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Economic Shock Transmission through Global Value Chains: An Assessment using Network Analysis

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Abstract This paper examines the role of some key economies in the economic contagion across global value chains using input-output analysis and complex network statistics. The empirical research focuses on China, France, Germany, Italy, Japan, Korea, the United Kingdom, and the United States. A range of novel measures were used to measure the nature and extent of global value chain relationships. The empirical results reveal that, because of the high interdependence and interconnectedness in the global value chain networks, the transmission of an economic shock in China and the United States will be fast, wide, and in-depth in the global value chain networks. Sample countries are more exposed to an economic shock in China than a shock in the other four big economic partners, namely the United States, Germany, Japan, and Korea.

Keywords Global value chain · Trade · Network analysis · COVID-19 · Economic shock transmission

JEL Classification F13 · F14 · C65 · C67

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Introduction

The speed with which the coronavirus disease spread and its impact indicate that the world is now widely interdependent and interconnected with global production and trade organized as global value chains (GVCs). The initial economic slowdown in an economy as big as China spread in the global economy through disruptions in the production of many countries because the Chinese supply chain constitutes a large part of total foreign inputs in exports (Javorcik, 2020). It is interesting to examine the mechanisms of transmission resulting from such economic shocks.

This paper examines the economic contagion across GVCs caused by an economic shock in a single country via application of input-output analysis and complex network statistics on a data set from the World Input-Output Database (Groningen Growth and Development Centre, 2016) for the year 2014. This dataset covers 54 sectors and 44 countries, including 28 members of the European Union (EU), and 15 other economies: Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Norway, Russia, South Korea, Switzerland, Taiwan, Turkey, the United States (U.S.), and an extra area representing the rest of the world (ROW), which includes the remaining countries (Timmer et al., 2016).

The speed of transmission of a domestic slowdown into the entire GVC network depends on the share of the import–export flows among countries (*weighted in-degree* and *weighted out-degree),* the diversification of import–export flows of each country (e*ntropy of weighted in-degree* and *entropy of weighted out-degree)*, and the influence of each country on the trade network (*weighted in-eigen centrality* and *weighted out-eigen centrality)*. The direct economic contagion from country to country is also investigated. Finally, the sectors most vulnerable to domestic economic shocks are identified. The discussion of the results focuses on eight countries, namely, China, France, Germany, Italy, Japan, Korea, the United Kingdom (UK), and the U.S., which are more likely to transmit a domestic shock across GVCs due to their high relative (dominant) position in the international trade based on our finding (i.e., high *weighted in-degree* and high *weighted out-degree*).

Our findings indicate that an economic shock in countries with a dominant position propagates through the GVC networks to other countries. An economic shock in these countries (e.g., China, Germany, and the U.S.) was expected to have a greater impact on the GVC network than on the rest of the countries. The higher direct impact was from China on Korea, Germany, Japan, and the U.S. Finally, it was assumed that a domestic economic shock transmits through the sectoral GVC networks where the country exhibits higher dominance and influence. Therefore, an economic shock in China would spread at the first stage in the sectoral networks of manufacture of electrical equipment, manufacture of basic metals (as an importer of intermediate goods), and manufacture of computers, electronic and optical products (as an exporter of intermediate goods).

Literature Review and Research Questions

With respect to GVCs, the value chain is the full range of activities that firms and workers perform to bring a product from conception to end-use and beyond (Gereffi & Fernandez-Stark, 2011). More specifically, the GVC of a final product

includes the value-added of all activities directly and indirectly needed to produce it (Timmer et al., 2014)

Participation in GVCs induces firms to face the strategic choice between switching partners in the various stages of production or breaking the chain through partial repatriation. In both cases in ordinary conditions, firms consider the switching and transaction costs. However, an economic shock or a deep recession in a big economy would cause significant cross-sectoral effects in the network countries because of the GVC structure. In the GVC networks, the countries tend to group together around some central countries that act as hubs (Amador & Cabral, 2017).

In recent years, the literature applied network analysis to investigate the participation of each country, the correlations and influences between countries and sectors, and the evolution of world trade in GVCs. Ferrantino and Taglioni (2014) examined the relationship of GVC trade with total trade and found that GVC trade in complex products is more sensitive to downturns than the trade of simple products. Cerina et al. (2015) found that world production is conducted nationally or regionally, and micro shocks could lead to fluctuations, because there is a high but asymmetric connection among industries. Amador and Cabral (2015) concluded that GVCs and offshoring positively affect productivity at the industry and firm levels. Amador and Cabral (2017) concluded that GVCs are very centralized and asymmetric networks with a few hubs (large economies) that are exposed to the spread of idiosyncratic shocks. Xiao et al. (2017) found that different forms of value-added trade networks are relevant. Countries with central positioning tend to attach to peripheral countries with low strength while the network communities are stable. Pang and Wang (2018) found that the global production network is highly hierarchical dominated by a few large economies and the strengthening of interdependence is related to asymmetry.

