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Abstract: Global supply chains have become increasingly important in international trade over the past decade. Nevertheless, it remains difficult to quantify the role of supply-chain trade in transmitting and amplifying shocks, given the challenge of identifying and tracing the exogenous shocks across economies. This paper argues that the lockdown of Hubei province in China due to the Coronavirus (COVID-19) outbreak provides a natural experiment to study the importance of China's role in global value chains. Since the lockdown started during the Lunar New Year, Hubei's migrant workers who went home could not return to workplaces in other provinces, resulting in a massive labor supply shock. I feed the supply shock through a Ricardian model with intermediate goods and sectoral linkages to study trade and welfare effects across several economies. While welfare in China is the most strongly affected, the shock also has sizeable implications for the US and the UK. However, close neighbors such as South Korea and Japan gain from the shock. There are large variations regarding the sectoral contributions to the aggregate welfare changes. The model also performs well in predicting bilateral export changes.

Keywords: COVID-19; Labor supply shock; Global supply chains; Sectoral linkages; Productivity effect; Welfare effect

JEL: F10, F11, F14, F17, F41

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1 Introduction

Global supply chains have changed the pattern of trade by allowing international production fragmentation. While countries benefit from access to cheaper intermediate goods and a wider variety, they also face more risks. Both theoretical and empirical studies have shown the importance of global supply chains in propagating shocks across borders and amplifying aggregate fluctuations. [2] Nevertheless, studies on how a shock in one country impact the international trade and welfare in other countries via global supply chains remain scant, largely due to the difficulty of identifying exogenous shocks. This paper argues that Hubei's lockdown provides a natural experiment to study the influence of a labor supply shock in China on international trade and welfare through global supply chains.

The lockdown of Hubei province started in January and ended in late March. When the lockdown began in late January, it was the Chinese New Year. Millions of migrant workers returned home to celebrate the festival. Due to the lockdown, Hubei's migrants were unable to travel outside the province and thus could not go back to work. This resulted in a massive and unanticipated labor supply shock in Hubei and other provinces. The supply shock was then propagated and amplified via regional and global supply chains, in which Hubei is deeply involved due to its central location in China. According to Zheng et al. (2020), 34% of the communication equipment, computer and other electronic equipment produced by Hubei were used as intermediate inputs by other Chinese provinces in 2015. Moreover, as one of Hubei's pillar industries, the electrical machinery equipment accounted for 27% of China's total exports in 2019. Given the importance of Hubei in supply-chain trade, the lockdown provides a unique window to understand the impact of labor supply disruptions on global value chains.

A key feature of Hubei's lockdown that enables me to focus on the labor supply shock in China is the timing. When Hubei entered the lockdown in January, other economies worldwide were still relatively untouched. Only in late March did some other countries start quarantines. This fact limited the impact from other foreign countries' lockdown on international trade.[3] Certainly, some other events could

[2] Carvalho and Tahbaz-Salehi (2019) provide a great summary of the recent development on this topic.

[3] Although some countries in Europe took lockdown measure in late March, the drop in exports of the European Union only started to show up in April. See: Eurostat News Release, https://trade.ec.europa.eu/doclib/docs/2013/december/tradoc_151969.pdf. Latest access:

have happened within China over this period and it is more realistic to incorporate all of them. However, other types of shocks complicate the problem and may encounter endogeneity issues. Besides, although China has experienced structural upgrade, the main export-oriented sectors are still relatively labor-intensive (Lin, Wang, et al., 2018). Given the fact that labor mobility is highly restricted over the period, a labor supply shock, even cannot fully capture the effect, should at least be one of the largest contributors of the first-order effect.[4] Furthermore, this paper does not claim the labor supply shock is the only source of the changes in international trade and welfare, but rather shows that it matters even other factors are not considered.

I build a Ricardian model with sectoral linkages and trade in intermediate goods to analyze the effects of the labor supply shock. This model was introduced by Caliendo and Parro (2015) to study the trade and welfare effects of NAFTA. I adopt this model to estimate how the sectoral labor supply shocks caused by the COVID-19 in China change welfare and trade patterns worldwide. This model enables me to study the total welfare changes and further decompose the welfare changes into terms of trade effect and what I introduce as "productivity effect". Caliendo and Parro (2015) use terms of trade effect, which is a multi-lateral weighted change in exporter prices relative to the change in importer prices, to measure the welfare changes from NAFTA's tariff reductions. Here I borrow the name to study the welfare changes caused by Hubei's lockdown. The productivity effect demonstrates the pure impact of a labor productivity shock on aggregate welfare in an economy.[5] The decomposition displays each source's importance in transmitting and amplifying the original labor supply shock through global supply chains.

To feed the sectoral supply shocks through the model, I need to identify their magnitude. I adopt an approach from Luo and Tsang (2020) to measure the shocks. They estimate the sectoral labor productivity shocks in each province by calculating the proportions of Hubei's migrants working in that province. As mentioned before, the lockdown limited migrant workers from traveling back to

17.Nov.2020

[4]First-order effect here means the immediate impact on the supply-side. Rio-Chanona et al. estimate the first-order effects in the United States and find that impacts from the supply-side are much larger than from the demand-side.

[5]"A change in labor productivity is most easily interpreted as a technology or supply shock," as Shimer (2005) stated.

the provinces they worked in before the lockdown. Therefore, the share of Hubei's workers in each industry offered a good approximation for the sectoral shock magnitude in other provinces. How about the losses in Hubei? I consider two different ranges of losses: minor losses (case one) and full losses (case two). While the former assumes the loss in output is proportional to the labor share in production, the latter assumes a full stoppage of Hubei's production. The real situation should lie somewhere in between.

By treating December 2019 as the starting point, I calibrate the model using data from the World Input and Output Database (WIOD) and the OECD Structural Analysis (STAN) Database. I obtain the monthly trade flows from the International Trade Centre (ITC) as the latest data was not available in other commonly used databases. However, one drawback of this database is that the data could not be collected at an aggregate level, i.e., only one bilateral trade flow can be downloaded each time. To provide a timely estimation subject to the data limitation, I consider six other economies: Japan, the Republic of Korea (Korea hereafter), the European Union (27 countries, EU hereafter), the United Kingdom, the United States, and the rest of the world (ROW hereafter). Although the number of selected economies (except for ROW) is relatively small, they are highly representative and account for approximately 50% of China's total exports in 2019. Moreover, the overall effects should not be significantly influenced by the number of economies. Since commodities are defined by the Harmonized Commodity Description and Coding System (HS) 2017 at the 6-digit level, I use the United Nations concordance table to concord them into 2-digit International Standard Industrial Classification of All Economic Activities (ISIC) Revision 4 divisions. I get 19 sectors after clustering, which contain agricultural, mining, all manufacturing sectors in ISIC Rev 4 and an aggregated service sector.

Using real income to measure welfare, the estimated welfare reductions in China are 2.15% and 4.20% under the assumptions of minor and full losses in Hubei. Whereas the UK and the US are hit the most severely, Japan and Korea's real income increase. After decomposing the welfare effects into terms of trade effects and productivity effects, I find the former explains the major parts. The productivity effects only have very limited impacts on other economies' welfare. In case one, productivity effects in economies except China are all negative but above -0.1%. Interestingly, the terms of trade effects are positive in five out of seven economies, including China. The improved terms of trade in China are due to the higher export prices, which compensate for the decreases in volume. While for the other economies, the intuition behind the higher terms of trade is that the higher prices in China lead firms to substitute relatively cheaper goods in those countries for China's exports. Regarding the magnitude, the overall effect depends on the relative increases in multi-lateral and multi-sector weighted export and import prices. Korea's terms of trade increase by 0.3% and 0.4%, respectively, in both cases, which are the highest among all.

To further understand the sources of the aggregate welfare changes, I study the sectoral contributions. There is a large amount of heterogeneity across sectors. Nevertheless, a handful of sectors can explain the major parts of the welfare changes. For China, the $19^t h$ sector explains 50% of the productivity effect, given this sector is a sum of all non-manufacture sectors except for agriculture and mining. The main contributors in other economies are Computer, Auto and Other transport as expected because those sectors are the hardest hit and are export-oriented in China. Thus increases in their prices and decreases in their output have significant impacts on total welfare. For instance, the Computer and the Other Transport sectors contribute 27.45% and 59.12% to Korea's productivity effect and -15.79% and -21.12% to the US's terms of trade effect in case one. Except for those sectors, the Mining sector plays an important role in enhancing terms of trade in the US and the rest of the world.

World output decreases by 0.14% in case one and 0.24% in case two. The impacts are still impressive given the short period under study and the ignorance of second-order effects such as the contagion through supply chains. The Computer sector and the Minerals sector are the most affected. The former's output falls by 0.66% and the latter by 0.49%.

Finally, I conduct several counterfactual exercises to reexamine the importance of the sectoral linkages and trade in intermediate goods, and the robustness of the baseline results. In the first exercise, I drop the intermediate goods and assume all exports are the final goods. Secondly, I test what will happen if there is no sectoral interdependence. I find the welfare effects become negligible without the intermediate goods and drop to around half to one-third of the benchmark levels without the sectoral linkages. In my last exercise, I relax the restriction of sector 19 from assuming services are non-tradable. I find including trade in services has a very small effect on the baseline results.

This paper is closely related to articles that examine the importance of production networks in national and international trade. Caliendo and Parro (2015) provide evidence of the significant role of sectoral linkages in international trade and welfare analysis. My paper confirms their finding that when the intermediate goods or input-output linkages are ignored, the estimated welfare reductions are much lower. The main difference between my work and theirs is that I use an exogenous labor supply shock while they use a trade shock from tariff reductions. My work also complements theirs by showing that the model is able to isolate the influence of productivity changes on welfare. In a later work, Caliendo et al. (2018) study how the disaggregated productivity changes across US states are transmitted through the intersectoral and interregional trade linkages. They also treat productivity changes as exogenous to the model and investigate the influences of regional and sectoral productivity changes on welfare. I use a similar technique but focus on international trade and global welfare changes.

Another related set of papers study the role of supply chains in amplifying disruptions caused by natural disasters. For example, Carvalho et al. (2016) study the influence of the Great East Japan Earthquake of 2011 through the supply chains using a general equilibrium model with input-output linkages. They find the shock is propagated through both the downstream and upstream chains and has significant indirect effects. Similarly, Barrot and Sauvagnat (2016) and Boehm, Flaaen, and Pandalai-Nayar (2019) examine the transmission of shocks via firm-level linkages in the United States using country-level data and cross-country data separately. My work complements these studies with a quantitative exercise to show that the labor supply shock in China, caused by an unexpected disaster, has a large impact on the global economy from a macro perspective.

