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RESEARCH ARTICLE

Supply Chain Fragmentation and the Global Trade Elasticity: A New Accounting Framework

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Abstract
In this paper, we offer a new framework to measure cross-border supply chain fragmentation and its impact on the global trade elasticity. Firstly, we introduce the supply chain fragmentation ratio that sums the volume of imports by all countries that participate in a particular supply chain. We find that supply chain fragmentation slowed down after 2010 for most goods, but not for services. We demonstrate the importance of using trade and production data at constant prices in measuring fragmentation trends. Secondly, we quantify the impact of fragmentation on the elasticity of trade to world GDP, extending the framework of Bems et al. (Am Econ Rev Pap Proc 101(3):308–312, 2011). We account for trade effects from fragmentation within supply chains as well as asymmetric shocks to final demand. We find that the declining pace of fragmentation accounted for more than a third of the decline in the global trade elasticity after 2010.

JEL Classification F14 · F15 · F62

1 Introduction

How can we track cross-border supply chain fragmentation and its impact on the global trade elasticity? The contribution of this paper is twofold. We first introduce the supply chain fragmentation (SCF) ratio. This is a novel measure of fragmentation that sums the volume of imports by all countries that participate in a particular supply chain. It takes account of imports by the country in which the product is finalised as well as imports by other countries in upstream stages of production. The new fragmentation measure is interesting in itself, and has a concrete application in

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analyses of the global trade elasticity. We embed the SCF ratio in a within-between decomposition framework to account for the elasticity of trade to world GDP in the vein of Bems et al. (2010, 2011). We quantify and compare the effects of changes in cross-border fragmentation of production ("within supply chain" effects) as well as asymmetric demand shocks in final demand (leading to "between supply chain" and “final trade” effects).

Our SCF ratio can be thought of as a “trade multiplier” associated with production of final output in a specific supply chain. A chain is defined by the industry (and country) in which the good is finalised. The SCF ratio is different from, and complements, a wide set of other measures that capture the effects of cross-border production fragmentation. This literature is generally geared towards a characterisation of the (upstream or downstream) position of individual firms, industries or countries in global value chains and their value added contributions to trade, as reviewed in Johnson (2018). Instead, we focus on the total of trade flows in the overall supply chain. Importantly, and different from the other indicators, the SCF ratio is measured in volume terms. This novel feature makes it suitable for tracking real changes in fragmentation as it does not confound price changes for intermediates with changes in volumes. We show how the measure can be derived from a newly constructed set of world input–output tables expressed at previous year prices. Applying the data, we find that the pace of cross-border fragmentation slowed down after 2008 for most goods, but we find no evidence of a widespread reversal. Notable exceptions are supply chains of electronics and wearing apparel that required fewer imports in 2014 than in 2008. Supply chains of services continued to fragment internationally, also after 2009. In addition, we demonstrate the importance of using data on trade and production volumes alongside nominal values in analysing fragmentation trends over longer periods.

Our second contribution is in embedding the SCF ratio in a within-between decomposition framework to account for the elasticity of trade to world GDP in the vein of Bems et al. (2010, 2011; BJY hereafter). The BJY framework assumes a fixed nominal input–output structure that allows for different *levels* of supply chain fragmentation across products, but ignores the effects of *changes* in fragmentation. This shortcut is suitable for their analysis of trade over short time periods, such as the global trade collapse of 2008/2009. It is less suited, however, for analysis over the longer run as substitution of intermediate inputs across and within countries will occur as a response to relative price movements, changes in trade policies as well as technological advances. The decompositions provided in BJY also had a residual that was not accounted for because of their use of fixed input–output structures. We show that this residual is sizeable in analyses of trade over longer periods and that it contains useful information on changes in fragmentation. Put otherwise, our decomposition is *exact*: the sum of the decomposition elements matches the actual trade data.

