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Propagation of Overseas Economic Shocks through Global Supply Chains: Firm-level Evidence*

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Abstract
Recently, global supply chains are often disrupted because of trade policies and natural disasters. This study simulates the effect of disruption of imports from and exports to various regions on the total production of Japanese firms, incorporating propagation of the economic effect through domestic supply chains at the firm level. We find that the negative effect of disruption of intermediate imports grows exponentially as its duration and level increase because of downstream propagation. In particular, disruption of imports of electrical parts and components from Asia including China largely affects the manufacturing production of Japanese firms. In addition, the negative effect of disruption of imports from a specific region is more closely related to how importers are linked with other domestic firms than the import value from the region. Furthermore, the negative effect of import disruption can be largely mitigated by reorganization of domestic supply chains, even if the newly connected suppliers are limited to suppliers of competitors, i.e., firms sharing a supplier with the focal firm. Our findings suggest that when trade restrictions are imposed, the economic losses can vary substantially depending on their target industries, duration, and level, and the available substitutions.

Keywords: Global supply chains; trade disruption; simulation

JEL classification: L14

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1 Introduction

In recent years, global supply chains are frequently disrupted by natural disasters, military conflicts, and trade policies. For example, "lockdown" of cities and regions by the Chinese government to prevent the spread of COVID-19 in the early stage of its pandemic reduced production of Chinese firms and demand of Chinese consumers. Accordingly, exports of material, parts, and components from and imports of final products to China declined (Friedt & Zhang, 2020), leading to a substantial reduction in production in other countries because of shortage of supply and demand (Guan *et al.*, 2020; Meier & Pinto, 2020). Moreover, policies of the United States, Japan, and European countries to reorganize global supply chains of high-tech products, such as semi-conductors, for national security concerns (White House, 2021; Cabinet Secretariat of Japan, 2022; European Union, 2022) have reduced imports of parts and components from China particularly to the US and Japan (Todo, 2022). Most recently, economic sanctions on Russia because of the Russo-Ukrainian War disrupted exports of natural resources and manufacturing supplies from Russia and Ukraine (Kilpatrick, 2022). The Russo-Ukrainian War may further result in the "New Cold War" in which economies of the US and its allies are decoupled from those of Russia and China at least partially.

Under these circumstances, it is quite important to understand the effect of disruption of international trade on the domestic production. In particular, how decoupling from China affects the domestic economy is of great interest because China has become a major hub in global supply chains. One major issue when we estimate the effect of supply-chain disruption is that disruptions of imports and exports do not simply affect importers and exporters but affect the whole economy because of propagation of the shock through domestic supply chains. For example, in the wake of the Great East Japan earthquake, the total production loss in Japan was 100 times as large as the production loss in the areas directly affected by the earthquake (Inoue & Todo, 2020).

Therefore, this paper estimates the effect of disruptions of imports of inputs from or exports of outputs to various regions, including China, on the domestic production of Japan by simulating an agent-based model on large-scale data of more than one million firms that contain detailed supply-chain information and imports and exports at the firm level. Our model and simulations extend those used in Inoue & Todo (2019a,b, 2020), Inoue *et al.* (2020), and Inoue (2021) that focus on propagation of economic shocks through domestic supply chains by incorporating imports and exports. To the authors' best knowledge, this study is the first to simulate the economic effect of disruptions of global supply chains using model and data at the firm level.

This study is also related to several strands of literature. First, some studies estimate the economic effect of disruptions of global supply chains. For example, McKibbin & Fernando (2020) develop a multi-country and multi-industry model that combines a dynamic stochastic general equilibrium (DSGE) model and a computable general equilibrium (CGE) model and estimate the effect of reductions in labor and demand because of the pandemic of COVID-19 in a particular region on the production of major economies. Guan *et al.* (2020) employ an agent-based model with multiple countries and industries that incorporates substitution of disrupted supply chains and estimate the economic effect of lockdown of a region on another. Both studies use international input-output (IO) tables to identify input-ouput linkages across countries and industries and find that the economic effect of lockdown in a region propagates through the input-output linkages and thus can be substantial. A major shortcoming of these studies is that they use input-output linkages at the country-industry level and ignore complexity of supply chains at the firm level that can aggravate propagation of economic shocks (Acemoglu *et al.*, 2015; Barabási, 2016; Inoue & Todo, 2019a). In particular, Inoue & Todo (2019a) find that analysis based on IO tables without firm-level supply chains is most likely underestimate the economic effect of supply chain disruption to a great extent. We follow the latter strand of literature and incorporate firm-level supply chains to examine the economic effect of supply chain disruption more accurately.

Second, several other studies take an econometric approach to investigate the propagation of foreign shocks because of natural disasters on the domestic production through supply chains, using firm-level data. This approach is first utilized to examine propagation through domestic supply chains (Barrot & Sauvagnat, 2016; Carvalho *et al.*, 2021) and subsequently extended to international propagation. For example, Boehm *et al.* (2019) find a negative effect of the Great East Japan earthquake because of shortage of parts and components from Japan. By contrast, Kashiwagi *et al.* (2021) use data covering major firms in the world and their major supply-chain partners and find no significant effect of Hurricane Sandy that hit the US in 2012 on sales of suppliers or clients outside the US of firms directly affected by the hurricane. Although this econometric approach can clarify whether and how much a reduction in supply and demand of foreign firms affects the production of their supply-chain partners, it cannot estimate its total effect on the whole economy.

Finally, some other studies estimate how imports from China affect the importer economy, particularly its employment, using econometric approaches. Acemoglu *et al.* (2016a,b) use industry-level data for the US and find that the level of penetration of imports from China lowered employment in the US manufacturing industry. They further find that the negative effect of Chinese imports on US employment propagate through input-output linkages and is largely exacerbated. Dauth *et al.* (2017) and Kainuma & Saito (2022) apply this framework to Germany and Japan, respectively. Using a similar framework but firm-level data in addition to industry-level data for Japan, Fabinger *et al.* (2017) analyze how the effect of imports from China on sales of Japanese firms propagate upstream (i.e., from importers to their suppliers) and downstream (i.e., from importers to their clients). Although these studies highlight negative effects of imports from China on domestic manufacturing industries in importer countries, their analytical framework does not reveal how disruptions of imports from China affect the domestic production.

2 Data

This study uses two sets of data. One is the Company Information Database and Company Linkage Database of Tokyo Shoko Research (TSR) for 2020 that contain attributes for most firms in Japan, including small- and medium-sized enterprises (SMEs), and up to 24 domestic clients and suppliers of each firm. Although suppliers and clients of large firms may exceed 24, they can be identified by the information provided by the suppliers and clients. Accordingly, the TSR data can identify most major supply-chain links between firms in Japan. After dropping firms without sales information, the number of firms and supply-chain links in the sample is 966,627 and 3,544,343, respectively.

The other data source is the Basic Survey of Japanese Business Structure and Activities (*Kigyo Katsudo Kihon Chosa*, hereafter the BSJ) collected annually by the Ministry of Economy, Trade and Industry. The BSJ targets firms in Japan with 50 employees or more and the initial capital of 30 million yen or more, i.e., relatively large firms. The response rate of the BSJ in 2019 is 78.8%, and the number of respondent firms was 37,162. The BSJ data include information on imports of inputs from and exports of outputs of firms to broadly classified foreign regions and countries, i.e., Asia, China, Europe, North America, the Middle East, and other regions. Throughout the paper, we follow the definition of regions used in the BSJ data and denote East Asia including China, Southeast Asia, South Asia, and Central Asia as "Asia" and West Asia as "the Middle East." We combine the TSR data with trade information at the firm level taken from BSJ data, using firm identification numbers for the BSJ that are also included in the TSR data. Because the number of firms in the BSJ data is substantially smaller than that in the TSR data, we have to ignore imports and exports of small firms that are not included in the BSJ data. However, the total imports and exports of firms in the BSJ data are 47.7 and 83.0 trillion yen, respectively, whereas the total imports and exports of Japan in 2019 taken from the custom data are 78.6 and 76.9 trillion yen (Ministry of Finance, 2022), respectively[3]. Therefore, we assume that the BSJ data cover most exports of Japanese firms. Most exporters may be included in the BSJ data, because only productive and thus large firms can usually export (Melitz, 2003; Wakasugi *et al.*, 2008). The total exports in the BSJ data exceed those from the custom data, possibly because indirect exports of firms through traders are double-counted as exports of both producers and traders in the BSJ data. By contrast, imports in our data are undervalued because imports of small and medium-sized enterprises (SMEs) are not included. In particular, imports from China in our data, 8.55 trillion yen, are particularly undervalued, compared with those in the BSJ data, 18.5 trillion yen. This is possibly because a number of SMEs that import inputs rely on imports from China. By contrast, imports from Asia except for China in our data are 13.5 trillion yen are relatively closer to those in the BSJ data, 18.9 trillion.

