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Lockdowns require geographic coordination because of the propagation of economic effects through supply chains[1]

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Abstract

To prevent the spread of COVID-19, many governments have imposed regional or national lockdowns, resulting in economic stagnation across broad areas because the shock of the lockdown propagated to other regions through supply chains. Using supply-chain data of 1.6 million firms in Japan, this study examines how the economic effect of lockdowns in multiple regions interact with each other, particularly focusing on possible differences between synchronous and asynchronous lockdowns. Our major findings are twofold. First, when multiple regions coordinate the timing of their lockdowns, particularly when they impose and lift lockdowns synchronously, their economic losses are smaller than when they do so asynchronously without any coordination. Second, the benefit of synchronous lockdowns in multiple regions is larger when they are connected through a larger number of supply-chain links. Our results suggest a need for policy coordination across regions and countries when lockdowns are imposed.

Keywords: COVID-19; lockdown; coordination; supply chains; simulation; propagation
JEL classification: L14

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1 Introduction

To prevent the spread of COVID-19 starting in late 2019, many governments imposed "lockdown" on cities, regions, or entire countries, shutting down or shrinking economic and social activities. In April 18, 2020, when the first wave of COVID-19 severely hit the world, 158 countries required closing of workplaces at least for some sectors or categories of workers [Hale et al., 2020] (Figure 1). The number of locked-down countries declined to 95 in October 16, 2020 because some countries lifted restrictions, while it increased again to the second peak of 121 in April 11, 2021.

Restrictions associated with lockdown reduce the economic activity of regions in lockdown because of requirements of closing workplaces and shortage of labor in workplaces. More importantly, the negative economic effect of lockdown propagates through supply chains, i.e., supplier-client relationships among firms, to other regions that are not necessarily locked down. There are two channels of such propagation, as theorized in Barrot and Sauvagnat [2016], Carvalho et al. [2016], and Bonadio et al. [2020]. First, when a firm shrinks its production due to lockdown, its client firms may have to reduce production because of lack of supply of intermediate goods and services. Second, its suppliers also reduce production because of demand shortages.

The propagation of economic shocks because of natural disasters through supply chains is evidenced in the academic literature, utilizing past disasters in the United States [Barrot and Sauvagnat, 2016, Kashiwagi et al., 2018] and the Great East Japan earthquake in 2011 [Boehm et al., 2019, Carvalho et al., 2016, Inoue and Todo, 2019a,b]. More recent works estimate the economic effect of anti-COVID-19 lockdown while accounting for supply chain propagation using input–output (IO) linkages at the country-sector level [Bonadio et al., 2020, Guan et al., 2020, McCann and Myers, 2020, McKibbin and Fernando, 2020, Arriola et al., 2020, Haddad et al., 2020]. Moreover, the propagation effect of lockdown in Tokyo is estimated, using data for Japan with detailed supply-chain information at the firm level [Inoue and Todo, 2020].

However, one important aspect not fully examined in the literature is how the economic effect of lockdown in different regions and countries interacts with each other and whether the interaction magnifies the total economic effect of lockdown. If this interaction occurs, coordination among policies in different regions and countries may alleviate the magnification of the economic effect, as discussed in the literature on inter-regional and international policy coordination in the presence of spillover effects [Kremer and Miguel, 2007, Taylor, 2013].

The experience of Sweden in the early period of the COVID-19 pandemic suggests the need for policy coordination. Sweden did not require closing of workplaces in the first wave of the COVID-19 pandemic in 2020 to minimize the economic effect of the pandemic, while its neighboring countries, such as Finland, Norway, and Denmark, did so. Later, Sweden required closing of workplaces in some sectors from November, 2020 to May, 2021, together with its neighboring countries. While the growth rate of Sweden's gross domestic product (GDP) during the first wave was comparable to that of its neighbor countries', it achieved a higher GDP growth in the synchronous lockdown than in the asynchronous lockdown and its neighboring countries [Eurostat, Hale et al., 2020]. These experiences of Sweden motivated us to examine the difference in the economic effect between synchronous and asynchronous lockdown in particular.

A limited number of studies discuss the need for coordination of policies related to COVID-19. For example, Ruktanonchai et al. [2020] demonstrate that non-pharmaceutical interventions, such as socialdistancing and lockdown, need coordination across countries to maximize their effectiveness at reducing transmission of COVID-19. They find that simultaneous implementation and relaxation of interventions is effective. Acharya et al. [2020] find that although international coordination of policies for domestic containment of infection and trade tariffs results in better health and economic outcomes, higher tariffs than optimal are imposed in the market equilibrium because of a prisoners' dilemma situation. Bonadio et al. [2020] argue the difficulty of coordination because of public opinions that are not necessarily based on scientific evidence. However, no study has examined the need for coordination when multiple governments impose lockdown to minimize their negative economic effect, incorporating its propagation through supply chains, except for Inoue et al. [2020] who focus on the effect of lifting, rather than imposing, lockdown.

To fill the gap, this study investigates the effect of regional coordination of lockdown on production, simulating an agent-based model of production based on supply-chain data of 1.6 million firms in Japan. Agent-based models that incorporate interactions of agents through networks have been widely used in social science recently [Axtell et al., 2006, LeBaron and Tesfatsion, 2008, Gomez and Lazer, 2019]. Specifically, we compare production loss from "synchronous lockdown" imposed and lifted in multiple prefectures simultaneously and that from their "asynchronous lockdown" imposed and lifted in different timing.

We hypothesize that synchronous lockdown leads to a smaller loss of production in the whole economy than asynchronous lockdown. This is because in asynchronous lockdown, firms in different locked-down prefectures that are linked through supply chains are affected by the direct effect of lockdown in their own prefecture and additionally by the propagation effect from lockdown in other prefectures, while in synchronous lockdown, firms in locked-down prefectures are already affected by the direct effect and may not be substantially affected by the propagation effect. However, this hypothesis may not be supported, depending on the structure of supply chains across regions [Acemoglu et al., 2015, 2020, Inoue and Todo, 2019a,b], as explained in detail in Section 2.4 later. Therefore, we will particularly look into the role of the structure of supply chains, such as the strength of supply chain links between prefectures, in the need for the policy coordination.

The rest of the paper is structured as follows. Section 2 describes data and simulation methods, and Section 3 presents the simulation results and discussion. Section 4 concludes.

Figure 1: The number of countries that required closing of workplaces for some sectors or categories of workers or all but essential workplaces. Source: Hale et al. [2020].

2 Methods

2.1 Data

This study uses data collected by Tokyo Shoko Research (TSR), particularly, the Company Information Database and Company Linkage Database. The former dataset contains attributes for each firm, including its address, industry classification, and sales, while the latter consists of its clients and suppliers in Japan. We specifically use the data for 2016, the latest available year at the time of this study. The number of firms in the dataset is 1,668,567, and the number of supply chain links is 5,943,073. The data cover most firms in Japan, except for micro enterprises, and most major supply chain relationships between them. Because sales of each supplier from each client and final consumers are not available in the data, we estimate the transaction volume between each firm pair using that between each sector pair taken from the 2015 Input-Output (IO) Tables for Japan [Ministry of Economy, Trade and Industry, Japan, 2015], as described in detail in Supplementary Information A.1. In this estimation process, we classify firms into 187 industries according to the IO Tables. Some firms are dropped from the sample because they lack total sales in the data. Accordingly, the number of firms in the sample is 966,627 whereas the number of links is 3,544,343.

Several characteristics of supply chains in the sample as a network should be noted. First, the number of links of each firm, or the degree, follows a power-law distribution [Inoue and Todo, 2019a], as is commonly observed in many natural and social networks [Barabási, 2016]. Second, the average number of steps between firms, or the average path length in supply chains, is 4.8. Compared with the number of firms in the network, this is surprisingly small. Such a network is commonly called a small-world network [Watts and Strogatz, 1998]. Finally, using the same TSR dataset, previous studies [Inoue and Todo, 2019a, Fujiwara and Aoyama, 2010] find that 46–48% of the firms are included in the giant strongly connected component (GSCC), in which all firms are directly or indirectly connected through directed links. In other words, approximately a half of the firms are involved in numerous cycles in the GSCC.

Accordingly, unstable behaviors would emerge because of the many feedback loops of the supply chains, as the literature suggests [Inoue and Todo, 2019a].

2.2 Model

Overview and key assumptions

We employ the dynamic agent-based model of Inoue and Todo [2019a,b, 2020], which is an extension of the model of Henriet et al. [2012]. In the model, firms are linked through supply chains. Specifically, each firm utilizes a fixed amount of labor and various intermediates provided by its suppliers, produces its product, and sells it to client firms and final consumers. Supply chains are pre-determined by the data and do not change: Even after disruption of supply chains, firms cannot find any new supplier or client.

We assume a Leontief production function where production of one unit of a product requires a certain amount of each intermediate good and labor. The proportion of each intermediate required for production of a product by a particular firm is predetermined by the data. Products are assumed to be specific to each sector that is determined by the IO tables [Ministry of Economy, Trade and Industry, Japan, 2015], and hence a firm's suppliers in the same sector provide the same intermediate product. Each firm holds an inventory of intermediates from suppliers in case of shortage of supplies, whereas it holds no inventory of its own product and immediately delivers it to clients.

In this model, firms are not maximizing their profits, and hence there is no price or market mechanism. Rather, each firm demands a certain amount of intermediates to each supplier to satisfy the demand for its product from its clients and consumers. In the initial period before lockdown, or on day 0, the demand for and supply from any firm are equal to each other. At the end of day 0, lockdown is imposed in some regions (prefectures in the case of Japan). Accordingly, the production capacity of affected firms declines, and thus the demand for the product of a firm may surpass its supply. In that case, the firm rations its product to its suppliers and consumers according to a rule based on their pre- and post-lockdown demand, as explained later in detail.

An overview of the model is depicted in Figure 2. The source code to execute the model is on GitHub, as is the correspondence between the code and the model[§].

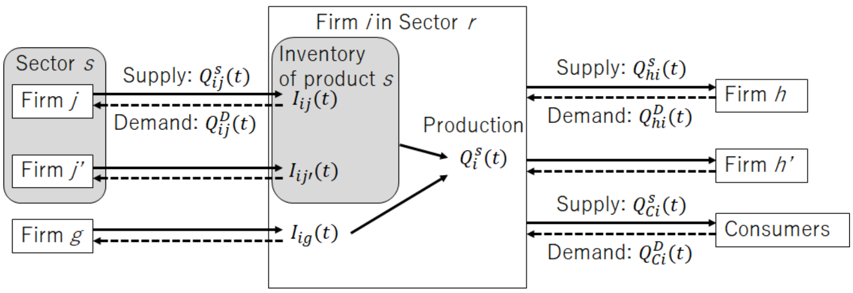

Figure 2: Overview of the agent-based model. Products flow from left to right, whereas orders flow in the opposite direction. The equation numbers correspond to those in the main text.

[§]The URL for an anonymized repository is `https://anonymous.4open.science/r/ProductionNetworkSimulator-461E`

Demand and supply in the pre-lockdown period

Let us now describe the economy without any lockdown at the initial day, or on day 0. We denote the daily supply of the intermediate product of supplier i to client h on day t by $Q_{hi}^S(t)$ and the daily supply of firm i to the final consumers by $Q_{Ci}^S(t)$. Then, the production of firm i on day 0, which is assumed to be equal to the total demand for i's product initially, is given by

$$Q_i^S(0) = \Sigma_h Q_{hi}^S(0) + Q_{Ci}^S(0). \tag{1}$$

We assume that each firm predicts that the demand for its product on day t is equal to that on the previous day, $Q_i^D(t-1)$. To meet the demand, firm i needs supplier j's product of an amount $Q_{ij}^S(0)Q_i^D(t-1)/Q_i^S(0)$ because $Q_{ij}^S(0)$ represents the supply of j's product to i in the initial state and $Q_i^D(t-1)/Q_i^S(0)$ is the ratio of the current demand to the initial supply.

In addition, firms demand for intermediates for inventories to prepare for supply chain disruptions. Specifically, firm i has an inventory of the intermediate produced by firm j at the beginning of day t (i.e., before firm i uses the intermediate for production on day t), $I_{ij}(t)$ and aims to restore this inventory to a level equal to a given number of days n_i of the utilization of supplier j's product, $n_i Q_{ij}^S$. We assume that n_i is randomly determined by a Poisson distribution where the mean is n. Following Inoue and Todo [Inoue and Todo, 2019a], n is set to 9 such that the model replicates the economic reaction to the Great East Japan earthquake. In addition, to avoid a bullwhip effect, i.e., large fluctuations across simulations, n_i is assumed to be equal to or larger than 4.* When the actual inventory $I_{ij}(t)$ is smaller than its target $n_i Q_{ij}^S$, firm i increases its inventory gradually by $1/\tau$ of the gap in one day such that it reaches the target in τ days. We assume that $\tau = 6$, following Hallegatte [2008].