Finally, this paper is also closely related to the rapidly increasing research about the pandemic's impact through global supply chains under various setups. Some of this research focuses on the influence of COVID-19 on a particular country, e.g. Inoue and Todo (2020); Fadinger, Schymik, et al. (2020); Baqaee and Farhi (2020); and Pichler et al. (2020). Others focuses on the different measures such as social distancing and quarantine taken in many countries around the world, e.g. Barrot, Grassi, and Sauvagnat (2020), Mandel and Veetil (2020), Bonadio et al. (2020). The most relevant paper is a parallel but independent work by Eppinger et al. (2020). They use the Ricardian model extended by Antras and Chor (2018) to estimate the welfare effects of Hubei's lockdown. The main difference is that they back out the sectoral labor supply shocks by estimating the initial output drops in January and February in China. Using the data of 2017-2019, they first estimate the expected output in 2020 and then use the differences between the expected and the observed values to back out the shocks. Moreover, they take intermediate and final goods' prices to be fixed when estimating the shocks. My work differs from theirs in three dimensions: (i) I use the number of migrant workers from Hubei to other provinces to identify the labor supply shock. (ii) My event window is from January to March, while they only consider January and February. (iii) I further decompose the welfare effects and study the different contributors. My results are partly consistent with theirs that the welfare losses are reduced by 40% when restricting the supply chain trade. However, the magnitude of my estimation is much lower due to the different timing and identification approach.

The remainder of the paper is organized as follows. Section 2 sets up the Ricardian model with sectoral linkages and trade in intermediate goods. Section 3 describes the source of data and calibration techniques. The baseline results are displayed and discussed in section 4. Section 5 makes further extensions and compares the results with the baseline. Section 6 concludes.

2 Model

The model is based on the Ricardian model with sectoral linkages, trade in intermediate goods and sectoral heterogeneity in production, developed by Caliendo and Parro (2015). This model is a supply-side model. Since the COVID-19 is commonly recognized as a first-order supply shock, the model serves the goal of this paper well. I modify the model by assuming the tariffs are zero, and the productivity shocks are the only exogenous shocks. I derive the theoretical decomposition of the welfare effect into terms of trade effect and productivity effect.

2.1 Households

There are N countries and J sectors. Labor is mobile across sectors, but immobile across countries. In each country n $\in$ N, there are L_n households. Households maximize the following utility by consuming final goods C_n^j from each sector j:

$$u(C_n) = \prod_{j=1}^{J} (C_n^j)^{\alpha_n^j}, \quad \sum_{j=1}^{J} \alpha_n^j = 1. \tag{2.1}$$

subject to the budget constraint

$$I_n = w_n L_n + D_n. \tag{2.2}$$

where I_n is income, w_n is the wage, L_n is the labor supply and D_n is the trade deficit.

2.2 Firms of intermediate goods

In each country n, firms in sector j produce a continuum of intermediate goods $\omega^j \in [0, 1]$ with labor l_n and composite intermediate goods $m_n^{k,j}(\omega^j)$. Firms have different efficiency level $z_n^j(\omega^j)$ for the production and the production function is at constant returns to scale, given by

$$q_n^j(\omega^j) = z_n^j(\omega^j)[l_n^j(\omega^j)]^{\gamma_n^j} \prod_{k=1}^{J} [m_n^{k,j}(\omega^j)]^{\gamma_n^{k,j}}, \tag{2.3}$$

where $\gamma_n^{k,j}$ is the share of the composite intermediate goods $m_n^{k,j}(\omega^j)$ from sector k for the production of ω^j. γ_n^j is the share of value-added and $1 - \gamma_n^j = \sum_{k=1}^{j} \gamma_n^{k,j}$.

The price of the intermediate good ω^j is determined by the unit cost of the firms. Denote the price of the composite goods from sector k by P_n^k, the cost of an input bundle c_n^j is given by

$$c_n^j = A_n^j w_n^{\gamma_n^j} \prod_{k=1}^{J} \left(P_n^k\right)^{\gamma_n^{k,j}} \tag{2.4}$$

where $A_n^j = \prod_{k=1}^{J} (\gamma_n^{k,j})^{-\gamma_n^{k,j}} (\gamma_n^j)^{-\gamma_n^j}$ is a constant.

In order to solve for P_n^k, I need to consider the production of the composite intermediate goods.

2.3 Firms of composite intermediate goods

The composite intermediate goods Q_n^j functions as both the final consumption goods and the input of the intermediate goods mentioned in Section 2.2. [6]

[6]Denote the composite goods produced by firms in country n, sector j as Q_n^j. Then the market clear condition for Q_n^j is

$$Q_n^j = C_n^j + \sum_{k=1}^{J} \int m_n^{j,k}(\omega^k) d\omega^k.$$

To produce Q_n^j, firms search for the suppliers with the lowest cost across all countries. [7] The production function of Q_n^j is

$$Q_n^j = \left[\int r_n^j(\omega^j)^{1-1/\sigma^j} d\omega^j\right]^{\sigma^j/(\sigma^j-1)} \quad (2.5)$$

where $\sigma^j > 0$ is the elasticity of substitution across intermediate goods in sector j and $r_n^j(\omega^j)$ is the demand for ω^j.

To maximize profits, the demand for $r_n^j(\omega^j)$ is given by

$$r_n^j(\omega^j) = \left(\frac{p_n^j(\omega^j)}{P_n^j}\right)^{-\sigma^j} Q_n^j \quad (2.6)$$

where p_n^j is the lowest unit price of ω^j and P_n^j is the unit price for the composite intermediate good

$$P_n^j = \left[\int p_n^j(\omega^j)^{1-\sigma^j} d\omega^j\right]^{\frac{1}{1-\sigma^j}} \quad (2.7)$$

2.4 International Trade

Trade in goods from country n to country i in sector j incurs the standard "iceberg" costs Samuelson (1954), which means transferring one unit of good to country n requires producing $d_{ni}^j \geq 1$ units of such good in country i. d_{ii}^j is normalized to one and $d_{ni}^j d_{ik}^j \geq d_{nk}^j$.

Therefore, the price of one unit intermediate good ω^j in country n that is produced in country i is

$$p_{ni}^j = \frac{c_i^j d_{ni}^j}{z_i^j(\omega^j)}.$$

Since the firms are searching for the lowest cost supplier, the actual price paid is the minimum across all countries,

$$p_n^j = \min\{p_{ni}^j; i = 1, ..., N\}. \quad (2.8)$$

To get a simple expression for the distribution of prices, I follow Eaton and Kortum (2002) to assume the country $n's$ efficiency distribution is Frechet and is independent across countries, sectors and goods. The exact formula of price of the composite goods P_n^j is

$$P_n^j = \kappa^j [\Phi_n^j]^{-1/\theta^j}, \quad (2.9)$$

[7] An important feature for this model is that the production of the composite intermediate goods Q_n^j requires the intermediate goods ω^j as inputs. Thus the productions of intermediate goods and composite intermediate goods are interrelated.

where

$$\kappa^j = \left[\Gamma\left(\frac{\theta^j + 1 - \sigma^j}{\theta^j}\right)\right]^{1/(1-\sigma^j)},$$

and Γ is the Gamma function. I also assume that $\sigma^j < 1 + \theta^j$ to ensure a well defined price index. Some sectors are non-tradable by assuming the local suppliers are providing goods with the lowest costs. For those sectors, $d^j_{ni} = \infty$ and $P^j_n = \kappa^j (T^j_i)^{-1/\theta^j} c^j_n$. Note P^j_n is also the price for final goods that consumers buy. The consumption price index is $P_n = \prod_{j=1}^J (P^j_n/\alpha^j_n)^{\alpha^j_n}$.

2.5 Expenditure shares

To link the model with data, the fraction of country $n's$ expenditure on goods of sector j from country i is necessary. Define X^j_{ni} as country $n's$ expenditure of sector j goods from country i and X^j_n as country $n's$ total spending on sector j goods, then the share of sector j goods from country i is[8]

$$\pi^j_{ni} = \frac{X^j_{ni}}{X^j_n} = \frac{T^j_i (c^j_i d^j_{ni})^{-\theta^j}}{\Phi^j_n} = \frac{T^j_i (c^j_i d^j_{ni})^{-\theta^j}}{\sum_{i=1}^N T^j_i (c^j_i d^j_{ni})^{-\theta^j}} \tag{2.10}$$

2.6 Total Expenditure and trade balance

Total expenditure of country n on sector j goods is calculated by adding the firms' spending and households' spending, given by

$$X^j_n = \sum_{k=1}^J \gamma^{j,k}_n \sum_{i=1}^N X^k_i \pi^j_{in} + \alpha^j_n I_n, \tag{2.11}$$

where $I_n = w_n L_n + D_n$. The sectoral $j's$ deficit is given by the difference between the country $n's$ import from all other countries and its export to the world, $D^j_n = \sum_{i=1}^N X^j_{ni} - X^j_{in}$. The national deficit is the sum of all sectoral deficits, $D_n = \sum_{j=1}^J D^j_n$. D_n is exogenously given in the model, but the sectoral deficits are endogenous. The sum of all economies' deficits is zero, $\sum_{n=1}^N D_n = 0$.

Combing all the conditions, we get [9]

$$\sum_{j=1}^J \sum_{i=1}^N X^j_n \pi^j_{ni} - \sum_{j=1}^J \sum_{i=1}^N X^j_i \pi^j_{in} = D_n \tag{2.12}$$

[8]This is calculated by using

$$X^j_{ni} = Pr[\frac{c^j_i d^j_{ni}}{z^j_i(\omega^j)} \leq \min_{h \neq i} \frac{c^j_j d^j_{nh}}{z^h_i(\omega^j)}] X^j_n,$$

and equations (2.9) and (2.10).

[9]The non-tradable sectors will not influence the result as they cancel out.

2.7 Equilibrium

The equilibrium is written in relative changes.[10] This approach is introduced and used by Dekle, Eaton, and Kortum (2007, 2008). Using the changes from the original equilibrium reduces the data requirements as the parameters that do not change are canceled out. This significantly simplifies the calibration and makes the comparison straightforward. Besides, this approach does not require the assumption of bilateral symmetries, which is rejected by many empirical studies. I measure the sectoral labor supply shocks due to Hubei's lockdown by the changes in labor productivity as Luo and Tsang (2020). To be more specific, the changes in T_n^j, which measure the overall efficiency in producing any good ω^j in country n. Eaton and Kortum (2002) treat T_n^j as country n's state of technology and governs the absolute advantages across the continuum of goods. A lower T_n^j, in my case, means firms are less likely to have high efficiency draws for any good ω^j. This is a reasonable description for the COVID shock as most goods, if not all, should be produced less efficiently.

