Measuring Global Supply Chain Vulnerabilities Using Trade Network Analysis Method

Cui Xiaomin, Xiong Wanting, Yang Panpan*, and Xu Qiyuan

Institute of World Economics and Politics (IWEP), Chinese Academy of Social Sciences (CASS), Beijing, China

Abstract: *With the trade network analysis method and bilateral country-product level trade data of 2017-2020, this paper reveals the overall characteristics and intrinsic vulnerabilities of China's global supply chains. Our research finds that first, most global supply-chain-vulnerable products are from technology-intensive sectors. For advanced economies, their supply chain vulnerabilities are primarily exposed to political and economic alliances. In comparison, developing economies are more dependent on regional communities. Second, China has a significant export advantage with over 80% of highly vulnerable intermediate inputs relying on imports of high-end electrical, mechanical and chemical products from advanced economies or their multinational companies. China also relies on developing economies for the import of some resource products. Third, during the trade frictions from 2018 to 2019 and the subsequent COVID-19 pandemic, there was a significant reduction in the supply chain vulnerabilities of China and the US for critical products compared with other products, which reflects a shift in the layout of critical product supply chains to ensure not just efficiency but security. China should address supply chain vulnerabilities by bolstering supply-side weaknesses, diversifying import sources, and promoting international coordination and cooperation.*

Keywords: *Supply chain vulnerabilities, trade network analysis, export centrality variance index, import centrality variance index*

JEL Classification Code: F10, F14

DOI: 10.19602/j.chinaeconomist.2023.01.05

1. Introduction

In recent years, international geopolitical risks, trade frictions and the COVID-19 pandemic have prompted countries to prioritize industrial chain security. The global financial crisis of 2008 was followed by slowing growth in major economies. Trade protectionism and populism gave rise to uncertainty in global economic policies, taking a toll on cross-border trade and investment. In 2018-2019, China-US trade frictions escalated with repercussions for other countries and multinational companies involved in the industrial chains. Since 2020, the COVID-19 pandemic has erupted across the world with long-term effects. Supply chain issues and travel restrictions have upended the global division of labor, aggravating concerns over global supply chain stability and security. Companies diversified supply chains by scattering investments. Countries doled out fiscal subsidies to nudge companies to re-shore or re-adjust overseas production centers. In theoretical and policy research, it is of growing importance to measure supply chain vulnerabilities for various countries comprehensively and objectively.

The landscape of globalization is experiencing profound adjustments. In this context, industrial

* CONTACT: Yang Panpan, email: pamelapanda@126.com.

chain security becomes vital to China's economic stability and development. During the 14th Five-Year Plan period (2021-2025), China's domestic situation and international environment are faced with turbulent change. Domestically, China's economy is in a critical transition from rapid growth to high-quality development characterized by an improving economic structure and shifting growth dynamism. Internationally, the world is experiencing changes that have not been seen in a century. The international situation is volatile and regional conflicts are escalating. Populism, unilateralism, and trade protectionism are on the rise. The balance of power is shifting as the major-power contest intensifies. Against this backdrop, it is of great significance to protect supply chain security for critical industries. On one hand, critical industries concern China's national and economic security, underpinning its high-quality economic development. On the other hand, critical industries involve a long R&D cycle and high material, human, and financial capital inputs that rely on foreign supplies of choke point technologies.

An industrial chain tends to be more vulnerable if it is more complex and relies on fewer suppliers of key intermediate inputs. With the deepening and sophisticating international division of labor, global industrial chains become intrinsically more vulnerable, as reflected in the susceptibility of complex industrial chain activities to a changing external environment (Johnson and Guillermo, 2012). Complex industrial chain activities require intermediate inputs to be traded across borders twice or more. An industrial chain is vulnerable when it becomes longer and involves more production processes and countries. In this sense, trade frictions, major-power relations and changing external environment may all create shocks to complex industrial chain activities. Judging by the relationship of trade networks, intermediate inputs are more critical if their suppliers are more concentrated, and industrial chains involving more critical intermediate inputs are more complex - yet remain more vulnerable as well. The industrial vulnerabilities of intermediate inputs may, therefore, be measured at the levels of import and export. Intermediate inputs are more supply-chain-vulnerable if their exports - or imports - are concentrated in a handful of countries.

Based on the trade network analysis method, this paper creates a set of indicators for measuring supply chain vulnerabilities at global and country levels. Specifically, this paper can be divided into four parts. (i) The trade network analysis method is employed to create supply chain vulnerability indicators at global- and country-product levels and employs bilateral country-product-level trade data for measurement. (ii) The characteristics of intermediate inputs in vulnerable global supply chains are examined by country and industry to discuss differences in the supply chain vulnerabilities of various economies and possible causes of such vulnerabilities. (iii) China's supply chain vulnerabilities are examined in detail. Other indicators of supply chain vulnerabilities are also examined and demonstrated to be inferior to those created in this paper. (iv) Using panel data from 2017 to 2020, this paper will discuss changes in the supply chain vulnerabilities of major economies during China-US trade frictions and the COVID-19 pandemic.

This study is of great theoretical and practical relevance. In the research literature, supply chain discussions have focused on aggregate volume and structural characteristics of industry categories, leaving little space for industrial chain vulnerabilities. According to our analysis, most supply-chain-vulnerable products belong to subsectors and can be identified only with six- or even ten-digit product codes data. Despite their modest value, those products are indispensable to an industry with few substitutes and vital to national security and high-quality economic development. Such categories as high-tech products and strategic emerging industries - though encompassing supply-chain-vulnerable products - are too broad for choke point products and technologies to be identified and not specific to supply-chain issues. Case studies on individual products or industries help identify products and technologies critical for industrial chain security; however, they cannot reveal the entire picture of industrial chain security in various countries.

From the research perspective of trade networks, this paper offers a quantitative method to identify a country's industrial chain vulnerabilities. Based on the classical theories of international trade and social network analysis, this method may reveal the characteristics of supply chain vulnerabilities and the theoretical rationale. While most countries attach great importance to supply chain security, they lack the tools to measure supply chain vulnerabilities. This paper puts forth a method for measuring the supply chain vulnerabilities that can be applied to segmented products in various countries, which helps to identify how the changing external environment affects their supply chain vulnerability. It also provides theoretical and empirical evidence for implementing supply chain security.

The remainder of this paper is arranged as follows: Section 2 is a survey of literature studies. Section 3 elaborates on the method and data for creating vulnerability indicators at the global- and country-product levels. Section 4 examines the overall characteristics and regional differences of global supply chain vulnerabilities. Section 5 reveals China's supply chain vulnerabilities and their characteristics and discusses other indicators for supply-chain-vulnerable products and the advantages of indices created in this paper. Based on the panel data of 2017-2020, Section 6 discusses the relative change in the supply chain vulnerabilities of major economies during China-US trade frictions and the COVID-19 pandemic. Section 7 is conclusions and policy implications.

2. Survey of Literature Studies

Supply chain vulnerabilities can hardly be measured by competitiveness indicators for imported goods. In discussing the competitiveness of trade goods, existing studies have employed a plethora of indicators, including the volume of imports and exports, price (Manova and Zhang, 2012), international market share, market penetration, revealed comparative advantage, trade competitive index, revealed competitive advantage (Mao and Zhang, 2013), trade powerhouse index (Mao, 2019; Yao, 2019), and substitution elasticity (Kee and Tang, 2016). With a larger import volume, a country will suffer larger economic disruptions in case of a supply chain glitch. A larger export volume of goods means greater domestic manufacturing strength of such goods. A greater relative price difference between import and export goods suggests a higher level of product heterogeneity and quality difference (Greenaway et al., 1994).

A greater substitution elasticity means a higher level of substitutability of imported intermediate inputs by domestic intermediate inputs, which means a decrease in import has a limited impact on domestic production. On the contrary, a smaller substitution elasticity means a lower level of substitutability and a greater potential impact of import disruptions. Overall, traditional competitiveness indicators - e.g., market penetration, international market share, and revealed comparative advantage - share similarities with the import market concentration index employed in this paper. However, absent in traditional competitiveness indicators is information for measuring overall supply concentration, making it hard to precisely identify supply chain vulnerability at the product level.