Santoni and Taglioni (2015), using eigenvector centrality, confirmed the tripolar structure of the global economy (Asia, America, Europe) and found that integration into the supply network is more important than the demand network, as the elasticity of gross exports to supply-side integration is more than twice the elasticity to demand-side integration. Amador et al. (2018) identified the important but distinct role of large economies (Germany, the U.S., China, and Japan) and the cyclical triangular relationships in GVCs. Said and Fang (2019) found that a few countries concentrate the distribution of global trade but to a declining degree, letting Russia, India, and Saudi Arabia become central. Guan et al. (2020) examined the propagation process of intermediate products and the interdependence from a given GVC sector to its upstream and downstream sectors.

The increasing interdependence and interconnectedness among countries of GVC networks attracted economic research to examine the risk (Kexin et al., 2015) or response to shocks (Klimek et al., 2019). Starting with China, many countries responded to the coronavirus pandemic by locking down economic and social activity. More specifically, the collapse of the Chinese economy in the first months of 2020 spread at an unprecedented rate in the global economy. It is assumed that domestic shocks in countries with an influential position in the GVC network as importers or exporters could spread those shocks to their affiliates.

Also, if these countries' imports and exports are concentrated in a few trade partners, more countries could be directly affected. In addition, if these countries' trade partners are also influential in the GVC network as importers and exporters, the network may be propagated. Hence, a domestic shock in a country with an important relative position in the GVC network, with concentrated imports and exports, and that cooperates with highly influential countries would have greater ability to spread the shock within the GVC network.

Based on this discussion, the following research questions (RQ) are posited:

RQ1: Which countries could transmit a domestic economic shock across the whole GVC network?

RQ2: Which countries have been directly exposed to another country's domestic economic shock in the GVCs?

RQ3: Which sectors in GVC networks are most vulnerable to domestic economic shocks?

Data and Methods

This empirical research used the latest available data (2014) from the World Input Output Database (WIOD) (Groningen Growth and Development Centre, 2016). The data cover 54 sectors and 44 countries, including 28 members of the EU, 15 other economies (Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Norway, Russia, South Korea, Switzerland, Taiwan, Turkey, the U.S.), and the rest of the world (ROW), which includes the remaining countries (Timmer et al., 2016). The WIOD reports data on gross trade flows in current prices. Leontief's decomposition technique was applied, following previous literature (Timmer et al., 2015; Koopman et al., 2010; Johnson & Noguera, 2012; Johnson, 2014; Koopman et al., 2014; Xu & Dietzenbacher, 2014). The proposed technique involves the following steps.[1]

The elements of the international input-output matrix $a_{i[\mu]\to j[\nu]}$ are the gross trade flows of product μ from country j used as input from sector ν in country i. The elements $a_{i[\mu]\to j[\nu]}$ are expressed in millions of U.S. dollars. Dividing the element with $\sum_{\nu=1}^{54}\sum_{i=1}^{44} a_{i[\mu]\to j[\nu]}$ the matrix B is derived with the intermediate input coefficients, representing the intermediates required, producing one unit of output in each sector. The Leontief Inverse $(I - B)^{-1}$ is calculated, where I is the identity matrix. Let C denote the vector of consumption for each sector and country. The sectoral output level matrix is calculated as $Q= (I - B)^{-1}C$. Finally, the value-added exports for all sectors that are involved in any stage of production of C outside the country are given by the matrix $VA=F (I - B)^{-1}C$, where F denotes the diagonal matrix of value-added to gross output ratios in all sectors in all countries. The elements of the VA, $\mathcal{V}_{i[\mu]\to j[\nu]}$, $\mu, \nu = 1, 2, .., 54$ and i, j = 1, …, 44, denote the value-added exports from country i (from supply sector μ) to country j (for the examined sector ν). Hence, the

[1] The R package "decompr" was used to implement the Leontief's decomposition technique (Quast & Kummritz, 2015).

value-added exports of country i (from all supply sectors) to country j for sector ν are derived as:

$$v_{i\to j[\nu]} = \sum_{\mu=1}^{54} v_{i[\mu]\to j[\nu]}. \tag{1}$$

The total value-added flows into country j are: $\sum_{i=1}^{44} v_{i\to j[\nu]}$. The global value-added flows of the sector v are: $TVA_v = \sum_{j=1}^{44}\sum_{i=1}^{44} v_{i\to j[\nu]}$

