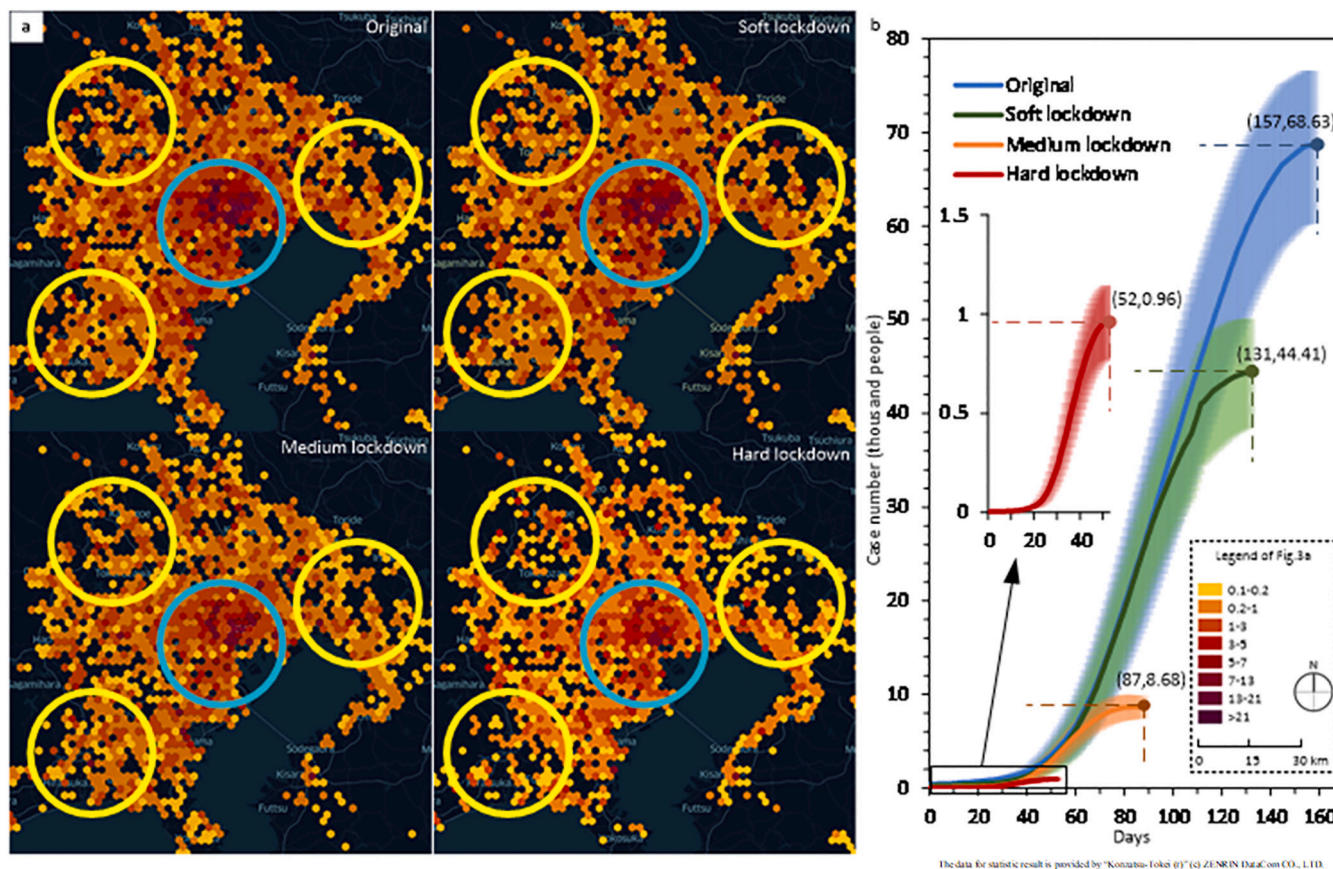


Fig. 4. Mobility intensity and epidemiological performances of different lockdown policies. a. Mobility intensity in the center area of the Greater Tokyo Area under the different lockdown policies. The dark color represents the high mobility intensity, and the light represents low intensity. The number in the legend represents the percentage of people who have ever stayed at (or passed by) a specific cell. For example, when one cell's color is the darkest one, that means more than 21% of the total population have ever stayed at (or passed by) this cell during the lockdown period. If the value is less than 0.1%, we will not show the cell's color anymore. The blue circle represents the Greater Tokyo Area center area where also has a high resident population density. The three yellow circles represent the main commuting channel areas from the surrounding cities to the Tokyo center. It is clear that with the increase of the strengthening of lockdown policy, the mobility in the center area of the Greater Tokyo Area trends to be sparser. b. Epidemiological performances of different lockdown policies or baselines. Different colors represent different lockdown policies or baselines. The ending color point of each curve represents the pandemic ending time under the lockdown policy when the TCN does not increase anymore. The value in the bracket and nearby the ending color point represents the ending time and TCN of each policy. For example, the value of the medium lockdown (87, 8.68) means the pandemic duration is 87 days, and TCN is 8.68 thousand people. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