We thus add to a stream of work that focuses on the role of supply chains in the dynamics of world trade (Yi 2003). This literature aims to explain the low elasticity of world trade to global GDP in recent years relative to its strong historical performance. Between 2012 and 2017, world trade barely kept pace with the volume growth of global GDP. A prolonged period of near unitary trade elasticities is exceptional, and has not been observed since the mid-1970s (Escaith and Miroudot 2015; Constantinescu et al. 2020). A large literature has tried to explain the decline in trade elasticity. Aslam et al. (2018) provide estimations of import demand functions (in the vein of Bussière et al. 2013) and simulations in a multi-country general equilibrium model (in the vein of Eaton et al. 2016). Their findings suggest an important role for asymmetric demand shocks, in particular as spending on investment goods declined in the aftermath of the global financial crisis in 2008–2009. Investment spending is generally more trade-intensive than spending on services that are typically domestically produced. Fragmentation trends were also found to be important for global trade. Constantinescu et al. (2020) showed that the decline in the long-run trade elasticity in the 2000s correlates strongly with a waning pace of fragmentation (see also IMF 2016). In this paper, we provide for the first time a (nonparametric) decomposition framework that allows for a quantitative comparison of the effects of demand shocks as well as the pace of fragmentation of supply chains.

We use our framework to analyse the decline in the world trade elasticity during the period from 2000 to 2014. The elasticity dropped from 2.16 points before the crisis (during 2000–2007) to 1.03 points after the crisis (during 2011–2014). We find that changes in final demand mix and in fragmentation trends both accounted for a sizeable part of this decline. Supply chain fragmentation ("within supply chain" effects) boosted the global trade elasticity by 0.44 points before the crisis but only 0.05 points after. The declining pace of fragmentation thus accounted for more than a third of the decline in the trade elasticity: 0.39 (= 0.44–0.05) out of the 1.13 (= 2.16–1.03) points. Changes in final demand were also important for the high trade elasticity pre-crisis: global demand shifted in particular towards investment goods. This boosted trade in intermediates as these supply chains were more intensive in intermediates trade ("between supply chain" effects), contributing 0.19 points to the trade elasticity pre-crisis. Increased trade in final products (“final trade effects”) contributed 0.54 points pre-crisis, in particular as local production was replaced by imports from China. Both effects petered out, contributing −0.06 and 0.04 points, respectively, during 2011–2014. In conclusion, changes in the structure of global final demand no longer pushed the trade elasticity above one after the 2008–2009 crisis.

The remainder of the paper is organised as follows. In Sect. 2 we outline our new measure of supply chain fragmentation, and compare with related measures. In Sect. 3 we discuss data required for its measurement. Section 4 presents our findings on levels and trends in supply chain fragmentation. In Sect. 5 we present our accounting framework for the global trade elasticity. Section 6 provides empirical results. Section 7 concludes, arguing the need for joint analysis of final demand and fragmentation trends in future studies of world trade dynamics.

2 A New Measure of Supply Chain Fragmentation

We propose a novel measure of cross-border supply chain fragmentation (SCF) based on all imports made along a particular supply chain: the SCF ratio. We show how it can be computed on the basis of international input–output data in Sect. 2.1 and discuss the difference with other measures of trade that relate to cross-border production fragmentation in Sect. 2.2.

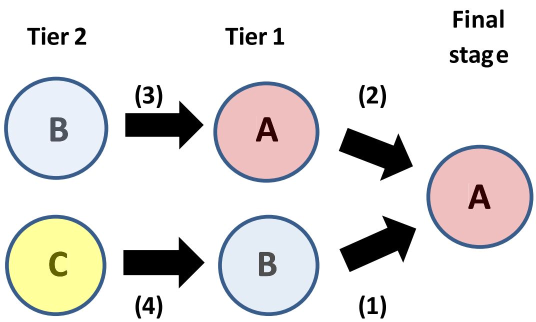

Fig. 1 Example of supply chain. *Note*: The SCF ratio for the final product in this supply chain is given by the sum of all imports (flows 1, 3 and 4), divided by the output value of the final good

2.1 The Supply Chain Fragmentation (SCF) Ratio

The SCF ratio can be calculated for any supply chain structure and we illustrate this with the example given in Fig. 1. The figure shows a fictitious production set-up with three participating countries (A, B and C). This particular chain combines a modular structure ("spider" in the language of Baldwin and Venables 2013) with two sequential processes ("snakes"), thus representing a rather general type of supply chain.[1] The good is finalised in country A and countries B and C contribute in upstream stages of production. Arrows indicate flows of intermediate goods and services. The SCF ratio for the final product is given by the sum of all imports in this supply chain (flows 1, 3 and 4), divided by the value of the final good.