The TSR data do not contain sales of each firm to final consumers and the transaction volume of each supply chain link. We estimate the former by dividing the final consumption of each industrial sector, taken from the IO table of Japan in 2015 (Ministry of Internal Affairs and Communications, the Cabinet Office, the Financial Services Agency, the Ministry of Finance, the Ministry of Education, Culture, Sports, Science and Technology, the Ministry of Health, Labour and Welfare, the Ministry of Agriculture, Forestry and Fisheries, the Ministry of Economy, Trade and Industry, the Ministry of Land, Infrastructure, Transport and Tourism, and the Ministry of Environment, Japan, 2015), among all firms in the sector in proportion to their sales. In addition, we estimate the transaction volume of each link using the following algorithm. First, each supplier's total sales less sales to final consumers are tentatively divided among its clients in proportion to the clients' sales. Second, the tentative volume of each supplier-client transaction is summed up within each pair of industries. Then, we adjust the inter-firm transaction volume so that the sum of the estimated volume within any industry pair is equal to the actual volume taken from the IO table of Japan in 2015.

3 Model

3.1 Overview

We extends dynamic agent-based models of Inoue & Todo (2019a,b, 2020) and Henriet *et al.* (2012) that focus on domestic supply chains by incorporating imports of inputs and exports of outputs. This subsection and Figure 1 overview the model, whereas we will explain more details in the subsequent subsections.

The model assumes that firms in a country are linked with each other through domestic supply chains and are also linked with foreign input and output markets through international trade. Each firm utilizes a fixed amount of labor and various intermediates provided by its domestic suppliers and imported from foreign countries, produces its product, and sells it to domestic and foreign client firms and final consumers. Following a Leontief production function, each firm utilizes a certain amount of each intermediate good and labor to produce one unit of its product. What and how much intermediate goods are required vary across firms and are determined by the data. Products are sector-specific, and hence, all firms in a particular sector produce the same product. Sectors are defined by Japan Standard Industrial Classification defined in 2013 (Ministry of International Affairs and Communications, 2013) and categorized into 1,460. Because our data include values of imported inputs from each of broadly defined foreign regions but not product types of the imported inputs, we assume that the sectoral classification of the input imported by a firm is the same as that of the product of the firm. Suppliers and clients are

[3]We also use BSJ data for 2018 to check the overall trend in the data and the validity of the use of the data for 2019.

pre-determined by the data and do not change in principle. In other words, even after disruption of supply chains, firms cannot find any new supplier or client. However, in exercises in the later section, firms can find other suppliers to find substitutions. Each firm holds an inventory of intermediates purchased from each manufacturing firm in case of shortage of supplies, whereas no inventory is assumed for service inputs. Moreover, when the inventory of intermediates from suppliers in the same sector, it is substitutable. In addition, firms hold no inventory of their own product and immediately deliver it to clients and consumers.

We do not assume profit maximization, following other agent-based models for simplicity. Instead, we assume that each firm follows several rules that determine the demand for each intermediate good and the supply of its product to its clients and consumers. In the initial period, or day 0 without any economic shock, the demand and supply of each firm's product are the same. At day 1, an economic shock, such as policies and natural disasters, disrupts imports from or exports to particular foreign regions. After the shock, firms directly facing disrupted supply chains reduce production because of shortages of supply of inputs or demand for outputs. Further, the shock propagates to other firms through supply chains. Because of the reduction in production, the demand for a firm's product may surpasses its supply. If so, the firm determines how its production is allocated to its client firms and consumers following a rationing rule.

3.2 Supply and demand

In the followings, we denote the daily supply of the intermediate product of supplier i to client h on day t by $Q^{\mathrm{S}}_{hi}(t)$, the supply to the final consumers by $Q^{\mathrm{S}}_{Ci}(t)$, and the exports to region a by $Q^{\mathrm{EX}}_{ai}(t)$. Then, the production of firm i on day 0 is given by

$$Q^{\mathrm{S}}_{i}(0) = \Sigma_h Q^{\mathrm{S}}_{hi}(0) + Q^{\mathrm{S}}_{Ci}(0) + \Sigma_a Q^{\mathrm{EX}}_{ai}(0). \tag{1}$$

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

In addition, firms demand for intermediates to hold their inventories in case of supply chain disruption. Specifically, firm i has an inventory of the intermediate produced by firm j 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, $n_i Q^{S}_{ij}(0)$. We assume that n_i is randomly determined by a Poisson distribution where the mean is n. Note that there is data indicating inventory of each firm's own products but not about inventory of intermediate goods used by each firm. Therefore, we rely on this probabilistic assignment. In this paper, we assume that a Poisson distribution where $n = 12$ and further that any n_i smaller than 12 is changed to 12 to avoid a bullwhip effect, i.e., large fluctuations across simulations. When the actual inventory $I_{ij}(t)$ is smaller than its target $n_i Q^{\mathrm{S}}_{ij}(0)$, 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 $Q^{\mathrm{D}}_{ij}(t)$, is given by

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

As is mentioned in Section 3.1, the inventory should not be considered for a service supplier. This aspect is realized by the second term is omitted and $Q^{\mathrm{D}}_{ij}(t)$ is always equal to $Q^{\mathrm{S}}_{ij}(0)$, where j belongs to a service sector.

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

$$Q_i^{\mathrm{D}}(t) = \Sigma_h Q_{hi}^{\mathrm{D}}(t) + Q_{Ci}^{\mathrm{D}} + \Sigma_a Q_{ai}^{\mathrm{EX}}(0). \tag{3}$$

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

3.3 Disruption of supply chains

Now, suppose that imports of intermediate goods from some foreign countries or regions are disrupted because of a trade policy or natural disaster. When facing shortage of imports of an intermediate product from region a, firm i can use its inventory of the intermediate, including the inventory of the same intermediate from other domestic suppliers in the same sector and imports from other regions. Therefore, the maximum possible production of firm i limited by the product inventory of the sector-s intermediate on day t, $\bar{Q}_{i(s)}^{\mathrm{S}}(t)$, is given by

$$\bar{Q}_{i(s)}^{\mathrm{S}}(t) = \frac{\Sigma_{j\in s} I_{ij}(t)}{\Sigma_{j\in s} Q_{ij}^{\mathrm{S}}(0)} Q_i^{\mathrm{S}}(0), \tag{4}$$

where $\Sigma_{j\in s} I_{ij}(t)$ is firm i 's total inventory of the intermediate of sector s, including imports, on day t, and $\Sigma_{j\in s} Q_{ij}^{\mathrm{S}}(0)$ is the amount of intermediate s required to produce the initial production level of firm i. Because we assume a Leotief production function, the maximum possible production of firm i on day t is constrained by the availability of inputs and given by:

$$Q_{\mathrm{max}i}^{\mathrm{S}}(t) = \mathrm{Min}_s(\bar{Q}_{i(s)}^{\mathrm{S}}(t)). \tag{5}$$

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

$$Q_i^{\mathrm{S}}(t) = \mathrm{Min}\left(Q_{\mathrm{max}i}^{\mathrm{S}}(t), Q_i^{\mathrm{D}}(t)\right). \tag{6}$$

In alternative scenarios, we assume that exports of products to some foreign countries or regions are stopped because of a trade policy or natural disaster. In this case, the demand for firms exporting to the foreign regions declines by the amount of the exports. The supply of firm i is still determined by equation (6).

In either scenario, it is noted that supply and demand of firms that are not directly engaged in international trade may be affected by the supply-chain disruption because of propagation of its effect through supply chains.