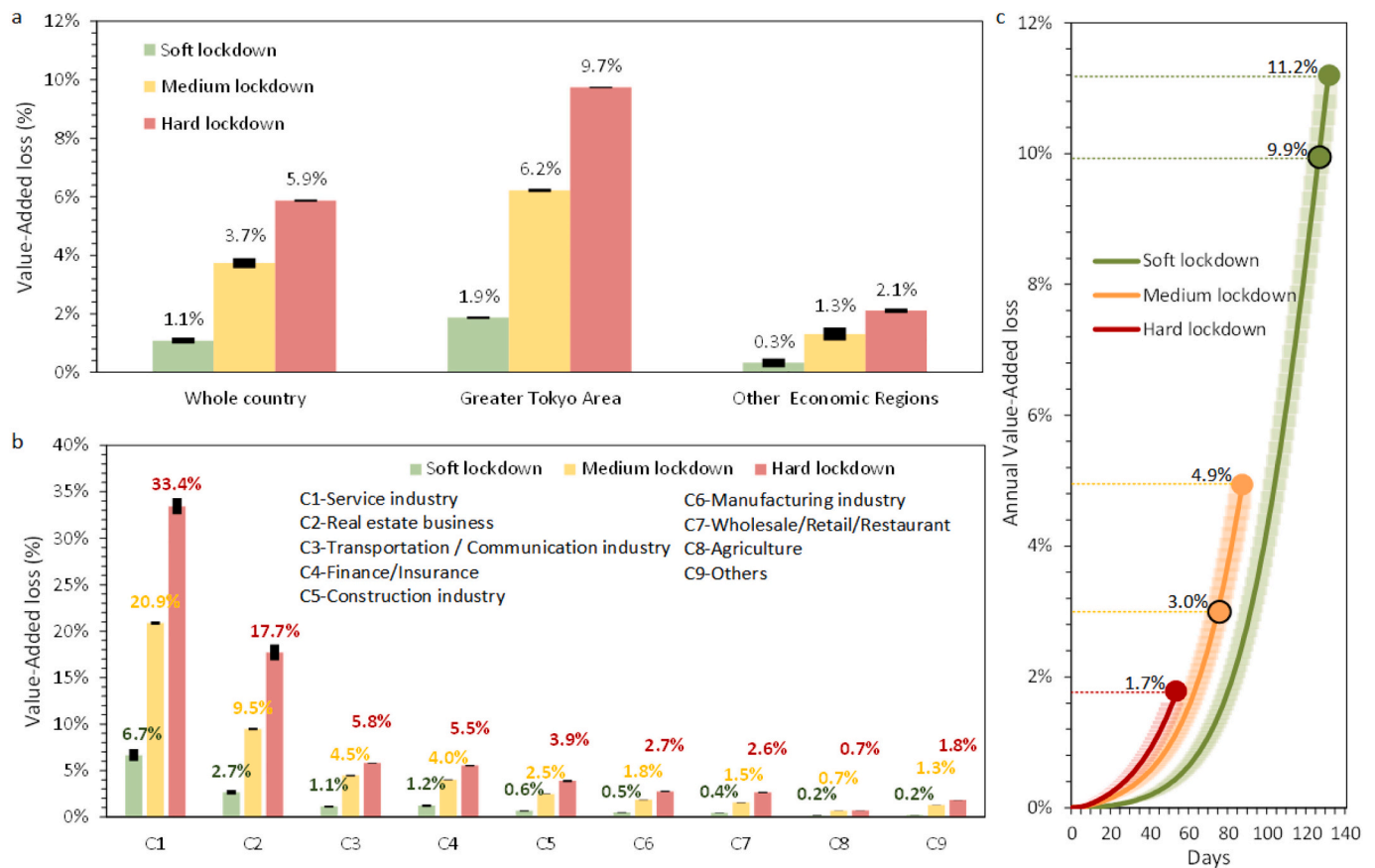


Fig. 5. Economic damage caused by fixed schedule lockdown and dynamic adjusting lockdown under different intensity level policies. a. The monthly value-added losses in different economic regions. Based on the real case of the Tokyo lockdown, we simulated the economic damage caused by a one-month lockdown (fixed schedule) under different intensity level policies. We took the value-added loss as the measurement of economic damage. b. The monthly value-added losses in 11 different industries under one-month lockdown. Black boxes represent the confidence interval of value-added loss values. c. The annual value-added losses under dynamic adjusting lockdown policies. The ending color point of each curve represents the pandemic ending time under the lockdown policy when the TCN does not increase anymore. The color points with a black frame represent the ending time under the risky decision to lift the lockdown policy as early as the TCN increase rate is less than 100 per day. The values nearby the points show the corresponding values of annual value-added losses.

economic damage associated with different lockdown policies. Due to local store closures and inactive consumption, a locked-down metropolitan area suffers severe economic damage. In the Greater Tokyo Area, value-added loss reaches 1.9%, 6.2%, and 9.7% under the soft, medium, and hard lockdown policies. Additionally, as the center of the national economy, the shutdown of the metropolitan area also brings a huge negative effect on other economic regions. Therefore, regarding the whole country, the economic damage could reach a high level. Specifically, the Greater Tokyo Area lockdown causes 1.1% value-added loss to Japan