Combined with the two purposes, i.e., production and inventory, firm i's demand for the product of its supplier j on day t, denoted by $Q_{ij}^D(t)$, is given by

$$Q_{ij}^D(t) = Q_{ij}^S(0)\frac{Q_i^D(t-1)}{Q_i^S(0)} + \frac{1}{\tau}\left[n_i Q_{ij}^S(0) - I_{ij}(t)\right]. \tag{2}$$

Accordingly, total demand for the product of supplier i on day t, $Q_i^D(t)$, is given by the sum of total demand from its client firms and final consumers:

$$Q_i^D(t) = \Sigma_h Q_{hi}^D(t) + Q_{Ci}^D. \tag{3}$$

On day 0, we assume that the level of inventory is equal to its target level ($n_i Q_{ij}^S(0) = I_{ij}(0)$) and that the demand for the product of firm i on the previous day is equal to its production ($Q_i^D(t-1) = Q_i^S(0)$). Therefore, there is no excess supply or demand on day 0: $Q_{ij}^D(0) = Q_{ij}^D(0)$ and $Q_i^D(0) = Q_i^D(0)$

*Although it is preferable to obtain n_i for each firm from data because the inventory size may critically affect the magnitude of the effect of propagation of shocks [Pichler et al., 2021, Reissl et al., 2021], our data do not include such information. However, the main purpose of the present paper is to compare the propagation effect between coordinated and uncoordinated restrictions across regions, not to the size of the propagation effect. Therefore, our use of calibrated values of n_i is justified.

Reduction in production capacity because of lockdown

Now, suppose some regions of the economy imposes lockdown at the end of day 0. The lockdown shrinks the production capacity of firms in two ways. First, because the lockdown requires some workplaces in the regions to be closed and some workers to stay home and thus leads to shortage of facility and labor. If firm i is in a locked-down region, its production capacity is assumed to decline by the proportion $\delta_{sr(i)}$ that is determined by the sector s and region r of the firm as defined later in Section 2.3. In other words, the maximum production assuming no supply shortage but only labor shortage of firm i on day $t(\geq 1)$, $\bar{Q}_i^S(t)$, is given by

$$\bar{Q}_i^S(t) = Q_i^S(0)(1 - \delta_{sr(i)}). \tag{4}$$

Second, the production of firm i is also limited by shortage of supplies when its suppliers are affected by the lockdown. When facing shortage of supplies from supplier j, firm i can use its inventory of the supplies. Because firms in the same sector produce the same product, firm i can use the intermediate good from any supplier in the same sector interchangeably. Therefore, the maximum possible production of firm i limited by the product inventory of the sector-s intermediate on day t, $\bar{\bar{Q}}_{i(s)}^S(t)$, is given by

$$\bar{\bar{Q}}_{i(s)}^S(t) = \frac{\Sigma_{j\in s} I_{ij}(t)}{\Sigma_{j\in s} Q_{ij}^S(0)} Q_i^S(0), \tag{5}$$

where $\Sigma_{j\in s} I_{ij}(t)$ is firm i 's total inventory of the intermediate produced in sector s on day t, and $\Sigma_{j\in s} Q_{ij}^S(0)$ is the amount of intermediate s required to produce the initial production level of firm i.

Then, we can determine the maximum production of firm i on day t, considering two constraints faced by i:

$$Q_{\max i}^S(t) = \text{Min}\left(\bar{Q}_i^S(t), \text{Min}_s(\bar{\bar{Q}}_{i(s)}^S(t))\right). \tag{6}$$

Therefore, the supply of firm i on day t is either determined by the maximum production capacity when it is smaller than the demand or otherwise by the demand and thus given by

$$Q_i^S(t) = \text{Min}\left(Q_{\max i}^S(t), Q_i^D(t)\right). \tag{7}$$

Rationing of production

When the total demand for firm i's product is greater than its production capacity, the firm cannot satisfy the demand of its clients and consumers and thus have to ration its production to them, following Inoue and Todo [2019a]. Suppose that firm i has clients $j \in \{1, ..., J\}$ and the aggregate of final consumers. Let us denote the ratio of the demand of client j for the product of firm i to its initial demand by $q_{ji}^D(t) \equiv Q_{ji}^D(t)/Q_{ji}^S(0)$ and the corresponding ratio for the demand of final consumers by $q_{Ci}^D(t) \equiv Q_{Ci}^D(t)/Q_{Ci}^S(0)$.

The supply to each client and consumer is determined by the following steps. At the beginning of step x, the amount of production that has not been rationed and remains to be rationed is defined as $Q_i^R[x]$. We also define the minimum ratio of the current demand to the initial demand by $q_{\min}^D(t) \equiv \text{Min}(q_{ji}^D(t), q_{Ci}^D(t))$. In the first step where $x = 1$ and $Q_i^R[1] = Q_i^S(t)$ by definition, if

$$Q_i^R[x] \geq q_{\min}^D(t) Q_i^D(t), \tag{8}$$

firm i rations to each client firm and consumer the amount of its demand multiplied by the minimum demand ration $q^D_{\text{min}}(t)$. The remaining of the production, $Q^R_i[x+1] = Q^R[x] - q^D_{\text{min}}(t)Q^D_i(t)$, is handed over to the second step. In the second step, a client firm or the aggregate consumer that satisfies its demand (or whose rate of the current demand to the initial demand is at the minimum) is dropped. By contrast, if equation (8) does not hold in the first step, firm i rations to each client and consumer the amount of its demand multiplied by the ratio of the remaining production to demand defined by $q^D_{\text{r-d}_i} \equiv Q^R_i[x]/Q^D_i(t)$. Accordingly, the remaining of the production $Q^R_i[x+1]$ is equal to $Q^R_i[x] - q^D_{\text{r-d}_i}(t)Q^D_i(t)$ and handed over to the second step. In the further steps, we will repeat this procedure until $Q^R_i[x]$ becomes zero. In this rationing process, any of the clients obtains a positive amount of the production, whereas clients with a smaller $q^D_{ji}(t)$, i.e., those that demand less after the lockdown relative to the pre-lockdown demand, can meet a larger portion of their demand.

Under this rationing policy, the inventory of firm j's product held by firm i on day $t+1$ is updated to

$$I_{ij}(t+1) = I_{ij}(t) + Q^S_{ij}(t) - Q^S_{ij}(0)\frac{Q^D_i(t-1)}{Q^S_i(0)}. \tag{9}$$

This equation combined with equations (2) and (7) determines the demand of firm i for the intermediate good supplied by firm j on day $t+1$, $Q^D_{ij}(t+1)$, and the total demand for firm i's product $Q^D_i(t+1)$. The supply of firm i on day $t+1$, $Q^S_i(t+1)$, is then determined by equations (4-7).

In the model, the production shock by lockdown propagates upstream to clients because of shortage of supply and downstream to suppliers because of shortage of demand. However, because the supply shortage can be mitigated by inventory and supplier substitution, downstream propagation is likely to be slower than upstream propagation.

Caveats of the model

We build this model to simulate the behavior of the shock propagation. However, because our model is quite simple, some factors that may potentially affect the propagation are not incorporated.

First, the model does not consider prices or markets. If the supply of a product does not meet its demand, its price increases so that client firms reduce its demand. We do not consider this market mechanism but assume rationing rules to deal with excess demand for simplicity. Moreover, in the rationing rules, we ignore possible long-term contracts between suppliers and their clients that determine a specific amount of transactions between them. Second, our model does not consider exogenous changes in final consumption because of lockdown, although such changes, for example, larger demand for essential products and smaller demand for tourism, were observed in practice. However, it should also be mentioned that our model considers changes in demand for intermediate goods because of lockdown and that the final consumption of each product changes because of the reduction in its production. Third, we assume no labor mobility across firms although lockdown leads to a reduction in labor supply in each firm to a certain degree. Fourth, we assume that firms cannot find any new suppliers when facing a supply shortage from their current suppliers, i.e., supply chains are fixed over time. Because of these shortcomings of the model above, the results of our model should be interpreted as results of lockdown in the short run.

Another important issue is that our simulation analysis includes firms in the service sector and hence assumes that inputs from the service sector can be stored as inventory, as those from the manufacturing sector. This assumption is mostly because of technical reasons: If there is no inventory of certain products, a bullwhip effect is likely to occur in the simulation and the results fluctuate substantially. To avoid this, we keep this unrealistic assumption. In addition, the sectoral classifications used in this study include the wholesale and retail sectors. One problem of dealing with wholesalers and retailers in the methodology above is that we assume any wholesaler sell the same sector-specific product to its retailer, although they may sell different products, such as computers and automobiles, in practice. This assumption may result in easier substitution among wholesalers in our simulations. Moreover, the TSR data report only the location of the headquarters of each firm, not the location of its branches. Because firms' headquarters are concentrated in Tokyo, production activities in Tokyo and thus the propagation effect of lockdown in Tokyo are most likely to be overvalued in our analysis. Finally, we ignore international supply chain links in our simulations, which is of great interest in practice [OECD, 2021], although the model can be expandable to consider international supply chains [Inoue, 2021]. In the present paper, because of lack of data on international supply chains, we stick with domestic supply chains.

2.3 Lockdown in Japan

In Japan, "lockdowns" or social and economic restrictions to prevent the spread of COVID-19 were imposed at the prefecture level by declaring the state of emergency [The Prime Minister of Japan and His Cabinet, 2020]. It was first declared on 7 April 2020 in seven prefectures, Tokyo, Osaka, Fukuoka and their neighboring prefectures, because these jurisdictions are metropolitan areas and thus showed a large number of confirmed COVID-19 cases. On 16 April, the state of emergency was expanded to all 47 prefectures. Then, it was lifted for 39 prefectures on 14 May, for an additional three on 21 May, and finally, for the remaining five prefectures on 25 May. After that, the state of emergency was declared and lifted in some prefectures occasionally, as subsequent waves of COVID-19 came back and forth.

One notable characteristic of the state of emergency in Japan is that the government cannot require people to stay home or businesses to close down with enforcement but can only request to do so. Therefore, the level of restrictions in lockdown is lower in Japan than in other countries. However, under strong social pressure in Japan, people and businesses voluntarily restrict their activities to some extent. Using data from smartphones, Yabe et al. [2020] find that human mobility in Tokyo declined by 50% one week after the first state of emergency. Therefore, we use the term "lockdown" to express the state of emergency throughout this paper, although lockdown usually implies strict and enforceable restrictions.

The human mobility data suggest that economic activities in the state of emergency suffer from labor shortage because some workers must stay at home. This is consistent with the assumption of our model in Section 2.2 that the production capacity of firms declines because of labor shortage. However, we cannot observe the extent to which each firm or sector reduced its production capacity in the actual state of emergency. Therefore, we assume the rate of reduction in production capacity for each sector by modifying that in the literature [Guan et al., 2020, Bonadio et al., 2020, Dingel and Neiman, 2020] to fit the case of Japan.

Following Bonadio et al. [2020], we first assume that the sector-specific reduction rate is determined by the degree of exposure to COVID-19 multiplied by the share of workers who cannot work at home. The degree of exposure to COVID-19 is taken from Guan et al. [2020] and set to be 0.1 for lifeline sectors, 0.5 for some low-exposure sectors, and 1 for other ordinary sectors. The share of workers working from home for each sector is taken from Dingel and Neiman [2020] who rely on data for the US. For example, in sectors in which exposure to the virus is low (50%) and 13.4% of workers can work at home, such as the agriculture sector, the rate of reduction is 43.3% ($= 0.5 \times (1 - 0.134)$). Sectors with ordinary exposure (100%) and a lower share of workers working at home (33.2%), such as the textile sector, reduce production capacity by 66.8% ($= 1.0 \times (1 - 0.332)$).

However, Inoue et al. [2020] find that using these reduction rates, the simulated production loss in Japan because of the first state of emergency is substantially larger than the actual loss. In other words, the reduction rates based on data from the US [Dingel and Neiman, 2020] are too high for Japan, possibly because of the voluntary nature of its lockdown. According to Inoue et al. [2020], the reduction rates in production capacity for Japan that generate the best fit between the simulated and actual production loss are the benchmark reduction rates following the literature multiplied by 0.268. This study uses these adjusted reduction rates taken from Inoue et al. [2020]. The reduction rate for each sector before and after the adjustment is shown in Table A.1 of the Supplementary Information.