The weights of the GVC network for sector v with order 44 are:

$$w_{i\to j[\nu]} = \frac{v_{i\to j[\nu]}}{\sum_{j=1}^{44}\sum_{i=1}^{44} v_{i\to j[\nu]}}. \tag{2}$$

The $w_{i\to j[\nu]}$ represents the share of value-added exports from country i to country j over the global value-added flows (including self-loops) of sector v. This weight formula incorporates the sum of all transactions from country i to country j, as described by Alves et al. (2018) and Angelidis et al. (2021). The diagonal part of the weight matrix is the domestic component, while the off-diagonal part is the foreign component of the countries (Criscuolo & Timmis, 2018). As the purpose was to examine the economies' role in the global value network, the focus is on the foreign component. Therefore, constructing the weight matrix $w_{i\to j[\nu]}$ with zero diagonal elements, $w_{i\to i[\nu]} = 0$ is the next step.

The construction of the weight matrix $W^{[\nu]}$ from the value-added exports $\mathcal{V}_{i[\mu]\to j[\nu]}$ was based on input-output analysis (Miller & Blair, 2009). The WIOD (Groningen Growth and Development Centre, 2016) provided bilateral trade data for the 44 countries and 54 sectors. Fifty-four sectoral networks were constructed, with nodes for the 44 countries and links for the share of import-export value-added flows among countries (nodes). Next, the metrics used in the network analysis are presented.

The *weighted in-degree* is the sum of the shares of the flows to country i. The *weighted out-degree* is the sum of the shares of the flows from the country i. The weighted degree (Barrat et al., 2004) for each sector ν and each node i=1, 2, … , 44, was constructed from the weights (1), (2):

$$\deg_i^{[\nu]in} = \sum_{j=1}^{44} w_{j\to i[\nu]} \tag{3}$$

$$\deg_i^{[\nu]out} = \sum_{j=1}^{44} w_{i\to j[\nu]}. \tag{4}$$

The degrees in Eqs. (3) and (4) show the relative position of the country i in the network since they were estimated for the value-added shares over the global value-added flows of sector v. The country with the highest *weighted in-degree* has the relative position of the largest importer or dominant importer. The country with highest *weighted out-degree* has the relative position of the largest exporter or the

dominant exporter. For each country i, the *weighted in-degree* and *weighted out-degree* 54-dimensional vectors were obtained:

$$\begin{pmatrix} \deg_i^{[1]\text{in}} \\ \vdots \\ \deg_i^{[54]\text{in}} \end{pmatrix} \tag{5}$$

$$\begin{pmatrix} \deg_i^{[1]\text{out}} \\ \vdots \\ \deg_i^{[54]\text{out}} \end{pmatrix}. \tag{6}$$

It was expected that, in the case of a domestic shock, the countries with high degrees would affect their direct trade partners more intensively than the countries with low degrees.

Entropy as a measure for diversification (Frenken, 2007) captures the GVCs diversity of import sources and export buyers (Alves et al., 2018). The diversification of the incoming and outgoing weights for each sector ν was assessed by the entropies of each node-country i for each sector ν. The in-entropy of country i is:

$$\mathcal{S}_i^{[\nu]in} = -\sum_{j=1}^{44} \rho_{j\to i[\nu]}^{in} \bullet \log_2\left(\rho_{j\to i[\nu]}^{in}\right), \quad \text{with values } 0 \le \mathcal{S}_i^{[\nu]in} \le \log_2(43)$$

where $\rho_{j\to i[\nu]}^{in} = \frac{w_{j\to i[\nu]}}{\Sigma_{j=1}^{44} w_{j\to i[\nu]}}$

is the distribution of the incoming weights of node i for each sector ν. Analogous is the definition of the out-entropy of country i for exports. It is not presented for the economy of space. Both normalized entropies are:

$$\mathcal{I}_i^{[\nu]in} = \frac{\mathcal{S}_i^{[\nu]in}}{\log_2(43)} \tag{7}$$

and

$$\mathcal{I}_i^{[\nu]out} = \frac{\mathcal{S}_i^{[\nu]out}}{\log_2(43)}. \tag{8}$$

For each country i, the normalized in-entropy and out-entropy 54-dimensional vectors were obtained:

$$\begin{pmatrix} \mathcal{I}_i^{[1]in} \\ \vdots \\ \mathcal{I}_i^{[54]in} \end{pmatrix} \tag{9}$$

and

$$\begin{pmatrix} \mathcal{I}_i^{[1]out} \\ \vdots \\ \mathcal{I}_i^{[54]out} \end{pmatrix}. \tag{10}$$