Write the variables after the shock as x' and define $\hat{x} = \frac{x'}{x}$. [11]

$$\hat{c}_n^j = \hat{w}_n \prod_{k=1}^{J} \left(\hat{P}_n^k\right)^{\gamma_n^{k,j}} \tag{2.13}$$

$$\hat{P}_n^j = \left[\sum_{i=1}^{N} \pi_{ni}^j \hat{T}_i^j (\hat{c}_i^j)^{-\theta^j}\right]^{-1/\theta^j} \tag{2.14}$$

$$\hat{\pi}_{ni}^j = \hat{T}_i^j \left(\frac{\hat{c}_i^j}{\hat{P}_n^j}\right)^{-\theta^j} \tag{2.15}$$

$$X_n'^j = \sum_{k=1}^{J} \gamma_n^{j,k} \sum_{i=1}^{N} X_i'^k \pi_{in}'^j + \alpha_n^j (w_n L_n + D_n) \tag{2.16}$$

$$\sum_{j=1}^{J} \sum_{i=1}^{N} X_n'^j \pi_{ni}'^j - \sum_{j=1}^{J} \sum_{i=1}^{N} X_i'^k \pi_{in}'^j = D_n \tag{2.17}$$

[10]The original equilibrium is the following : Given $L_n, D_n, T_n^j, d_{ni}^j$ and τ_{ni}^j, an equilibrium is a wage vector $\mathbf{w} \in R_{++}^N$ and prices $\{P_n^j\}_{j=1,n=1}^{J,N}$ that satisfy equilibrium conditions (2.4), (2.11), (2.12), (2.13) and (2.14).

[11]Note the deficits remain the same after the shock because I want to make sure the only source of all changes in the model is $\hat{T}_n^j$.

2.8 Welfare

The welfare effects are one key of the exercise. I first derive the representation of the total welfare changes and then decompose the welfare changes into terms of trade and productivity effects. The name "terms of trade effect" is borrowed from Caliendo and Parro (2015), which measures the multilateral weighted sectoral change in export and import prices. I introduce the name " productivity effect" to measure how the import-weighted sectoral productivity changes influence welfare. The welfare of country n is measured by real income,

$$W_n = \frac{I_n}{P_n} = \frac{w_n L_n}{P_n} + \frac{D_n}{P_n}$$

Since we are interested in the changes, we get the following by totally differentiating the above equation:

$$dlnW_n = \frac{w_n L_n}{I_n} d\ln w_n - d\ln P_n. \tag{2.18}$$

After some simplification[12], we finally get

$$d\ln W_n = \frac{1}{I_n}\left(\sum_{j=1}^{J}\sum_{i=1}^{N} E_{ni}^j d\ln c_n^j - M_{ni}^j d\ln c_i^j\right) + \frac{1}{I_n}\sum_{j=1}^{J}\sum_{i=1}^{N} M_{ni}^j \frac{1}{\theta^j} d\ln T_i^j, \tag{2.19}$$

where E_{ni}^j is the sector j's exports from country n to country i and M_{ni}^j is the imports of country n from country i. The first term is known as multi-lateral and multi-sectoral terms of trade effect and the second term is the productivity effect, which measures the change welfare due to the productivity change. Notice that it is not sufficient to say an increase in the input costs in country n relative to country i contributes positively to country n's welfare, because it also depends on the relative values of exports and imports of country n. However, it is clear from the second part of (2.19) that an increase in productivity in other countries (T_n^j) will enhance country n's welfare if the trade elasticity $\theta^j > 0$. [13] This is intuitive since higher productivity in country n indicates a lower price there. As countries are always searching for suppliers with the lowest costs, it benefits all countries.

3 Calibration and Simulation

To analyze the trade and welfare effects, I calibrate the model parameters using the data from the World Input Output Database and the OECD STAN

[12] The derivations are in Appendix B.

[13] Here I adopt the same concept of trade elasticity from Caliendo and Parro (2015), which is the dispersion of productivity θ^j.

Database. As the latest version of the World Input-Output Table (WIOT) is the 2014 Table, I assume the parameters did not change from 2014 to 2020. The underlying assumption is that the massive supply shocks are likely to swamp the small changes in the parameters. I also need the bilateral trade flows data in December 2019, which are collected from the International Trade Centre.

3.1 Data and Calibration

I need to calibrate four parameters, γ_n^j, $\gamma_n^{j,k}$, α_n^j and θ^j, to solve equations (2.13) to (2.17).

γ_n^j and $\gamma_n^{j,k}$ are calibrated using data from WIOT. γ_n^j is the share of value added. It is calculated by sectoral value-added VA_n^j and gross production Y_n^j: $\gamma_n^j = \frac{VA_n^j}{Y_n^j}$. $\gamma_n^{j,k}$ is the share of sector k's spending on sector j's intermediate goods in country n, times $(1 - \gamma_n^j)$. It measures the importance of sector j's intermediate goods in sector k's production. WIOT has detailed sectoral consumption of intermediate goods.

α_n^j is the final consumption share of sector j's goods in country n. I use the total expenditure minus the intermediate expenditure in sector j, divide by the total final absorption in country n to estimate it. To calculate the total expenditure, I sum the sectoral imports of each country. The final absorption is calculated by value added plus the trade deficit in each sector. I collect the trade flows data for 2014 from the OECD STAN database. Note the parameters for the EU and the ROW are calculated using the average of all countries involved.

For the remaining parameters θ^j, I use Caliendo and Parro (2015)'s estimations with 99% sample and I correct the Chemicals sector's elasticity as China is an outlier in this sector. The parameters are displayed in Table 1.

Finally, the sectoral bilateral trade flows are collected from the International Trade Centre's Trade Map Database. [14] Trade Map provides detailed monthly import and export data at Harmonized System 6 digits (HS6) level. I obtain the sectoral data for the seven economies in December 2019. I use the concordance table provided by the World Integrated Trade Solution (WITS) to convert trade flows into International Standard Industrial Classification Rev 4 divisions. After merging some sectors, I get 19 sectors in total, where the 19th sector is the ag-

[14] https://www.trademap.org, last accessed: 16.Oct.2020.

gregation of all non-manufacture sectors other than Agricultural and Mining (see Appendix A1). Note the exports from the ROW to the world are the sum of other six economies' imports from the ROW. The gross productions are not available for December, 2019, thus I back out the values by assuming the share of domestic consumption as a proportion of gross production in each economy remained the same between 2014 and 2019.

Number	Sectors	θ^j
1	Agriculture	9.11
2	Mining	13.53
3	Food	2.62
4	Textiles	8.10
5	Wood	11.5
6	Paper	16.52
7	Petroleum	64.85
8	Chemicals	-0.64
9	Rubber and plastic	1.67
10	Minerals	2.41
11	Basic metals	3.28
12	Metal products	6.99
13	Computer	8.53
14	Electrical equipment	12.91
15	Machinery	1.45
16	Auto	1.84
17	Other transport	0.39
18	Other manufacturing	3.98
19	Other activities	8.22

Table 1: Sectoral trade elasticity

Note: The values are obtained from Caliendo and Parro (2015) Table 1, 99% sample. Parameter for the Chemicals sector is adjusted according to their footnote 42. The value for Sector 13 is the average of Office, Communication and Medical sectors in the original paper.

3.2 Productivity shocks

I also need the sectoral productivity shocks ($\hat{T}_i^j$) for China, which by assumption, are exogenous to the model. I adopt the approach in Luo and Tsang (2020) to estimate the productivity shocks by measuring the sectoral labor losses due to the lockdown of Hubei province. The magnitude of shocks in each province is approximated using the proportion of Hubei's migrants working in that province. Since 80% of the migrants went home during the Lunar New Year, the lockdown prevented them from travelling back to work. I further consider two cases for Hubei's lockdown, assuming minor losses and full losses of Hubei's production respectively. However, not all of the sectoral productivity shocks are available in Luo and Tsang (2020). As six sectors are missing, I need to make further assumptions about the productivity shocks in those sectors.[15] I assume the productivity shocks are -5% in case one and -15% in case two for those sectors. 5% is the average of Luo and Tsang's estimation, while 15% is the magnitude of China's manufacturing production reduction during January and February.[16]

The productivity shocks under these two cases are displayed in Table 2.

[15]These six sectors are Petroleum, Chemicals, Rubber and plastic products, Computer, Electrical equipment, Motor vehicles, and Other transport equipment. According to the industrial value added data from the National Bureau of Statistics of China, those sectors have similar losses.

[16]Source: National Bureau of Statistics of China:
http://www.stats.gov.cn/tjsj/zxfb/202003/t20200316_1732232.html.
Last accessed: 16.Oct.2020.

Number	Sectors	Case one	Case two
1	Agriculture	-4.5%	-8.7%
2	Mining	-1.9%	-3.7%
3	Food	-2.2%	-7.4%
4	Textiles	-1.3%	-5.5%
5	Wood	-1.2%	-3.9%
6	Paper	-1.2%	-3.9%
7	Petroleum	-5.0%	-15.0%
8	Chemicals	-1.4%	-5.0%
9	Rubber and plastic	-5.0%	-15.0%
10	Minerals	-2.1%	-6.8%
11	Basic metals	-1.1%	-3.7%
12	Metal products	-1.1%	-3.7%
13	Computer	-5.0%	-15.0%
14	Electrical equipment	-5.0%	-15.0%
15	Machinery	-1.3%	-4.9%
16	Auto	-5.0%	-15.0%
17	Other transport	-5.0%	-15.0%
18	Other manufacturing	-4.4%	-8.3%
19	Other activities	-6.8%	-6.8%

Table 2: Productivity shocks

4 Results and Discussion

4.1 Welfare effects

The welfare changes for each economy due to the productivity shocks in China are displayed in Table 3. In the first case, when the sectoral shocks are mild and relatively uniform, the welfare decreases are smaller than in the second case for all economies except Japan and Korea. After decomposing the welfare changes into two parts, terms of trade (TOT) effect and productivity effect, I find the major sources of the welfare effects are the TOT effects in most economies.

	Welfare effect		Terms of trade effect		Productivity effect	
	Case one	Case two	Case one	Case two	Case one	Case two
China	-2.15%	-4.20%	0.03%	0.01%	-2.18%	-4.21%
Japan	0.13%	0.23%	0.14%	0.29%	-0.02%	-0.05%
Korea	0.13%	0.21%	0.19%	0.39%	-0.06%	-0.18%
EU27	0.02%	-0.04%	0.05%	0.04%	-0.03%	-0.08%
UK	-0.11%	-0.20%	-0.08%	-0.13%	-0.02%	-0.07%
US	-0.11%	-0.19%	-0.09%	-0.14%	-0.02%	-0.05%
ROW	-0.04%	-0.11%	0.01%	0.03%	-0.05%	-0.14%

Table 3: Welfare effects from the productivity shocks

For China, the productivity effects are high in both cases and are the main contributors to the welfare declines. All other economies are affected moderately if only productivity effects are taken into account. Korea and the ROW are the most affected, where the drops in welfare are 0.06% and 0.05% in the first case, and 0.18% and 0.14% in the second case. Japan, the UK, and the US are weakly affected. However, the magnitude is not very different across all economies. Since China's sectoral productivity shocks are the only source of the productivity effects, the direct influences on other economies are limited.