This paper is closely related to research on international trade based on the network analysis method. Compared with traditional empirical research methodology for international trade, research on trade issues using the network analysis method may characterize the heterogeneous attributes and status of various nodes (countries), the impact of a third country on bilateral trade, and the structural interdependence of trade networks (De Benedictis et al., 2014), complementing the traditional analytical paradigm focused on individual countries.

For instance, Fagiolo et al. (2010) and Schiavo et al. (2010) revealed the center-periphery characteristics of trade networks having close trade ties with most countries and extremely close ties with a few countries, especially rich countries. Based on the BACI-CEPII database, De Benedictis et al. (2014) calculated the centrality indices of 178 countries between 1995 and 2010 to describe the network topological structure of the global trade network. After investigating the evolution of the global trade network structure using the network analysis method, Jiang et al. (2018) discussed China's changing role in the global trade network. With centrality and modularity indicators for network analysis, Korniyenko et al. (2017) evaluated the supply vulnerabilities of intermediate inputs at the HS 6-digit level. Based on the existing research, this paper employs more detailed data and indices for measuring supply chain vulnerabilities at the country-product level.

This paper is also related to the research literature on the topic of market concentration. Aside from vulnerabilities in the supply of intermediate inputs due to the existence of core exporters, concentration in the import source countries also contributes to supply chain vulnerabilities. This paper employs the Herfindahl-Hirschman Index to measure the concentration of import sources. This index was first put forth by Herfindahl (1950) and Hirschman (1945) but was later extensively used to measure the level of competition in various domains, including market monopoly (Chen and Zhu, 2011; Zhao et al., 2018), industry concentration (Qiao et al., 2007; Mao, 2015), competition for air routes (Xu et al., 2011), regional competition of banks (Cai and Dong, 2016), and city cluster competitiveness (Zhang et al., 2019). When a country's import sources for a certain type of product are relatively concentrated or have close economic ties with the sources of impact, the country becomes more likely to suffer repercussions, i.e., more exposed to supply chain risks. Using the network analysis method and the input-output correlation, Liu et al. (2020) investigated the paths of economic shock across regions and sectors. Compared with this paper, their research is primarily focused on vulnerabilities arising from input-output correlation across regions and sectors in China rather than vulnerabilities in the import supply chains and choke point technologies.

3. Creation of Indicators and Data Set

In this paper, we try to create supply chain vulnerability indicators at the global-product and country-product levels. Notably, this paper is primarily concerned with vulnerabilities from the perspective of supply chain polarization rather than vulnerabilities stemming from the undersupply of goods in the general sense.

3.1 Global Perspective

Supply chain vulnerabilities at the global-product level are measured by the export centrality variance index (Jiang et al., 2018; Barrat et al., 2004; Korniyenko et al., 2017). This index reflects supply chain vulnerabilities arising from the existence of core participants in a trade network. For instance, the US, the UK, and France accounted for 46.7%, 10.3%, and 9.0% of global aircraft engine export in 2018, respectively. Global aircraft manufacturing would come to a standstill should those three countries halt production amid an external shock. The accounting method for the export centrality variance index is explained as follows. First, the equation for calculating the centrality index of product k from country i in year t is specified below:

$$c_{ikt} = \sum_{j \neq i}^{N_{kt}-1} \frac{m_{jikt}}{\left(\sum_l m_{jlkt}\right) / N_{jkt}} \tag{1}$$

In equation (1), i and j denote country; N_{kt} is the total number of countries that import product k; m_{jikt} is the total amount of product k imported by country j from country i in year t; N_{jkt} is the total number of source countries from which country j imports product k in year t. In a weighted directed network, therefore, the centrality index c_{ikt} for country i is the total export of product k by country i after standardization by the average level of importing countries.

Second, the standard deviation of countries with respect to the centrality index of product k (observations excluding those with trade flows being 0) is defined as the vulnerability index of such product, i.e. the centrality variance:

$$C_{kt} = \sqrt{\frac{\sum_i \left(c_{ikt} - \bar{c}_{kt}\right)^2}{N_{kt} - 1}} \tag{2}$$

In equation (2), $\overline{c}_{kt}$ is the mean value of centrality c_{ikt} of product k for different countries in period t. Products above the 75th percentile[1] of the sample values of the centrality variance index are regarded as high-vulnerability products.

3.2 Country Perspective

The vulnerability index at the country-product level is created based on the export centrality variance index after excluding the home country's export. First, take China for instance, the equation for the export centrality variance index after excluding the home country's export is the same as equations (1) and (2), but China's export data are excluded before calculation. The export centrality variance index ($C_{-j,kt}$) after excluding the home country's export may reflect the export influence of other countries for a certain type of product, i.e. the concentration of overall external supply. Second, the concentration index of the import market (Herfindahl-Hirschman Index, HHI) is calculated, i.e., the quadratic sum of given product shares imported by country j from all partner countries ($\forall i$):

$$h_{jkt} = \sum_{i \neq j}^{N_{jkt}-1} \left(\frac{m_{jikt}}{\sum_i m_{jikt}} \right)^2 \tag{3}$$

This index reflects the concentration of a country's actual import sources. Higher concentration in the actual import sources of a product means a high level of supply chain vulnerability of the product. Theoretically, h_{jkt} index is closer to 1 if country j's import sources are more concentrated, or closer to $1/N_{jkt}$ if its import sources are more scattered. In extreme circumstances, if country j only has one import source for product k, h_{jkt} is 1; if country j has N_{jkt} import sources for product k with the same share for each, h_{jkt} is $1/N_{jkt}$. Lastly, the composite vulnerability index at the country-product level is created based on the export centrality variance index and the import concentration index. The export centrality variance index and the import market concentration index are standardized[2] to arrive at the z-score of each indicator (x_{kt}), also known as the standard score.

$$\tilde{x}_{kt} = \frac{x_{kt} - \overline{x}_t}{se(x_{kt})} \tag{4}$$

In equation (4), x_{kt} is a certain indicator; $\overline{x}_t$ and $se(x_{kt})$ respectively denote the mean value and standard deviation of such an indicator for product k at time t. After the quantitative effect is excluded, various indicators become more comparable. Since the value of $\tilde{x}_{kt}$ is within the range of $(-\infty, +\infty)$, we further use the cumulative distribution function of the normal distribution to convert it into a function within the range of (0, 1) to avoid the disturbance of sign to the result.

$$\hat{x}_{kt} = \int_{-\infty}^{\tilde{x}_{kt}} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz \tag{5}$$

In equation (5), e is a natural logarithm. The product between the two converted indicators is defined as the composite vulnerability index of country j for product k:

$$y_{jkt} = \hat{C}_{-j,kt} \times \hat{h}_{jkt} \tag{6}$$

where, $\hat{C}_{-j,kt}$ and $\hat{h}_{jkt}$ are the market concentration variation index of exports from countries other than country j and the market concentration index for country j's imports after standardization, respectively.

Then, we may take a further step to measure the supply chain vulnerabilities of high-tech

[1] With different percentiles, the distribution characteristics of high-fertility products are generally robust at the country and industry levels.

[2] The kernel density plots of the export and import centrality variance indices are rather close to normal distribution, and the two are not highly correlated with each other.

intermediate inputs. Compared with generally vulnerable intermediate inputs, high-tech vulnerable intermediate inputs concern national security and people's livelihoods with broader economic implications. Most high-tech vulnerable intermediate inputs are subject to technology barriers and harder to substitute. Many of them coincide with choke point technologies to which countries have attached great importance. Based on technology density (R&D spending as a share of total sales volume), Eurostat issued the third revision of the Standard International Trade Classification (SITC Rev.3) codes, including nine categories of aviation and aerospace, computer-office equipment, electronic-communication equipment, pharmaceuticals, scientific instruments, electrical equipment, mechanical equipment, chemicals, and weapons.

This paper further corresponds to the SITC Rev.3 codes to the Harmonized Commodity Description and Coding System of 2017 edition ("HS" for short) from UN Comtrade to identify the supply chain vulnerability of high-tech intermediate inputs.