2.4 Conceptual framework and hypothesis

The primary research question in this study is whether synchronous or asynchronous lockdown of more than one prefectures results in a larger loss of production of all prefectures, i.e., GDP in Japan. This subsection provides a conceptual framework to answer the question.

For this purpose, suppose that firm A in prefecture X is a supplier of firm B in prefecture Y. Further suppose that X and Y impose synchronous lockdown so that both X and Y reduce their production capacity simultaneously. In this case, the reduction in production of supplier A does not substantially affect its client B, because B is already affected by the lockdown. By contrast, if the two prefectures impose lockdown asynchronously, firm B reduces production twice, once by the lockdown of its own prefecture Y and once by shortage of supplies from A because of the lockdown of the other prefecture X. Therefore, the total production loss from asynchronous lockdown is likely to be larger than that from synchronous lockdown. Although the example above is quite simple, the same argument can be applied to the case where firms in different prefectures are indirectly connected through supply chains. Therefore, we hypothesize that the effect of synchronous lockdown of multiple prefectures on the production loss in the whole economy is smaller than the effect of their asynchronous lockdown.

However, this hypothesis may not be supported, depending on the structure of supply chains. First, if firms in prefecture X are not linked with those in Y, firms in X are not affected by lockdown of Y. Therefore, synchronous and asynchronous lockdown of the two prefectures should result in the same production loss. Second, the larger effect of asynchronous lockdown may be minimized by substitution of suppliers [Barrot and Sauvagnat, 2016, Kashiwagi et al., 2018, Inoue and Todo, 2019a,b]. For example, if firm B is also connected with supplier C in another prefecture Z that is not in lockdown, the disrupted supplies from A may be substituted for by supplies from C. If this substitution effect is sufficiently large, the propagation effect of asynchronous lockdown may be similar to that of synchronous lockdown. Finally, if firms in prefectures X and Y are strongly connected with each other and with firms in other prefectures through a number of links, synchronous lockdown of X and Y may generate severe cascading of economic shocks throughout the economy, leading to a complete failure of the system [Inoue and Todo, 2019a]. Such system failure or phase transition is observed in propagation of shocks through financial networks in practice (e.g., in the Global Financial Crisis) and in simulation studies depending on the network structure [Acemoglu et al., 2015]. If this is the case, the effect of synchronous lockdown may be larger than the effect of asynchronous lockdown that results in moderate production loss in a long run.

In conclusion, we generally expect a larger economic effect of asynchronous lockdown of multiple regions than that of their synchronous lockdown, but there are possibilities that the hypothesis is not empirically supported depending on the structure of supply chains.

2.5 Simulations

Using the agent-based model, supply chain data, and the estimated reduction rates in production capacity because of lockdown, we simulate how the effect of lockdowns in various prefectures on the production loss differs, depending on whether lockdowns in different prefectures are imposed synchronously or asynchronously. For this purpose, we take the following three steps.

Propagation effect of lockdown in one prefecture

First, to check the presence and size of the propagation effect, we start with the investigation of how the effect of lockdown in only one prefecture propagates to other prefectures. In each of the benchmark scenarios, we assume strict lockdown of a particular prefecture that restricts its economic activities in all sectors for four weeks. In other words, during the lockdown period, each firm in the locked-down prefecture reduces its production capacity as determined by the sectoral reduction rate explained in Section 2.3, while the production capacity of firms in other prefectures does not change. In each scenario, we run Monte Carlo simulations 30 times, randomly choosing the inventory size, n_i, for each firm. The number of runs in each scenario is sufficiently large because the simulated GDP (total value added) does not vary substantially across the 30 runs, or its standard deviation is less than 0.5% of the actual GDP.

In each scenario where only one prefecture imposes lockdown, we average the production loss, i.e., gross regional product (GRP) without any lockdown less GRP simulated in the scenario, of each prefecture over the 30 runs to evaluate the geographic propagation effect. In addition, to check how the level of restrictions affect the production loss, we experiment with various levels by changing its sectoral coverage and duration. We assume three additional types of sectoral coverage: (1) the accommodation and leisure sectors only; (2) the restaurant sector in addition to (1); and (3) the retail sector in addition to (2). Supplementary Information A.2 presents the list of sectors in each type. In addition, we assume three more types of the duration of a lockdown: 1, 2, and 3 weeks. It is noted that the total effect of lockdown may not be proportional to its sectoral coverage and duration because how the effect propagates to the whole economy through supply chains depends on how the affected sectors are connected with other sectors and how the propagation is magnified over time.

Effect of synchronous and asynchronous lockdown in two prefectures

Second, to discuss the need for policy coordination, we examine how the effect of lockdowns in two prefectures on their production differ depending on whether the lockdowns are synchronously or asynchronously imposed. Specifically, we experiment with all possible combinations of the two prefectures, i.e., $47 \times 46/2$ scenarios, running 30 Monte Carlo simulations in each scenario and averaging the production loss over the 30 runs. In these scenarios, we focus on the most strict lockdown assuming that both prefectures restricted the activities of all sectors for four weeks, although we check the robustness of our results by assuming other types of lockdown as described above. We further assume that in the synchronous scenario, both prefectures impose the lockdown simultaneously, while in the asynchronous scenario, only one of the two imposes its lockdown for the first four weeks, followed by a four-week lockdown by the other.

Then, we compare the loss of total production of Japan, i.e., the GDP loss, averaged over the 30 runs between the two scenarios. Further, we examine how the difference in the GDP loss between the synchronous and asynchronous lockdown is determined by characteristics of the two prefectures, focusing on the number of supply chain links between them, the geographic distance between them, and the sum of their GRP.

Effect of the synchronous and asynchronous lockdowns in all prefectures

Finally, we consider scenarios where all prefectures impose lockdown of all sectors for four weeks and compare the effect of synchronous lockdown in all prefectures on the GDP loss with the effect of their asynchronous lockdown. In the case of the synchronous lockdown, we assume that all prefectures impose lockdown for four weeks at the beginning of a three-month period. We run 30 simulations, changing the inventory size, n_i in Section 2.2, of each firm. In an asynchronous lockdown, we also assume that each prefecture imposes lockdown for four weeks but randomly set its initial date during the three-month period, while at least one prefecture starts its lockdown at the beginning of the period. We run the simulation 100 times, changing the timing of lockdown in each prefecture and the inventory size of each firm.

3 Results and Discussion

3.1 Effect of lockdown in one prefecture

Figure 3 shows how lockdown of all sectors in one prefecture for four weeks affects the loss of production in other prefectures. In the figure, each cell presents the production loss of the prefecture in the horizontal axis as a percentage of its GRP because of lockdown in the prefecture in the vertical axis. Dark red cells indicate a large production loss, while yellow and purple cells indicate a moderate and small loss, respectively.

The diagonal cells are mostly orange or red, showing a large negative effect of the lockdown of a prefecture on its own production. Off the diagonal line, cells are mostly purple, or the production loss in a prefecture because of lockdown of another prefecture is mostly less than 1% of its GRP. This finding implies that when only one prefecture imposes lockdown on all sectors for four weeks, the propagation effect on other prefectures is quite limited. However, the horizontal line of green and blue cells in the upper part of Figure 3 suggests that lockdown of Tokyo, the largest industrial prefecture in Japan, has a large negative effect on production in other prefectures. In particular, prefectures that are geographically close to Tokyo, such as Saitama and Gunma, and those that are not close to Tokyo but relatively backward, such as Wakayama and Ehime, are largely affected possibly because of their heavy supply chain reliance on Tokyo. In addition, lockdown in other economically more advanced and larger prefectures, such as

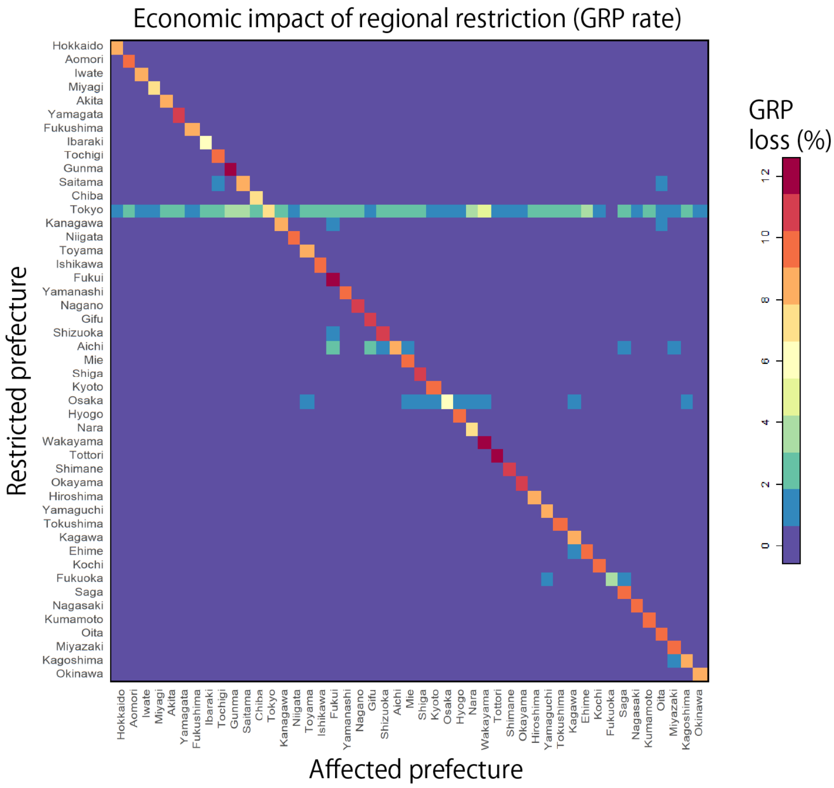

Figure 3: Economic impact of lockdown of all sectors for four weeks in one prefecture. Each cell presents the production loss of the prefecture in the horizontal axis as a percentage of its gross regional product (GRP) because of lockdown in the prefecture in the vertical axis.

Osaka and Aichi, is found to have a large propagation effect on others.

One possible reason for the negligible propagation from lockdown in other prefectures, except for the most industrial prefectures, is substitutability of inputs. Our model in Section 2.2 assumes that when inputs from a supplier are disrupted by lockdown, firms can substitute other suppliers in the same sector for the disrupted suppliers. Therefore, if a firm is linked with a supplier in the prefecture in lockdown but also with others in the same sector in other prefectures without lockdown, the propagation effect of lockdown can be largely alleviated. Therefore, unless large economies with a number of suppliers are locked down, the propagation through supply chains can be minimal.

TSR data does not include information of the location of establishments of each firm, except for its headquarter and a firm possibly has multiple establishments in different locations. As is discussed in Supplementary Information B, we merge establishments data to the TSR data and run the same simulation. We find that the result with establishments does not differ from the one with only headquarters in this section. Therefore, we use the model with headquarters in other sections as well.

In addition, we show in Figure 4 the correlation between GRP of a prefecture and the total loss of GDP (not GRP) in Japan because of lockdown of the prefecture. Both axes are log scaled. We find a clear positive correlation between the two, implying that lockdown of an economically large prefecture results in the total loss of GDP in Japan including the loss of GRP in other prefectures. However, we also find that lockdown of prefectures with similar GRP do not necessarily generate GDP loss of a similar size. For example, although GRP of Osaka, Aichi, and Kanagawa is quite similar to each other, lockdown of Osaka results in a far larger GDP loss in Japan than lockdown of Aichi or Kanagawa. Fukuoka is another example of a large propagation effect. These findings imply that the structure of supply chains of each prefecture plays an important role in determining the propagation effect of its lockdown.