as a whole under soft lockdown, 3.7% under medium lockdown, and 5.9% under hard lockdown. In addition to the overall loss, we also indicated the economic damage in different industries (Fig. 5b). The results show that most of the metropolitan economies experience a downturn. The service industry, real-estate business, and transportation/communication industry are the top three most severely affected sectors. Additionally, as the intensity of lockdown measures increases, upstream industries are gradually impacted by economic chain reactions.

Considering that the government may extend or diminish the lockdown duration according to changes in the TCN increase, we assumed that the government would lift the lockdown policy once the TCN does not increase anymore. Under this assumption, we simulated economic damage again under a dynamic adjusting scenario (Fig. 5c). The results show that, although the hard lockdown hits the economy most severely when considering the lockdown duration, hard lockdown is the most economical measure, compared with the soft and medium lockdown

policies. The lockdown duration trends to be more sensitive to the value-added loss than lockdown intensity since the economic impacts' propagation grows exponentially during the medium-term of the damage. Therefore, with a shorter implementation duration, hard lockdown caused lighter economic damage (a 1.7% annual value-added loss) than soft lockdown, which caused up to 11.2% annual value-added loss. Moreover, suppose the government makes a risky decision to lift the lockdown policy as early as the TCN increase trends to less than 100 per day. In that case, stricter lockdown policies also have a larger economy saving space than do lighter policies.