To better understand which sectors are the main driving forces of the productivity effects, I further consider the sectoral contributions. Figure 1 and Table 4 present the results in case one. From the subplot of China in Figure 1, the productivity effect mainly comes from the non-tradable sector (Other activities).[17] Because this sector sums all non-manufacture sectors except for Agriculture and Mining, it is reasonable to see a high contribution to the aggregate effect. The Other transport sector and the Auto sector both account for more than 10%. For the other economies, the Computer sector and the Other Transport sector play the most critical roles. The results are consistent with the fact that these sectors comprise a large part of China's total exports. According to Figure 1, the Other transport sector is the largest contributor to the productivity effect for all economies, following by the Computer sector. According to Table 4, the Computer and Other Transport sectors contribute 27.45% and 59.12% to Korea's welfare reduction in case one and 28.55% and 61.50% in case two. For the ROW, the Other

[17] I also take the non-tradable sector into account, which is different from Caliendo and Parro (2015) since they are interested in the changes in tariffs, where the non-tradable sectors do not play any role.

transport sector also explains more than 50% of the productivity effect in both cases. This is not only because China is exporting a lot of other transport equipment, but also because the sectoral trade elasticity is low. The Chemicals sector contributes negatively to all countries, since its elasticity of trade θ^j is negative (see Table 1).

Sectors	China		Japan		Korea		EU27		UK		US		ROW	
	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod
Agriculture	-1.61%	4.60%	0.12%	0.39%	-0.18%	0.40%	7.69%	0.36%	-1.61%	0.16%	2.69%	0.20%	-4.22%	1.40%
Mining	-24.64%	1.02%	-29.00%	1.96%	-30.53%	0.60%	-14.20%	0.05%	7.31%	0.01%	11.96%	0.00%	26.40%	0.13%
Food	-3.70%	5.18%	-1.87%	3.91%	-1.35%	2.37%	1.22%	1.11%	-4.27%	0.85%	-2.22%	1.17%	3.58%	1.44%
Textiles	10.82%	0.55%	-1.18%	3.47%	-2.11%	3.22%	3.54%	2.54%	-6.76%	2.05%	-6.26%	2.73%	-3.21%	2.39%
Wood	0.00%	0.19%	-0.32%	0.12%	-0.43%	0.09%	1.24%	0.17%	-1.52%	0.16%	-0.74%	0.15%	0.03%	0.06%
Paper	0.20%	0.11%	0.78%	0.07%	0.61%	0.05%	3.81%	0.05%	0.09%	0.06%	-0.83%	0.14%	-1.95%	0.07%
Petroleum	2.55%	0.29%	4.55%	0.05%	10.19%	0.41%	26.76%	0.11%	7.66%	0.12%	3.54%	0.05%	-20.12%	0.41%
Chemicals	-6.20%	-14.67%	3.00%	-20.33%	4.48%	-29.36%	-2.43%	-12.76%	-12.42%	-11.07%	-7.11%	-8.00%	7.74%	-9.50%
Rubber and plastic	2.84%	6.30%	1.28%	17.98%	1.55%	7.22%	-2.37%	12.66%	-4.01%	18.89%	-1.43%	12.99%	0.19%	9.71%
Minerals	2.34%	3.38%	0.57%	2.37%	-0.42%	4.59%	0.69%	2.25%	-1.05%	2.41%	-0.73%	2.02%	-1.25%	2.83%
Basic metals	-8.23%	2.43%	3.04%	1.74%	6.23%	3.02%	-0.79%	0.83%	9.98%	0.23%	-0.99%	0.19%	2.57%	1.49%
Metal products	5.56%	0.36%	0.26%	2.05%	1.70%	0.89%	1.59%	0.85%	-2.08%	0.81%	-3.68%	1.29%	-2.07%	0.72%
Computer	12.30%	2.87%	9.75%	27.51%	14.57%	27.45%	-3.76%	20.65%	-12.57%	12.55%	-15.79%	18.55%	-0.51%	15.07%
Electrical equipment	6.74%	1.18%	9.19%	4.46%	5.46%	2.53%	5.27%	4.48%	-6.29%	3.72%	-4.01%	3.33%	-7.13%	3.28%
Machinery	4.75%	3.94%	10.31%	6.63%	4.82%	6.32%	4.67%	10.96%	-5.84%	8.55%	-3.72%	8.94%	-6.20%	7.60%
Auto	-0.84%	13.29%	22.20%	9.99%	14.33%	5.71%	-12.27%	8.86%	-11.50%	7.82%	-21.12%	9.61%	9.67%	4.43%
Other transport	3.68%	18.92%	2.13%	30.08%	0.81%	59.12%	4.09%	34.47%	3.26%	41.27%	-8.88%	32.50%	-0.75%	53.09%
Other manufacturing	3.01%	0.47%	0.45%	7.56%	-0.23%	5.37%	-3.61%	12.37%	-1.77%	11.41%	-4.31%	14.11%	2.41%	5.37%
Other activities	0.00%	49.60%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 4: Sectoral contributions to the aggregate effects (case one)

Computer
Textiles
Electrical equipment
Metal products
Machinery
Other transport
Other manufacturing
Rubber and plastic
Petroleum
Minerals
Paper
Wood
Other activities
Auto
Agriculture
Food
Chemicals
Basic metals
Mining
-0.25
0.00
0.25
0.50
China
Auto
Machinery
Computer
Electrical equipment
Petroleum
Basic metals
Chemicals
Other transport
Rubber and plastic
Paper
Minerals
Other manufacturing
Metal products
Agriculture
Other activities
Wood
Textiles
Food
Mining
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
Japan
Computer
Auto
Petroleum
Basic metals
Electrical equipment
Machinery
Chemicals
Metal products
Rubber and plastic
Other transport
Paper
Other activities
Agriculture
Other manufacturing
Minerals
Wood
Food
Textiles
Mining
-0.2
0.0
0.2
0.4
0.6
Korea
Petroleum
Agriculture
Electrical equipment
Machinery
Other transport
Paper
Textiles
Metal products
Wood
Food
Minerals
Other activities
Basic metals
Rubber and plastic
Chemicals
Other manufacturing
Computer
Auto
Mining
-0.1
0.0
0.1
0.2
0.3
EU

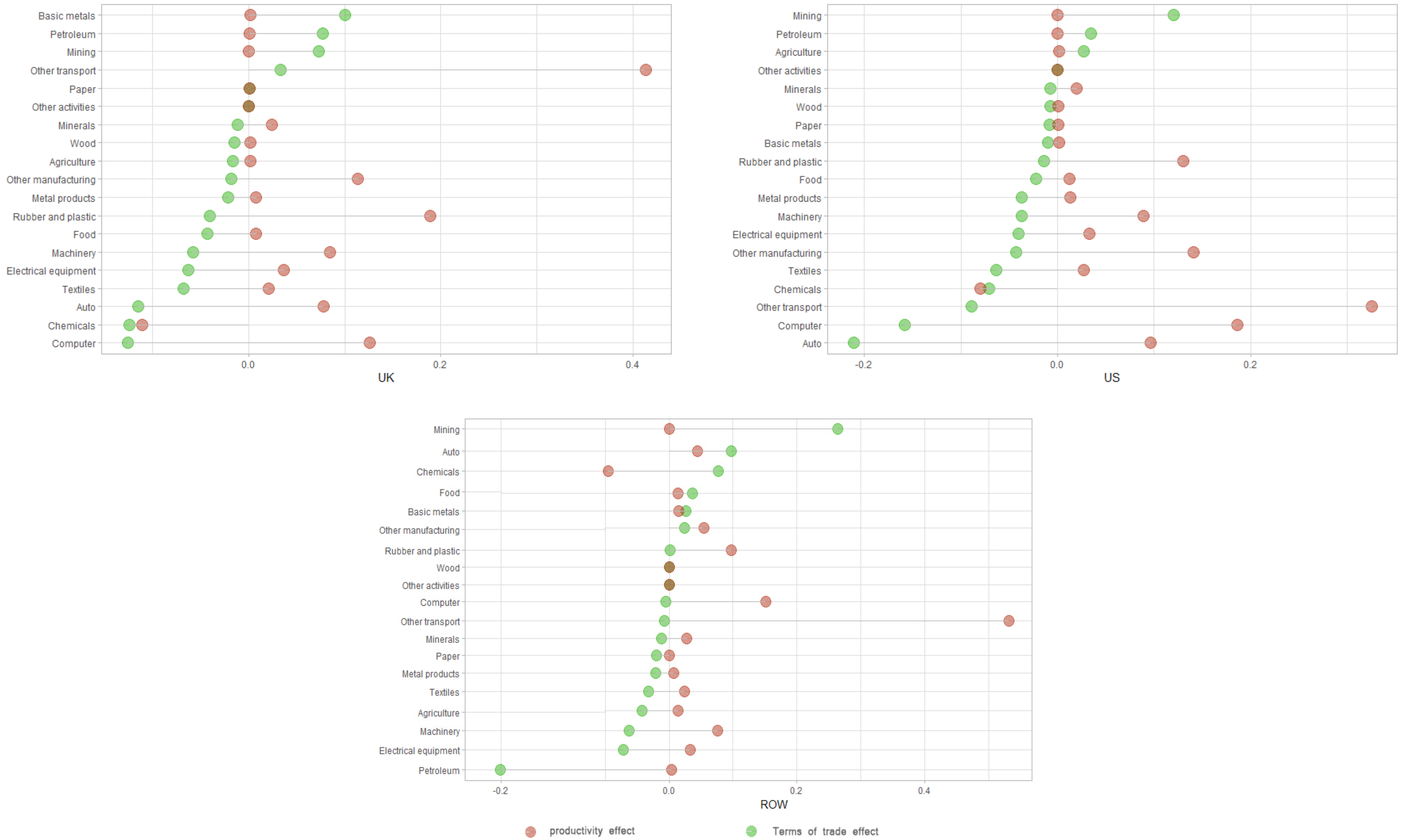

Figure 1: Sectoral contributions to the aggregate effects (case one). Note: The figure presents sectoral contributions to total welfare changes in each economy due to the productivity in China. The red points show the productivity effects and the green points show the terms of trade effects. The unit of the x-axis is percentage (%).