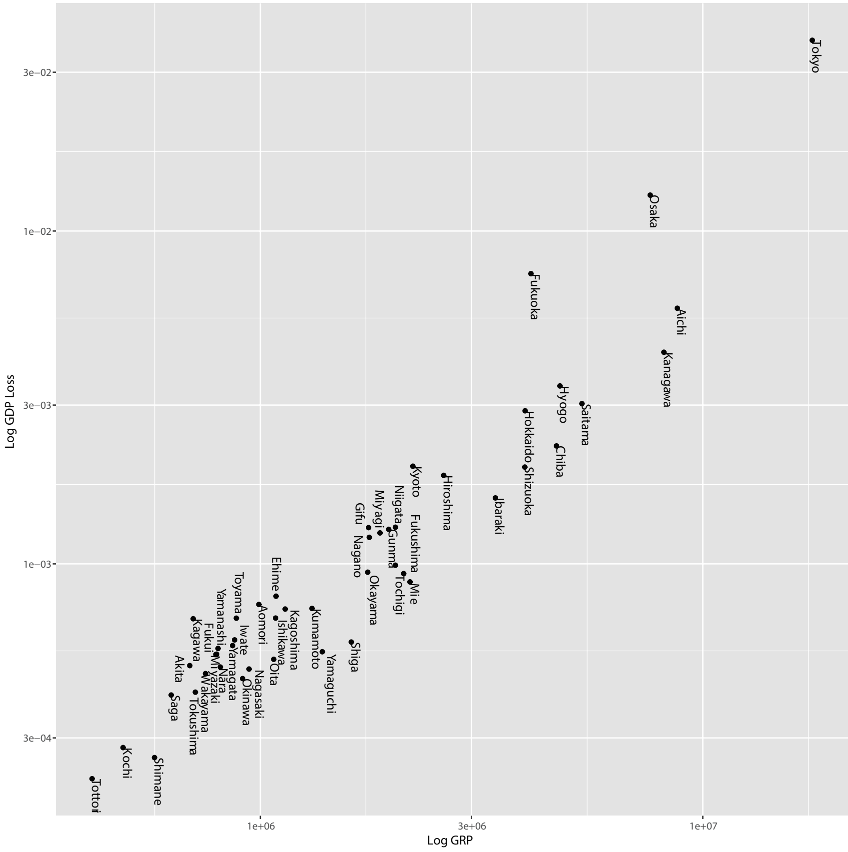

Figure 4: The correlation between GRP of a prefecture and the loss of GDP because of lockdown of the prefecture. The horizontal axis presents the GRP of the locked-down prefecture in log, whereas the vertical axis shows the GDP loss caused by the lockdown in log. Lockdown is assumed to restrict all sectors for four weeks. Each labels indicates the name of the locked-down prefecture.

We also experiment with different sectoral coverage and duration of lockdown, as explained in Section 2.5. Figure 5 show the results that are corresponding to Figure 3 but assume different sectoral coverage, whereas Figure C.1 show the results for lockdown in one week, shorter duration. Results from simulations assuming lockdown for two and three weeks are omitted, because the difference between the different scenarios is negligible.

Figure 5 shows the smaller sectoral coverage results in the smaller effect. Since the three sectoral types, i.e., the accommodation and leisure sectors, the restaurant sector, and the retail sector, are often taken as targets of activity restrictions, the results are important in practice. The results come from the position of the sectors in the supply chains. They are downstream sectors because the service sectors and directly connected to final consumers, not other sectors. Since the propagation of the effect is limited toward the upstream compared with the downstream, those sectors show the small propagation effect.

Figures 3 and 5 clearly show that while the propagation effect of lockdown is smaller when the sectoral coverage is smaller or the duration is shorter, our main finding that the effect is mostly negligible except for the scenarios where a major industrial prefecture imposes lockdown. Therefore, in the subsequent analysis, we will present only results from the scenarios where lockdown is imposed on all sectors for four weeks, although we confirm the robustness of the main results by assuming different types of lockdown.

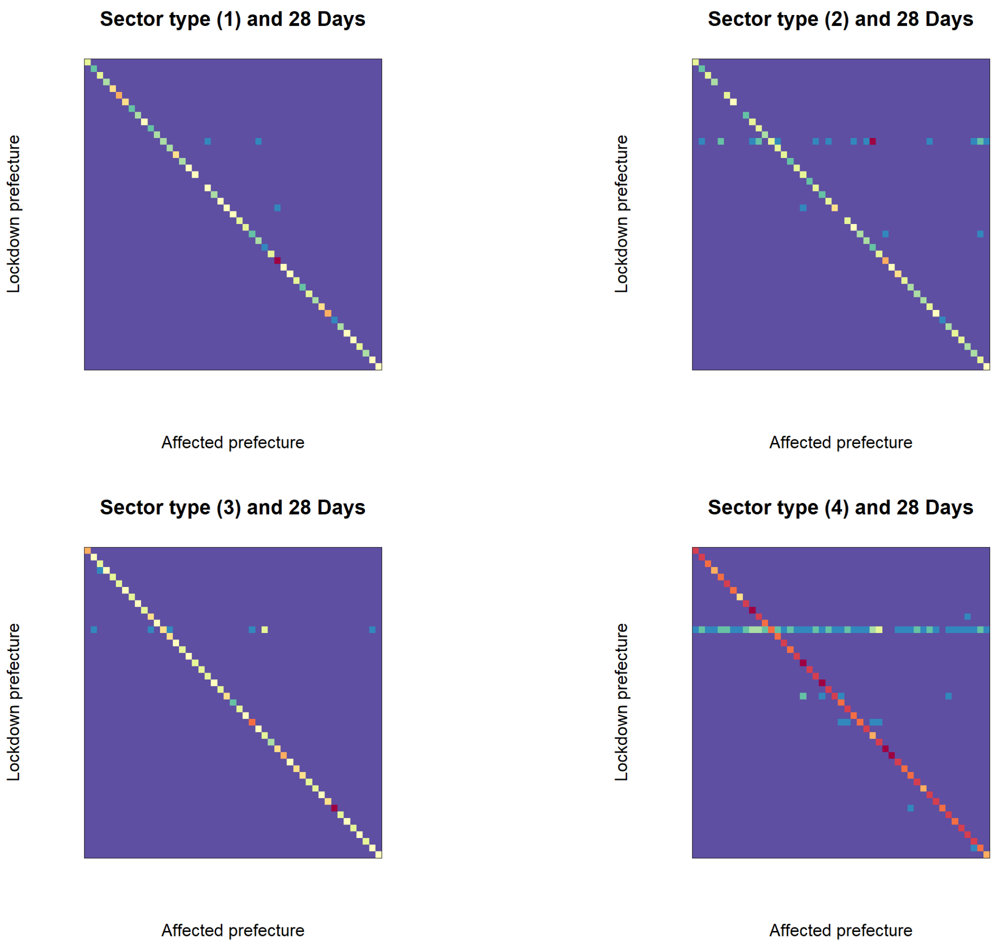

Figure 5: Economic impact of lockdown of some sectors for four weeks in one prefecture. Each cell presents the production loss of the prefecture in the horizontal axis as a percentage of its gross regional product (GRP) because of lockdown in the prefecture in the vertical axis. Each panel shows results from lockdown of (1) the accommodation and leisure sectors, (2) the restaurant sector in addition to (1), (3) the retail sector in addition to (2), and (4) all sectors.

3.2 Effect of synchronous and asynchronous lockdown in two prefectures

We now turn to scenarios where two prefectures impose lockdown synchronously or asynchronously to examine which timing of lockdown results in a smaller total production loss in Japan. We particularly highlight the results from lockdown of all sectors for four weeks as mentioned earlier.

As Section 3.1 found that lockdown in Tokyo has a large propagation effect, not comparable to lockdown in any other prefecture, we first focus on synchronous and asynchronous lockdown of Tokyo and another prefecture and present the loss of GDP because of the lockdown as a percentage of GDP in Figure 6. We find that synchronous lockdown of Tokyo and any other prefecture leads to a smaller loss of GDP than asynchronous lockdown of the same pair. Based on the conceptual consideration in Section 2.4, this finding implies that any prefecture is strongly linked with Tokyo through supply chains. Therefore, asynchronous lockdown affect the prefecture twice, once by its own lockdown and once by lockdown of Tokyo, leading to a larger total effect. Moreover, Section 2.4 suggests that the effect of asynchronous lockdown can be similar to the effect of synchronous lockdown when supplier substitution across prefectures is widely available to firms or even smaller when the interaction between synchronous lockdown leads to a cascading and devastating effect. However, our result implies that firms in Tokyo may not be substitutable for firms in other prefectures not in lockdown. In addition, lockdown of Tokyo and any other prefecture does not generate a cascading effect.

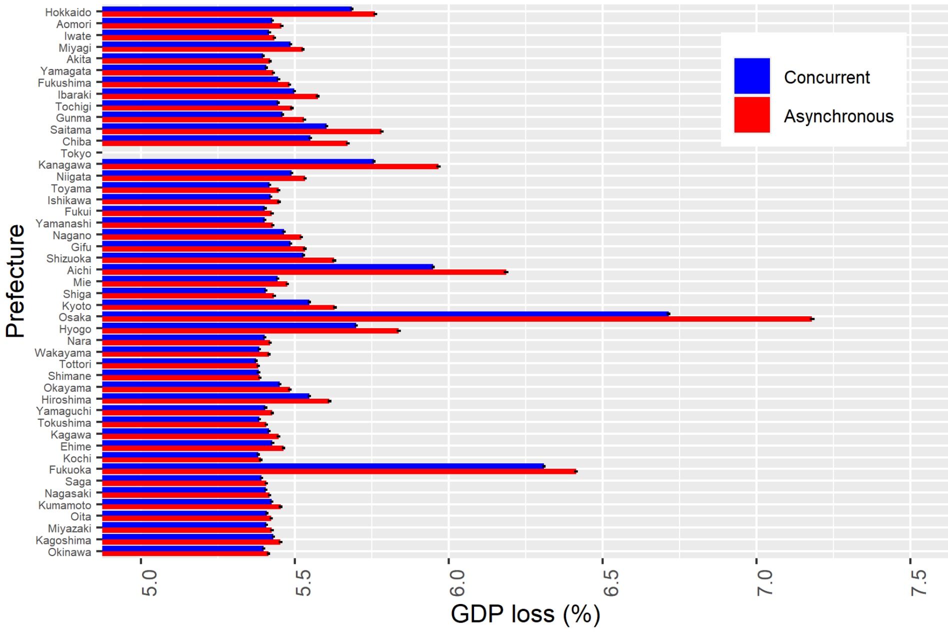

Figure 6: Economic impact of synchronous and asynchronous lockdown of Tokyo and another prefecture. The blue and red bars show the average of the loss of GDP because of synchronous and asynchronous lockdown, respectively, of Tokyo and another prefecture shown in the vertical axis over 30 simulations. Lockdown is assumed to be imposed on all sectors for four weeks. The black lines indicate standard errors of the GDP loss.

Another notable finding in Figure 6 is that the difference between the synchronous and asynchronous lockdown is the larger when the partner prefecture of Tokyo is more industrial prefectures, such as Kanagawa, Aichi, and Osaka. These results imply that the industrial prefectures are strongly linked with Tokyo through supply chains so that benefits of synchronous lockdown are large. In addition, synchronous lockdown of Tokyo and another major industrial prefecture does not cause a cascading effect, possibly because lockdown in Japan is not very restrictive (Section 2.3). Moreover, the difference is the largest when the partner is Osaka, although the GRP of Kanagawa is larger than that of Osaka (Figure 4). This evidence suggests that while Osaka is smaller in economic size than Kanagawa, it is a more important hub of supply chains following Tokyo. Firms in Tokyo and Osaka are inevitable to each other and cannot be substituted for by firms in other prefectures. Therefore, the two prefectures can be substantially affected by their asynchronous lockdown.

We further simulate all the possible combination of two prefectures. However, because showing the results from all combinations requires too much space, we just show the GDP loss from synchronous and asynchronous lockdown of Aichi, Osaka, or Tottori and another prefecture in the Supplementary Information D. Aichi and Osaka are major industrial prefectures, while the GRP of Tottori is the smallest.

As we find in Figure 7, the GDP loss from asynchronous lockdown is always greater than that from synchronous lockdown. The difference in the case of Tottori is negligible, because Tottori does not have many supply chain links with other prefectures and thus are not affected by lockdown in other prefectures.