More formally, suppose we want to measure the SCF ratio of a final good z, denoted by θ_z. The good is finalised in industry s in country i.[2] Let $a(u,k)(s,i)$ be the value of intermediates from industry u in country k supplied to industry s in country i to produce one unit of its gross output. The total of imports needed in the last stage of production (θ_z^0) is given by simply summing the flows of intermediates from all countries in this stage and excluding domestic deliveries (e.g. flow 2 in Fig. 1):

$$\theta_z^0 = \sum\nolimits_{(u,k)} a(u,k)(s,i) - \sum\nolimits_u a(u,i)(s,i) \tag{1}$$

In turn, producers of the intermediates supplied to (s,i) require another set of intermediates. We track all imports needed in this stage (θ_z^1) by multiplying outputs in this stage $y_z^1(u,k)$, the output in industry u in country k in tier 1 of the production chain of z, with the intermediates that are required, again excluding domestic deliveries:

$$\theta_z^1 = \sum\nolimits_{(t,j)} \sum\nolimits_{(u,k)} \left[a(t,j)(u,k)\right]\left[y_z^1(u,k)\right] - \sum\nolimits_t \sum\nolimits_{(u,k)} \left[a(t,k)(u,k)\right]\left[y_z^1(u,k)\right] \tag{2}$$

Note that θ_z^1 does not only include imports by country i that finalises the good (e.g. flow 3 in Fig. 1), but importantly also imports by any other country $k \neq i$ that is a

[1] We thus use the "chain" concept to indicate any sequentially ordered production set up which can be much broader than a simple "snake" set up.
[2] Throughout this section a "good" can refer to services as well as to physical goods.

tier 1 producer in the chain (e.g. flow 4 in Fig. 1). Continuing this line of reasoning for more upstream suppliers, we define θ_z as the sum of all shipments that cross borders in any stage of production:

$$\theta_z = \theta_z^0 + \theta_z^1 + \theta_z^2 + \cdots + \theta_z^N = \sum_{(t,j)} \sum_{(u,k)} \left[a(t,j)(u,k)\right]\left[y_z(u,k)\right] - \sum_t \sum_{(u,k)} \left[a(t,k)(u,k)\right]\left[y_z(u,k)\right] \tag{3}$$

where $y_z(u,k)$ denotes the output in (u,k) summed over all N stages of the production chain of z. It is important to note that y_z s are not directly observable in the data as survey-observations by statistical institutes typically only cover inputs and outputs for one plant or industry, not for individual stages. Instead we follow a standard procedure in studies that analyse cross-border production chains. We assume that the input requirements $a(t,j)(u,k)$ are the same in all stages of production and can be derived from an input–output table by dividing the use of the intermediate inputs supplied by industry t in country j to industry u in country k by the gross output of the latter (Leontief 1953).[3] Under these assumptions one can derive the outputs $y_z(u,k)$ using the so-called Leontief inverse of the international input requirements matrix. The appendix provides a matrix statement of this result.

Subsequently, we single out the cross-border flows of intermediates from (t,j) to (u,k) required for one unit of z, indicated by $m_z^{Int}(t,j)(u,k)$. And we define the SCF ratio for chain z as all imports, M_z^{Int}, required for the production of all final output of the chain, f_z, such that

$$\theta_z = M_z^{Int}/f_z = \sum_{(t,j)} \sum_{(u,k)} m_z^{Int}(t,j)(u,k), \quad \text{SCF ratio in base year.} \tag{4}$$

So far, we considered the SCF ratio in the base year, put otherwise it is stated in current-year prices. This is suitable for comparisons of cross-border fragmentation across different product chains at one particular moment of time. However, it is not suitable for tracking changes over time as it confounds differential price changes for intermediates with changes in volumes. It is well known that trade in goods used higher up in supply chains, such as natural materials, generally has a lower price elasticity (Balassa and Kreinin 1967; Bridgman 2012). We therefore need to net out price changes and trace import volumes, rather than values, over time.[4]

Let subscript t indicate a year and $\widehat{x_{[0,t]}} \equiv (x_t - x_0)/x_0$ denote the volume change in a variable x between t and 0. In Eq. (4), the SCF ratio in the base year 0 is stated as a summation of import flows. The corresponding volume change between t and 0 is then given by the weighted sum of the volume changes of the sum elements:

[3] Conceptually, this assumption is not needed as long as goods produced with different techniques are classified as output of different industries. This assumption is more likely to hold for more finely grained data as discussed in the data section.