5.4. Pareto optimal solution set of lockdown strategy

The above result proves that hard lockdown is the optimal measure in epidemiological and economic aspects when the government dynamically adjusts the lockdown duration. Meanwhile, in addition to adjusting the duration, the government also can optimize the policy mix by implementing different levels of lockdown in different regions. Here, as shown in Fig. 6a, we figured out specific strategies concerning the regional lockdown policy mix for the Greater Tokyo Area (there are four administrative regions, with one central city and three surrounding satellite city groups, which are Tokyo city, Chiba prefecture, Saitama prefecture, and Kanagawa prefecture). We found the Pareto optimal solution set of lockdown strategy includes two policy mixes: the first one is a whole-hard-lockdown mode, which has the least number of cases (H-H-H-H in Figure6a); the second one is a “basin” model, in which Tokyo

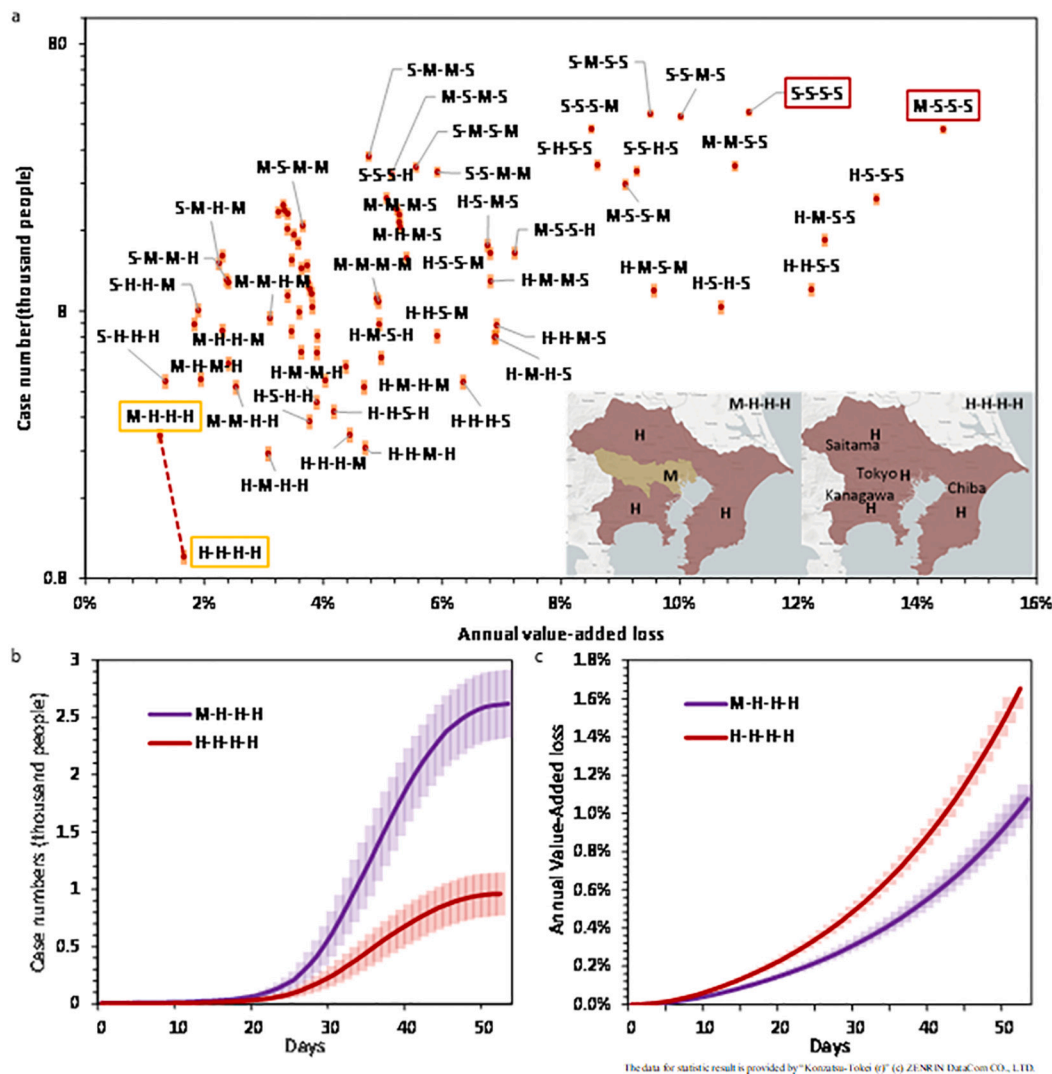


Fig. 6. Epidemiological performance and economic damage of different lockdown policy mixes. a. The exhaustive examples of the policy mix. Each point represents a policy mix plan, and the data label of the point shows the description of the policy mix. S represents soft lockdown, M is for medium lockdown, and H is for hard lockdown. The first letter represents the policy level in Tokyo city, the second is for Chiba prefecture, the third is for Saitama prefecture, and the last is for Kanagawa prefecture. For example, H-M-S-S means Tokyo city implements hard lockdown, Chiba prefecture implements medium lockdown, Saitama and Kanagawa implement soft lockdown. The orange boxes show the confidence intervals for both epidemiological performance and economic damage. The red dotted line connects the Pareto optimal policy mix solutions. The maps show the implementations of the optimal policy mixes. As the same, red is for hard lockdown, orange is for medium lockdown, and green is for soft lockdown. b. Epidemiological performances of different lockdown policies in the Pareto optimal solution set. Different colors represent different lockdown policies. c. The annual value-added losses under dynamic adjusting lockdown policies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

city chooses medium lockdown, but the surrounding satellite cities choose hard lockdown (M-H-H-H in Figure 6a). Although the “besieging” model caused 1.6 thousand cases more than did the whole-hard-lockdown mode (Fig. 6b), the former strategy minimizes the economic damage from 1.7% to 1.1% (Fig. 6c). On the contrary, the whole-soft-lockdown mode is the worst strategy in terms of epidemiological performance (S-S-S-S in Fig. 6a); and the “volcano” mode, i.e. implementing medium lockdown in Tokyo city and implementing soft lockdown in the surrounding satellite cities, causes the most significant economic damage (M-S-S-S in Fig. 6a). These results reveal that cutting off intercity commuting from surrounding satellite cities to the central city is significant in mitigating the virus pandemic. When considering reducing economic damage, moderately easing the lockdown degree in the central city while strictly controlling the external input is also an optimal strategy.