3.4 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. Suppose that firm i has clients $h \in \{1, ..., H\}$, final consumers, and importers. The supply to each client, consumer, and importer is determined by the following steps where the demand of agents that is relatively small compared with their initial demand is prioritized (Inoue & Todo, 2019a). To explain the procedure, let us define the amount of production that has not been rationed and remains to be rationed at the beginning of step x as $Q_i^{\mathrm{R}}[x]$. We also denote the minimum ratio of the current demand to the initial demand by $q_{\min}^{\mathrm{D}}(t) \equiv \mathrm{Min}(q_{hi}^{\mathrm{D}}(t), q_{CEXi}^{\mathrm{D}}(t))$. Here, $q_{hi}^{\mathrm{D}}(t) \equiv Q_{hi}^{\mathrm{D}}(t)/Q_{hi}^{\mathrm{S}}(0)$ is the ratio of the demand of client h for the product of firm i to its initial demand, and $q_{CEXi}^{\mathrm{D}}(t) \equiv (Q_{Ci}^{\mathrm{D}}(t) + \Sigma_a Q_{ai}^{\mathrm{EX}}(t))/(Q_{Ci}^{\mathrm{S}}(0) + \Sigma_a Q_{ai}^{\mathrm{EX}}(0))$ is the corresponding ratio for the sum of the demand of final consumers and importers.

In the first step, $x = 1$ and $Q_i^{\mathrm{R}}[1] = Q_i^{\mathrm{S}}(t)$ by definition. At every step the following equation is evaluated.

$$Q_i^{\mathrm{R}}[x] \geq q_{\min}^{\mathrm{D}}(t) Q_i^{\mathrm{D}}(t). \tag{7}$$

If equation 7 holds, firm i rations to each client firm, consumer, and importer the amount of its demand multiplied by the minimum demand ratio $q_{\min}^{\mathrm{D}}(t)$. The remaining of the production, $Q_i^{\mathrm{R}}[x+1] = Q^{\mathrm{R}}[x] - q_{\min}^{\mathrm{D}}(t) Q_i^{\mathrm{D}}(t)$, is handed over to the next step. In addition, the demand from each client firm, consumer, and importers is removed by the ratio, q^{D}. Therefore, a client firm or the aggregate consumers and importers that satisfies its demand (or whose rate of the current demand to the initial demand is the minimum) is dropped. On the other hand, if equation (7) does not hold at some step x, firm i rations to each client, consumer, and importer the amount of its demand multiplied by the ratio of the remaining production to demand defined by $q_{\text{r-d}i}^{\mathrm{D}} \equiv Q_i^{\mathrm{R}}[x]/Q_i^{\mathrm{D}}(t)$. At this step, the procedure ends because $Q_i^{\mathrm{R}}[x+1]$ becomes zero.

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

$$I_{ij}(t+1) = I_{ij}(t) + Q_{ij}^{\mathrm{S}}(t) - Q_{ij}^{\mathrm{S}}(0) \frac{Q_i^{\mathrm{S}}(t-1)}{Q_i^{\mathrm{S}}(0)}. \tag{8}$$

This equation combined with equations (2) and (6) determines the demand of firm i for the intermediate good supplied by firm j on day $t+1$, $Q_{ij}^{\mathrm{D}}(t+1)$, and the total demand for firm i's product $Q_i^{\mathrm{D}}(t+1)$. The supply of firm i on day $t+1$, $Q_i^{\mathrm{S}}(t+1)$, is then determined by equation (6).

4 Simulations

Using the agent-based model and firm-level data with supply-chain information, we simulate how disruption of imports or exports by a trade policy or natural disaster affects the total production of Japan. In particular, we simulate the model using a number of scenarios in five dimensions: (1) the type of trade (imports, exports, or both); (2) the target region (the world, Asia, China, Asia except for China, North America, Europe, the Middle East, and others); (3) the duration of disruption (two weeks, four weeks, or two months); (4) the level of disruption, i.e., the rate of reduction in imports from or exports to the target region (20, 40, 60, or 80%), and (5) industries of which imports or exports are disrupted (all or one of the manufacturing industries). For example, in one scenario, we assume a reduction of imports of all intermediate products from the world by 60% for four weeks and simulate the total production of Japan day by day. In another, we assume a reduction in imports of electrical machinery, equipment, and supplies from China by 80% for two months. Tables 2 and 3 present detailed industry classifications used in the simulations.

Then, we calculate the ratio of the reduction in the total production because of the disruption to the total production without any disruption during the disruption period, denoted as the reduction rate. In scenarios where we assume disruption in a particular industry, we additionally compute how much the industry-specific disruption reduces the production of the own industry and each of other industries. By so doing, we can examine spillovers of the effect of industry-specific disruption across industries.

5 Results

5.1 Disruption of imports

The results from assuming disruption of imports are presented in Figure 2. The upper-left panel illustrates the rate of reduction in production when imports from the whole world are disrupted. Throughout this paper, we define production by total gross sales, rather than value added production, i.e., sales less input values. The disruption at any level for two weeks causes a negligible reduction in production. This is because firms are assumed to hold inventories of intermediates including imported inputs for amount of nine days of their use on average (Section 3.2) and thus do not necessarily reduce production for a while after the disruption. However, the reduction rate becomes non-negligible four weeks after the start of the disruption when its strength is high: 0.9 and 2.9% from the reduction in imports by 60 and 80%, respectively. When the disruption lasts for two months, the corresponding reduction rate becomes far larger to 10.7 and 25.9%. This exponential growth of the reduction in production is due to propagation of the effect of disruption of imports to direct and indirect clients of importers through supply chains. When imports reduce by 80% for two months, the total value of disrupted imports is 5.9 trillion yen whereas the reduction in the total production because of the disruption is 92 trillion yen, or 15.6 times as large as the disrupted imports. Therefore, the propagation effect is quite large. It is also noted that as the level of disruption increases, the reduction rate in production increases exponentially. When the level of a 2-month disruption doubles from 40 to 80%, the reduction rate in production becomes 14 times. This finding implies that a small difference in the initial shock is enhanced substantially in the long run.

Other panels of Figure 2 show the simulation results assuming disruption of imports from various regions in particular. All panels share the same characteristics from the simulation of the disruption of imports from the world mentioned just above: exponential growth in the reduction rate in production as the duration or level of disruption increases. Comparing between the panels, we observe that the largest effect comes from disruption of imports from Asia. Distinguishing between China and other Asia, we find that the effect of China and other Asia is quite similar: the disruption of imports from China and other Asia for two months by 80% reduces total production by 14.8 and 14.3%, respectively. The large effect of Asia is obviously due to its large share in imports of intermediate goods to Japan. However, it should be emphasized that imports from China in our data are undervalued more than those from other Asia, as mentioned in Section 2.

We further examine what factors affects the propagation of the shock and find that the effect of disruption of intermediate imports from each region is not closely correlated with the value of imports from the region, but with supply-chain links of Japanese firms with the region. For example, disruption of import from China would lead to a large reduction in production: 15% of the total production if imports are reduced by 80% for two months. The reduction associated with of disruption of imports from China is slightly larger than the corresponding figure for other Asia and substantially larger than that for the Middle East, although imports from China, 8.6 trillion yen in our data, are much smaller than from other Asia, 13.5 trillion yen, and slightly smaller than from the Middle East, 9.8 trillion yen, as shown in the left panel of Figure 3. Further, the middle and right panels of Figure 3 indicate that the effect of disruption of imports from a particular region is affected by the number of importers from the region and the total number of clients of the importers, i.e., how the exporting region is linked with Japanese firms, rather than the value of imports from the region.

5.2 Disruption of exports

Panels in Figure 4 illustrates simulation results for disruption of exports to different regions. We find three notable differences between the effects of import and export disruption. First, the rate of reduction in production because of export disruption declines as its duration prolongs, although the reduction rate increases exponentially in the case of import disruption. For example, the upper-left panel indicates that when exports to the world are disrupted by 80% for two weeks, the total production of Japan declines by 4.4%. When the duration becomes four weeks and two months, respectively, the reduction rate in production declines to 3.5 and 2.6%. Second, the rate of reduction in production is proportional to the level of disruption, i.e., the rate of reduction in exports. For example, when exports to the world disrupted by 20, 40, 60, and 80% for two months, the total production declines by 0.65, 1.3, 1.9, and 2.6, respectively (the upper-left panel of Figure 4). Finally, disruption of imports of intermediate goods cause a far greater impact on the total production of the economy than disruptions of exports of final products, although the total imports in the data used in our simulation, 45 billion yen, are approximately a half of the total exports, 81 billion yen. Moreover, the share of imports in the total value of intermediates, 2.8%, is substantially smaller than the share of exports in the total production, 16.7%.