	China	Japan	Korea	EU	UK	US	ROW
Agriculture	0.03%	1.69%	1.04%	1.57%	1.92%	1.94%	1.48%
Mining	0.82%	1.96%	1.52%	1.67%	1.28%	1.37%	1.25%
Food	0.81%	1.92%	1.98%	2.05%	2.05%	2.42%	2.23%
Textiles	1.08%	2.04%	1.91%	1.74%	1.47%	2.45%	1.96%
Wood	0.83%	1.93%	1.67%	1.92%	1.90%	2.43%	1.84%
Paper	1.22%	2.06%	2.01%	1.96%	1.91%	2.31%	2.18%
Petroleum	1.24%	1.43%	1.96%	1.98%	2.04%	1.79%	1.62%
Chemicals	1.51%	2.49%	2.02%	2.56%	1.98%	1.90%	2.34%
Rubber and plastic	1.45%	2.37%	1.78%	2.14%	1.73%	2.14%	2.27%
Minerals	1.36%	2.07%	2.11%	2.02%	2.42%	2.16%	1.93%
Basic metals	1.51%	2.22%	2.06%	2.27%	2.58%	2.63%	1.96%
Metal products	1.57%	2.18%	1.72%	1.78%	1.53%	2.12%	2.06%
Computer	1.90%	2.11%	1.84%	1.79%	1.59%	1.32%	2.11%
Electrical equipment	1.71%	2.40%	1.86%	1.97%	1.89%	1.94%	2.14%
Machinery	1.68%	2.05%	1.88%	1.93%	1.94%	2.22%	2.19%
Auto	2.88%	3.40%	2.66%	2.89%	2.80%	3.11%	3.10%
Other transport	2.08%	2.54%	2.11%	2.06%	2.54%	2.52%	2.51%
Other manufacturing	0.73%	2.36%	1.97%	1.78%	1.49%	2.13%	2.29%
Other activities	1.09%	1.82%	1.57%	1.60%	1.89%	1.91%	1.74%

Table 5: Changes in sectoral costs (case one)

The terms of trade effects display some interesting features. Although China is hit seriously by the productivity shocks, the terms of trade improve in both cases, so do Japan, Korea, and the ROW. However, the UK and the US suffer from welfare reductions as their terms of trade deteriorate. The EU has a higher TOT in case one and a lower TOT in case two. To understand the reason, we need to look at the changes in input costs in Table 5, as the export price is increasing in $\hat{c}$. [18] From equation (2.19), the terms of trade effect is determined by the differences between the multilateral-weighted changes in export and import prices. According to Table 5, every sector has a higher price after the shock, but the magnitude of the increase is different. Thus the overall effect will depend on the relative increases in export-weighted and import-weighted prices.

The Computer sector contributes a significant proportion to China's improved TOT, following by Textiles and Electrical equipment. The Computer sector's

[18] I only present the cost changes in case one here, as case two shows a similar pattern. Results for case two are shown in Appendix A4.

price increases by 1.9% in China, which is a relatively high increase compared with other economies'. Because this is a leading export sector in China, it has a positive contribution (see Table 4). On the contrary, China is a net importer in the automotive industry. Since the EU and Japan, the two largest auto exporters to China, both have significant rises in their prices, the Auto sector contributes -0.84% to China's TOT. Korea and Japan's costs of production after the shocks as well as the sectoral contributions are relatively similar. However, the largest contributors to the increased TOT of Japan and Korea are the Auto sector and the Computer sector, respectively.

The United Kingdom and the United States experience the highest TOT losses. Sectors related to natural resources like basic metals and petroleum improve UK's TOT due to increased export prices, but 13 out of 19 sectors contribute negatively, leading to a final reduction in welfare. The Computer sector and the Auto sector contribute -15.79% and -21.12% to the US's TOT. The US is a net importer in those two sectors. China and the ROW account for 80% of the US's imports of computers, and their prices increase significantly. Thus the higher import price swamps the increased export price in the US.

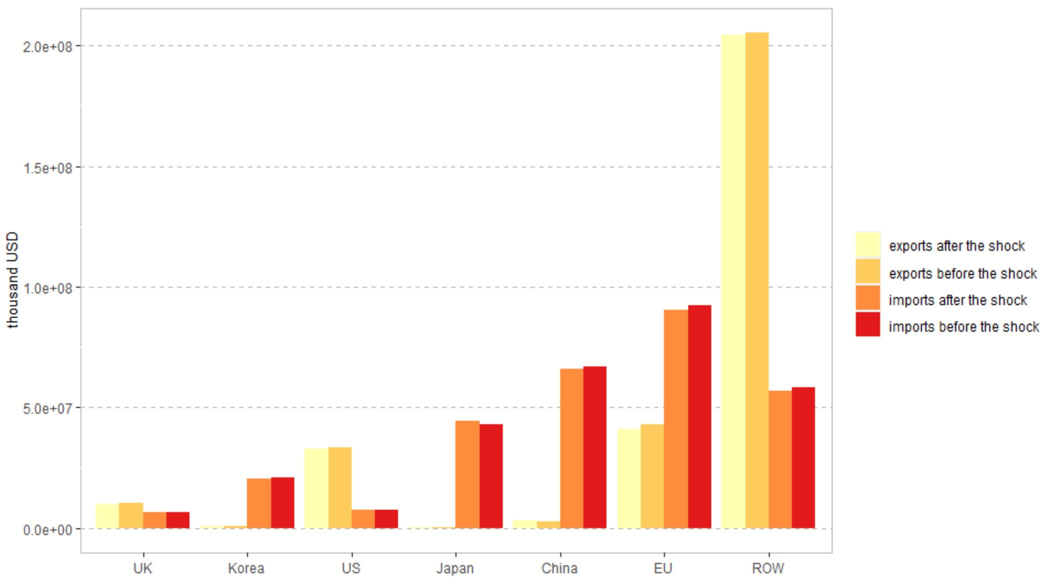

Figure 2: Trade flows in the Mining sector before and after the shock

The ROW also has a lower welfare, resulting from the productivity effect. But its TOT improve by 0.01% and 0.03% in both cases. The largest contributor to the positive TOT effect is the Mining sector. From Table 4, the Mining sector contributes 26.4% to the ROW's TOT. Figure 2 shows the Mining sector's trade flows. It is evident that the ROW's Mining sector is so important that it could easily dominate the welfare change.

4.2 Output changes

Regarding the output changes, world output drops by 0.14% in case one and 0.24% in case two. The impacts are still impressive given the short period under study and the ignorance of second-order effects such as the contagion through the supply chains. I display the changes in the world sectoral output in Table 6 for case one. According to Table 6, every sector has a lower output in the new equilibrium. The Computer sector and the Minerals sector are the most affected. The former's output falls by 0.66%, and the latter by 0.49%.

	China	Japan	Korea	EU27	UK	US	ROW	Sectoral Total
Agriculture	-0.58%	0.33%	0.21%	-0.50%	-1.25%	-0.85%	0.20%	-0.25%
Mining	0.16%	-6.38%	-5.22%	-5.52%	-1.70%	-0.02%	0.79%	-0.10%
Food	-1.03%	0.59%	0.09%	-0.12%	-0.08%	0.26%	0.10%	-0.19%
Textiles	0.44%	-0.82%	-0.65%	0.70%	2.15%	-3.03%	-0.86%	-0.06%
Wood	0.09%	-0.03%	0.10%	-0.74%	-0.40%	-2.07%	0.19%	-0.24%
Paper	0.16%	0.14%	0.02%	0.51%	0.50%	-0.79%	-2.22%	-0.25%
Petroleum	2.60%	9.33%	-9.28%	-6.17%	-4.84%	0.62%	14.18%	-0.33%
Chemicals	-1.94%	0.83%	0.60%	0.32%	-0.07%	0.33%	0.29%	-0.36%
Rubber and plastic	-1.80%	0.22%	1.14%	0.17%	0.73%	0.70%	0.20%	-0.41%
Minerals	-1.31%	0.44%	0.74%	-0.43%	-0.25%	0.50%	0.46%	-0.49%
Basic metals	-1.76%	-0.04%	0.67%	-0.39%	-0.79%	-0.07%	0.73%	-0.48%
Metal products	-1.36%	0.00%	0.97%	0.79%	1.03%	0.38%	-0.19%	-0.17%
Computer	-3.65%	-0.44%	1.50%	1.70%	2.81%	4.43%	-0.95%	-0.66%
Electrical equipment	-1.13%	-2.32%	2.11%	1.24%	1.85%	1.69%	-0.69%	-0.39%
Machinery	-1.92%	0.92%	0.76%	0.62%	0.55%	0.59%	0.35%	-0.26%
Auto	-1.63%	0.18%	0.78%	0.45%	0.48%	0.49%	0.13%	-0.23%
Other transport	-2.05%	0.55%	0.44%	0.55%	0.26%	0.57%	0.37%	-0.23%
Other manufacturing	-0.04%	-0.28%	0.39%	0.72%	1.25%	0.28%	-0.99%	-0.04%
Other activities	-1.10%	0.49%	-0.30%	-0.61%	-0.12%	0.46%	0.29%	-0.05%
Total	-1.10%	0.54%	-0.32%	-0.66%	-0.15%	0.46%	0.30%	-0.14%

Table 6: Output changes in case one

One common feature across all economies is that the Computer sector responds very strongly. Why? First, because this sector is hit by a higher than average productivity shock in China and the production cost increases a lot. Table 2 shows the sectoral shock is -5% in case one, which is relatively big. In case two, when the shock rises from 5% to 15%, output in the Computer sector drops by 1.2% (see Appendix Table A5). Second, the Computer sector is large. It accounts for 27%, 21% and 29% of China, Japan and Korea's total exports. When China's exports become relatively expensive, firms switch to cheaper sources such as the UK and the US. Therefore, the UK and the US have higher sectoral output. Though all responses are strong, they differ in their signs. For example, the US's output increases by 4.43% while Japan's output drops by 0.44%. This is partly due to the different shares of intermediate goods as input. The Computer sector uses around 30% intermediate goods as input in the US. While in Japan, it uses 53% intermediate goods. Since intermediate goods in other sectors become more expensive, Japan's computer production is further reduced.

In generally, sectors produce less in China if they are hit harder, but the magnitude of reductions varies. With a 5% productivity shock, the Auto sector's output declines by 1.63% while the Electrical equipment sector by 1.13%. This indicates the importance of sector linkages. The Electrical equipment sector relies heavily on other sectors, but the Auto sector is more independent. Another influential factor is the reaction of the other economies. For example, the Petroleum sector is also hit by a 5% shock in China, but it produces 2.6% more than before the shock. This is because the EU, the UK, and Korea produce much fewer petroleum products. When the shock becomes -15% in the Petroleum sector in case two, China produces even more, indicating its comparative advantage in producing coke and refined petroleum products.

4.3 Changes in exports and model performance

A handful of sectors explain the main changes in exports as Table 7 shows. For China and Japan, the Petroleum sectors gain the most. For Korea, the EU, the UK, and the US, the Computer sectors exhibit the largest increases in their export shares. While for the ROW, the changes are small and uniform across all sectors.