3.3 Data Treatment

In this paper, we perform an analysis based on the global bilateral country-product level import data at the HS 6-digit level provided by the UN Comtrade database from 2017 to 2020, China's import and export data at the HS 8-digit level, as well as US import data at the HS 10-digit level from the United States International Trade Commission (USITC).[3] Developed by the World Customs Organization (WCO), the Harmonized System (HS) is an international nomenclature for the classification of goods. The first HS six digits are the international generic code, and the rest are country codes and additional codes for regulatory, taxation or statistical purposes. Based on the HS 6-digit bilateral trade data, we introduce product trade data at the more detailed HS 8-digit and HS 10-digit levels to increase the accuracy of identifying supply-chain-vulnerable products for specific countries.[4] UN Comtrade data are reported in the HS format of the 2012 edition. The General Administration of Customs China (GACC) and the USITC report data in HS codes of the 2017 edition, and the corresponding HS 2012 and HS 2017 forms are from the United Nations Statistics Division.

This paper identifies intermediate and capital goods based on the Broad Economic Categories Rev.5 (BEC Rev.5) and excludes consumer goods. The classification codes of BEC Rev.5, HS2012, and HS2017 are from the UN Statistics Division. Compared with BEC Rev.4, BEC Rev.5 offers a more detailed product classification and is more effective at identifying intermediate inputs.[5] Take the bilateral HS 6-digit import data from UN Comtrade for instance, after the above treatment, we ended up with trade data for 4,004 intermediate and capital goods for a maximum of 159 countries or regions from 240 trade partners between 2017 and 2020. Our benchmark analysis is carried out based on data from 2017 given the slow change in global and national supply chain vulnerabilities over time and the need to avoid interference from China-US trade frictions and the COVID-19 pandemic. Section 6 will use panel data from 2017-2020 to discuss changes in the supply chain vulnerabilities of major economies during China-US trade friction and the COVID-19 pandemic.

---

[3] In UN Comtrade data, inconsistencies may exist in trade data reported by importing and exporting countries. Since imported goods are subject to tariffs and have better quality of data, this paper performs an analysis of trade data reported by importing countries. Our calculations exclude such circumstances as importing countries that are the same as exporting countries, trading partners equaling global aggregation, regions within a national territory but outside the customs territory, international organizations, and non-specific countries or regions.

[4] One of China's choke point technologies, for instance, is stepper lithography machines for manufacturing semiconductor or integrated circuits (IC). The HS 8-digit code for stepper lithography machines is 84862031, of which the first six digits 848620 refers to a sector that also includes non-chokepoint technologies like "oxidation, dispersion, annealing and other heat treatment equipment".

[5] BEC classification divides products into the four categories of consumer goods, capital goods, intermediate inputs, and others. According to the global bilateral HS 6-digit product trade data of 2017, trade goods in the mixed category of consumer, intermediate and capital goods account for around 9.3% with a limited impact on the conclusions.

4. Global Supply Chain Vulnerabilities

4.1 Overall Characteristics

Based on the number and value of high-vulnerability exports, we may assess the global supply chain influence of each economy. In Figure 1, US, China, and Germany are at the first echelon in terms of such influence, and Japan, South Korea, China's Taiwan, and advanced economies in Europe such as the UK, France, and Italy are at the second echelon. Most small advanced and emerging economies except China are at the third through fifth echelons, followed by resource-rich economies that export a few commodities with a large economic value.

China's export of high-vulnerability products is the largest by value, which is consistent with the high degree of its export orientation and status as the world's factory floor. Between 2017 and 2020, China ranked among the top three in the world for the export of over 2,400 out of 4,004 HS 6-digit intermediate inputs and among the top three in the world for the export of over 800 types out of 1,001 HS 6-digit high-vulnerability products (including 519 types for which it ranked first between 2017 and 2020). This means that China has an apparent export advantage of over 80% of high-vulnerability intermediate inputs.

When COVID-19 disrupted China's domestic production, major economies suffered supply chain glitches, which is especially the case for products - such as electrical and mechanical devices - that rely on the global division of labor. When COVID-19 spread overseas and Chinese factories resumed production, China's domestic capacity helped mitigate an international supply crunch. However, some sectors could see a decline in the export of intermediate inputs as external demand shrank.

In terms of industry characteristics, most supply-chain-vulnerable products are characterized by a high degree of technology density and relatively high average unit price. In terms of product volume, an average of 34.3% and 9.8% of highly vulnerable products were from the two sectors of electrical, mechanical and audiovisual equipment (HS-2: 84 and 85) and optical and medical instruments (HS-

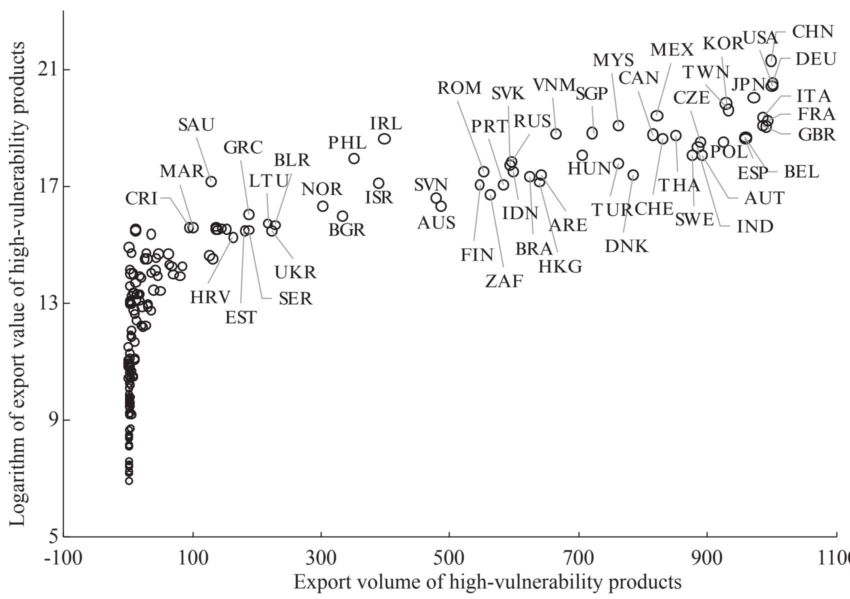

Figure 1: Value and Volume of High-Vulnerability Product Exports from Major Economies (2017)

Note: High-vulnerability products are products in the top 25% of the centrality variance index at the global level. Scatter labels in the chart are ISO 3-letter alphabets as the abbreviated English names of the corresponding economies. HS 6-digit products are ranked by the descending order of export value, and observations with the shares of export value at the bottom 1% are excluded to avoid an overestimation in the export volume of vulnerable products arising from minuscule exports.
Source: UN Comtrade and data compiled by the authors.

2: 90), respectively, over a period from 2017 to 2020, which accounted for 18.2% and 4.2% of the total number of products, respectively. In terms of product value, electrical, mechanical and audiovisual equipment made up 49.0% of high-vulnerability products, which is higher than the share of these products in the value of the total intermediate inputs (32.5%) and higher than the number share of high-vulnerability products (34.3%). This reflects a relatively high average product value of the electrical, mechanical and audiovisual equipment sector.

On the contrary, the share of base metals and their products in total product value is significantly smaller than the share in the total number of products, reflecting a modest average value of products in this category. The average unit prices of high-vulnerability products in various sectors are significantly higher than the average price of all products. A possible reason is that the supply countries of those products are concentrated with a strong buyer's monopoly and that most of these products are from technology-intensive sectors. Overall, the characteristics of high-vulnerability products at the sector level is consistent with the general expectations for supply-chain-vulnerable products, which indirectly verifies the effectiveness of the identification method in this paper.