These differences are stemming from the following three reasons. First, the effect of import disruption, i.e., reductions in supplies of inputs, can be partially absorbed by utilizing inventory of disrupted inputs. Therefore, the effect of import disruption is quite small initially. By contrast, the effect of export disruption, i.e., reductions in demand, cannot be absorbed but rather is aggravated by inventory usage. When exporting firms face shrinkage of their exports, their demand for intermediate products also shrinks. Because exporters hold inventories of their intermediates, they use the inventories for shrunk production and drastically reduce their purchases from their suppliers immediately after the export disruption. As a result, production of their suppliers declines substantially, leading to large initial reductions in production of the suppliers' suppliers.

Second, although the initial effect of import disruption is alleviated by the use of inventory of inputs, its effect is aggravated over time as inventory is used up. Moreover, the effect propagates downstream through supply chains because a reduction in production of a firm results in a reduction in production of clients of the firm. The propagation is gradual because of inventory of inputs of the clients but can be substantial after a while. By contrast, how the effect of export disruption is influenced by inventory is opposite. Once excess inventories of intermediates are used shortly after export disruption, exporters purchase more intermediates from their suppliers, and thus the total production increases compared with that immediately after the disruption. In the long run, the rate of reduction in the total production should converge to the ratio of exports to the total production.

Finally, the effect of import disruption is "leveraged" or propagated to more firms as the shock goes downstream to clients through input shortages. However, there is no such leverage effect of export disruption, because firms facing a reduction in demand directly or indirectly because of export disruption simply reduce their production by the reduced demand. As a result, the rate of reduction in production because of import disruption increases exponentially as the level of disruption rises, while the reduction rate because of export disruption is proportional to the level. In addition, for the same reason, the effect of export disruption to each region is proportional to the value of exports to the region. Accordingly, the largest effect of export disruption comes from the disruption of exports to Asia except for China, followed by North America and then China (Figure 4).

5.3 Disruption of imports and exports

We now assume that both imports and exports are simultaneously disrupted and show the simulation results in Figure 5. The rate of reduction in the total production by the simultaneous disruptions is similar to the sum of the reduction rate by import and export disruptions. As a result of the reduction because of the export disruption, the reduction rate is non-zero immediately after the beginning of the disruption. After that, because the increase in the reduction rate by the import disruption is greater

(Figure 2) than its decrease by the export disruption (Figure 4), the reduction rate increases over time. For example, when imports from and exports to the world reduce by 80% for two weeks, four weeks, and two months, the total production declines by 4.4, 5.1, and 25.5%, respectively.

5.4 Industry-level analysis

Further, we perform industry-by-industry analysis. Specifically, we investigate how disruption of imports in a particular manufacturing industry by 80% for two months affect production in each of all industries. Industries of which imports are disrupted are limited to manufacturing industries and defined at the two-digit level according to the Japan Standard Industrial Classification (Ministry of International Affairs and Communications, 2013). Industries that are affected by the disruption are defined at the one-digit level for non-manufacturing industries and at the two-digit-level for manufacturing industries, so that we can examine the effect of a manufacturing industry on broadly defined non-manufacturing industries and detailed manufacturing industries. Tables 2 and 3 show the definitions of these industries.

The results are presented in Figure 6. The upper left panel shows the results from assuming disruption of imports in a particular sector from the world. Several findings are notable. First, disruption of manufacturing imports (sectors E09-E32) largely reduces production in manufacturing sectors, while its effect on non-manufacturing sectors (A-D and F-T) is limited, except for the mining industry (C). Second, among the manufacturing industries, disruption of imports in most light industries, such as the food and beverage industry (E09-10), the wood and furniture industry (E12-13), and the paper industry (E14), does not largely affect other manufacturing industries. By contrast, when a heavy manufacturing industry is affected, the effect propagates to other industries.

When we focus on disruption of imports from Asia in the upper right panel of Figure 6, we find that the effect of disruption of imports of the electrical machinery and equipment (E29), and the information and communication electronics equipment industry (E30) on the total production is the largest (the top panel of Figure 7). This finding highlights the importance of imports of electrical parts and components from Asia to the manufacturing production in Japan. We further distinguish between imports from China and other Asia and show the results in the middle left and right panels of Figure 6, respectively and find some differences. Most notably, in the case of disruption of imports from China, the information and communication electronics equipment industry (E30) is quite important to the Japanese economy, while it is not for other Asia. In addition, disruption of imports in the chemical (E16) and ceramic (E21) industries from other Asia has a large effect, while that from China does not (the middle and bottom panels of Figure 7). Disruption of imports from North America and Europe reduces the production of Japan negligibly (the bottom panels of Figure 6), suggesting a minor role of these regions in supply chains of Japanese firms as input suppliers.

5.5 Substitution of suppliers

Finally, to examine how much the propagation of the negative effect of import disruption on production can be mitigated by substitution of domestic suppliers, we simulate three modified models. In our benchmark model explained in Section 3, after import disruption, firms cannot be linked with suppliers or clients without any prior link to deal with supply chain disruption. However, in the first modified model, we assume that when a client firm faces a reduction in the transaction volume with one of its suppliers, it may be linked with any nother supplier from the set of firms in the same industry. In addition, because this matching assumption may be too strong from practical perspectives, we alternatively assume that clients firm facing supply disruption can find another supplier that was not directly linked but indirectly linked through supply chains before the disaster in a few steps. For example, Figure 8 shows that firm

D is indirectly linked with supplier C through B and E, and A and C belong to the same industry. Therefore, when the transaction between A and D declines after a shock, we assume that firm D may procure its supplies from C depending on the production capacity of C, because information about firm C flows through supply chains to D. Such endogenous network revolution based on the current network is empirically found in Uzzi (1996) and Matous & Todo (2017). Finally, to highlight the importance of supplier substitution, we also experiment with another model that assumes no substitution between suppliers even when suppliers are in the same industry. In other words, this model implicitly assumes that each firm produces a product specific to the firm.

When we assume disruption of 80% of imports from the world for two months in the modified model with random matching of new suppliers, our benchmark simulation assuming possible substitution between current suppliers in the same industry found a reduction in the total production by 25.9% (Section 5.1). The reduction in the total daily production is depicted by the brown line in Figure 9. The reduction increases to 36.9% when we assume no supplier substitution, as shown by the green line in the figure. By contrast, the total production reduces by 19.8% and 20.8% using the alternative models with post-disruption matching with new suppliers randomly (the blue line) and through pre-disruption supply chains (the red line), respectively.

These results clearly suggest that the negative effect of import disruption can be mitigated by more flexible reorganization of domestic supply chains. In addition, we find that matching with new suppliers indirectly linked through supply chains leads to a production reduction similar to that assuming matching with any supplier. This finding implies that although suppliers indirectly linked through supply chains in a few steps are limited compared with the whole set of suppliers, reorganization of supply chains only within neighboring firms can lead to a large improvement in the negative effect of import disruption.

6 Discussion and Conclusions

Our results in the previous section provide several implications, particularly to recent trade policies which may have to be restrictive to protect national security. First, we find that the negative effect of disruption of intermediate imports on the total production increases exponentially as their duration or level increases. In addition, the effect of import disruption is substantially larger than the effect of export disruption. These findings are due to the fact that the effect of import disruption propagates downstream through supply chains and is thus magnified. Therefore, policy makers should be careful about the large and growing negative effect of import disruption when trade restrictions are necessary for national security concerns.

Second, the negative effect of disruption of imports from a region is more closely related to how domestic supply chains are linked with importers than the import values. From a policy perspective, this finding implies that to minimize the economic effect of restrictions on imports from a region, policy makers should be concerned about supply chain links between the exporting region and Japanese firms, rather than simply focusing on the value of imports.