	China		Japan		Korea		EU27		UK		US		ROW	
Sector	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Agriculture	1.76%	1.92%	0.62%	0.59%	0.45%	0.47%	5.13%	5.13%	1.08%	1.05%	5.33%	5.12%	2.37%	2.37%
Mining	1.13%	1.16%	0.15%	0.14%	0.95%	0.91%	8.41%	8.08%	19.56%	19.36%	25.80%	26.00%	30.01%	30.04%
Food	1.59%	1.57%	0.80%	0.79%	1.03%	1.04%	6.00%	6.07%	3.99%	4.01%	3.78%	3.78%	5.53%	5.52%
Textiles	14.53%	14.80%	1.29%	1.25%	2.24%	2.23%	5.43%	5.50%	2.83%	2.93%	1.07%	1.03%	3.54%	3.52%
Wood	0.88%	0.96%	0.07%	0.07%	0.03%	0.03%	1.12%	1.11%	0.15%	0.15%	0.36%	0.33%	0.83%	0.83%
Paper	0.96%	1.07%	1.11%	1.08%	0.89%	0.90%	2.15%	2.20%	1.34%	1.38%	0.95%	0.90%	0.74%	0.72%
Petroleum	3.37%	4.63%	8.24%	10.36%	10.65%	9.46%	9.60%	8.77%	7.41%	6.85%	8.23%	8.08%	0.60%	0.72%
Chemicals	4.60%	4.38%	7.61%	7.58%	11.04%	11.20%	10.58%	10.71%	9.85%	9.90%	11.33%	11.48%	10.66%	10.69%
Rubber and plastic	3.45%	3.36%	2.47%	2.44%	2.39%	2.43%	2.16%	2.19%	1.41%	1.43%	2.01%	2.03%	2.18%	2.18%
Minerals	2.80%	2.73%	1.17%	1.15%	0.62%	0.62%	1.22%	1.23%	0.56%	0.56%	0.78%	0.78%	0.81%	0.82%
Basic metals	3.32%	3.24%	6.80%	6.69%	8.42%	8.47%	4.20%	4.21%	11.95%	11.92%	3.69%	3.63%	6.97%	7.05%
Metal products	5.20%	5.14%	2.32%	2.26%	2.90%	2.98%	2.82%	2.89%	1.45%	1.51%	1.50%	1.48%	1.61%	1.60%
Computer	27.23%	26.24%	21.21%	20.65%	29.31%	29.72%	11.39%	11.65%	8.08%	8.40%	13.66%	14.47%	12.41%	12.31%
Electrical equipment	8.37%	8.41%	11.03%	10.38%	6.81%	7.00%	5.46%	5.57%	2.94%	3.02%	3.30%	3.34%	2.47%	2.45%
Machinery	8.56%	8.27%	13.52%	13.43%	8.39%	8.51%	9.25%	9.40%	5.81%	5.88%	8.12%	8.14%	5.15%	5.15%
Auto	2.14%	2.06%	17.10%	16.82%	10.44%	10.57%	7.55%	7.65%	8.93%	9.05%	5.62%	5.68%	8.29%	8.30%
Other transport	3.31%	3.20%	3.34%	3.21%	2.97%	3.00%	5.28%	5.34%	9.61%	9.51%	2.26%	1.52%	3.18%	3.11%
Other manufacturing	6.79%	6.85%	1.15%	1.11%	0.46%	0.46%	2.25%	2.29%	3.03%	3.11%	2.21%	2.22%	2.67%	2.64%

Table 7: Export shares by sector before and after the productivity shocks (case one)

A natural question that arises is whether the model performs well in generating trade flows after the shocks. If so, the new bilateral flows should be consistent with the observed data in March 2020. Thus I compare the simulated data and the real observations. The observed trade flows are again obtained from the International Trade Centre and are converted from the HS6 into ISIC Rev4.[19] The exports of the ROW is again the sum of the other six economies' imports.

	China	Japan	Korea	EU27	UK	US	ROW
Case one	0.950	0.870	0.972	0.710	0.602	0.645	0.832
Case two	0.938	0.868	0.976	0.722	0.613	0.660	0.846

Table 8: Correlations between the simulated and observed exports (Mar 2020)

Table 8 shows the correlations between the simulated data and real data in March, 2020. The model performs well in general, especially for China, Korea, and the ROW. The observed and predicted bilateral exports are plotted in figure 3. It is clear that some countries have lower correlations because the simulated exports are much higher in the Mining sector. One possible explanation is that the

[19] As monthly data for China stopped updating in that database in year 2020, I have to download the data from the General Administration of Customs of China. However, only HS2 level data is available instead of the HS6 level, meaning the direct conversion is infeasible. Therefore, I calculate the proportion of each HS2 level product in the converted ISIC sector by using the HS6 level data in Dec 2019 from ITC and then assume the proportions did not change from Dec 2019 to Mar 2020. Finally, I compare the converted data with the directly obtained HS2 data in Dec 2019 from the General Administration of Customs and make adjustments to ensure the consistency.

Mining sector is highly restricted by natural resource availability and could not has dramatic changes in reality. The same logic applies to the Petroleum sector in Japan. Nevertheless, the model has a satisfactory predict power using only sparse parameters.

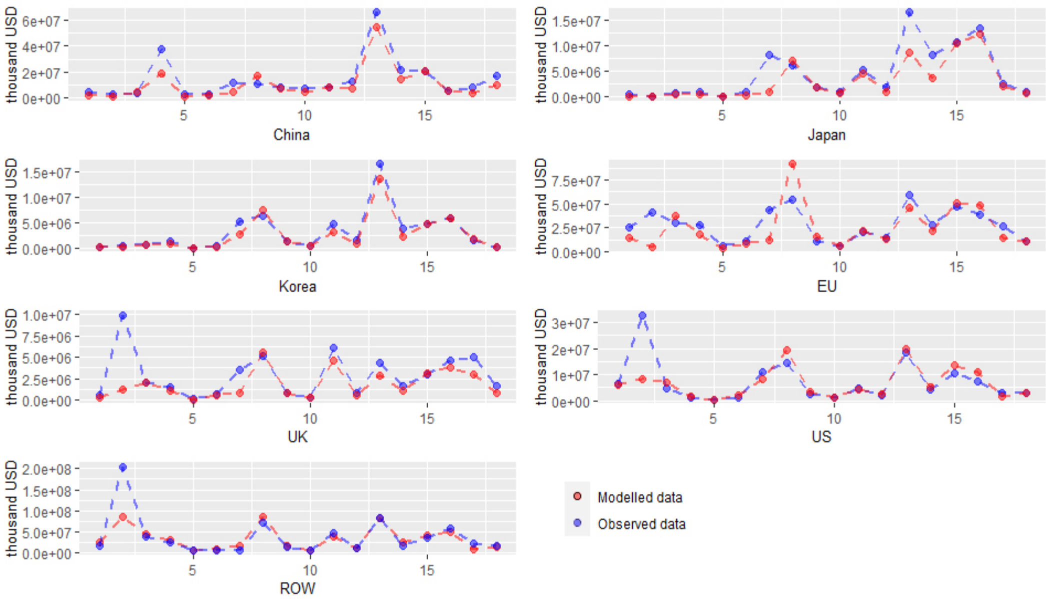

Figure 3: Comparisons between simulated data and observed exports (Mar 2020). Note: This figure presents the observed and simulated sectoral exports in March 2020 for each economy. The x-axis shows sector numbers, which are the same as in Table A1. Only 18 sectors are considered due to the high volume of trade in services (the 19^{th} sector).

5 Further extensions

This section quantifies the welfare effects and compares with the benchmark results in section 4 performing different counterfactual exercises. I first estimate the welfare effects across different models and confirm the importance of the intermediate goods and sectoral linkages. Then I assume the same shocks happen in other economies to compare the differences in welfare effects. Finally, I introduce the trade in services and show it does not influence the baseline results significantly.

5.1 Model Comparison

This section compares the welfare effects of the same shocks using different models. Table 9 compares the benchmark results in section 4 with a model without the Input-Output structure and a model without intermediate materials as input. The welfare effects become negligible when labor is the only input for production.

Without the sectoral linkages, the welfare effects drop to about one-third to a half of the benchmark levels, but the signs remain the same. The results are consistent with Eppinger et al. (2020)'s finding that the welfare loss due to the Covid-19 shock in China is reduced by 40% in the median country without sectoral linkages. The decomposition shows that the reductions in other economies mainly come from the terms of trade effects instead of the productivity effects.

	Welfare effect			Terms of trade effect			Productivity effect		
	Baseline	No Materials	No IO	Baseline	No Materials	No IO	Baseline	No Materials	No IO
China	-2.15%	-0.80%	-1.33%	0.03%	-0.05%	-0.05%	-2.18%	-0.74%	-1.27%
Japan	0.13%	0.00%	0.06%	0.14%	0.00%	0.07%	-0.02%	0.00%	-0.02%
Korea	0.13%	0.00%	0.06%	0.19%	0.02%	0.08%	-0.06%	-0.01%	-0.02%
EU27	0.02%	0.00%	-0.02%	0.05%	0.00%	0.00%	-0.03%	0.00%	-0.02%
UK	-0.11%	0.00%	-0.04%	-0.08%	0.00%	-0.01%	-0.02%	0.00%	-0.02%
US	-0.11%	0.00%	-0.04%	-0.09%	0.00%	-0.02%	-0.02%	0.00%	-0.02%
ROW	-0.04%	-0.01%	-0.02%	0.01%	0.01%	0.03%	-0.05%	-0.02%	-0.05%

Table 9: Comparison across models

5.2 Comparison across economies

Another way to show China's importance in global value chains is to compare the welfare effects assuming the same sectoral shocks occur in other economies. For example, if the same supply shock happens in Japan, what will the welfare losses be in other economies? Will the impact be more severe or less? How about Korea? To answer these questions, I conduct three exercises:

1. I assume the same sectoral shocks happen in the other six economies separately and test the welfare effects.
2. I assume there is a uniform 20% supply shock in all sectors for each of the seven economies and test the welfare effects.
3. I raise the shock level to 50% and make the comparison again.

In the first two exercises, the influences from other economies' shocks are very limited compared with the benchmark results. Most of the economies only suffer from a 0.1% welfare loss when the shocks happen in another economy other than China. Figure 3 shows the results in exercise 3: a uniform 50% sectoral productivity shock in each economy respectively. Shocks in China have the most significant welfare effects on other economies, following by the EU. Interestingly, the US's shock does not affect other economies much, which is in line with the fact that the US runs huge trade deficits.

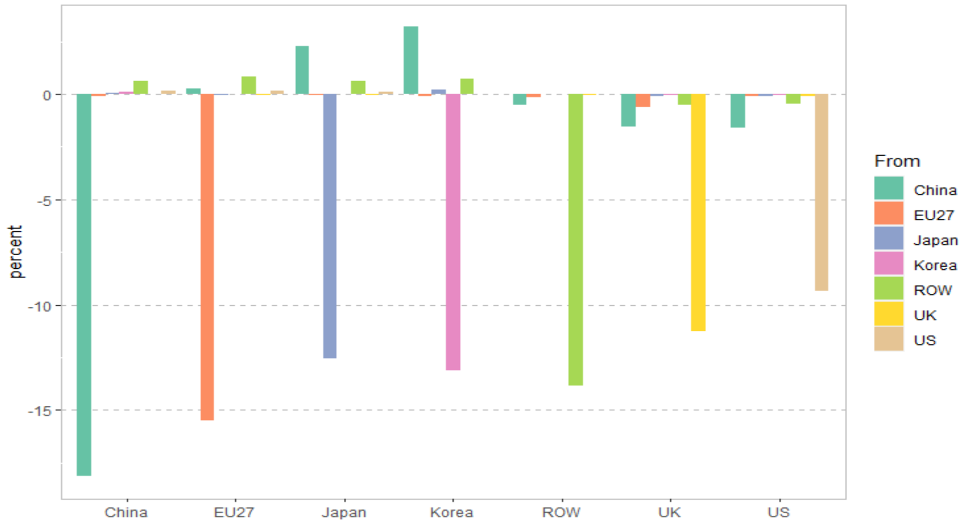

Figure 4: Comparison of a 50% uniform labor supply shock. Note: This figure presents the welfare changes in all economies when there is a 50% labor supply shock in all sectors in one specific economy. The legend shows where the shock originates from and the x-axis shows the economy affected.