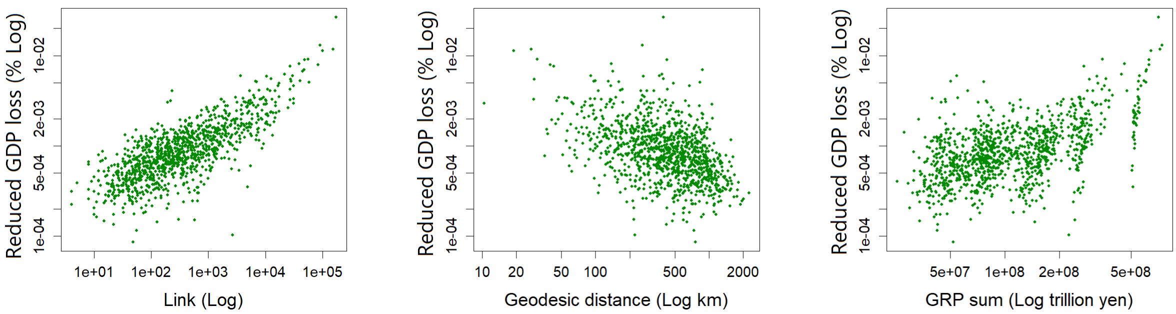

Figure 7: Relationships between the difference in the GDP loss between synchronous and asynchronous lockdown of all prefecture pairs and their selected characteristics. The vertical axis shows the GDP loss from asynchronous lockdown of two prefectures less the GDP loss from their synchronous lockdown, as a ratio to the sum of their gross regional product (GRP). The horizontal axis in the left, middle, and right panels respectively shows the number of supply chain links between the two prefectures in log, the distance between the two prefectural capitals in log, and the sum of GRP of the two.

In addition, Figure 7 plots the relationship between the difference in the GDP loss between synchronous and asynchronous lockdown for each prefecture pair and characteristics of the pair, i.e., the number of supply chain links between the two prefectures (the left panel), the geographic distance between the two prefectural capital cities (middle), and the sum of GRP of the two prefectures (right). Spearman's rank correlation coefficient between the difference in the GDP loss and the number of supply chain links is 0.74, showing a high correlation. This result supports the hypothesis in Section 2.4 that if two prefectures are strongly connected, asynchronous lockdown leads to a larger GDP loss than synchronous lockdown. The geodesic distance is negatively correlated with the difference in the GDP loss, and Spearman's rank correlation coefficient of the two is -0.47. The negative correlation may arise because shorter geodesic distance is often associated with more links. However, because the correlation coefficient is higher for the number of supply chain links than for geodesic distance, economic relationships should be considered to be more important than geographic relationships. The sum of GRP of two prefectures is positively correlated with the difference in the GDP loss with a correlation coefficient of 0.49. This is because two prefectures with large GRP are likely to have many large firms and thus have many links between them.

3.3 Effect of synchronous and asynchronous lockdown in all prefectures

Finally, we consider scenarios where all 47 prefectures impose lockdown on all sectors for four weeks either synchronously or asynchronously during a three-month period. As explained in Section 2.5, we run 30 simulations in the case of synchronous lockdown, changing the inventory size of each firm, and 100 simulations in the case of asynchronous lockdown, changing the timing of lockdown of each prefecture additionally. Figure 8 shows changes in the loss of daily GDP (daily GDP in the pre-pandemic period less the simulated GDP) from the 30 simulations assuming synchronous lockdown (blue lines) and the 100

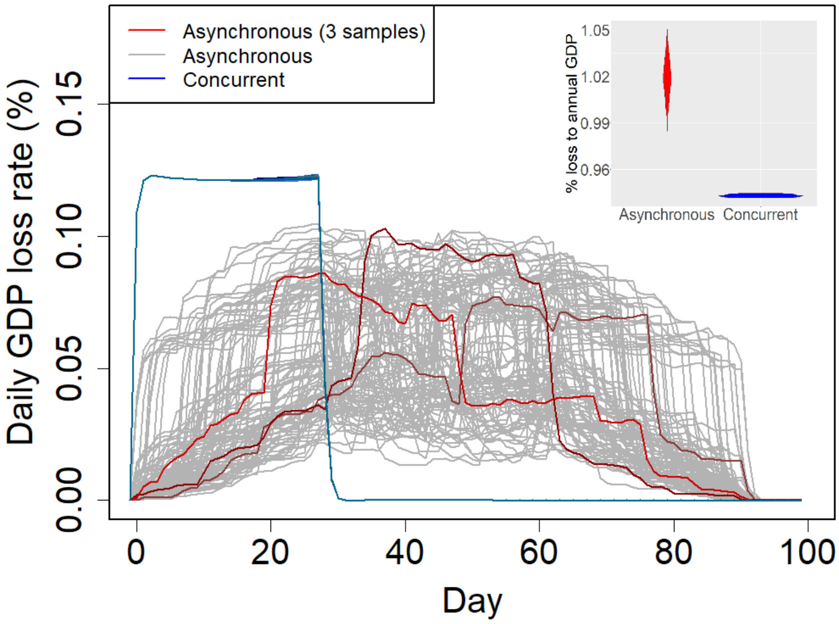

Figure 8: The loss of GDP because of synchronous and asynchronous lockdown of all prefectures. The vertical axis shows the loss of daily GDP, i.e., daily GDP in the pre-COVID-19 period less daily simulated GDP assuming synchronous (blue lines) or asynchronous (red and brown lines) lockdown of all prefectures, divided by daily GDP in the pre-COVID-19 period. The horizontal axis shows the number of days from the start. Synchronous lockdown is imposed in all sectors in all prefectures simultaneously for four weeks at the beginning of the three-month period. Asynchronous lockdown in each prefecture is imposed in all sectors for four weeks from a randomly selected initial date during the three-month period. We run 30 simulations in the case of synchronous lockdown, changing the inventory size of each firm, and 100 simulations in the case of asynchronous lockdown, changing the timing of lockdown of each prefecture additionally. The inset figure shows the violin plot of the GDP loss from synchronous (blue) and asynchronous (red) lockdown.

simulations assuming asynchronous lockdown (red and gray lines). The red lines presents three particular simulations assuming asynchronous lockdown to highlight the difference from simulations assuming synchronous lockdown. Any of the three red lines shows that because of lockdown of prefectures in different timing, the loss of GDP is positive for a long period of time, leading to a large total effect, while the blue lines show that the effect of synchronous lockdown is large but temporal. The red lines jump up suddenly and jump down approximately 30 days later because of lockdown of Tokyo. The average loss of GDP from the synchronous lockdown is 4.69 trillion yen or 43.8 billion US dollars and smaller than that from the asynchronous lockdown, 5.11 trillion yen or 47.6 billion US dollars. The difference is statistically significant with a p value of less than 10^{-10}, according to a Wilcoxon rank sum test. This finding is consistent with those in the previous subsection, confirming the hypothesis in Section 2.4 that the effect of synchronous lockdown of multiple regions on production is smaller than the effect of their asynchronous lockdown because of strong supply chain links between regions.

4 Conclusion

This study examines whether synchronous or asynchronous lockdown of multiple regions results in larger production loss when we incorporate propagation of the economic effect through supply chains, using a simulation approach and detailed supply chain data for Japan. We hypothesize that the effect of synchronous lockdown is smaller than that of asynchronous lockdown, because the latter causes the economy multiple times by the propagation effect. Our simulations focusing lockdown in two prefectures and in all prefectures firmly support this hypothesis.

Our results imply that coordination of lockdown policies across regions and countries is necessary to minimize the economic impact of COVID-19. Specifically, governments are suggested to impose lockdown simultaneously, rather than in different timing from each other, although the coordination requires more cost than the independent impose. A similar suggestion is provided by Ruktanonchai et al. [2020] who claim the need for synchronous lockdown in various countries to minimize the effect of COVID-19 on infections. The results of this study and Ruktanonchai et al. [2020] clearly show that lockdown should be imposed in various regions and countries simultaneously so that the health and economic effect can be minimized.

However, it should also be emphasized that the difference in the economic effect between synchronous and asynchronous lockdown in multiple regions depends on the structure of supply chains across regions. Our conclusion holds particularly when regions are linked strongly through supply chains but not so when regions are isolated with each other. Moreover, if inputs are highly substitutable across regions, the propagation effect of other locked-down regions on regions not locked down can be largely mitigated. In that case, the shortcoming of asynchronous lockdown can not be substantial. Therefore, lockdown should be coordinated among countries densely connected through supply chains. Considering the effect of policy coordination on infections [Ruktanonchai et al., 2020], governments may be interested in coordination among regions with short geographical distance or with high human traffics. However, our analysis shows that governments should also be concerned about economic relations among regions to maximize the overall effect of policy coordination.

Finally, although we find benefits of coordination of lockdown policies, it is possibly difficult to achieve such coordination in the market equilibrium. For example, Acharya et al. [2020] employ a model with infection and trade and find that coordination of policies for domestic containment and tariffs cannot be achieved from the view point of tariff wars. Biancotti et al. [2020 (accessed November 3, 2021] argue that policy coordination is difficult from a political economy perspective because governments often respond to public opinions more than scientific evidence. Because our analysis is based on an agent-based model and treats lockdown policies as exogenous, we cannot examine whether optimal policy coordination can be achieved in the market equilibrium. Rather, our analysis emphasizes the need for policy coordination even when it is not achieved by market forces.

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Supplementary Information

A Data

A.1 Supply chains

In the TSR data, the maximum number of suppliers and clients reported by each firm is 24. However, because we consider that supplier-client relations from the two directions, a firm can have more than 24 suppliers or 24 clients. Accordingly, the maximum number of suppliers and clients is *** and ***, respectively. Since the TSR data include the address of the headquarters of each firm, we can obtain the longitude and latitude of each headquarters using the geocoding service provided by the Center for Spatial Information Science at the University of Tokyo.

Because the TSR data do not include the volume of each transaction between two firms, we estimate the volume using the following steps. First, we divide each supplier's sales among its clients in proportion to the clients' sales to create a tentative sales value. Second, we use the IO table of Japan in 2015 [Ministry of Economy, Trade and Industry, Japan, 2015] to modify the tentative values to the final values so that the total volume corresponds to GDP. Specifically, we aggregate the tentative values at the firm-pair level to create the total sales for each pair of industrial sectors. We then divide the total sales for each industrial sector pair by the transaction values for the corresponding pair in the IO tables. The ratio is then used to adjust the transaction values between firms. The final consumption of each industrial sector is assigned to all firms in the sector using their sales as a weight.

A.2 Sectoral differences in production capacity after restrictions

There are no available firm- or sector-level data on reductions in production capacity (i.e., $P\text{cap}$ in the model) during the restriction in Japan. Here, we assume that the rate of reduction on production capacity for each sector is given by the degree of the aggregated reduction due to exposure to the virus [Bonadio et al., 2020] multiplied by the share of workers who cannot work at home [Guan et al., 2020]. Both of the cited studies address the global situation in April and May of 2020. The rate of reduction due to exposure to the virus is determined by how many workers in the sector reduced their activities to avoid contact with others to prevent infections. Because the reference [Guan et al., 2020] defines the rate of reduction uniformly worldwide, we modify the rate for some sectors that clearly differ in the case of Japan. Table A.1 shows the reduction rate for each sector assumed in the reference [Guan et al., 2020].

Although it is assumed that the reduction rate is applicable to any country, there must be a difference between the real rate of the country and the assumed reduction rate. Inoue et al. [Inoue et al., 2020] estimate this difference for Japan. First, they estimate the GDP loss by using a real economic loss estimated by the Indices of All Industry Activities (IAA) for April and May of 2020. The estimated loss is 7.52 trillion yen (71.2 billion U.S. dollars at 107 yen / dollar.) or 2.5% of yearly GDP. If we use the reduction rate derived as explained above, the estimated GDP loss is 35.0 trillion yen (327 billion U.S. dollars). It can be presumed that the actual reduction rate is smaller than the worldwide reduction rate. Therefore, the rate is adjusted by multiplying the worldwide reduction rate by the same weight so that the simulation estimation fits the IAIA estimation. The weight of 32.3% provides the closest fit to the

IAIA estimation. In this study, we use this weight and the worldwide reduction rate as the adjusted reduction rate shown in Table A.1.

The simulations are conducted with different categories of industrial sectors. We consider four different coverage levels: (1) the accommodation and leisure sectors only; (2) the restaurant sector plus (1); (3) the retail sector plus (2); (4) all sectors. The correspondence of sectors to levels is shown in Table A.1. Note that the levels are nested, e.g., sectors categorized into level (1) are also included in level (2).

Table A.1: Sector-specific rates of reduction in production capacity. Sectors are classified according to the JIS classification [of International Affairs and Communications, 2013 (accessed June 1, 2020] at the two-digit level, except for industries 560, 561, and 569, for which we use three-digit codes to reflect current circumstances. The sector names are abbreviated. Table A.2 lists the sector descriptions and abbreviations. The level indicates the industrial categories for the simulations.