Third, although a reduction of imports by a large degree (e.g., 80%) for a long period (e.g., two months) largely reduce the total production in Japan, import disruption that last two weeks or shorter or reduce imports by 40% or less would negligibly affect the domestic economy (Figure 2). This finding provides another policy implication. Even when restrictions on intermediate imports from China are inevitable for national security purposes or any other reason, they may not drastically jeopardize Japan's domestic production if their strength is sufficiently small or their duration is sufficiently short.

Finally, our experiments reveal that substitution of suppliers can mitigate the negative effect of import disruption. This finding confirms the importance of supplier substitution for robust and resilient supply chains that has been empirically found in several previous studies (Barrot & Sauvagnat, 2016; Inoue & Todo, 2019a,b; Kashiwagi *et al.*, 2021). Managerial and policy implications from this finding are that firms should form more flexible supply chains to prepare for possible import and export disruption and that governments should support these activities of firms.

Several caveats of this study should be noted. First, our model allow changes in supply chain links after import or export disruption tentatively, but not permanently. Second, our analysis is based on an agent-based model without any price. Because of the two shortcomings, our conclusion should be viewed with caution and applied to only short-term analysis. Therefore, the long-term scenarios where we assume import or export disruption for two months may have lead to an overvaluation of the effect of supply chain disruption. Third, our trade data are based on the BSJ data in which only large firms are included, and thus, imports are particularly undervalued (Section 2). Because small and medium-sized enterprises that import inputs often rely only on China, imports from China in our data (Section 2) and their effect on production in our simulation may be underestimated. Finally, because the TSR or BSJ data do not contain information on supply chains between establishments, we assume supply chains at the firm level, rather than at the establishment level. Although our assumption can capture possible links between non-headquarter establishments through their headquarters, our data may undervalue the complexity of domestic supply chains and thus may underestimate the effect of import disruption.

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Figures and Tables

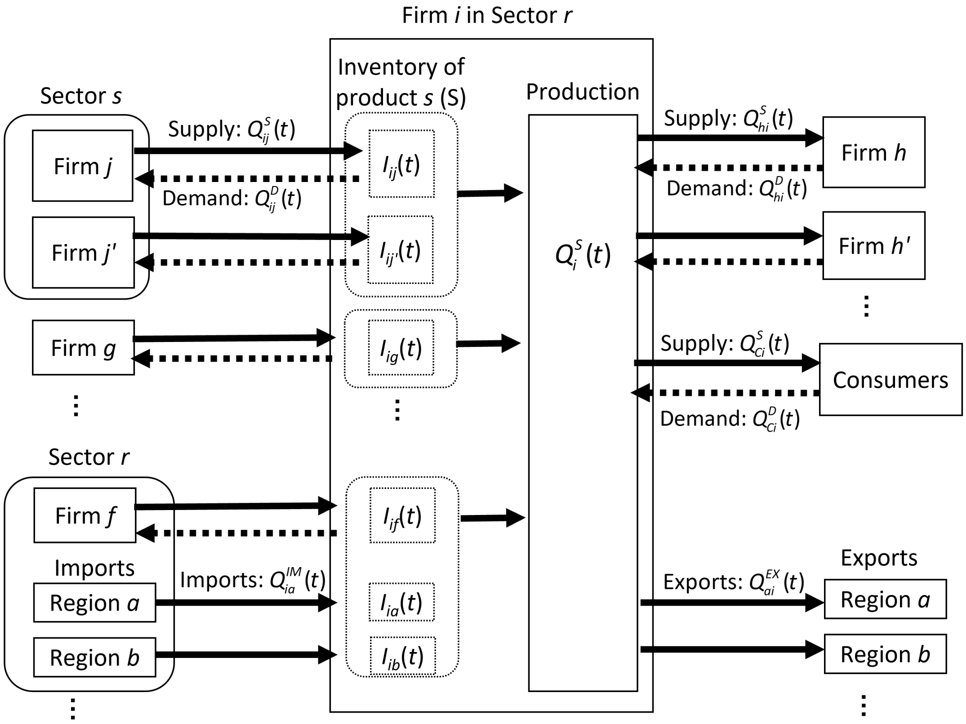


Figure 1: Overview of the agent-based model. Products flow from left to right, whereas orders flow in the opposite direction. The equation numbers correspond to those in the main text.

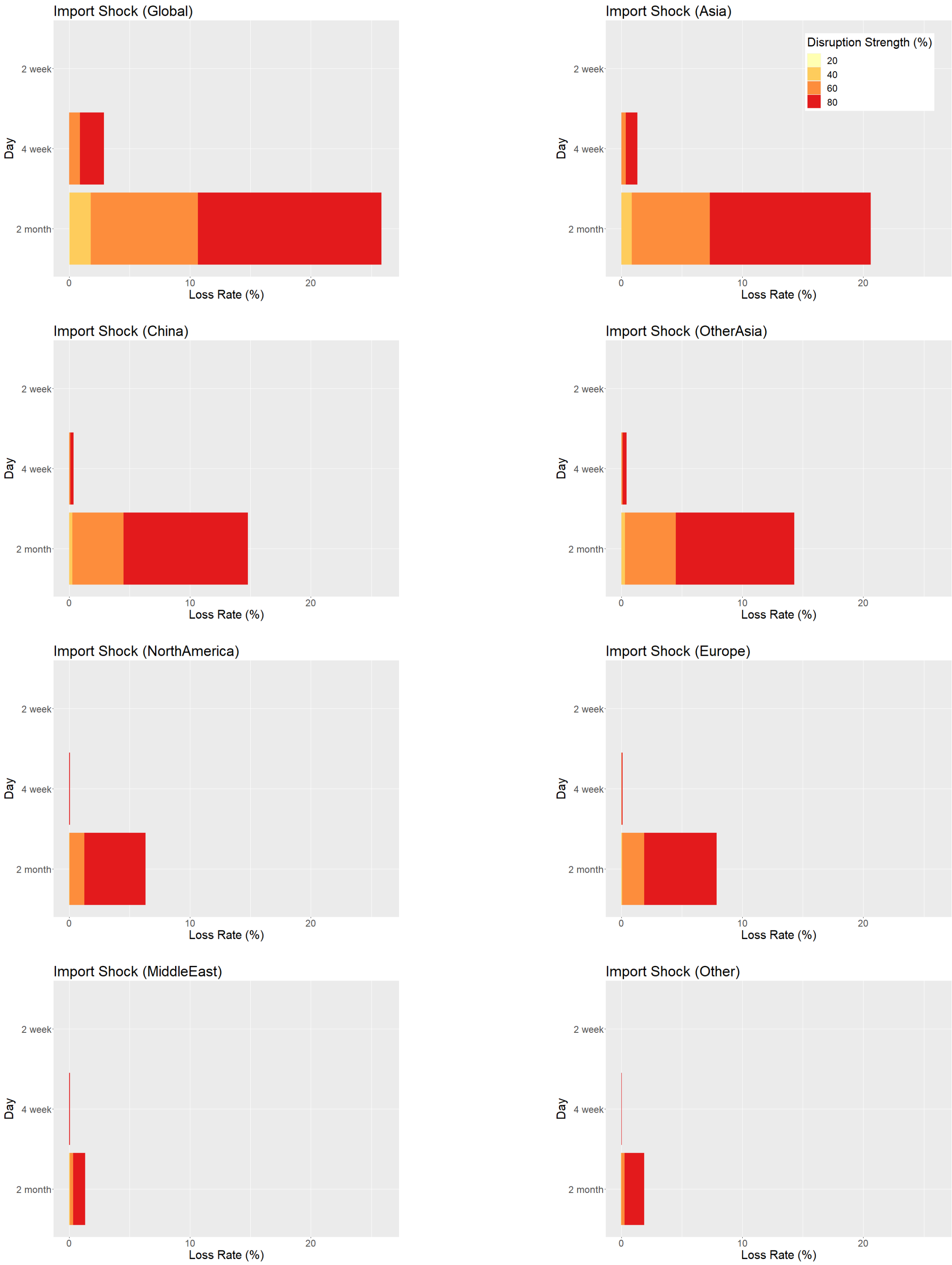


Figure 2: Import shock: This figure shows the rate of reduction of the total production in Japan to the total production when imports from a particular region is disrupted to a particular degree for a particular duration. “Global“, “Asia”, “China”, “OtherAsia”, “NorthAmerica”, “Europe”, “MiddleEast”, “Other” indicate respectively disruption of imports from all Asian countries, China, countries in Asia except for China, the United States of America and Canada, countries in Europe, countries in the Middle East, and other countries.