4.2 Country (Regional) Differences

The research methodology in this paper also applies to analyzing the supply chain vulnerabilities of all countries and regions. In the interest of length, the following sections will focus on the different characteristics of supply chain vulnerabilities for economies of different categories, as well as China's supply chain vulnerabilities. First, the supply chain vulnerabilities of advanced economies are mostly related to electrical, mechanical and chemical products. In 2017, 27.7% and 17.4% of vulnerable products for the four countries of US, Germany, Japan, and South Korea were from the electrical, mechanical (HS-2:84-90) and chemical products (HS-2:28-38) sectors. Among them, vulnerabilities exist for 209 high-tech products at the HS 10-digit level in US supply chains, accounting for 23.5% of total US imports of high-tech intermediate inputs. Supply chain vulnerabilities exist for 29.2% (77 types), 27.1% (73 types), and 26.9% (73 types) of high-tech intermediate inputs at the HS 6-digit level for Germany, Japan, and South Korea, respectively.

The characteristics of supply chain vulnerabilities of advanced economies are characterized by regional communities.[6] Supply chain vulnerabilities of North American and Asian economies are concentrated within the region, i.e. the Asia-Pacific community. In terms of value, the US imports nearly half of its vulnerable products from China, 30% from the North America Free Trade Area (NAFTA), and the remaining 20% from the EU, the UK, and other advanced economies. With a high level of economic integration, Europe has confined supply chain vulnerabilities within the region and is dependent primarily on the US and China. Stable political and economic alliances have assured transatlantic supply chain security.

Lastly, developing economies have more widely distributed supply chain vulnerabilities and are even more dependent on regional communities. In 2017, there were 845 to 966 types of intermediate inputs at the HS 6-digit level with supply chain vulnerabilities for India, Indonesia, Brazil, Mexico, and South Africa, of which 26.4% and 15.4% were electrical, mechanical and chemical products, respectively. These figures are 1.3 and 2.0 percentage points, respectively, smaller than the average values of US, Germany, Japan, and South Korea. Many developing countries have also shown supply chain vulnerabilities for metal products, textiles, and miscellaneous products; however, their agricultural and primary product supply chains are relatively secure. Generally speaking, countries and regions with poorer domestic industrial strengths have a more scattered distribution of supply-chain-vulnerable sectors, and those with greater industrial strengths have a higher concentration of supply-chain

[6] In a complex network, a group of nodes with close ties can be seen as a community, whose superiority or inferiority can be assessed by such indicators as modularity.

vulnerabilities toward electrical, mechanical and chemical products.

Regionally, developing economies like India, Indonesia, Brazil, Mexico, and South Africa tend to be dependent on China. Their imports of supply-chain-vulnerable products from China averaged 21.1% to 55.4% in 2017. Among them, Mexico was the least dependent, and India was the most dependent on China. In addition, most developing countries relied on their regional communities. For instance, Brazil and Mexico relied on North American industrial chains, India and Indonesia on Asian industrial chains, and South Africa on the Europe industrial chains. China's supply chain vulnerabilities are exposed to advanced economies like US, Europe, Japan, and South Korea. China is heavily and extensively dependent on the participating states of the US-led Wassenaar Arrangement.

5. China's Supply Chain Vulnerabilities

This section will use the above-mentioned vulnerability indicators to examine China's supply chains and investigate their strengths and weaknesses in the global production network.

5.1 Overall Status

In 2017, China imported a total of 6,043 types of intermediate inputs at the HS 8-digit level, which can be classified into four groups (Figure 2) based on the export centrality variance index of products from countries other than China, the import market concentration index, and the 75th percentile of sample index values for the two indices. Among them, Group 1 includes products with the export centrality variance index and the import concentration index both above the 75th percentile of their corresponding sample index values. Those products are subject to significant supply chain vulnerabilities that are hard to change. In 2017, 194 types of products at the HS 8-digit level belonged to this group, accounting for 1.2% of the import value.

Group 2 includes products with the export centrality variance index above the 75th percentile of their sample index values and the import concentration index below the 75th percentile of their sample index values. Such products are characterized by smaller supply chain vulnerabilities due to scattered import sources, which are likely to worsen due to a concentration of overall external supply. In 2017, 1,313 types of products belonged in this group, accounting for 46.7% of the import value.

Group 3 includes products with the export centrality variance index below the 75th percentile of their sample index values and the import concentration index above the 75th percentile of their sample index values. Such products are subject to significant supply chain vulnerabilities due to a concentration of import sources, but there is room for improvement as the overall external supply is scattered. In 2017, there were 1,316 products in this category, accounting for 6.0% of the import value.

Group 4 includes products with the export centrality variance index and the import concentration index both below the 75th percentile of their sample index values. Such products are subject to smaller and more stable supply chain vulnerabilities. In 2017, 3,220 types of products belonged to this group, accounting for 46.1% of the total import value.

5.2 Industry Differences

5.2.1 Vulnerability assessment for sectors at the HS 2-digit level

The composite vulnerability indices at the China-Product (HS-8) level are aggregated based on China's imports of products at the HS 8-digit level as a share of its total import and imports of products from advanced economies at the HS 8-digit level as a share of its total imports from advanced economies to obtain the composite vulnerability index at the China-Sector (HS-2) level. China's three sectors with the highest supply chain vulnerabilities are electrical, mechanical and audiovisual equipment (HS-2:85), transport vehicles (HS-2:87), and mechanical equipment (HS-2:84). The composite vulnerability index of electrical, mechanical and audiovisual equipment is more than three times those of the latter two

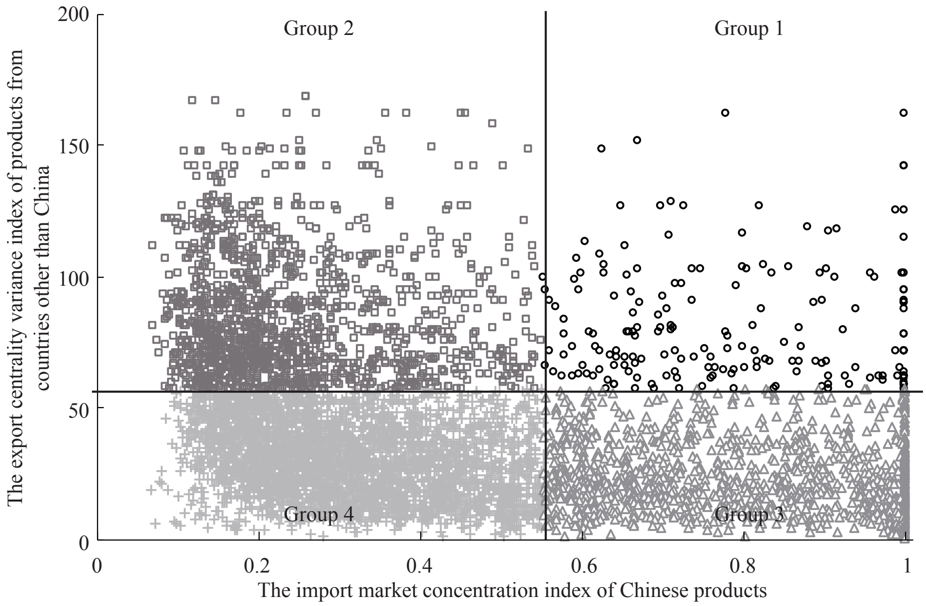

Figure 2: Distribution of China's Export Centrality Variance Index and the Import Concentration Index for Products at the HS 8-Digit Level (2017)

Note: Horizontal and vertical dotted lines are the 75th percentiles of relevant indicators.

Source: UN Comtrade, the General Administration of Customs China (GACC) and data compiled by the authors.

sectors. Sectors with higher composite vulnerability indices are characterized by a high concentration of overall external supply, a concentration of import sources, a diversity of product subcategories, and significant import volumes.

In addition, the vulnerability indices weighted by the share of China's imports from advanced economies for the sectors of transport vehicles, optical and medical instruments, pharmaceuticals, and aircraft and spacecraft are significantly higher than the vulnerability indices weighted by the share of those products in China's total imports. The vulnerability indices of such sectors as animal and vegetable oils and fats, timber and timber products, and oilseeds (HS-2:12) weighted by the share of imports from advanced economies are smaller than the vulnerability indices weighted by the share in total imports. The implication is that the supply chain vulnerabilities of China's technology-intensive sectors are mainly exposed to advanced economies, and those of its natural resource sectors are especially exposed to developing countries.