5.3 Adding trade in services

Finally, I remove the restriction that services are non-tradable. The trade in services data is collected from the World Bank and OECD International Trade in Service Statistics (ITSS) database. As only annual trade flows are available, I divide each series by twelve to get monthly flows.[20] Then I divide the bilateral exports by an economy's total exports to get proportions of trade with each partner. The proportions are assumed to be constant until December 2019 to construct the trade flows in that month. I incorporate the trade in services and estimate the new equilibrium again. Table 10 compares the baseline results with the new results. The welfare reductions are mitigated in the US and the UK but aggravated in the EU and the ROW. The results for China are similar, while the TOT increase by 0.04% compared with the benchmark.

[20]The latest available data is in year 2019 for the US and the UK, in 2018 for Japan, Korea, and EU, and in 2016 for China.

	Welfare effect		Terms of trade effect		Productivity effect	
	Baseline	With service	Baseline	With service	Baseline	With service
China	-2.15%	-2.14%	0.03%	0.07%	-2.18%	-2.20%
Japan	0.13%	0.13%	0.14%	0.15%	-0.02%	-0.02%
Korea	0.13%	0.22%	0.19%	0.30%	-0.06%	-0.07%
EU27	0.02%	-0.01%	0.05%	0.01%	-0.03%	-0.03%
UK	-0.11%	-0.03%	-0.08%	0.00%	-0.02%	-0.03%
US	-0.11%	-0.09%	-0.09%	-0.07%	-0.02%	-0.02%
ROW	-0.04%	-0.08%	0.01%	-0.02%	-0.05%	-0.06%

Table 10: Adding trade in services

6 Conclusion

This paper estimates the trade and welfare effects of Hubei's lockdown in China on several economies by a Ricardian model with sectoral linkages and trade in intermediate goods. I calibrate the model parameters using the data from STAN and WIOD. I study two ranges of productivity shocks, assuming a minor loss and a full loss in Hubei, according to the approach developed by Luo and Tsang (2020). China's welfare decreases by 2.15% in the first case and 4.20% in the second case. The UK, the US, and the ROW all have lower welfare levels in both cases. However, Japan and Korea's real incomes increase. The Auto sector in Japan and the Computer sector in Korea are the largest contributors. Those sectors gain from substituting China's exports.

I derive a theoretical representation for welfare decomposition, and I introduce a new way to measure the influence of a productivity change on welfare. After decomposing the welfare effects into terms of trade effect and productivity effect, the former accounts for much more of the changes in all economies except for China. Sectors vary a lot in their responses, depending on the sectoral linkages and the industrial sizes. Generally, export-oriented sectors in China contribute more to welfare changes given similar shock levels.

World output falls by 0.14% and 0.24% in two cases separately. The numbers are still striking given the short period under consideration. China loses 1.10% output in case one. The EU, Korea, and the UK's output falls while Japan, the US, and the ROW produce more in case one. World sectoral output also responds differently. While the Computer sector's production drops by 0.66%, the Other transport sector's output falls by 0.04%. Similar results are found in case two, although the magnitude is larger. After comparing the simulated data and the observed data in March 2020, I find the model performs remarkably well using relatively sparse parameters.

Finally, I conduct various exercises and compare the results with the benchmark. Comparison across models implies the importance of sectoral linkages and intermediate goods, while comparison across countries reassures that China is playing a significant role in global value chains. Adding trade in services confirms the robustness of the baseline findings.

It is necessary to emphasize that this exercise only considers the lockdown of Hubei province without thinking about the further transmission of the virus. Thus the results only reflect a very small part of the influence of COVID shock on the world economy. Nevertheless, Hubei's lockdown provides a natural experiment to study the importance of China's role in global supply chains. Although the shock only happens in China, it affects countries worldwide rapidly and strongly. As the global trade pattern may change after the pandemic, how to optimize the supply chains in each country would be a useful and interesting future research direction.

Appendices

A Table

Number	Sector abbreviation	ISIC Rev 4 sectors
1	Agriculture	D01T03: Agriculture, forestry and fishing
2	Mining	D05T09: Mining and quarrying
3	Food	D10T12: Food products, beverages and tobacco
4	Textiles	D13T15: Textiles, wearing apparel, leather and related products
5	Wood	D16: Wood and products of wood and cork
6	Paper	D17T18: Paper products and printing
7	Petroleum	D19: Coke and refined petroleum products
8	Chemicals	D20T21: Chemicals and pharmaceutical products
9	Rubber and plastic	D22: Rubber and plastic products
10	Minerals	D23: Other non-metallic mineral products
11	Basic metals	D24: Basic metals
12	Metal products	D25: Fabricated metal products
13	Computer	D26: Computer, electronic and optical products
14	Electrical equipment	D27: Electrical equipment
15	Machinery	D28: Machinery and equipment, nec
16	Auto	D29: Motor vehicles, trailers and semi-trailers
17	Other transport	D30: Other transport equipment
18	Other manufacturing	D31T33: Other manufacturing; repair and installation
19	Other activities	D36T99: Other activities

Table A.1: Sector List

Number	Name	Country list
1	China	CHN: China
2	Japan	JPN: Japan
3	Korea	KOR: Korea
		AUT: Austria
		BEL: Belgium
		BGR: Bulgaria
		CYP: Cyprus
		CZE: Czech Republic
		DEU: Germany
		DNK: Denmark
		ESP: Spain
		EST: Estonia
		FIN: Finland
		FRA: France
		GRC: Greece
		HRV: Croatia
4	EU27	HUN: Hungary
		IRL: Ireland
		ITA: Italy
		LTU: Lithuania
		LUX: Luxembourg
		LVA: Latvia
		MLT: Malta
		NLD: Netherlands
		POL: Poland
		PRT: Portugal
		ROU: Romania
		SVK: Slovak Republic
		SVN: Slovenia
		SWE: Sweden
5	UK	GBR: United Kingdom
6	US	USA: United States of America
7	ROW	ROW: Rest of the world

Table A.2: Country list

Sectors	China		Japan		Korea		EU27		UK		US		ROW	
	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod	TOT	Prod
Agriculture	-2.22%	4.60%	0.13%	0.26%	-0.13%	0.27%	8.12%	0.24%	-1.57%	0.11%	2.54%	0.13%	-4.33%	0.91%
Mining	-25.13%	1.03%	-24.31%	1.32%	-26.48%	0.41%	-13.34%	0.03%	6.40%	0.00%	10.79%	0.00%	24.86%	0.08%
Food	-4.19%	9.01%	-1.56%	4.53%	-1.11%	2.76%	2.12%	1.28%	-3.95%	0.98%	-1.79%	1.36%	3.03%	1.63%
Textiles	9.07%	1.20%	-0.85%	5.06%	-1.42%	4.72%	4.06%	3.68%	-5.96%	2.98%	-5.19%	3.97%	-2.75%	3.40%
Wood	-0.19%	0.31%	-0.27%	0.13%	-0.36%	0.10%	1.29%	0.19%	-1.37%	0.18%	-0.62%	0.16%	0.04%	0.07%
Paper	0.00%	0.18%	0.67%	0.08%	0.51%	0.06%	3.65%	0.06%	0.12%	0.07%	-0.65%	0.15%	-1.85%	0.07%
Petroleum	1.96%	0.45%	4.03%	0.05%	9.16%	0.43%	24.96%	0.11%	7.24%	0.12%	3.22%	0.05%	-19.06%	0.41%
Chemicals	-7.13%	-27.10%	2.89%	-25.02%	5.22%	-36.35%	-2.53%	-15.62%	-10.75%	-13.58%	-5.61%	-9.81%	7.28%	-11.39%
Rubber and plastic	2.44%	9.78%	1.22%	18.58%	1.54%	7.50%	-2.43%	13.02%	-3.41%	19.46%	-1.15%	13.38%	0.39%	9.78%
Minerals	1.76%	5.65%	0.50%	2.64%	-0.25%	5.16%	0.74%	2.50%	-0.89%	2.69%	-0.57%	2.25%	-0.99%	3.08%
Basic metals	-8.86%	4.22%	2.71%	2.02%	5.11%	3.52%	-1.13%	0.96%	8.74%	0.27%	-0.91%	0.22%	2.96%	1.68%
Metal products	4.71%	0.63%	0.34%	2.38%	1.63%	1.03%	1.78%	0.98%	-1.78%	0.93%	-3.01%	1.49%	-1.82%	0.82%
Computer	13.35%	4.45%	9.10%	28.43%	16.49%	28.55%	-3.84%	21.24%	-12.44%	12.93%	-15.31%	19.11%	-0.56%	15.18%
Electrical equipment	6.36%	1.83%	8.33%	4.61%	5.72%	2.63%	5.03%	4.61%	-5.75%	3.83%	-3.62%	3.43%	-6.82%	3.30%
Machinery	4.94%	7.69%	9.61%	8.61%	5.42%	8.26%	4.94%	14.16%	-6.22%	11.06%	-3.82%	11.57%	-6.29%	9.62%
Auto	-0.52%	20.62%	30.44%	10.32%	18.62%	5.94%	-16.44%	9.12%	-18.62%	8.05%	-27.67%	9.90%	12.82%	4.46%
Other transport	5.72%	29.35%	2.59%	31.09%	0.77%	61.50%	-0.52%	35.46%	3.75%	42.52%	-10.12%	33.48%	1.50%	53.48%
Other manufacturing	1.45%	0.46%	0.47%	4.91%	-0.05%	3.51%	-3.07%	8.00%	-1.03%	7.39%	-3.39%	9.14%	2.65%	3.40%
Other activities	0.00%	25.65%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table A.3: Sectoral contributions to the aggregate effects (case two)