The countries with high normalized in-entropy are importers with diversified sources and value-flows. Correspondingly, countries with high normalized out-entropy have the most diversified export destinations and value flows. It was expected that the countries exhibiting high *entropy of weighted out-degree* would spread their domestic economic shock directly to many trade partners in the framework of the GVCs. On the other hand, countries with low *entropy of weighted out-degree* would transmit their domestic shock to only a few trade partners. Consequently, in the case of a domestic shock in countries with high *entropy of weighted out-degree*, the contagion on the direct partner's economies was expected to be wider in the network and narrower for the countries with low *entropy of weighted out-degree*. The discussion for the *entropy of weighted in-degree* is analogous.

For each sector ν and each node i=1, 2, … , 44, the in-eigen centrality $eig_i^{[\nu]in}$ of country i at sector ν is the i-component of the left normalized eigenvector (Perron–Frobenius), associated with the dominant eigenvalue $z_0^{[\nu]}$ of the weight matrix $w_{i\to j[\nu]}$:

$$\begin{pmatrix} w_{1\to 1[\nu]} & \cdots & w_{1\to 44[\nu]} \\ \vdots & \ddots & \vdots \\ w_{44\to 1[\nu]} & \cdots & w_{44\to 44[\nu]} \end{pmatrix}^T \bullet \begin{pmatrix} eig_1^{[\nu]in} \\ \vdots \\ eig_{44}^{[\nu]in} \end{pmatrix} = z_0^{[\nu]} \bullet \begin{pmatrix} eig_1^{[\nu]in} \\ \vdots \\ eig_{44}^{[\nu]in} \end{pmatrix}.$$

Analogous is the definition of the eigen-centrality $eig_i^{[\nu]out}$ for exports. It is not presented for economy of space. The eigenvector centrality (Bonacich, 1972) measures the influence of a node on the network. A country with high *in-eigen centrality* imports from countries with a high relative position as importers in the network. Correspondingly, a country with high *out-eigen centrality* exports to countries with a high relative position as exporters in the network. A domestic shock in a country with high eigen centrality will propagate faster into the network through its trade partners.

In the context of the first research question posed, four combinations were examined. First is the case of countries with low *weighted in-eigen centrality* and low *entropy of weighted in-degree*. The trade partners of these countries have a low relative position in the network and their imports are concentrated in a few partners. A low spread of a domestic shock into the network was expected.

Second is the case of countries with low *weighted in-eigen centrality* and high *entropy of weighted in-degree*. The trade partners of these countries have a low relative position in the network while their imports are diversified. Low to medium spread of a domestic shock into the network was expected.

Third is the case of countries with high *weighted in-eigen centrality* and low *entropy of weighted in-degree*. These countries import from countries with a high relative position as importers while their imports are concentrated to only a few trade partners. It was expected that the spread of a domestic shock into the network would be indirect through their main trade partners.

Fourth is the case of countries with high *weighted in-eigen centrality* and high *entropy of weighted in-degree*. Their trade partners also import from countries with high relative positions as importers and their imports are diversified. High direct spread of the domestic shock into the network was expected. The arguments are similar for the exporting country.

To respond to the second research question about the cross-country direct economic contagion, the *weighted out-degree* of country *i* and the *weighted in-degree* from country *i* to country *j* was used. It was expected that an economic shock in country *i* would directly affect country *j* if country *i* exhibits a high *weighted out-degree* and country j exhibits a high in-weight from country *i*. On the other hand, if the two indicators are low, a limited spread of the economic shock from *i* to *j* was expected. The intermediate combinations do not provide a definite result.

Finally, to respond to the third research question, the sectors that will first propagate the domestic economic shocks in the network, it was assumed that these sectors exhibit higher weighted degree and eigen centrality. Therefore, a benchmark of the top 20% of the country's sectoral distribution was set. In these sectors, the country has a higher relative position and their affiliates also have a higher relative position than the other sectoral GVC networks. If a country *i* and its suppliers exhibit a high *weighted in-degree* in a sector, it is expected that the domestic shock would directly affect the sectoral GVC network.

Empirical Results and Discussion

This section reports the findings of the network analysis. The countries that are more likely to transmit a domestic shock across GVCs are identified, the direct economic contagion from country to country is examined and finally, the sectors most vulnerable to domestic economic shocks are identified. Table 1 presents the cross-sectoral average and the standard deviation of the estimated metrics for the selected countries.