5.2.2 Vulnerabilities of products at the HS 8-digit level

In 2017, 1,520 out of 6,043 types of intermediate inputs imported by China were subject to supply chain vulnerabilities. Those intermediate inputs can be divided into two categories by import sources. The first category of intermediate inputs is heavily dependent on imports from advanced economies (above 50%) with high export centrality variance indices and import market concentration indices. Most of such products are capital-intensive or technology-intensive, or resource goods related to those two types of products for sectors such as electrical, mechanical, chemical and transportation equipment and instruments.

The second category is products heavily dependent on imports from developing economies (above 50%) with high import market concentration indices. However, the export centrality variance indices of products in the second category are generally eclipsed by those of products in the first category. Part of the products in the second category are finished goods made by factories invested by enterprises from advanced economies in developing countries, and others are natural resource products made by developing countries with local production advantages.

In addition, China's supply chain vulnerabilities existed for 200 types of high-tech intermediate input at the HS eight-digit level in 2017. They include 51 types of electrical, mechanical and audiovisual equipment, 41 types of mechanical equipment, and 40 types of optical and medical instruments, which altogether account for 66%, as well as 24 types of inorganic chemicals, 23 types of organic chemicals and 15 types of pharmaceuticals, totally accounting for 31%. Regionally, the Chinese mainland was the most dependent on six economies for the import of high-vulnerability high-tech intermediate inputs, including the EU, Japan, the US, China's Taiwan, Malaysia, and South Korea. About half of those products were imported from the EU (38 types), Japan (32 types), and the US (31 types) as the primary sources of import. Such regional dependence varied across different sectors.

5.3 Other Indicators for Supply-Chain-Vulnerable Products

Based on the composite vulnerability index, this paper further employs traditional competitiveness and other network indicators to discuss other characteristics of supply-chain-vulnerable products, including the volume of import, the ratio between import and export values, the ratio of import and export unit prices, and the tendency of agglomeration.[7] The purpose is to find out the advantages of the supply chain vulnerability index created in this paper over other indicators.

5.3.1 Import volume

Import volume is the most fundamental indicator for measuring the external dependence of supply chains. Based on this indicator, we may create other indicators like import dependence and the import penetration ratio. A larger import volume, however, does not mean greater supply chain vulnerabilities. In 2017, crude oil was China's largest import product at the HS 8-digit level, accounting for 15.9% of its total imports of intermediate inputs. However, global crude oil supply and China's crude oil import sources are both scattered,[8] so much so that regional crude oil supply interruptions caused a little impact on China's crude oil imports. In this sense, crude oil is not a supply-chain-vulnerable product. Most of China's supply-chain-vulnerable products at the HS 8-digit level are of modest import volumes.

In 2017, only seven types of China's vulnerable products at the HS 8-digit level exceeded a share of 1% of total intermediate imports. "Other integrated circuit memory devices" accounted for 8.5% of the Chinese mainland's import of intermediate inputs in the same year, and over 90% of them were from South Korea, China's Taiwan, and Japan. This modest percentage, however, does not mean that a supply glitch of those vulnerable products has a small impact on the economy. Although the import of stepper lithography machines made up a mere 0.5‰ (514 million US dollars) of China's total import of intermediate inputs in 2017, lithography machines are critical for manufacturing semiconductor devices, whose supply chain disruptions could threaten the long-term development of China's semiconductor industry[9] worth 192.5 billion US dollars in 2021.

---

[7] The supply chain vulnerability of intermediate inputs is also subject to the elasticity of substitution between imported products and domestic comparable products. According to Kee and Tang (2016), the average elasticity of substitution between China's domestic intermediate inputs and imported intermediate inputs was 2.752 between 2000 and 2007. For sectors with greater industrial chain vulnerabilities such as electrical and mechanical products, instruments and apparatuses, plastic products and chemical products, the elasticities of substitution of imported intermediate inputs with domestic goods were rather low and fell in the range between 1.892 and 2.539 in 2007. The elasticity of substitution for the intermediate inputs of transportation equipment increased from 2.663 to 4.212, reflecting an improvement in the domestic supply of intermediate inputs for transportation equipment, but gaps could remain in terms of more specific parts and components.

[8] In 2017, Russia, Saudi Arabia and Angola were top three source countries for China's crude oil imports, accounting for 14.6%, 12.5% and 12.3% of total imports, respectively. Russia, Canada and Iran were the world's top three crude oil exporters, accounting for 16.2%, 9.4% and 8.4% of global total crude oil exports, respectively.

[9] See "Global semiconductor units shipped reach all-time highs in 2021 as the industry ramps up production amid shortage" published by the Global Semiconductor Alliance (GSA) in 2022. https://www. semiconductors.org/global-semiconductor-sales-units-shipped-reach-all-time-highs-in-2021-as-industri-ramps-up-production-amid-shortage/.

5.3.2 Ratio between import and export values

Since export may serve as the proxy variable of a country's manufacturing capacity, some studies have used the ratio between import and export values or the inter-sector trade index to assess product vulnerability. Such indicators apply mainly to mineral, timber, agricultural, and other inter-sectoral trade products. Most of such products show no vulnerability in the dimensions of overall external supply and China's import sources and are inconsistent with the core technologies concerning industrial chain security. The ratio between import and export, therefore, is not an appropriate criterion for identifying industrial-chain-vulnerable products and should be used instead as a reference indicator.

For given supply-chain-vulnerable high-tech intermediate inputs, there were 18 types of products at the HS 8-digit level whose import value was 10 times their export value in 2017. Among them, seven types of products are from the sector of optical and medical instruments, six are from the three sectors of inorganic chemicals, organic chemicals, and pharmaceuticals, and three are from the mechanical equipment sector. With a limited domestic supply and significant supply chain vulnerabilities, those products are vital to China's high-tech industries and warrant great attention. For most products with high composite vulnerability indices, China imported those products much more than it exported. With its domestic market inundated with medium- and low-end products, China remains dependent on foreign suppliers for high-end products.

5.3.3 Ratio of import and export unit prices

Unit price is often used as an indicator for measuring product quality (Manova and Zhang, 2012). Comparing the import and export unit prices of products in the same category at the HS 8-digit level helps identify quality differences of such products and assess more precisely the supply chain vulnerabilities of various countries. Based on the composite vulnerability index and the ratio between import and export unit prices, it can be found that the import unit prices of most supply-chain-vulnerable products are higher than their export unit prices, indicating higher import quality relative to export quality. To some extent, this verifies the effectiveness of the composite vulnerability index for identifying supply chain vulnerabilities.

In 2017, the ratio between the import and export unit prices of high-tech supply-chain-vulnerable intermediate inputs was higher than 1.25[10] for 71.0% of supply-chain-vulnerable intermediate inputs and 77.3% of high-tech supply-chain-vulnerable intermediate inputs. This ratio was even higher than 10 for 17.7% and 26.0% of of the two groups of inputs, respectively. Among the 47 types of high-tech intermediate inputs with supply chain vulnerabilities and a ratio between import and export unit prices above 10, about 70% were from the three sectors of optical and medical instruments (16 types), electrical, mechanical and audiovisual equipment (10 types), and mechanical equipment (7 types). The vulnerable high-tech product with the biggest gaps between import and export unit prices was "special cameras for underwater/aerospace measurements and other purposes," whose import unit price was 2,699 times that of their export unit price. Those products were primarily imported from Germany (92.3%).

5.3.4 Other network indicators

Aside from the centrality indicators,[11] the average agglomeration coefficient and network diameter may also measure the topological attributes of trade networks from different dimensions. Korniyenko et al. (2017) employed the product between the average agglomeration coefficient and the network diameter

[10] In 2017, unit prices could not be calculated for 4.9% of the imported intermediate inputs due to a lack of consistent measurement units or quantitative statistics.