	China	Japan	Korea	EU	UK	US	ROW
Agriculture	-0.47%	2.38%	1.43%	2.22%	2.63%	2.68%	1.96%
Mining	0.54%	2.54%	1.88%	2.14%	1.65%	1.84%	1.60%
Food	0.69%	2.65%	2.74%	2.81%	2.82%	3.32%	2.91%
Textiles	1.19%	2.73%	2.66%	2.34%	1.96%	3.12%	2.55%
Wood	0.74%	2.66%	2.23%	2.60%	2.60%	3.17%	2.44%
Paper	1.21%	2.64%	2.53%	2.56%	2.50%	3.00%	2.78%
Petroleum	1.31%	1.92%	2.60%	2.59%	2.72%	2.41%	2.19%
Chemicals	1.65%	3.33%	2.83%	3.22%	2.53%	2.52%	2.96%
Rubber and plastic	1.68%	3.23%	2.47%	2.73%	2.34%	2.88%	3.00%
Minerals	1.39%	2.61%	2.67%	2.60%	3.01%	2.74%	2.48%
Basic metals	1.69%	2.91%	2.55%	2.86%	3.29%	3.32%	2.55%
Metal products	1.74%	2.86%	2.26%	2.36%	2.01%	2.77%	2.67%
Computer	2.70%	3.00%	2.81%	2.56%	2.27%	1.83%	3.01%
Electrical equipment	2.18%	3.30%	2.75%	2.68%	2.64%	2.64%	2.98%
Machinery	2.38%	2.93%	2.92%	2.87%	2.78%	3.20%	3.29%
Auto	6.06%	7.04%	5.11%	5.36%	4.61%	5.43%	5.75%
Other transport	3.81%	4.49%	3.56%	2.84%	4.01%	4.20%	4.77%
Other manufacturing	0.55%	3.11%	2.71%	2.34%	2.09%	2.81%	3.02%
Other activities	0.82%	2.30%	1.84%	1.98%	2.28%	2.37%	2.16%

Table A.4: Changes in sectoral costs (case two)

	China	Japan	Korea	EU27	UK	US	ROW	Sectoral Total
Agriculture	-1.53%	0.45%	0.13%	-0.96%	-1.40%	-1.20%	0.51%	-0.55%
Mining	1.16%	-8.56%	-6.72%	-6.96%	-2.54%	-0.47%	0.57%	-0.26%
Food	-2.31%	0.88%	0.04%	-0.07%	0.09%	0.42%	0.38%	-0.38%
Textiles	-0.29%	-0.86%	-1.39%	0.97%	3.16%	-2.95%	-0.49%	-0.25%
Wood	-0.40%	-0.16%	-0.09%	-0.94%	-0.57%	-2.45%	0.41%	-0.46%
Paper	-0.31%	0.26%	0.11%	0.53%	0.70%	-1.04%	-2.31%	-0.41%
Petroleum	5.30%	10.78%	-13.94%	-8.09%	-8.31%	-0.21%	12.75%	-0.54%
Chemicals	-3.94%	1.55%	1.24%	0.75%	0.29%	0.73%	0.76%	-0.65%
Rubber and plastic	-3.70%	0.55%	1.67%	0.81%	1.49%	1.33%	0.66%	-0.71%
Minerals	-2.67%	0.87%	1.16%	-0.22%	0.18%	1.02%	0.83%	-0.96%
Basic metals	-3.59%	0.13%	1.22%	0.08%	-0.47%	0.41%	1.21%	-0.93%
Metal products	-2.66%	0.25%	1.18%	1.28%	1.84%	0.88%	0.10%	-0.27%
Computer	-7.01%	-0.02%	1.26%	3.19%	4.71%	7.23%	-0.71%	-1.20%
Electrical equipment	-2.39%	-2.94%	1.31%	2.51%	2.42%	2.87%	-1.04%	-0.75%
Machinery	-3.83%	1.89%	1.25%	1.30%	1.39%	1.20%	0.74%	-0.48%
Auto	-3.45%	-0.50%	1.23%	1.09%	2.07%	1.26%	0.36%	-0.46%
Other transport	-4.14%	0.96%	0.76%	1.46%	0.78%	1.03%	0.66%	-0.42%
Other manufacturing	-1.13%	-0.03%	0.45%	1.43%	1.79%	0.75%	-0.88%	0.01%
Other activities	-2.25%	0.76%	-0.54%	-0.47%	0.06%	0.74%	0.43%	-0.05%
sum	-2.27%	0.80%	-0.61%	-0.54%	0.01%	0.74%	0.45%	-0.24%

Table A.5: Output changes after the shock (case two)

B Formular

B.1 Derivation of prices of the intermediate goods

To get a simple expression for the distribution of prices, I follow Eaton and Kortum (2002) to assume the country $n's$ efficiency distribution is Frechet:

$$F_n^j(z) = e^{-T_n^j z^{-\theta^j}}$$

and is independent across countries, sectors and goods. The parameter T_n^j controls the likelihood of the higher efficiency draw of z_n^j. θ^j is treated as common to all countries and decides the variation within the distribution. Thus a higher T_n^j means an absolute advantage in country n, sector j and a lower θ^j implies more heterogeneity across goods in countries' relative efficiencies.

Plugging the above expression into p_{ni}^j, we get its distribution

$$G(p_{ni}^j) = 1 - e^{-T_i^j (c_i^j d_{ni}^j)^{-\theta^j}} p^{\theta^j} \tag{B.1}$$

Thus the distribution of the lowest price of an intermediate good ω^j in country n has the following distribution

$$G(P_n^j) = 1 - \prod_{i=1}^{N}[1 - G(p_{ni}^j)] = 1 - e^{-\Phi_n^j p^{\theta^j}}, \tag{B.2}$$

where $\Phi_n^j = \sum_{i=1}^N T_i^j (c_i^j d_{ni}^j)^{-\theta^j}$.

The exact formula of price of the composite goods P_n^j is

$$P_n^j = \kappa^j [\Phi_n^j]^{-1/\theta^j}, \tag{B.3}$$

where

$$\kappa^j = \left[\Gamma\left(\frac{\theta^j + 1 - \sigma^j}{\theta^j}\right)\right]^{1/(1-\sigma^j)},$$

and Γ is the Gamma function. I also assume that $\sigma^j < 1 + \theta^j$ to ensure a well defined price index. Some sectors are non-tradable by assuming the local suppliers are providing goods with the lowest costs. For those sectors, $d_{ni}^j = \infty$ and $P_n^j = \kappa^j (T_i^j)^{-1/\theta^j} c_n^j$. Note P_n^j is also the price for final goods that consumers buy. The consumption price index is $P_n = \prod_{j=1}^J (P_n^j/\alpha_n^j)^{\alpha_n^j}$.

B.2 Derivation of the equation (2.14)

The exact formular of P_n^j is

$$P_n^j = \kappa^j \left[\sum_{i=1}^N T_i^j (c_i^j \tilde{d}_{ni}^j)^{-\theta^j}\right]^{-1/\theta^j},$$

After the change, it becomes

$$P_n^{\prime j} = \kappa^j \left[\sum_{i=1}^N T_i^{\prime j} (c_i^{\prime j} \tilde{d}_{ni}^j)^{-\theta^j}\right]^{-1/\theta^j},$$

Thus

$$\hat{P}_n^j = \frac{P_n^{\prime j}}{P_n^j} = \left[\frac{\sum_{i=1}^N T_i^{\prime j} (c_i^{\prime j} \tilde{d}_{ni}^j)^{-\theta^j}}{\sum_{i=1}^N T_i^j (c_i^j \tilde{d}_{ni}^j)^{-\theta^j}}\right]^{-1/\theta^j} = \left[\frac{\sum_{i=1}^N \hat{T}_i^j (\hat{c}_i^j)^{-\theta^j} T_i^j (c_i^j \tilde{d}_{ni}^j)^{-\theta^j}}{\sum_{i=1}^N T_i^j (c_i^j \tilde{d}_{ni}^j)^{-\theta^j}}\right]^{-1/\theta^j}$$

Then use equation (2.12) to substitute $\sum_{i=1}^N T_i^j (c_i^j \tilde{d}_{ni}^j)^{-\theta^j}$ by $\pi_{ni}^j T_i^j (c_i^j \tilde{d}_{ni}^j)$. Finally,

$$\hat{P}_n^j = \left[\sum_{i=1}^N \pi_{ni}^j \hat{T}_i^j (\hat{c}_i^j)^{-\theta^j}\right]^{-1\theta^j}$$

B.3 Derivation of the welfare decomposition

I start with the first part in equation (2.18). The change in wages ($\ln w_n$) can be written as a function of $\ln c$ and the sum of $\ln P_n^j$, according to equation (2.4).

$$d\ln w_n = \frac{1}{\gamma_n^j} d\ln c_n^j - \sum_{k=1}^{J} \frac{\gamma^{k,j}}{\gamma_n^j} d\ln P_n^k \tag{B.4}$$

Besides, the labor market clearing condition means

$$w_n L_n = \sum_{j=1}^{J} \gamma_n^j \sum_{i=1}^{N} E_{ni}^j.$$

Therefore, the first term of equation (2.18) becomes

$$\frac{w_n L_n}{I_n} d\ln w_n = \frac{1}{I_n} \sum_{j=1}^{J} \gamma_n^j \sum_{i=1}^{N} E_{ni}^j \left(\frac{1}{\gamma_n^j} d\ln c_n^j - \sum_{k=1}^{J} \frac{\gamma^{k,j}}{\gamma_n^j} d\ln P_n^k \right)$$
$$= \frac{1}{I_n} \left(\sum_{j=1}^{J} \sum_{i=1}^{N} E_{ni}^j d\ln c_n^j - \sum_{j=1}^{J} \sum_{k=1}^{J} \gamma_n^{k,j} \sum_{i=1}^{N} E_{ni}^j d\ln P_n^k \right)$$

Now I turn to the second part of equation (2.18). From the definition of the consumer price index, the change in P_n is the sum of weighted prices across all sectors,

$$d\ln P_n = \sum_{j=1}^{J} \alpha_n^j d\ln P_n^j = \sum_{j=1}^{J} \alpha_n^j \sum_{i=1}^{N} \pi_{ni}^j (d\ln c_i^j - \frac{1}{\theta^j} d\ln T_i^j) \tag{B.5}$$

To simplify the notifications, I substitute out α_n^j by combing the labor market clearing condition and the definition of expenditure equation (2.11) and get

$$\alpha_n^j = \frac{X_n^j}{I_n} - \frac{1}{I_n} \sum_{k=1}^{J} \gamma^{j,k} \sum_{i=1}^{N} X_i^k \pi_{in}^k \tag{B.6}$$

Therefore,

$$d\ln P_n = \frac{1}{I_n} \left(\sum_{j=1}^{J} X_n^j d\ln P_n^j - \sum_{j=1}^{J} \sum_{k=1}^{J} \gamma_n^{j,k} \sum_{i=1}^{N} E_{ni}^k d\ln P_n^j \right) \tag{B.7}$$

Finally, combining the first and second parts, I get

$$d\ln W_n = \frac{1}{I_n} \left(\sum_{j=1}^{J} \sum_{i=1}^{N} E_{ni}^j d\ln c_n^j - M_{ni}^j d\ln c_i^j \right) + \frac{1}{I_n} \sum_{j=1}^{J} \sum_{i=1}^{N} M_{ni}^j \frac{1}{\theta^j} d\ln T_i^j, \tag{B.8}$$

where E_{ni}^j is the sector j's exports from country n to country i and M_{ni}^j is the imports of country n from country i.

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