5.5. Reliability discussion

Based on our fine-grained bi-side simulation model, taking the Greater Tokyo Metropolis as a case study, we found that the lockdown policies are effective in reducing the number of cases; specifically, lockdown policies decrease the case number by 35.29%, 87.35%, and 98.60%, respectively, under the soft, medium, and challenging implementation levels. At the same time, the one-month lockdown under these three policies causes 1.1%, 3.7%, and 5.9% value-added loss in Japan. Further, we found that H-H-H-H (all high-level) and M-H-H-H (Medium in center but high-level in surround) mode are two optimal lockdown policy strategies in terms of optimal policy. The fundamental mechanism of the above phenomenon - the hard lockdown is the most economical measure compared with the soft and medium policies - is the duration period, since the hard lockdown can quickly terminate the pandemic.

Alvarez (2020) employed an SIR epidemiology model and a linear

economy model to formalize a simple optimal control model. Taking America as a case study, they concluded that the optimal policy prescribes a severe lockdown beginning two weeks after the outbreak, covers 60% of the population after a month, and is gradually withdrawn, covering 20% of the population after three months. Welfare under the optimal policy with testing is higher, equivalent to a one-time payment of 2% of GDP. As a comparison, our optimal lockdown strategy can reach a 1.1% economic loss. Although we took different regions as the case study, we believe that these results are comparable since the total population of Japan and America is of the same order of magnitude. Besides, Karin et al. (2020) employed SEIR models and stochastic network-based models for epidemics, concluded that a cyclic schedule of 4-day work and 10-day lockdown, or similar variants, can prevent a resurgence of the epidemic while providing part-time employment, which will subside the economic loss. However, they did not give any quantitatively economic analysis, only analyzed it based on experiences.

In general, our proposed method shows reliability – we examined our results by ground-truth data, and it achieves high accuracy with a 5.67% relative mean deviation (Fig. 7); spatialization – we employed big and detailed data (including 1.3 billion metropolitan trajectory data and 1.2 million financial transaction data, etc.) for individual-level activity tracking, instead of a macro statistical number; and reality - employed the ‘small-world’ model (Lin et al., 2021) to map the virtual data (part of population) to the real world (total population).