[11] There are various indicators in the research literature for measuring network centrality. This paper adopts the degree centrality for estimation since various indicators reflect similar degrees of node importance and the direction of trade needs to be differentiated in identifying supply chain vulnerabilities.

to calculate the agglomeration propensity index, which is believed to be able to measure the vulnerability of trade networks from the perspective of trade communities. A product network with a higher average agglomeration coefficient and longer diameter is more likely to form a community and entail greater network vulnerabilities. In 2017, intermediate inputs with higher global agglomeration propensities were primarily from the raw materials sector, including grease and base metals. In comparison, the trade community propensities were at medium and low levels for products dependent on the global division of labor such as electrical and mechanical products. In this sense, the agglomeration propensity index may not properly identify choke point products and technologies.

In addition, the calculation result of all node data employed in the agglomeration propensity index mainly reflects the global network vulnerability of a given product and cannot reflect the specific network vulnerability of each country. When the supply-chain-vulnerable products are given, however, the agglomeration propensity index can be employed to investigate the "small circle" traits of a specific product trade network. The composite vulnerability indices of Chinese products at the HS 8-digit level can be matched with the agglomeration propensity indices of global products at the HS 6-digit level to obtain the global network community characteristics of each intermediate input at the HS 6-digit level imported by China. For given supply-chain-vulnerable products, the top 30 products in terms of the agglomeration propensity ranking are almost all from the three sectors of electrical, mechanical and audiovisual equipment, mechanical equipment, and optical and medical instruments.

5.4 Supply Chain Vulnerabilities and Industrial Chain "Choke Points"

China's industrial chain "choke points" include products, technologies, and a combination of multiple factors. The composite vulnerability index provided in this paper may well identify "choke points" at the first level. "Choke points" at the second level can be discussed from the perspective of representative technologies. Referencing studies such as the European Commission's list of breakthrough innovations,[12] most of China's "choke point" technologies are related to the above-mentioned electrical and mechanical products, most of which are controlled by advanced economies like the US, Europe, Japan, and South Korea. This finding is consistent with the conclusions of our composite vulnerability index. However, "choke point" technologies in many areas cannot be emulated simply by acquiring relevant products. The underlying theoretical know-how, equipment and manufacturing experience and skills are the critical bottlenecks for late-moving countries to emulate.

"Choke points" at the third level refer to a combination of "choke points" from resources to technologies, products, and underlying theories. The reason is that in some frontier areas, "choke points" involve not just equipment and technology. An example is single-cell mass cytometry (CyTOF) for disease diagnosis and new drug research (Liu et al., 2019). This technology presents numerous "choke points" from element purification to mechanical micro-processing, mass spectrometers, and data algorithms based on bioinformatics, most of which are controlled by the US.

This example shows that China as the world's largest exporter of rare earths is still faced with "choke points" regarding the purification of rare earths. Moreover, the hundreds and thousands of supply-chain-vulnerable products revealed by the composite vulnerability index may lead to thousands or even tens of thousands of "choke points" from a combination of resources, technologies, products, and underlying theories under the magnifying effects of a combination of factors.

6. China-US Trade Frictions, the COVID-19 Pandemic and Supply Chain Vulnerabilities

[12] See "100 medical innovation and breakthroughs for the future" released by the European commission in 2019. https://ec.europa.eu/jrc/communities/en/community/digitranscope/ document/100-radical-innovation-breakthroughs-future.

The method for measuring supply chain vulnerabilities developed in this paper can be used to describe the static characteristics of - and trace the dynamic change in - global supply chain vulnerabilities. This section will use the panel data of 2017-2020 to discuss the impact of China-US trade frictions and the COVID-19 pandemic on the supply chain vulnerabilities of major economies.

6.1 Analysis of China-US Trade Frictions

In 2018-2019, tensions in China-US trade relations created shocks to bilateral and global industrial and supply chains. In 2018 and 2019, global trade growth slowed from 2017 due to China-US trade frictions. Adjustments occurred in the relative influence of various economies despite a modest change in the overall landscape of global industrial chains. In 2019, China, Germany, the US, Japan, and South Korea reported reductions in the export of high-vulnerability products with their relative influence on the decline, and China's Taiwan, Mexico, Malaysia, and Vietnam reported increases in the export of high-vulnerability products with their relative influence on the rise. This reflects the adverse impact of China-US trade frictions on both sides and other economies with complementary industrial chains, as well as the positive effect on economies with substitutive industrial chains. The sectoral characteristics of supply-chain-vulnerable products during 2018 and 2019 is similar to that in 2017, and electrical-mechanical and chemical products remained the two globally vulnerable sectors. However, adjustments occurred in the supply chain vulnerabilities between segmented products.

We utilize the waves of tariff imposition on Chinese and American products[13] to identify the years of trade friction with the dummy variable of time. Then, the interaction term among the dummy variable of vulnerable products, the dummy variable of listed products, and the dummy variable of time is utilized to identify the relative change in the supply chain vulnerabilities of critical commodities in both countries. The following regression is performed using data from China and the US between 2017 and 2019, respectively:

$$y_{kt} = \beta_0 + \sum_{\tau=2018}^{2019} \left(\beta_{1\tau} D_{k2017}^{fragile} \times D_\tau + \beta_{2\tau} D_k^{tariff} \times D_\tau + \beta_{3\tau} D_{k2017}^{fragile} \times D_k^{tariff} \times D_\tau \right) + \lambda_t + \xi_k \qquad (7)$$

In equation (7), y_{kt} is the composite vulnerability index of Chinese or American products in year t. $D_{k2017}^{fragile}$, D_k^{tariff} and D_τ respectively denote the dummy variables of the supply-chain-vulnerable products, the list of products subject to additional tariffs, and time. When the Chinese or American product k was recognized as a supply-chain-vulnerable product in 2017 (see Section 3 for the method of identification), $D_{k2017}^{fragile}$ is 1; otherwise, it is 0. If product k was subject to additional tariffs imposed by China or the US, D_k^{tariff} is 1; otherwise, it is 0. When $t=\tau$ ($\tau \in \{2018, 2019\}$), D_τ is 1; otherwise, it is 0. All regressions are controlled for the fixed effect at the levels of product and time.

Columns (1) and (4) in Table 1 display the result of the change in the composite vulnerability index of supply-chain-vulnerable products over time in 2017. Specifically, the regression coefficient of the interaction term between the dummy variable of supply-chain-vulnerable products in 2017 and the dummy variable of time for 2018 and 2019 is -0.032 and -0.041, respectively, both of which are significantly different from zero. This indicates that during China-US trade frictions in 2018 and 2019, the composite vulnerability index of supply-chain-vulnerable products significantly decreased relative to other products. A possible reason is that under trade frictions, both countries traded fewer critical products with each other to ensure supply chain security at the expense of efficiency.

Columns (2) and (5) list changes in the composite vulnerability index of the second wave of products subject to additional tariffs. Notably, this paper simultaneously considers the regression results of the interaction term for the three waves of products subject to additional tariffs. However,

[13] Data for 2021 are not included into our samples due to numerous omissions that led to deviations in the estimation of supply chain vulnerabilities.

the regression results of the interaction term between the first and third waves of products subject to additional tariffs are insignificant and thus not reported in Table 1 in the interest of length.

After comparing changes in the composite vulnerability index of listed products in each wave, we find a significantly negative regression coefficient of the interaction term between the second wave of products subject to additional tariffs during the trade frictions in 2019 and the dummy variable of time for 2019, as well as an insignificant regression coefficient of the interaction term between the first and third waves of commodities. A possible reason is that the monetary value of products in the first wave was relatively small with a high ratio of tariff exclusion (Yao et al., 2020), the second wave of products was larger in value with a smaller ratio of tariff exclusion and higher proportions of capital and intermediate inputs. Additionally, consumer goods made up a large proportion of the third group of products, for which actual implementation was weakened under the *Economic and Trade Agreement between the Government of the United States of America and the Government of the People's Republic of China*.

Columns (3) and (6) further compare relative change in the composite vulnerability index of listed supply-chain-vulnerable commodities. Results of the regression suggest that on the list of the second group of commodities subject to additional tariffs by China and the US, there was a larger reduction in the composite product vulnerability index for products with supply chain vulnerabilities in 2017, and the reduction was more significant during the actual implementation of the list in 2019.