Code	Sector (abbreviated)	Adjusted reduction rate	Reduction rate	Work-at -home rate	Exposure level	Rationale	Level
1	AGR.	1.16E-01	4.33E-01	1.34E-01	0.5	Low exposure	4
2	FRS.	1.16E-01	4.33E-01	1.34E-01	0.5	Low exposure	4
3	FIS.	1.16E-01	4.33E-01	1.34E-01	0.5	Low exposure	4
4	AQA.	1.16E-01	4.33E-01	1.34E-01	0.5	Low exposure	4
5	MIN.	1.71E-01	6.37E-01	3.63E-01	1	Ordinary	4
6	CNS.GEN.	2.03E-01	7.58E-01	2.42E-01	1	Ordinary	4
7	CNS.SPC.	2.03E-01	7.58E-01	2.42E-01	1	Ordinary	4
8	EQP.	2.03E-01	7.58E-01	2.42E-01	1	Ordinary	4
9	MAN.FOD.	2.04E-01	7.60E-01	2.40E-01	1	Ordinary	4
10	MAN.BEV.	2.04E-01	7.60E-01	2.40E-01	1	Ordinary	4
11	MAN.TEX	1.79E-01	6.68E-01	3.32E-01	1	Ordinary	4
12	MAN.LUM.	2.06E-01	7.68E-01	2.32E-01	1	Ordinary	4
13	MAN.FUR.	2.06E-01	7.68E-01	2.32E-01	1	Ordinary	4
14	MAN.PUL.	1.81E-01	6.76E-01	3.24E-01	1	Ordinary	4
15	PRT.	1.81E-01	6.76E-01	3.24E-01	1	Ordinary	4
16	MAN.CHM.	1.42E-01	5.29E-01	4.71E-01	1	Ordinary	4
17	MAN.PET.	1.74E-01	6.51E-01	3.49E-01	1	Ordinary	4
18	MAN.PLA.	1.89E-01	7.04E-01	2.96E-01	1	Ordinary	4
19	MAN.RUB.	1.89E-01	7.04E-01	2.96E-01	1	Ordinary	4
20	MAN.LET.	1.79E-01	6.68E-01	3.32E-01	1	Ordinary	4
21	MAN.CER.	1.90E-01	7.09E-01	2.91E-01	1	Ordinary	4
22	MAN.IRN.	1.96E-01	7.32E-01	2.68E-01	1	Ordinary	4
23	MAN.NFM.	1.96E-01	7.32E-01	2.68E-01	1	Ordinary	4
24	MAN.FBM.	1.86E-01	6.95E-01	3.05E-01	1	Ordinary	4
25	MAN.GNM.	1.62E-01	6.04E-01	3.96E-01	1	Ordinary	4
26	MAN.PRM.	1.62E-01	6.04E-01	3.96E-01	1	Ordinary	4
27	MAN.BSM.	1.62E-01	6.04E-01	3.96E-01	1	Ordinary	4
28	EPT.	8.92E-02	3.33E-01	6.67E-01	1	Ordinary	4
29	MAN.ELM.	1.55E-01	5.80E-01	4.20E-01	1	Ordinary	4

30	MAN.INF.	8.92E-02	3.33E-01	6.67E-01	1	Ordinary	4
31	MAN.TRN.	1.35E-01	5.04E-01	4.96E-01	1	Ordinary	4
32	MAN.MSC.	1.89E-01	7.05E-01	2.95E-01	1	Ordinary	4
33	ELE.	1.67E-02	6.23E-02	3.77E-01	0.1	Lifeline	3
34	GAS.	1.67E-02	6.23E-02	3.77E-01	0.1	Lifeline	3
35	HET.	1.67E-02	6.23E-02	3.77E-01	0.1	Lifeline	3
36	WTR.	1.67E-02	6.23E-02	3.77E-01	0.1	Lifeline	3
37	COM.	1.07E-02	4.01E-02	5.99E-01	0.1	Lifeline	3
38	BRD.	5.15E-03	1.92E-02	8.08E-01	0.1	Lifeline	3
39	INF.SVC.	2.60E-02	9.70E-02	9.03E-01	1	Ordinary	3
40	INT.	1.07E-02	4.01E-02	5.99E-01	0.1	Lifeline	3
41	INF.DST.	5.15E-02	1.92E-01	8.08E-01	1	Ordinary	3
42	RLW.TRP.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
43	PAS.TRP.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
44	FRE.TRP.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
45	WTR.TRP.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
46	AIR.TRP.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
47	WRH.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
48	SVC.TRP.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
49	PST.SVC.	1.88E-02	7.01E-02	2.99E-01	0.1	Lifeline	3
50	WHL.GEN.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	4
51	WHL.TEX.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	4
52	WHL.FOD.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	4
53	WHL.MAT.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	4
54	WHL.MCN.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	4
55	WHL.MSC.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	4
560	RTL.ADM.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	3
561	RTL.DPT.	1.41E-01	5.25E-01	4.75E-01	1	Closed	1
569	RTL.MSC.	1.41E-02	5.25E-02	4.75E-01	0.1	Lifeline	3
57	RTL.GEN.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	3
58	RTL.FOD.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	3
59	RTL.MCN.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	3
60	RTL.MSC.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	3
61	RTL.NST.	1.41E-01	5.25E-01	4.75E-01	1	Ordinary	3
62	FIN.BNK.	5.74E-02	2.14E-01	7.86E-01	1	Ordinary	3
63	FIN.ORG.	5.74E-02	2.14E-01	7.86E-01	1	Ordinary	3
64	FIN.LON.	5.74E-02	2.14E-01	7.86E-01	1	Ordinary	3
65	FIN.TRN.	5.74E-02	2.14E-01	7.86E-01	1	Ordinary	3
66	FIN.AUX.	5.74E-02	2.14E-01	7.86E-01	1	Ordinary	3
67	INS.	5.74E-02	2.14E-01	7.86E-01	1	Ordinary	3
68	RST.AGN.	1.13E-01	4.23E-01	5.77E-01	1	Ordinary	3
69	RTS.LES.	1.13E-01	4.23E-01	5.77E-01	1	Ordinary	3
70	RNT.	9.70E-02	3.62E-01	6.38E-01	1	Ordinary	3
71	SCI.	4.61E-02	1.72E-01	8.28E-01	1	Ordinary	3

72	SVC.PRF.	9.70E-02	3.62E-01	6.38E-01	1	Ordinary	3
73	ADV.	9.70E-02	3.62E-01	6.38E-01	1	Ordinary	3
74	SVC.TEC.	9.70E-02	3.62E-01	6.38E-01	1	Ordinary	3
75	ACM.	2.38E-01	8.89E-01	1.11E-01	1	Closed	1
76	EAT.	2.38E-01	8.89E-01	1.11E-01	1	Ordinary	2
77	DEL.	1.40E-02	5.21E-02	4.79E-01	0.1	Lifeline	3
78	LND.	1.40E-01	5.21E-01	4.79E-01	1	Ordinary	3
79	SVC.PSN.	1.40E-01	5.21E-01	4.79E-01	1	Ordinary	3
80	SVC.AMS.	1.40E-01	5.21E-01	4.79E-01	1	Closed	1
81	SCH.	2.30E-02	8.60E-02	8.28E-01	0.5	Low exposure	3
82	EDC.	2.30E-02	8.60E-02	8.28E-01	0.5	Low exposure	3
83	MED.	2.02E-02	7.53E-02	2.47E-01	0.1	Lifeline	3
84	HLT.	0.00E+00	0.00E+00	2.47E-01	0	Essential	3
85	WEL.	0.00E+00	0.00E+00	2.47E-01	0	Essential	3
86	PST.OFC.	9.70E-03	3.62E-02	6.38E-01	0.1	Lifeline	3
87	CAS.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
88	WAS.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
89	SVC.AUT.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
90	SVC.MCN.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
91	SVC.EMP.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
92	SVC.BUS.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
93	PLT.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
94	REL.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
95	SVC.MSC.	4.85E-02	1.81E-01	6.38E-01	0.5	Low exposure	3
96	GOV.INT.	1.38E-02	5.15E-02	4.85E-01	0.1	Lifeline	3
97	NA	1.38E-02	5.15E-02	4.85E-01	0.1	Lifeline	3
98	GOV.LOC.	1.38E-02	5.15E-02	4.85E-01	0.1	Lifeline	3
99	NEC	9.70E-02	3.62E-01	6.38E-01	1	Ordinary	3

Table A.2: Sector classifications and abbreviations.

Code	Description	Abbreviation
01	AGRICULTURE	AGR.
02	FORESTRY	FRS.
03	FISHERIES, EXCEPT AQUACULTURE	FIS.
04	AQUACULTURE	AQA.
05	MINING AND QUARRYING OF STONE AND GRAVEL	MIN.
06	CONSTRUCTION WORK, GENERAL INCLUDING PUBLIC AND PRIVATE CONSTRUCTION WORK	CNS.GEN.
07	CONSTRUCTION WORK BY SPECIALIST CONTRACTOR, EXCEPT EQUIPMENT INSTALLATION WORK	CNS.SPC.
08	EQUIPMENT INSTALLATION WORK	EQP.
09	MANUFACTURE OF FOOD	MAN.FOD.
10	MANUFACTURE OF BEVERAGES, TOBACCO AND FEED	MAN.BEV.
11	MANUFACTURE OF TEXTILE PRODUCTS	MAN.TEX
12	MANUFACTURE OF LUMBER AND WOOD PRODUCTS, EXCEPT FURNITURE	MAN.LUM.
13	MANUFACTURE OF FURNITURE AND FIXTURES	MAN.FUR.
14	MANUFACTURE OF PULP, PAPER AND PAPER PRODUCTS	MAN.PUL.
15	PRINTING AND ALLIED INDUSTRIES	PRT.
16	MANUFACTURE OF CHEMICAL AND ALLIED PRODUCTS	MAN.CHM.
17	MANUFACTURE OF PETROLEUM AND COAL PRODUCTS	MAN.PET.
18	MANUFACTURE OF PLASTIC PRODUCTS, EXCEPT OTHERWISE CLASSIFIED	MAN.PLA.
19	MANUFACTURE OF RUBBER PRODUCTS	MAN.RUB.
20	MANUFACTURE OF LEATHER TANNING, LEATHER PRODUCTS AND FUR SKINS	MAN.LET.
21	MANUFACTURE OF CERAMIC, STONE AND CLAY PRODUCTS	MAN.CER.
22	MANUFACTURE OF IRON AND STEEL	MAN.IRN.
23	MANUFACTURE OF NON-FERROUS METALS AND PRODUCTS	MAN.NFM.
24	MANUFACTURE OF FABRICATED METAL PRODUCTS	MAN.FBM.
25	MANUFACTURE OF GENERAL-PURPOSE MACHINERY	MAN.GNM.
26	MANUFACTURE OF PRODUCTION MACHINERY	MAN.PRM.

27	MANUFACTURE OF BUSINESS ORIENTED MACHINERY	MAN.BSM.
28	ELECTRONIC PARTS, DEVICES AND ELECTRONIC CIRCUITS	EPT.
29	MANUFACTURE OF ELECTRICAL MACHINERY, EQUIPMENT AND SUPPLIES	MAN.ELM.
30	MANUFACTURE OF INFORMATION AND COMMUNICATION ELECTRONICS EQUIPMENT	MAN.INF.
31	MANUFACTURE OF TRANSPORTATION EQUIPMENT	MAN.TRN.
32	MISCELLANEOUS MANUFACTURING INDUSTRIES	MAN.MSC.
33	PRODUCTION, TRANSMISSION AND DISTRIBUTION OF ELECTRICITY	ELE.
34	PRODUCTION AND DISTRIBUTION OF GAS	GAS.
35	HEAT SUPPLY	HET.
36	COLLECTION, PURIFICATION AND DISTRIBUTION OF WATER, AND SEWAGE COLLECTION, PROCESSING	WTR.
37	COMMUNICATIONS	COM.
38	BROADCASTING	BRD.
39	INFORMATION SERVICES	INF.SVC.
40	SERVICES INCIDENTAL TO INTERNET	INT.
41	VIDEO PICTURE INFORMATION, SOUND INFORMATION, CHARACTER INFORMATION PRODUCTION AND DISTRIBUTION	INF.DST.
42	RAILWAY TRANSPORT	RLW.TRP.
43	ROAD PASSENGER TRANSPORT	PAS.TRP.
44	ROAD FREIGHT TRANSPORT	FRE.TRP.
45	WATER TRANSPORT	WTR.TRP.
46	AIR TRANSPORT	AIR.TRP.
47	WAREHOUSING	WRH.
48	SERVICES INCIDENTAL TO TRANSPORT	SVC.TRP.
49	POSTAL SERVICES, INCLUDING MAIL DELIVERY	PST.SVC.
50	WHOLESALE TRADE, GENERAL MERCHANDISE	WHL.GEN.
51	WHOLESALE TRADE (TEXTILE AND APPAREL)	WHL.TEX.
52	WHOLESALE TRADE (FOOD AND BEVERAGES)	WHL.FOD.
53	WHOLESALE TRADE (BUILDING MATERIALS, MINERALS AND METALS, ETC)	WHL.MAT.
54	WHOLESALE TRADE (MACHINERY AND EQUIPMENT)	WHL.MCN.
55	MISCELLANEOUS WHOLESALE TRADE	WHL.MSC.