6. Conclusion

How to balance epidemiological performance versus economic damage caused by lockdown policies is one of the thorniest puzzles for governments during the COVID-19 pandemic and in future similar crises, if, unfortunately, they occur. Lockdown policies strongly restrict human mobility, which hence results in economic damage. A comprehensive quantificational analysis of the pros and cons of lockdown policies is enormously instructive to help governments cope with crises, save people's lives, and mitigate economic damage, but significant research gaps exist. Based on the global COVID-19 community mobility data, we figured out three types of metropolitan lockdown policies. Then we focused on how epidemiological performance versus economic damage differs under these different policies. We dissected a case study representative in the global context, the Greater Tokyo Area, basing that study on various datasets, including 1.3 billion metropolitan trajectory data, 1.2 million financial transaction data, etc. Firstly, we simulated human mobile behavior under lockdown and then tracked the spatio-temporal virus spread process and figured out the TCN under different lockdown policies.

On the other hand, we tracked the capital flows on the end-consumer and business networks in all industries. We then simulated the negative propagation of the economic impacts of different lockdown policies. We found that the lockdown policies effectively reduce the number of cases; specifically, lockdown policies decrease the case number by 35.29%, 87.35%, and 98.60%, respectively, under the soft, medium, and hard implementation levels. At the same time, the one-month lockdown under these three policies causes 1.1%, 3.7%, and 5.9% value-added loss in Japan. However, it is surprising that the hard lockdown is the most economical measure when considering pandemic duration compared with the soft and medium policies since the hard lockdown can quickly terminate the pandemic. Finally, we helped the government figure out two Pareto optimal solutions for lockdown strategy. From the results, we argued that: 1. Cutting off intercity commuting from surrounding satellite cities to the central city is significant in epidemiological and economic aspects; 2. Moderately easing the lockdown degree in the central city while strictly controlling the external input is also an optimal strategy to reduce economic damage while bringing the pandemic under control.

With the support of reliable and fine-grained datasets and the proposed comprehensive analysis framework, we believe our proposed

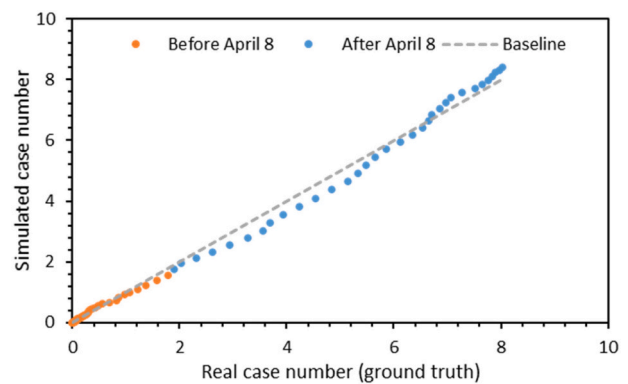


Fig. 7. Ground-truth Study of the Proposed Model. We validate our epidemic simulation result with the ground-truth accumulated case number from January 24th to May 8th, 2020, in the Greater Tokyo area. There is a soft lockdown policy in Greater Tokyo Metropolis before April 8th, when the Japanese government announced the state of emergency (orange points). After April 8th, the policy came to medium lockdown (blue points). Thus, we conduct the simulation corresponding to reality. The result reaches high accuracy with a 5.67% relative mean deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

findings can offer fundamental support for guiding governments in designing economic and social policies in the context of this particular stage. Additionally, the proposed methods are not limited to the studied COVID-19 lockdown case but are also practical for analyzing global cases of potential future waves of COVID-19 and similar crises.

Despite those strengths, shortcomings remain. Due to the limitation of data, what we have done is all about the situation in Japan. It is still unknown whether and to what extent regional differences may influence the optimal strategy. Besides, this study ignored imported people from abroad, focusing on the domestic population, ignoring some errors. In the future, we plan to expand the epidemic-economic model to a disaster-economic model and evaluate the method by data in more cities around the world.

CRedit authorship contribution statement

H.Z. and J.Y. designed the study. H.Z., Z.Z., and P. L. developed the algorithms and performed the analysis. H.Z., W.L., J.Y., X.S. and R.S. led the writing of the paper. H.Z. and P.L. revised the manuscript.

Declaration of competing interest

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

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