The U.S. is the most dominant exporter, on average, in the GVC networks, as demonstrated by the *weighted out-degree*. Germany is ranked second and China third. *Weighted out-degree* has a high standard deviation for these countries, indicating that their position as suppliers has a higher range of sectoral values. Germany is the most dominant importer, on average, in the GVCs networks, as demonstrated by the *weighted in-degree*. China keeps the second-highest relative position in the GVC network. The *weighted in-degree* for Germany and China exhibits high standard deviations indicating a high range of sectoral values. It is worth mentioning that China and Germany are the sectors with the highest maximum share as an importer of intermediate goods (i.e., manufacture of computers, electronic and optical products; sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services). On the other hand, in Germany, the fishing and aquaculture sector has the highest minimum share in the corresponding GVC network. These findings might indicate that Germany, having the higher share of value-added

Table 1 National cross-sectoral average and standard deviation of degrees, entropies and eigen-centralities, 2014

Country	Index					
	Weighted In-Degree	Weighted Out-Degree	Entropy of Weighted In-Degree	Entropy of Weighted Out-Degree	Weighted In-Eigen Centrality	Weighted Out-Eigen Centrality
Group 1						
U.S.	0.01	0.03	0.66	0.70	0.39	0.18
	(0.00)	*(0.03)*	*(0.08)*	*(0.07)*	*(0.23)*	*(0.07)*
China	0.02	0.02	0.60	0.60	0.35	0.32
	(0.01)	*(0.01)*	*(0.11)*	*(0.24)*	*(0.23)*	*(0.14)*
UK	0.01	0.01	0.71	0.75	0.18	0.12
	(0.00)	*(0.02)*	*(0.09)*	*(0.07)*	*(0.13)*	*(0.04)*
Japan	0.01	0.01	0.60	0.62	0.16	0.14
	(0.00)	*(0.01)*	*(0.09)*	*(0.18)*	*(0.14)*	*(0.08)*
Group 2						
Germany	0.02	0.02	0.75	0.82	0.24	0.31
	(0.01)	*(0.01)*	*(0.07)*	*(0.06)*	*(0.16)*	*(0.10)*
Korea	0.01	0.01	0.60	0.65	0.12	0.19
	(0.00)	*(0.01)*	*(0.08)*	*(0.10)*	*(0.09)*	*(0.09)*
Group 3						
France	0.01	0.01	0.70	0.75	0.15	0.17
	(0.00)	*(0.01)*	*(0.06)*	*(0.05)*	*(0.11)*	*(0.07)*
Italy	0.01	0.01	0.72	0.79	0.11	0.13
	(0.00)	*(0.00)*	*(0.07)*	*(0.04)*	*(0.08)*	*(0.06)*
Total Sample	0.01	0.01	0.67	0.70	0.08	0.09
	(0.01)	*(0.01)*	*(0.10)*	*(0.16)*	*(0.13)*	*(0.12)*

Standard deviation in parentheses. Measures have been calculated as the share of value-added imported/exported from a country over the global value-added flows (including self-loops) of each sector v. The total sample covers 44 countries (Online Supplemental Appendix) for 2014. Source: Own calculations using data from the WIOD (Groningen Growth and Development Centre, 2016)

imports, depends for its production on the importing value added of intermediate goods in all sectors. Therefore, Germany is a dominant importer in most sectoral GVC networks.

The U.S. is the most influential importer, on average, in the GVCs networks, as demonstrated by the *weighted in-eigen centrality*. It imports value added from importers with a high relative position in the GVCs, China, and Germany. China and Germany ranked in second and third place, respectively. The U.S. and China exhibit high standard deviations of *weighted in-eigen centrality*. These countries' sectoral imports are from a few countries that are strong buyers (i.e., publishing activities; manufacturing of textiles). Their imports in other sectors are diversified (i.e., repair and installation of machinery and equipment; construction) based on their *entropies of weighted in-degree.*

China is the most influential exporter, on average, in the GVCs networks, as demonstrated by the *weighted out-eigen centrality*, followed by Germany. Korea scores the third-highest value mainly because the larger share of exports goes to China, an indication that geographical proximity does matter. China exhibits the highest standard deviation of *weighted out-eigen centrality* because sectors like forestry and logging export a high share to a few countries which are also strong suppliers. Sectors like activities auxiliary to financial services and insurance activities export to many countries.