6.2 Impact of the COVID-19 Pandemic

Since 2020, the COVID-19 pandemic has erupted in various countries, taking a toll on the

Table 1: Relative Change in the Supply Chain Vulnerabilities of Critical Products for China and the US during China-US Trade frictions

Dependent variable: Composite vulnerability index	China			US		
	(1)	(2)	(3)	(4)	(5)	(6)
Dummy variable for supply-chain-vulnerable products in 2017 × Dummy variable for 2018	–0.032***		–0.022***	–0.022***		–0.025***
	(0.003)		(0.006)	(0.002)		(0.003)
Dummy variable for supply-chain-vulnerable products in 2017 × Dummy variable for 2019	–0.041***		–0.027***	–0.046***		–0.036***
	(0.004)		(0.006)	(0.003)		(0.004)
Dummy variable for products listed in the second wave of additional tariffs × Dummy variable for 2018		–0.002	–0.001		0.002	0.001
		(0.002)	(0.002)		(0.001)	(0.001)
Dummy variable for products listed in the second wave of additional tariffs × Dummy variable for 2019		–0.006**	–0.004*		–0.009***	–0.003**
		(0.003)	(0.002)		(0.002)	(0.001)
Dummy variable for products listed in the second wave of additional tariffs × Dummy variable for supply-chain-vulnerable products in 2017 × Dummy variable for 2018			–0.016**			0.007
			(0.007)			(0.005)
Dummy variable for products listed in the second wave of additional tariffs × Dummy variable for supply-chain-vulnerable products in 2017 × Dummy variable for 2019			–0.023***			–0.020***
			(0.008)			(0.005)
Fixed effect	Products at the HS 8-digit level, year			Products at the HS 10-digit level, year		
Total R^2	0.915	0.916	0.915	0.925	0.924	0.925
Sample size	17881	18237	17881	35540	36356	35540

Notes: Numbers in parentheses are robust standard errors. *** p<0.01, ** p<0.05, * p<0.1.

Source: Compiled by the authors.

global economy and disrupting global supply chains on both the demand and supply sides. During the pandemic, overall trade in global high-vulnerability products took a dive but developing Asian economies recorded increasing trade volumes of high-vulnerability products and relative influence over global industrial chains. The reason is that the COVID-19 pandemic disrupted the supply capacity of advanced economies led by the US and Europe, broadening their supply-demand gaps and thus creating an opportunity for countries like China with fewer COVID-19 cases and more complete supply chains to develop trade.

Sector-wise, the characteristics of global supply chain vulnerabilities in 2020 are roughly consistent with that in 2017, but the correlation coefficient is somewhat smaller than those for 2018-2019 and 2017, reflecting greater shocks of the pandemic to global industrial chains. During the pandemic, adjustments occurred in the sectoral distribution of global supply-chain-vulnerable products, resulting in a sharp increase in the number of supply-chain-vulnerable organic compound products. Similar to China-US trade frictions, change also occurred in the relative supply chain vulnerabilities between different products during the pandemic.

Based on the groupings of various types of products in relation to the COVID-19 pandemic and the temporal dummy variable of 2020 as the year of the pandemic's eruption,[14] this section identifies the relative impact of the COVID-19 pandemic on the vulnerabilities of some commodity supply chains using the interaction term among the dummy variable of vulnerable products, the dummy variable of pandemic-related products, and the dummy variable of time. COVID-related commodities include medical supplies, remote office devices, and home necessities. Specifically, medical supplies primarily include masks, hazmat suits, pharmaceuticals, and medical devices; remote office devices include computers, mobile phones, projectors, and other office machines and equipment; home necessities include furniture, toys, home appliances, bicycles, and transport vehicles. After identifying the HS codes of various commodities, we perform the following equation using Chinese and US data for 2017-2020:

$$y_{kt} = \beta_0 + \beta_{1,2020} D_{k2017}^{fragile} \times D_{2020} + \beta_{2,2020} D_k^{COVID} \times D_{2020} + \beta_{3,2020} D_{k2017}^{fragile} \times D_k^{COVID} \times D_{2020} + \lambda_t + \xi_k \quad (8)$$

In equation (8) D_k^{COVID} is the dummy variable of COVID-related products. The value is 1 if product k is COVID-related; otherwise, it is 0. Definitions of other variables are the same as in equation (7).

Columns (1) and (3) of Table 2 report the overall regression results of all pandemic-related commodities. The interaction term between the dummy variable of supply-chain-vulnerable products in 2017 and the temporal dummy variable of 2020 remains significantly negative, reflecting a continuous decrease in the composite vulnerability index of supply-chain-vulnerable products for China and the US during the pandemic.[15] The regression coefficient of the dual interaction term between the dummy variable of pandemic-related products and the dummy variable of time is significantly positive, and the regression coefficient of its triple interaction term with the dummy variable of vulnerable products and the dummy variable of time is negative. This suggests that in 2020, there was a sharper increase in the composite vulnerability index of pandemic-related products free from supply chain vulnerabilities as compared with other products, but the composite vulnerability index of pandemic-related products with supply chain vulnerabilities decreased in relative terms by a greater margin compared with non-pandemic-related products with supply chain vulnerabilities. A possible reason is that for global and regional economies, the COVID-19 pandemic has led to an increase in the concentration of supply sources of pandemic-related products free from supply chain vulnerabilities, causing the supply chain vulnerability index of such products to increase from the pre-pandemic level.

[14] Data for 2021 are not included into our samples due to numerous omissions that led to deviations in the estimation of supply chain vulnerabilities.

[15] According to the combined significance test, the sum between the dummy variable of time for year t ($t \in \{2018, 2019, 2020\}$) and the regression coefficient of its interaction term with the dummy variable of supply-chain-vulnerable products in 2017 is significantly different from 0, indicating a decrease in the absolute level of the composite vulnerability index for such products.

Table 2: Relative Change in the Supply Chain Vulnerabilities of Critical Products for China and the US during the COVID-19 Pandemic

Dependent variable: Composite vulnerability index	China		US	
	(1)	(2)	(3)	(4)
Dummy variable of supply chain vulnerable products in 2017 × Dummy variable of 2020	–0.021*** (0.003)	–0.021*** (0.003)	–0.040*** (0.002)	–0.040*** (0.002)
Dummy variable of COVID-related products × Dummy variable of 2020	0.013*** (0.005)		0.005* (0.003)	
Dummy variable of medical supplies × Dummy variable of 2020		–0.004 (0.004)		0.008 (0.005)
Dummy variable of home necessities × Dummy variable of 2020		0.020*** (0.007)		0.005 (0.004)
Dummy variable of remote office devices × Dummy variable of 2020		0.014 (0.009)		0.003 (0.007)
Dummy variable of COVID-related products × Dummy variable of supply chain vulnerable products in 2017 × Dummy variable of 2020	–0.016* (0.010)		–0.021*** (0.008)	
Dummy variable of medical supplies × Dummy variable of supply chain vulnerable products in 2017 × Dummy variable of 2020		0.010 (0.015)		–0.001 (0.017)
Dummy variable of home necessities × Dummy variable of supply chain vulnerable products in 2017 × Dummy variable of 2020		–0.010 (0.013)		–0.033*** (0.009)
Dummy variable of office products × Dummy variable of supply chain vulnerable products in 2017 × Dummy variable of 2020		–0.046** (0.019)		–0.006 (0.016)
Fixed effect	Products at the HS 8-digit level, year		Products at the HS 10-digit level, year	
Total R^2	0.893	0.894	0.903	0.903
Sample size	23724	23724	47134	47134

Notes: Numbers in parentheses are robust standard errors. *** p<0.01, ** p<0.05, * p<0.1.
Source: Compiled by the authors.

For COVID-related products with supply chain vulnerabilities, the pandemic has underscored the supply chain vulnerabilities and economic security attributes of those products, prompting China and the US to shift the supply chain arrangements for those products from efficiency first to a combination of efficiency and security considerations, causing the supply chain vulnerability index of such products to decline in relative terms of pre-pandemic levels. Columns (2) and (4) further divide the pandemic-related products into medical materials, remote office devices, and household necessities. It is found that the relative decline of the composite vulnerability index on pandemic-related products is primarily attributable to remote office devices in China but to home necessities in the US.