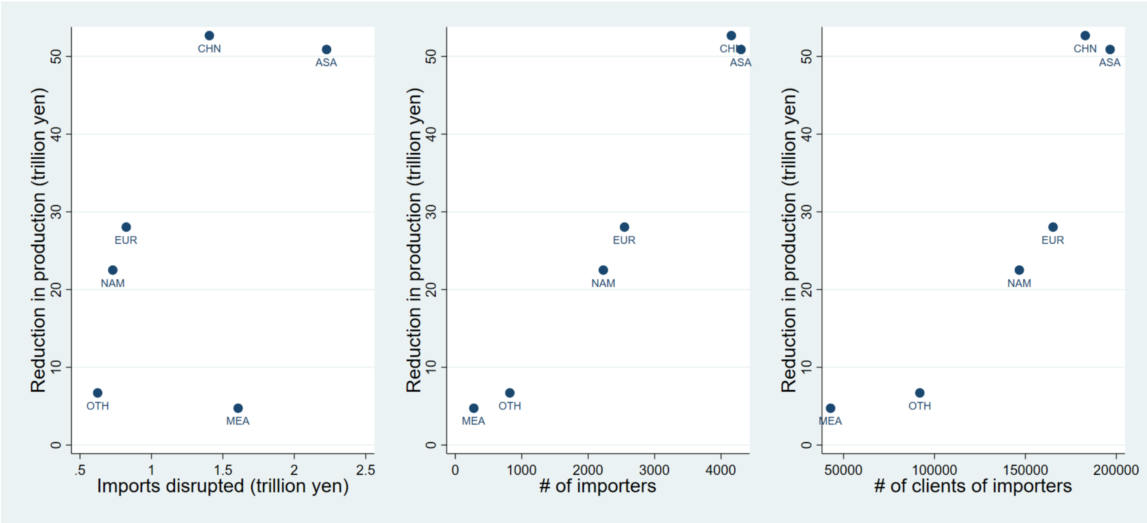


Figure 3: This figure shows correlation between the reduction in production because of import disruptions of the degree of 80% for two months (trillion yen) and each of the value of imports (trillion yen), the number of importers, and the total number of importers' clients by exporter region. CHN, ASA, NAM, EUR, MEA, and OTH represent China, Asia except for China, North America, Europe, Middle East, and others.

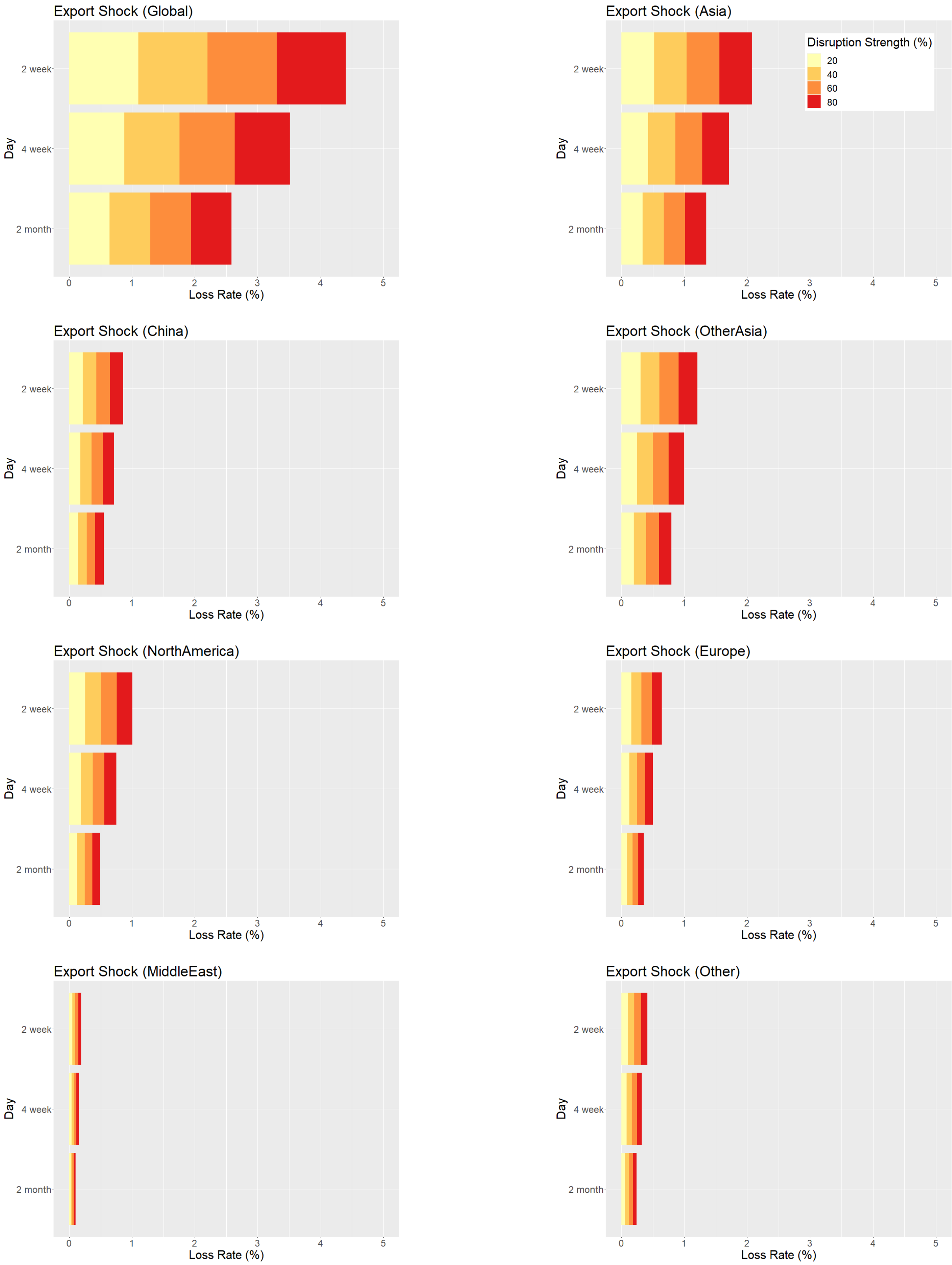


Figure 4: Export shock: This figure shows the rate of reduction of the total production in Japan to the total production when exports to a particular region is disrupted to a particular degree for a particular duration. “Global“, “Asia”, “China”, “OtherAsia”, “NorthAmerica”, “Europe”, “MiddleEast”, “Other” indicate respectively disruption of imports from all Asian countries, China, countries in Asia except for China, the United States of America and Canada, countries in Europe, countries in the Middle East, and other countries.