Germany, France, Italy, and the UK exhibit the highest import and export diversification, as demonstrated by the *entropy of weighted in-degree* and *entropy of weighted out-degree*, respectively, and low standard deviation of these entropies, on average, in the GVCs networks. This is an indication, on average, of a more uniform distribution of their imports/exports among their trade partners in most sectors. This result is because 28 countries (including the UK) of the 44 countries of the GVC networks were EU members. The total intra-EU share of the exchanged value added is approximately one-fifth of the total because of the free trade regime in the EU and the geographical proximity. It was expected that these countries would have more diversified imports/exports compared to the rest of the sample countries. In the case of an economic shock, this interdependence would have devastating consequences for their economies. The shock would be spread to many trade partners simultaneously. Finally, China exhibited the highest standard deviation both on the import and export sides because it imports/exports uniformly in some sectors and unevenly in others, as derived from the corresponding entropies.

Subsequently, the sample countries exhibit different behaviors in terms of the examined measures. Germany's average relative position as an importer in the GVC, as demonstrated by the *weighted in-degree*, is higher than that of the U.S. and China. Its import structure is more democratic as the shares of its suppliers are more uniformly distributed than in the other sample countries, as shown by the *entropy of weighted in-degree*. The U.S. and China exhibit a more oligarchic import structure due to concentration in only a few trade suppliers. However, those suppliers have a high relative position as importers in the GVC network, as derived from the *weighted in-eigen centrality*.

The relative position of the U.S. as an exporter of value-added is strong, as demonstrated by the *weighted out-degree*. Its export structure is more democratic with diversified shares of its buyers, as shown by the *entropy of weighted out-degree*. China's export structure is more oligarchic with concentrated exports to a few trade partners, as shown by *the entropy of weighted out-degree*, with a high relative position as exporters, as derived from the *weighted out-eigen centrality*. Germany's export structure is more democratic with diversified exports to many trade partners, as shown by the *entropy of weighted out-degree*, with a high relative position as exporters, as derived from the *weighted out-eigen centrality*.

China, Germany, and the U.S. could be classified as global value chain regulators, although with a different role. China could be characterized as a world factory (Sun & Grimes, 2017), as its relative position in the GVCs as importer and exporter is high with exports to countries with a high relative position as exporters. The U.S.

could be characterized as an original brand manufacturer (Gereffi & Fernandez-Stark, 2011) as its imports are smaller than its exports. U.S. imports are concentrated to a few trade partners, but its exports are diversified. Finally, Germany could be characterized as a world trader, as Germany re-exports part of the imported value added to many countries with a high relative position as exporters.

Based on the estimated metrics, the sample countries could be classified into three groups. The first group comprises the U.S., China, the UK, and Japan. These countries have lower relative position as importers than as exporters on average in the GVCs networks, as their *weighted in-degrees* are lower than their *weighted out-degrees*, they import from a few trade partners, as shown by their *entropies of weighted in-degree*, and their partners have high relative positions as importers, as derived from their *weighted in-eigen centralities*.

The second group comprises Germany and Korea. These countries present lower relative position as exporters than as importers, on average, in the GVC networks, as their *weighted out-degrees* are lower than their *weighted in-degrees*, and they export to a few trade partners, as shown by their *entropies of weighted out-degree*, with a high relative position as exporters, as derived from their *weighted out-eigen centralities*.

The third group comprises France and Italy. These countries present higher relative position as exporters than as importers, on average, in the GVCs networks, as their *weighted out-degrees* are higher than their *weighted in-degrees*, and they export to few trade partners, as shown by their *entropies of weighted out-degree*, with a high relative position as exporters, as derived from their *weighted out-eigen centralities*.

Countries Directly Exposed to Another Country's Domestic Economic Shock in the GVCs

The weighted out-degree of a country and in-weight from country to country were used to examine the cross-country direct economic contagion. Table 2 shows every case with a high probability of direct economic contagion for every possible pair of countries.

Based on our findings, there is a high probability that China's shocks propagate directly to Korea, Germany, Japan, and the U.S. Korea depends more on China's intermediates goods production than on those of Germany, Japan, and the U.S. The direct impact on France, the UK, and Italy are relatively small. It seems that there is indirect propagation mainly through Germany to these countries due to the increased flows among EU countries. This finding indicates the importance of the free trade regime in the EU and the geographic proximity to the GVC networks. The same is true for transactions between China, Korea, and Japan. It seems that preferential tariff schemes, geographical location, and the similar commercial culture among Asian countries advocated for the building of an Asian value chain sub-network.