7. Conclusions and Policy Implications

This paper employs the trade network analysis method to investigate global and China's supply chain vulnerabilities and discuss the impacts of China-US trade frictions and the COVID-19 pandemic on the supply chain vulnerabilities of major economies. Though consistent with traditional competitiveness indicators, the product vulnerability index created in this paper is better at identifying supply-chain-vulnerable products and choke point technologies and products. For the global trade network, the supply chain vulnerabilities of advanced economies are concentrated in electrical, mechanical and chemical products with spatial distribution characterized by trade communities.

Developing economies other than China have a broader distribution of supply chain vulnerabilities and are significantly dependent on China and its regional community. China boasts an obvious advantage for over 80% of high-vulnerability product exports; however, its supply chain vulnerabilities still exist. Specifically, vulnerabilities are prominent in the sectors of electrical, mechanical and audiovisual equipment, mechanical equipment, optical and medical instruments, and transport vehicles. In terms of dynamic characteristics, adjustments in global supply chain vulnerabilities are generally slow, but the supply chain vulnerabilities of China and the US for critical products declined in relative terms during the China-US trade frictions and the COVID-19 pandemic.

Based on the export centrality variance index and the import concentration index, this paper divides China's imports of intermediate inputs into four groups, and our research findings are vital for policy implications. Specifically, there is a fairly high concentration propensity of Group 1 and 2 products in the overall external supply. Priority consideration should be given to coping with supply chain vulnerabilities by bolstering supply-side weaknesses. For instance, the government should extend more support to fundamental research and bring about breakthroughs in core technologies. Although Group 3 products show a propensity for concentration at the import level, there is external room for improvement to cope with supply chain vulnerabilities via demand-side import strategies and international coordination and cooperation. For instance, the government should pursue opening up on a broader scale, encourage businesses to re-innovate based on introducing and assimilating foreign technology, and embrace international cooperation on various fronts. Such an approach is also applicable to Group 1 and 2 products with a high import concentration, with room for improvement in the overall external supply. Most products in Group 4 have smaller supply chain vulnerabilities, and attention needs to be paid to only two types of products with indicators close to the critical levels.

This study is of great theoretical and practical significance. For one, the research methodology employed in this paper can be used to observe the supply chain vulnerabilities of further segmented products in various countries. Such observations may help address the concerns of various countries over supply chain security. For another, our research methodology can be used to trace the supply chain vulnerabilities of global and regional economies and thus identify the impact of change in the external environment on supply chain vulnerabilities. This helps explain the determinants of supply chain vulnerabilities in a science-based manner and provides theoretical and data driven support for policymaking.

Of course, our study is also subject to limitations. For instance, our research on supply chain vulnerabilities is focused on intermediate inputs due to data limits without investigating service and technological vulnerabilities. In addition, our measurement of supply chain vulnerabilities is primarily based on the existing data without sufficient research on potential vulnerabilities, domestic production potentials and the adaptability of trade networks. In follow-up research, we will try to collect the service and technological data and consider other factors to increase the theoretical and practical relevance of the research. CE

References:

[1] Barrat, A., M. Barthélemy, R. Pastor-Satorras, and A. Vespignani. 2004. "The Architecture of Complex Weighted Networks." *Proceedings of the National Academy of Sciences of the United States of America*, 101(11): 3747-3752.

[2] Cai, J., and Y. Dong. 2016. "Banking Competition and Firms' Innovation: Empirical Evidence from Chinese Industrial Enterprises Database." *Journal of Financial Research*, 11: 96-111.

[3] Chen, L., and W. P. Zhu. 2011. "Innovative Competition and Endogenous Monopoly—A Judging Principle of Chinese Anti-trust Law." *China Industrial Economics*, 6: 5-15.

[4] De Benedictis, L., S. Nenci, G. Santoni, L. Tajoli, and C. Vicarelli. 2014. "Network Analysis of World Trade Using the BACI-CEPII Dataset." *Global Economy Journal*, 14: 287-343.

[5] Fagiolo, G., J. Reyes, and S. Schiavo. 2010. "The Evolution of the World Trade Web: A Weighted-network Analysis." *Journal of Evolutionary Economics*, 20: 479-514.

[6] Greenaway, D., R. Hine, and C. Milner. 1994. "Country-specific Factors and the Pattern of Horizontal and Vertical Intra-industry Trade in UK." *Review of World Economics*, 1: 77-100.

[7] Herfindahl, O. C. 1950. *Concentration in The Steel Industry*. Dissertation: Columbia University.

[8] Hirschman, A. O. 1945. *National Power and the Structure of Foreign Trade*. Berkeley, Los Angeles, London: University of California Press.

[9] Jiang, X. R., Y. C. Yang, and S. L. Wang. 2018. "Spatial and Temporal Patterns of Evolution of Global Trade Networks during 1985-2015 and Its Enlightenment to China's Geostrategy." *Geographical Research*, 37(3): 495-511.

[10] Johnson, R. C., and N. Guillermo. 2012. "Fragmentation and Trade in Value Added over Four Decades." *NBER Working Paper*, w18186.

[11] Kee, H. L., and H. W. Tang. 2016. "Domestic Value Added in Exports: Theory and Firm Evidence from China." *American Economic Review*, 106(6): 1402-1436.

[12] Korniyenko, M. Y., M. Pinat, and B. Dew. 2017. "Assessing the Fragility of Global Trade: The Impact of Localized Supply Shocks Using Network Analysis." *International Monetary Fund Working Paper*, No. 2017/030.

[13] Liu, S. J., Y. Han, and D. W. Wang. 2020. "An Impact Path Analysis of COVID-19 Outbreak in China and Policy Response." *Journal of Management World*, 36(5): 1-12, 51.

[14] Liu, X., W. Song, B. Y. Wong, T. Zhang, S. Y. Yu, G. N. Lin, and X. T. Ding. 2019. "A Comparison Framework and Guideline of Clustering Methods for Mass Cytometry Data." *Genome Biology*, 20(1): 297.

[15] Manova, K., and Z. Zhang. 2012. "Export Prices Across Firms and Destinations." *Quarterly Journal of Economics*, 127(1): 379-436.

[16] Mao, R. S. 2019. "A Measurement of Trade Power Index across Countries." *The Journal of World Economy*, 42(10): 23-48.

[17] Mao, R. 2015. "Industrial Agglomeration and Financing Constraints of Enterprises." *Journal of Management World*, 2: 58-71.

[18] Mao, R., and B. Zhang. 2013. "China's Export Competitiveness: Facts, Causes and Trends." *The Journal of World Economy*, 36(12): 3-28.

[19] Qiao, B., G. P. Li, and N. N. Yang. 2007. "The Evolution and New Development of the Industry Agglomeration Measurement." *Journal of Quantitative & Technological Economics*, 4: 124-133.

[20] Schiavo, S., J. Reyes, and G. Fagiolo. 2010. "International Trade and Financial Integration: A Weighted Network Analysis." *Quantitative Finance*, 10(4): 389-399.

[21] Xu, Shu, H. Li, and L. Gan. 2011. "Market Competition and China's Airline Pricing." *China Economic Quarterly*, 10(2): 635-652.

[22] Yao, X., H. Zhao, and Q. Y. Xu. 2020. "US Tariff Exclusion Process on China and Its Impacts on Industry Chain." *International Economic Review*, 5: 26-42.

[23] Yao, Z. Z. 2019. "Measuring the Trade Power: Theory and Methods." *The Journal of World Economy*, 42(10): 3-22.

[24] Zhang, F., Y. M. Ning, and X. Y. Lou. 2019. "Competitiveness and Regional Inequality of China's Mega-City Regions." *Geographical Research*, 38(7): 1664-1677.

[25] Zhao, R. L., C. R. Sun, and Y. B. Chen. 2018. "Minimum Wage and Firm's Markup." *The Journal of World Economy*, 41(2): 121-144.