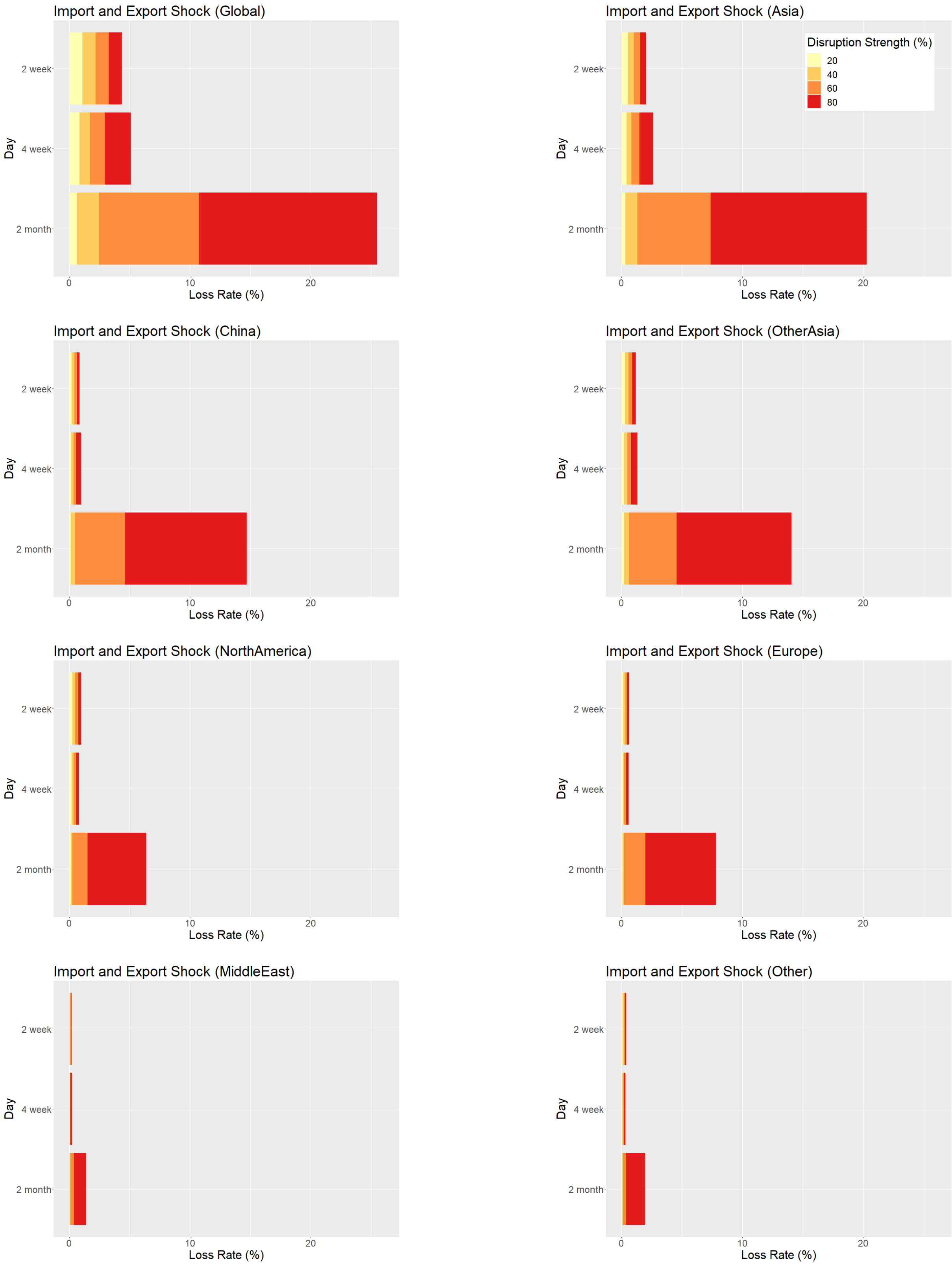


Figure 5: Import and export shock: This figure shows the rate of reduction of the total production in Japan to the total production when imports from and exports to a particular region is disrupted to a particular degree for a particular duration. “Global“, “Asia”, “China”, “OtherAsia”, “NorthAmerica”, “Europe”, “MiddleEast”, “Other” indicate respectively disruption of imports from all Asian countries, China, countries in Asia except for China, the United States of America and Canada, countries in Europe, countries in the Middle East, and other countries.

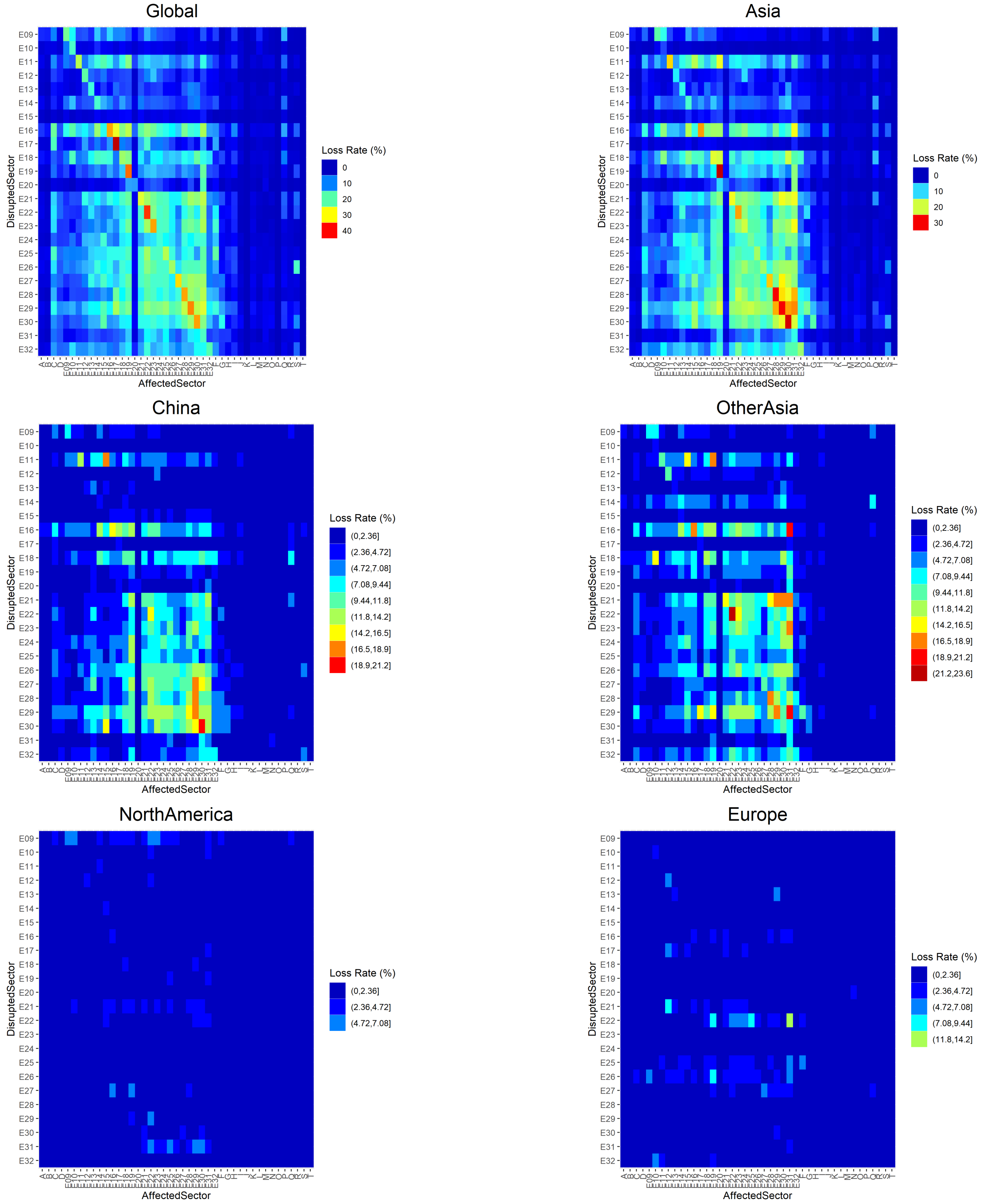
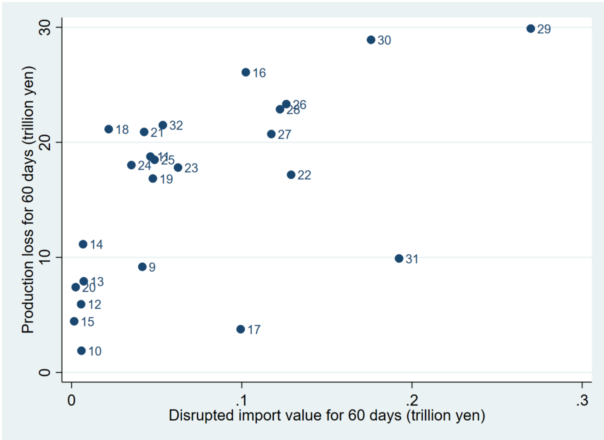
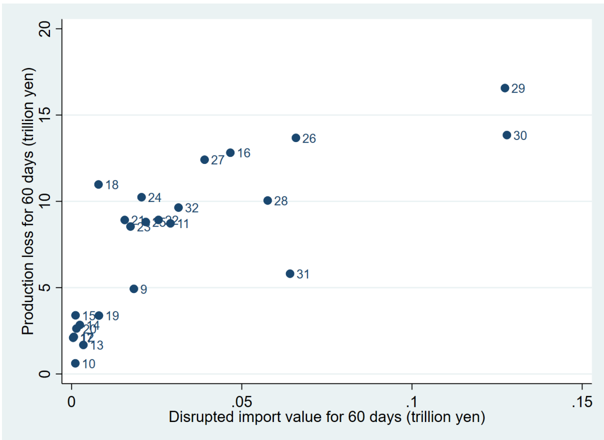


Figure 6: Import shock by industry: This heap map shows the rate of reduction in the production of the industry on the horizontal axis to its total production when imports from a particular region in the industry on the vertical axis is disrupted by 80% for two months. Industries on the vertical axis (disrupted industries) are at the two-digit level in the manufacturing sector, whereas industries on the the horizontal axis (affected industries) are at the one-digit level for non-manufacturing industries and at the two-digit-level for manufacturing industries. The “Global“, “Asia”, “China”, “OtherAsia”, “NorthAmerica”, and “Europe” indicate respectively disruption of imports from all Asian countries, China, countries in Asia except for China and the Middle East, the United States of America and Canada, and countries in Europe. Note that the color separations of “Global” and “Asia” are defined independently whereas the ones for the other panels are commonly defined.