560	ESTABLISHMENTS ENGAGED IN ADMINISTRATIVE OR ANCILLARY ECONOMIC ACTIVITIES	RTL.ADM.
561	DEPARTMENT STORES AND GENERAL MERCHANDISE SUPERMARKET	RTL.DPT.
569	MISCELLANEOUS RETAIL TRADE, GENERAL MERCHANDISE	RTL.GMN.
57	RETAIL TRADE, GENERAL MERCHANDISE	RTL.GEN.
58	RETAIL TRADE (FOOD AND BEVERAGE)	RTL.FOD.
59	RETAIL TRADE (MACHINERY AND EQUIPMENT)	RTL.MCN.
60	MISCELLANEOUS RETAIL TRADE	RTL.MSC.
61	NONSTORE RETAILERS	RTL.NST.
62	BANKING	FIN.BNK.
63	FINANCIAL INSTITUTIONS FOR COOPERATIVE ORGANIZATIONS	FIN.ORG.
64	NON-DEPOSIT MONEY CORPORATIONS, INCLUDING LENDING AND CREDIT CARD BUSINESS	FIN.LON.
65	FINANCIAL PRODUCTS TRANSACTION DEALERS AND FUTURES COMMODITY TRANSACTION DEALERS	FIN.TRN.
66	FINANCIAL AUXILIARIES	FIN.AUX.
67	INSURANCE INSTITUTIONS, INCLUDING INSURANCE AGENTS, BROKERS AND SERVICES	INS.
68	REAL ESTATE AGENCIES	RST.AGN.
69	REAL ESTATE LESSORS AND MANAGERS	RTS.LES.
70	GOODS RENTAL AND LEASING	RNT.
71	SCIENTIFIC AND DEVELOPMENT RESEARCH INSTITUTES	SCI.
72	PROFESSIONAL SERVICES, N.E.C.	SVC.PRF.
73	ADVERTISING	ADV.
74	TECHNICAL SERVICES, N.E.C.	SVC.TEC.
75	ACCOMMODATION	ACM.
76	EATING AND DRINKING PLACES	EAT.
77	FOOD TAKE OUT AND DELIVERY SERVICES	DEL.
78	LAUNDRY, BEAUTY AND BATH SERVICES	LND.
79	MISCELLANEOUS LIVING-RELATED AND PERSONAL SERVICES	SVC.PSN.
80	SERVICES FOR AMUSEMENT AND RECREATION	SVC.AMS.
81	SCHOOL EDUCATION	SCH.
82	MISCELLANEOUS EDUCATION, LEARNING SUPPORT	EDC.

83	MEDICAL AND OTHER HEALTH SERVICE	MED.
84	PUBLIC HEALTH AND HYGIENE	HLT.
85	SOCIAL INSURANCE, SOCIAL WELFARE AND CARE SERVICES	WEL.
86	POSTAL OFFICE	PST.OFC.
87	COOPERATIVE ASSOCIATIONS, N.E.C.	CAS.
88	WASTE DISPOSAL BUSINESS	WAS.
89	AUTOMOBILE MAINTENANCE SERVICES	SVC.AUT.
90	MACHINE, ETC. REPAIR SERVICES, EXCEPT OTHERWISE CLASSIFIED	SVC.MCN.
91	EMPLOYMENT AND WORKER DISPATCHING SERVICES	SVC.EMP.
92	MISCELLANEOUS BUSINESS SERVICES	SVC.BUS.
93	POLITICAL, BUSINESS AND CULTURAL ORGANIZATIONS	PLT.
94	RELIGION	REL.
95	MISCELLANEOUS SERVICES	SVC.MSC.
96	FOREIGN GOVERNMENTS AND INTERNATIONAL AGENCIES IN JAPAN	GOV.INT.
97	NATIONAL GOVERNMENT SERVICES	GOV.NAT.
98	LOCAL GOVERNMENT SERVICES	GOV.LOC.
99	INDUSTRIES UNABLE TO CLASSIFY	NEC

B Establishment level analysis for one-prefecture restrictions

TSR data does not include information of the location of establishments of each firm, except for its headquarter. However, a firm possibly has multiple establishments in different locations. To consider that, we utilize data from the Economic Census for Business Activity (hereafter the Census) collected by the Ministry of Internal Affairs and Communications and the Ministry of Economy, Trade and Industry [Ministry of Internal Affairs and Communications and Ministry of Economy, Trade and Industry, 2016]. This data includes all establishments in all industries in Japan. The establishments are micro-, small-, and medium-sized enterprises. We utilize the Census data for 2016 and the number of establishments is 5,880,504. The Census data is merged with the TSR data using firms' names, addresses, and telephone numbers. Then, 1,014,673 non-headquarter establishments are merged to the TSR data.

In the main text, the effect of the lockdown is given to a firm whose headquarter is located to the prefecture with the lockdown. Instead, we can consider establishments to give the shock of the lockdown. If an establishment is located in a region of a lockdown, a shock is given to the firm that owns the establishment. The shock to the firm is proportional to the size of the establishment. We use sales as the size of the establishment.

We conduct the one-prefecture restrictions for the model with the establishment using the same setting of the shock as the main text. The result is indicated in Figure B.1. Although, as an overall interpretation, the result is quite similar to the result with considering only the headquarters (Figure 4), the result with the establishment shows smaller the GRP loss rate.

The reason for the smaller loss rate can be attributed to a smaller supply side shock. First of all, the negative impact is amplified more in down streams than in up streams Inoue and Todo [2022] because if a firm cannot procure a intermediate goods and even if other it has enough other intermediate goods, a firm has to reduce the production and this process can amplify the initial shock. Since the model has the substitution process, a supply side shock can be absorbed if it is small. The model with the establishment model proportionally divide a shock by its establishment size, which results in a smaller supply shock. Therefore, the result with the establishment model shows the smaller loss rate.

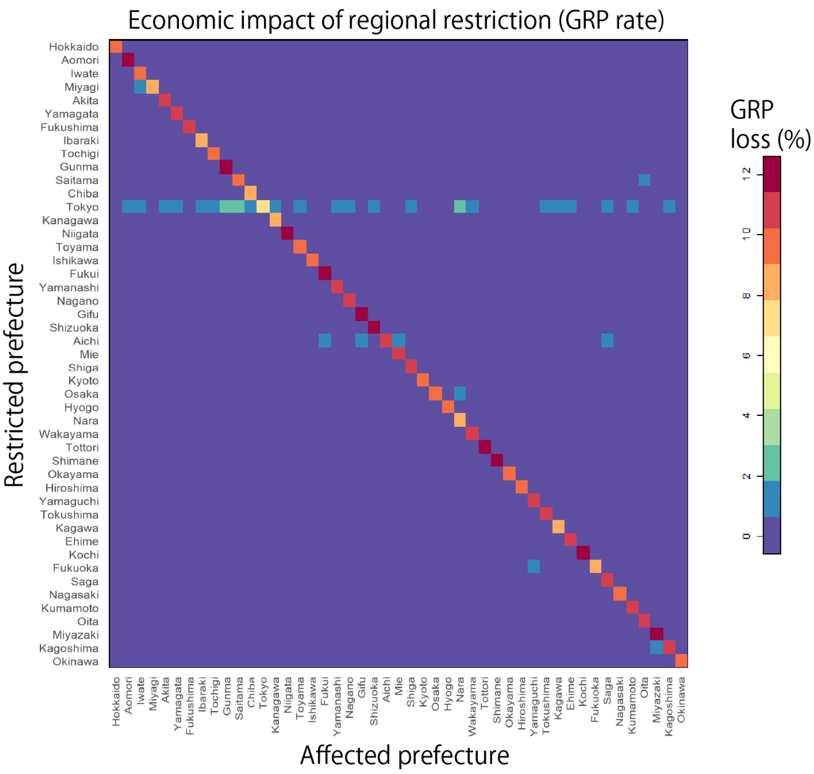

Figure B.1: Economic impact of lockdown of all sectors for four weeks in one prefecture. The impact is given to establishments. Each cell presents the production loss of the prefecture in the horizontal axis as a percentage of its gross regional product (GRP) because of lockdown in the prefecture in the vertical axis.

C Effects of one-prefecture restrictions: Other results

Figures C.1 indicates one-prefecture restriction for one week. The result is similar to Figure 5.

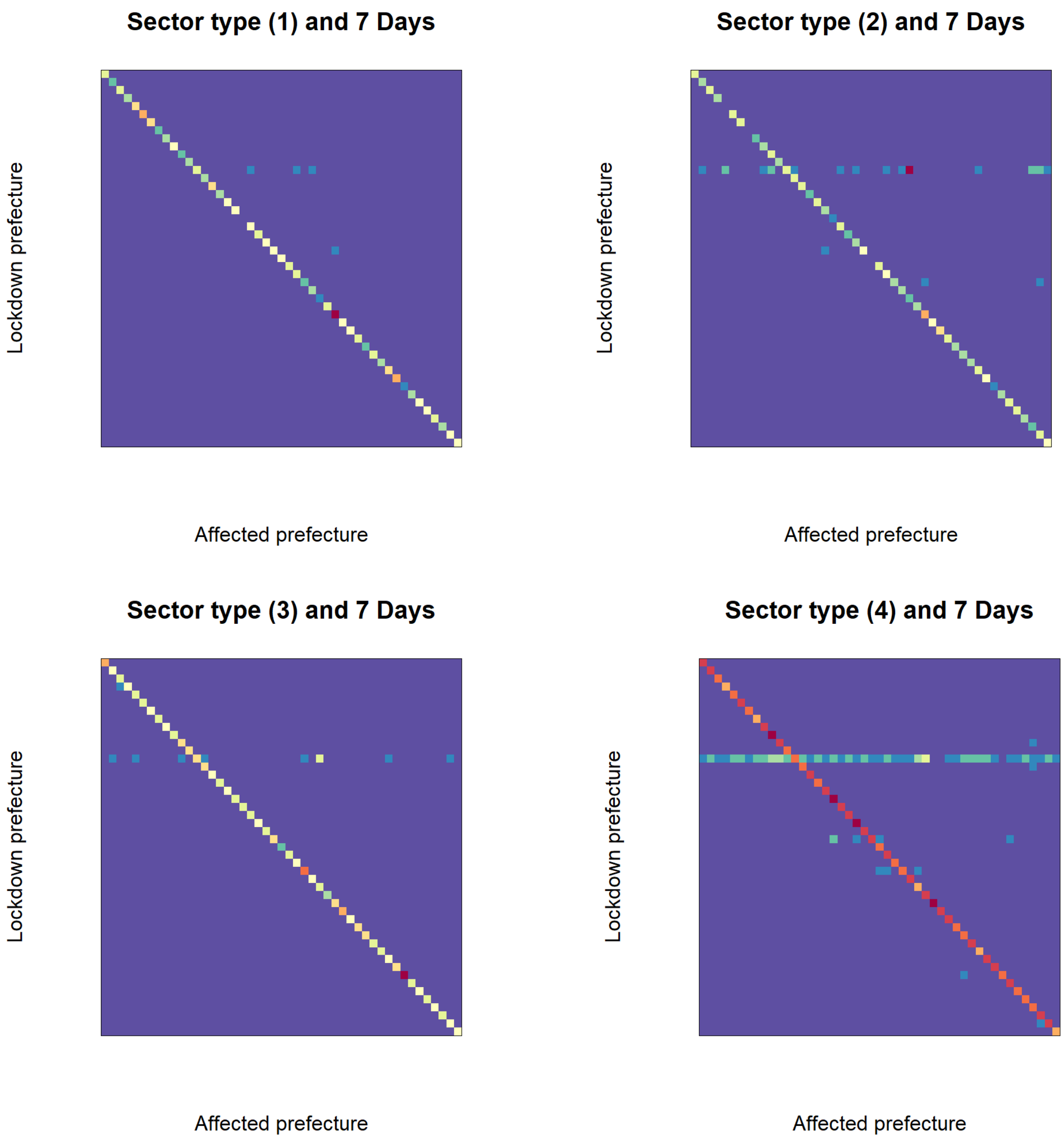

Figure C.1: Economic impact of regional restrictions for one week. Each row shows a restriction in a prefecture, and each element shows an economic loss caused by the restriction in the prefecture. The magnitude of the GRP loss is shown by colors. The restriction in this figure lasts 1 week. The sector types are (1) the accommodation and leisure sectors; (2) the restaurant sector plus (1); (3) the retail sector plus (2); and (4) all sectors.