Table 2 Exporter →importer pairs with high probability of economic contagion

Country A (as exporter)	Country B (as importer)
China	Korea, Germany, Japan, U.S.
U.S.	Germany, China, France, Korea, UK, Japan
Germany	France, Italy, UK, China
France	Germany
UK	Germany
Italy	Germany, France
Japan	China, Korea
Korea	China

The total sample covers 44 countries (Online Supplemental Appendix) for 2014. Source: Own calculations using data from the WIOD (Groningen Growth and Development Centre, 2016)

Sectors in GVC Networks Most Vulnerable to Domestic Economic Shocks

The economic shock in a country is transmitted initially in the sectoral GVC networks where this country exhibits higher dominance and influence. At a country level, dominant and influential sectors are characterized as those with degree and eigen centrality in the top 20% of the 54 sectors. In Table 3, the importing sector column includes sectors with high *weighted in-degree centrality* and *weighted in-eigen centrality*. Similarly, the exporting sector column includes the sectors with high *weighted out-degree centrality* and *weighted out-eigen centrality*.

It was expected that an economic shock in a country would be transmitted first to the suppliers and customers of the sector where this country exhibits higher dominance and influence. For example, an economic shock in China would be transmitted first to China's suppliers of electrical equipment and its customers of computers, electronic and optical products. Furthermore, an interruption regarding imports of electrical equipment will interrupt exports in sectors that utilize them as intermediate products. Correspondingly, an interruption in exports of computers, electronic and optical products will interrupt imports of these products in sectors that need them for production.

Furthermore, some sectors have commonalities not only between the importing and exporting sides, but also across countries. For example, the repair and installation of machinery and equipment sector has a high probability of economic contagion of a shock in Germany, France and Italy because they are all significant importers and exporters of VA. This could be explained by the free trade regime which favors the intra-EU. However, this finding may have important implications in the case of Brexit with high trade barriers that will have detrimental implications on the UK economy and its involvement in GVCs. Japan and Korea also have vulnerable sectors in common, such as the two sectors: manufacture of coke and refined petroleum products and water transport. This means that in these sectors, these countries import or export a high share of value added from or to other countries, which also import or export high shares, respectively. The current analysis of transactions in these GVC sectoral networks found that these countries exhibit high levels of trade

Table 3 Sectors with the top 20% weighted degree and weighted eigen centrality values (simultaneously)

Importing Sector	Country	Exporting Sector
Architectural and engineering activities; technical testing and analysis	U.S.	Manufacture of other transport equipment
		Administrative and support service activities
Manufacture of electrical equipment	China	Manufacture of computer, electronic and optical products
Manufacture of basic metals		
Repair and installation of machinery and equipment	Germany	Repair and installation of machinery and equipment
Manufacture of fabricated metal products, except machinery and equipment		Advertising and market research
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services		Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
Wholesale and retail trade and repair of motor vehicles and motorcycles		Manufacture of chemicals and chemical products
		Manufacture of motor vehicles, trailers and semi-trailers
Repair and installation of machinery and equipment	France	Repair and installation of machinery and equipment
Advertising and market research		Advertising and market research
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services		Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
Administrative and support service activities		
Repair and installation of machinery and equipment	Italy	Repair and installation of machinery and equipment
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services		Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
Manufacture of basic pharmaceutical products and pharmaceutical preparations		Manufacture of textiles, wearing apparel and leather products
		Manufacture of machinery and equipment n.e.c.
Manufacture of other transport equipment	UK	Repair and installation of machinery and equipment
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services		Advertising and market research
		Wholesale and retail trade and repair of motor vehicles and motorcycles
		Other professional, scientific and technical activities; veterinary activities
		Postal and courier activities

Table 3 (continued)

Importing Sector	Country	Exporting Sector
Manufacture of coke and refined petroleum products	Japan	Manufacture of coke and refined petroleum products
Manufacture of basic metals		Manufacture of basic metals
Manufacture of electrical equipment		Manufacture of other non-metallic mineral products
Water transport		Water transport
Water collection, treatment and supply		Water collection, treatment and supply
Manufacture of computer, electronic and optical products		Manufacture of electrical equipment
Manufacture of coke and refined petroleum products	Korea	Manufacture of coke and refined petroleum products
Manufacture of computer, electronic and optical products		Other professional, scientific and technical activities; veterinary activities
Manufacture of basic metals		Water collection, treatment and supply
Water collection, treatment and supply		Manufacture of basic metals
Manufacture of chemicals and chemical products		

The total sample covers 44 countries (Online Supplemental Appendix) and 54 sectors for 2014. Source: Own calculations using data from WIOD (Groningen Growth and Development Centre, 2016)

with each other. This phenomenon explains the important role that geographical location and commercial culture plays in this type of partnership. Therefore, fragmentation of this partnership could result in substantial damage to these economies and potentially collapse.

Concluding Remarks

This paper investigated the position of some key economies in the GVCs and the probability of economic contagion of a shock using network analysis. More specifically, the current study assessed: a) the exposure of domestic economic shocks across the GVCs, b) the exposure of domestic economic shocks across adjacent countries in the GVCs, and c) the sectors which are most vulnerable to domestic economic shocks.