(a) Panel A: Asia



(b) Panel B: China



(c) Panel C: Asia except for China

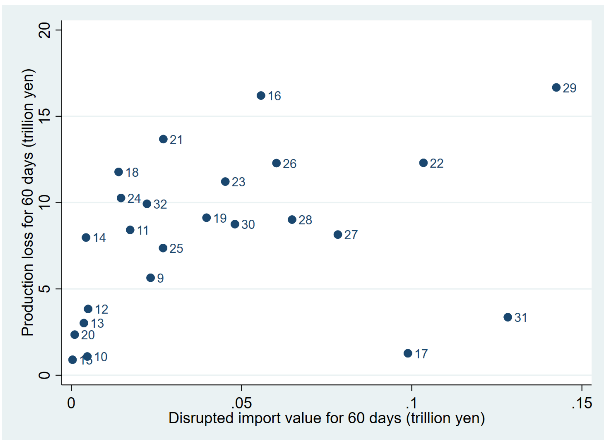


Figure 7: This figure shows correlation between imports of a particular industry from Asia (top), China (middle), and other Asia (bottom) by 80% for two months and the reduction in production because of the import disruptions (both in trillion yen). The number of each dot indicates the classification code for the focal industry in the manufacturing sector. The classification codes are explained in detail in Table 3.

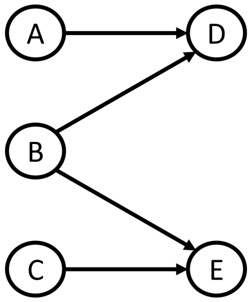


Figure 8: This figure illustrates how firms find new suppliers after supply chain disruption in an alternative model.

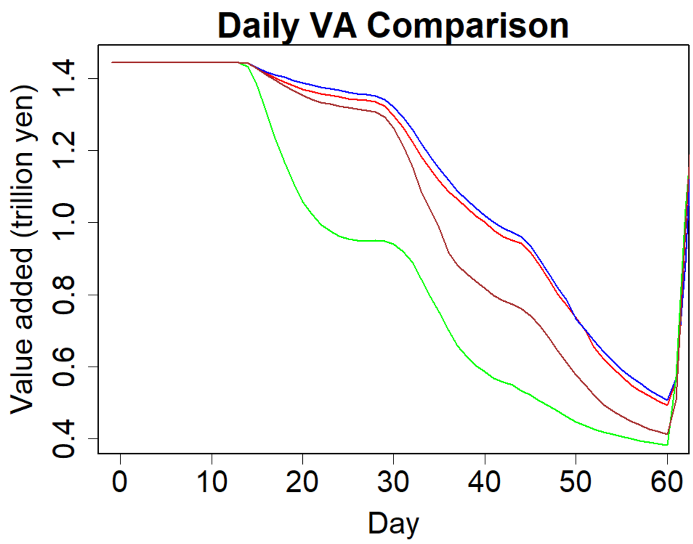


Figure 9: This figure illustrates changes in daily value added in total after disruption of imports from the world by 80% for 60 days. The green, brown, red, and blue lines indicate changes assuming no supplier substitution, substitution between current suppliers in the same industry, substitution with new suppliers randomly matched within the same industry, and substitution with new suppliers indirectly linked through supply chains, respectively.

Table 1: Overview of Japanese firms import to and export from foreign areas.

Area	Import Volume (trillion yen)	# of links	Export Volume (trillion yen)	# of links
Global	47.7	14,476	83.0	19,572
Asia	24.3	8,540	41.5	10,172
China	8.7	4,197	17.1	4,635
Other Asia	15.7	4,343	24.3	5,537
North America	4.6	2,257	19.0	3,339
Europe	5.2	2,575	12.4	2,951
Middle East	9.8	280	2.9	1,032
Other	3.8	824	7.2	2,078

Table 2: Japan Standard Industrial Classification (Rev. 13, 2013) Ministry of International Affairs and Communications (2013): 1-digit Level.

1-digit code	Industry
A	AGRICULTURE AND FORESTRY
B	FISHERIES
C	MINING AND QUARRYING OF STONE AND GRAVEL
D	CONSTRUCTION
E	MANUFACTURING
F	ELECTRICITY, GAS, HEAT SUPPLY AND WATER
G	INFORMATION AND COMMUNICATIONS
H	TRANSPORT AND POSTAL ACTIVITIES
I	WHOLESALE AND RETAIL TRADE
J	FINANCE AND INSURANCE
K	REAL ESTATE AND GOODS RENTAL AND LEASING
L	SCIENTIFIC RESEARCH, PROFESSIONAL AND TECHNICAL SERVICES
M	ACCOMMODATIONS, EATING AND DRINKING SERVICES
N	LIVING-RELATED AND PERSONAL SERVICES AND AMUSEMENT SERVICES
O	EDUCATION, LEARNING SUPPORT
P	MEDICAL, HEALTH CARE AND WELFARE
Q	COMPOUND SERVICES
R	SERVICES, N.E.C.
S	GOVERNMENT, EXCEPT ELSEWHERE CLASSIFIED
T	INDUSTRIES UNABLE TO CLASSIFY

Table 3: Japan Standard Industrial Classification (Rev. 13, 2013) Ministry of International Affairs and Communications (2013): 2-digit Level.

2-digit code for manufacturing industries	Industry
9	MANUFACTURE OF FOOD
10	MANUFACTURE OF BEVERAGES,TOBACCO AND FEED
11	MANUFACTURE OF TEXTILE PRODUCTS
12	MANUFACTURE OF LUMBER AND WOOD PRODUCTS, EXCEPT FURNITURE
13	MANUFACTURE OF FURNITURE AND FIXTURES
14	MANUFACTURE OF PULP, PAPER AND PAPER PRODUCTS
15	PRINTING AND ALLIED INDUSTRIES
16	MANUFACTURE OF CHEMICAL AND ALLIED PRODUCTS
17	MANUFACTURE OF PETROLEUM AND COAL PRODUCTS
18	MANUFACTURE OF PLASTIC PRODUCTS, EXCEPT OTHERWISE CLASSIFIED
19	MANUFACTURE OF RUBBER PRODUCTS
20	MANUFACTURE OF LEATHER TANNING, LEATHER PRODUCTS AND FUR SKINS
21	MANUFACTURE OF CERAMIC, STONE AND CLAY PRODUCTS
22	MANUFACTURE OF IRON AND STEEL
23	MANUFACTURE OF NON-FERROUS METALS AND PRODUCTS
24	MANUFACTURE OF FABRICATED METAL PRODUCTS
25	MANUFACTURE OF GENERAL-PURPOSE MACHINERY
26	MANUFACTURE OF PRODUCTION MACHINERY
27	MANUFACTURE OF BUSINESS ORIENTED MACHINERY
28	ELECTRONIC PARTS, DEVICES AND ELECTRONIC CIRCUITS
29	MANUFACTURE OF ELECTRICAL MACHINERY, EQUIPMENT AND SUPPLIES
30	MANUFACTURE OF INFORMATION AND COMMUNICATION ELECTRONICS EQUIPMENT
31	MANUFACTURE OF TRANSPORTATION EQUIPMENT
32	MISCELLANEOUS MANUFACTURING INDUSTRIES