D Effects of two-prefecture restrictions: Other results

Figures D.1, D.2, and D.3 show the results of the two-prefecture restrictions, in which one of the two prefectures is Aichi, Osaka, or Tottori, respectively. The restrictions are on all sectors for four weeks. There is no bar plot in the figure for each pivotal prefecture by definition. Since Tokyo has a dominant effect on other prefectures, as shown in Section 3.1, the bars with Tokyo exceed the horizontal limits. However, since Tokyo has been already discussed in the main text, the complete bars are not shown and reach to the edge of the graphs.

The "synchronous" label indicates that the two-prefecture restrictions, for example, Aichi and Hokkaido, are imposed simultaneously for four weeks. The corresponding result is the top blue bar in Figure D.1. The bar shows the GDP loss rate (entire supply chain loss). The denominator is the GDP for four weeks. The "asynchronous" label indicates the sum of the independent simulation, i.e., we test the scenarios with restrictions in Aichi and Hokkaido imposed independently. Then, we show the sum of the GDP losses from the independent simulations in the second-top red bar in Figure D.1.

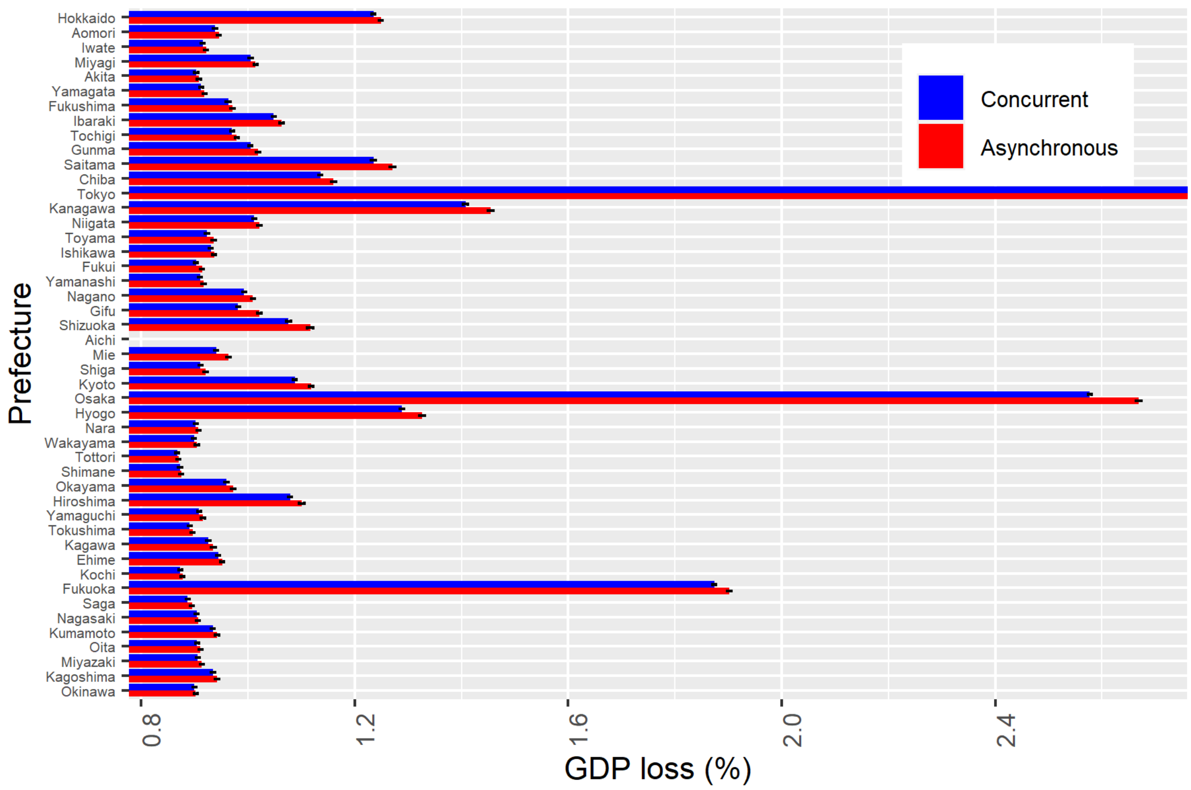

Figure D.1: Comparisons between simulations of synchronous and asynchronous restrictions in a given prefecture and Aichi. The restrictions are imposed on the two prefectures in each simulation. The prefectures with restrictions are indicated on the vertical axis , and the restrictions are imposed on all sectors for four weeks. The blue bars show the outcomes of the synchronous simulations, whereas the red bars show the GDP losses from the asynchronous simulations. The bars are the average of 30 Monte Carlo simulations. The black line segments are standard errors.

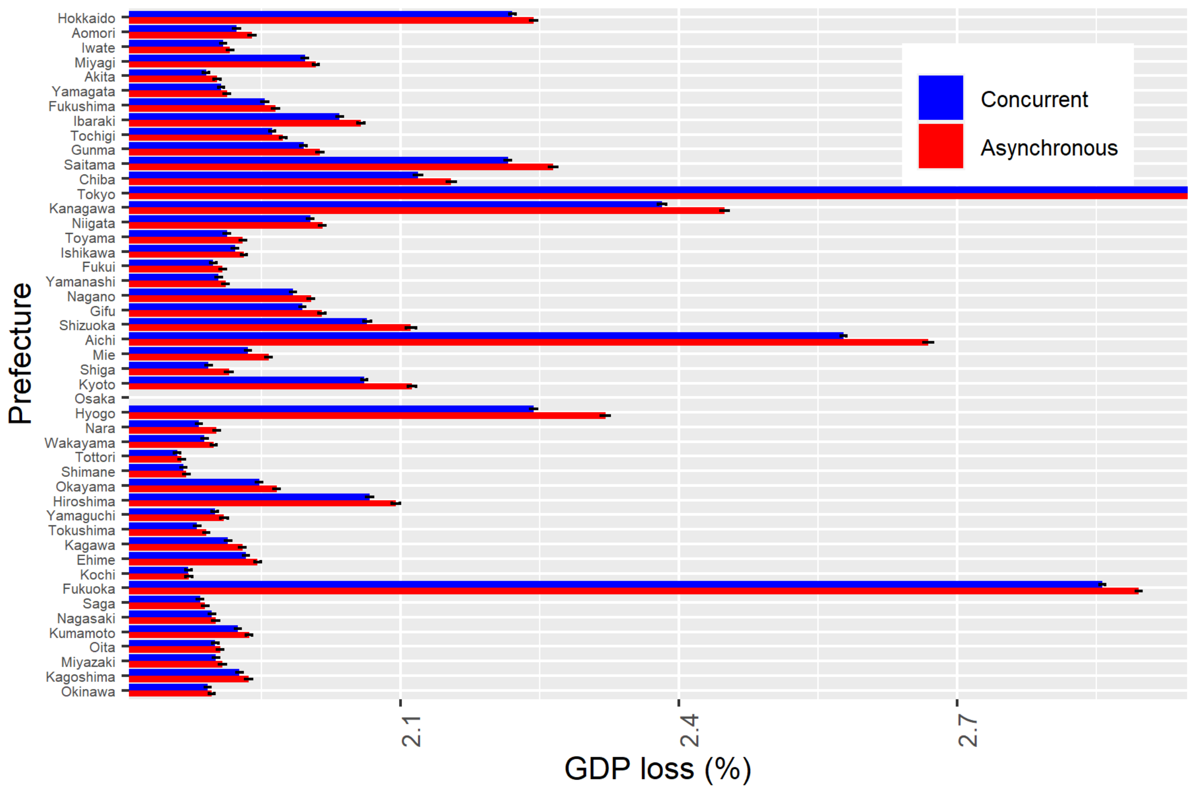

Figure D.2: Comparisons between simulations of synchronous and asynchronous restrictions in a given prefecture and Osaka. The restrictions are imposed on the two prefectures in each simulation. The prefectures with restrictions are indicated on the vertical axis. The restrictions are imposed on all sectors for four weeks. The blue bars show the outcomes of the synchronous simulations, whereas the red bars show the GDP losses from the asynchronous simulations. The bars are the average of 30 Monte Carlo simulations, and the black line segments are standard errors.

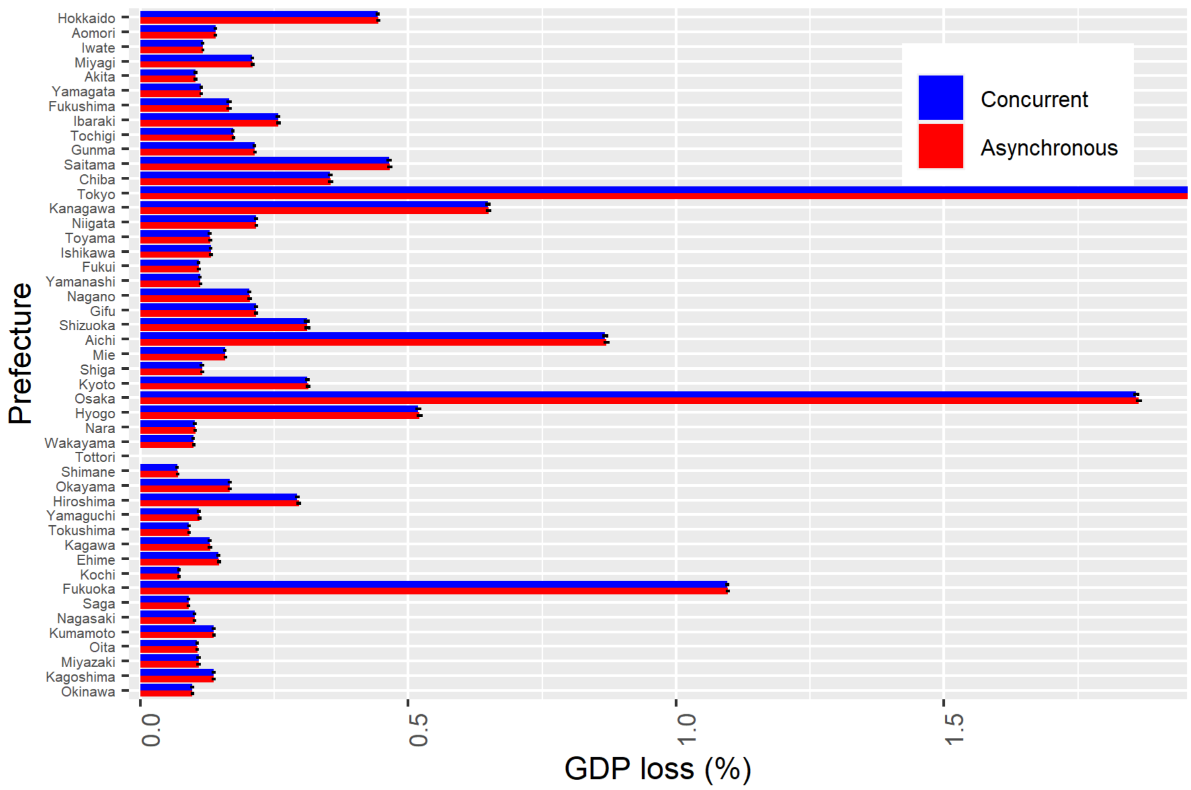

Figure D.3: Comparisons between simulations of synchronous and asynchronous restrictions in a given prefecture and Tottori. The restrictions are imposed on the two prefectures in each simulation. The prefectures with restrictions are indicated on the vertical axis. The restrictions are imposed on all sectors for four weeks. The blue bars show the outcomes of the synchronous simulations, whereas the red bars show the GDP losses from the asynchronous simulations. The bars are the average of 30 Monte Carlo simulations, and the black line segments are standard errors.