Social network analysis was used to analyze data from the WIDO for the period 2000-2014. For each sector, the corresponding GVC network was constructed. Complex network statistics such as the weighted degree, entropy, and eigen centrality were useful tools for the examination of each country's participation, diversification, and influence in the GVCs. The entropy metric in the GVCs networks permitted investigating the value-added import and export share distribution among the trade partners.

The innovation of this paper is twofold. First is the use of the entropy of weighted in- and out-degree to examine the democratic trade of intermediate goods structure. Second is the use of network analysis and entropy in evaluating the economic contagion of a domestic economic shock through the GVCs.

Based on the notably high values that the selected economies exhibited, China, the U.S., and Germany were characterized as GVC network regulators, each of which serves a special role: China as GVC factory, the U.S. as GVC brand developer, and Germany as GVC trader. Our results indicate that highly dominant countries are also highly influential in the propagation of domestic economic shocks across the GVCs networks. Hence, a shock in the large economies, namely China, Germany, and the U.S., is expected to have a larger impact on the economies of the GVC network other than France, Italy, Japan, and South Korea. Particularly, the estimated high degree, entropy, and eigen centrality combination for each country indicates that the Asian countries (namely China, Japan, and Korea) will have a high indirect impact on the network, through their main trading partners, while the European countries (namely Germany, France, Italy, and the UK) will have a high direct impact on the network. Finally, the U.S. will have a high indirect impact on its strong suppliers and a direct impact on customers of the network.

The combination of the estimated out-degree of the exporting country and in-weight of the importing country in bilateral trade indicates higher direct impact from: i) China to Korea, Germany, Japan, and the U.S., ii) the U.S. to Germany, China, France, Korea, UK, and Japan, iii) Germany to France, Italy, the UK, and China, iv) France and the UK to Germany, v) Italy to France and Germany, vi) Japan to China and Korea, and vii) Korea to China. Direct contagion will lead to indirect contagion with multiple negative effects on countries that

have commonalties at the first level of contagion, second level, and so on. In particular, directly affected countries directly affect other countries. For example, a shock in China will directly affect five countries. One of them is the U.S. which in turn will directly affect six countries, three of which (Germany, Korea, Japan) will have already been affected by China. Germany will be affected directly from China, indirectly from the U.S., and will directly affect four countries, two of which will have already been affected by the U.S. In 2014, the exported foreign value-added was 24.76% of the produced value-added. China exports 9.41% of this share, the U.S. exports 11.30%, and Germany exports 7.79%. Consequently, a shock in one of these countries will affect not only their best trade partners but also the partners of their partners (multi-level contagion).

It is expected that the domestic economic shock will be transmitted in the sectoral GVC networks where the country exhibits higher dominance and influence compared to other sectors. GVCs proved their resilience during the recent shock caused by the coronavirus pandemic, facilitating efficient production and delivery (Bonadio et al., 2020; Baldwin & Evenett, 2020). This shock reminded us of the uncertainty of international trade. Besides comparative advantage, continuity is equally important, but how can it be ensured with the least possible damage? Firms may be reluctant to dismantle existing GVCs facing severe but temporary shocks due to large sunk costs and economies of scale. The partial repatriation, breaking the value chain, may lead to excessive long-run costs of production, given that the home country is less competitive than the host country. Reshoring will add the long-run costs of switching partners. Doing nothing will lead to short-term losses due to transaction costs during the shock, which usually lead to a short severe recession and then to recovery. Diversification reduces the risk of being directly affected by a key supplier or buyer shock but may lead to increased costs from cooperating with countries with a narrower comparative advantage. We argue in favor of diversification.

The policy implications of our findings are substantial. First, the countries least exposed to their trade partners' economic shocks will pursue the implementation of industrial and trade policies that aim at diversification in both sectoral level and trade partnerships. Hence, the country should not rely on only a few dominant importer and exporter trade partners but should expand its trade network more uniformly. Furthermore, the countries should participate in as many sectoral GVC networks as possible in a more equi-proportionate way.

Large exposure to a shock does not necessarily mean persistent impact of the shock. What really matters is the nature of the shock. Identifying the nature of a shock can be helpful in future research.

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Data availability The data that support the findings of this study are openly available in the public domain: http://www.wiod.org/database/wiots16. An illustrated user guide to the World Input–Output Database is available at https://doi.org/10.1111/roie.12178. An overview of the sources and characteristics of the 2016 Release is available at https://www.rug.nl/ggdc/html_publications/memorandum/gd162.pdf.

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