[4] Analysing constant price import flows is also common in the estimation of standard import demand models (e.g. Levchenko et al. 2010).

$$\widehat{\theta}_{z[0,t]} = \sum_{(t,j)} \sum_{(u,k)} w^{Int}_{z,0}(t,j)(u,k) \times \widehat{m^{Int}_{z,[0,t]}}(t,j)(u,k), \tag{5}$$

with weights given by their nominal import shares: $w^{Int}_{z,0}(t,j)(u,k) = m^{Int}_{z,0}(t,j)(u,k) / \sum_{(t,j)} \sum_{(u,k)} m^{Int}_{z,0}(t,j)(u,k)$. The SCF ratio in year t is now given by multiplying the SCF ratio in the base year, $\theta_{z,0}$ as given in (4), with the volume growth between t and 0 as given in (5):

$$\theta_{z,t} = \left(\widehat{\theta}_{z,[0,t]} + 1\right)\theta_{z,0}, \qquad \text{SCF ratio in year t.} \tag{6}$$

Changes over multi-year periods should be derived through a chained Laspeyres index, shifting the weights annually. For example the change in the SCF ratio over the period $[0, t+1]$ is given by $\left(\widehat{\theta}_{z,[0,t]} + 1\right) \times (\widehat{\theta}_{z,[t,t+1]} + 1)$, where each growth rate is calculated on the basis of previous year prices. Chaining is important to account for substitution across inputs as relative prices and subsequently weights w change. The appendix provides computational details.

To track changes in supply chain fragmentation across a group of final products, it is useful to have an aggregate measure as well. This can be calculated as a weighted aggregate of the changes in individual chains, $\sum_z \left(f_z/F\right)\widehat{\theta}_z$, using shares in global final output as weights, with $F = \sum_z f_z$.

Our accounting framework also allows us to investigate the contribution of individual countries to global fragmentation trends. In particular, suppose we are interested in the supply chain imports sourced from a specific country C. To that end, one can calculate the SCF ratio based on imports from C only, appropriately restricting the summation in Eq. (5) using $j=C$.

2.2 Comparison with Other Measures of Supply Chain Trade

The SCF ratio is different from, and complements, a wide set of other measures that capture different aspects of global value chain production and trade, as surveyed in Johnson (2018). This literature is geared towards a characterisation of the role of individual firms, industries or countries in global value chains. Feenstra and Hanson (1999) proposed to measure the cost share of imported intermediates in a particular industry. This tracks imports in a particular stage of production (e.g. flow 1 in Fig. 1). As such it is a good measure of *offshoring* by the industry. Hummels, Ishii and Yi (2001) proposed to measure the import content of a country's exports. This measure includes imports by the industry that finalises the good, but also imports by other industries in the same country that contribute in the chain (e.g. flow 3 in Fig. 1). As such it is a good measure of a country's *vertical specialisation* in trade. Both these measures are insensitive to fragmentation in upstream stages of production that take place abroad. To measure fragmentation across the chain we track also imports by any other country in the chain (e.g. flow 4 in Fig. 1). As a corollary the SCF ratio does not have an upper bound, in contrast to the measures of Feenstra and

Hanson (1999) and Hummels et al. (2001) which are typically bounded by one.[5] The SCF ratio is unrestricted as imports in upstream stages contribute multiple times: their value is also embodied in the value of downstream trade flows.

In his overview article, Johnson (2018) also discusses measures of trade in terms of value added that differ from gross trade in the presence of cross-border fragmentation. Johnson and Noguera (2012) introduced the "value added exports" ratio, defined as the value added generated in a country and consumed abroad as a ratio to gross exports. It can be easily shown that fragmentation in a chain can occur without a change in this so-called VAX ratio. Suppose production of a final good requires two stages. Further suppose that the US initially carried out both stages at home and sold the final product to Mexico: the VAX ratio of the chain is 1 in this case. Suppose the final stage is now offshored to Mexico. Value added exports and gross exports of the US will decline proportionally, such that the VAX ratio will remain one. Yet, it is clear that international production fragmentation has occurred. The purpose of VAX measures is to rewrite gross trade flows between countries into value added flows. This is obviously related to supply chain fragmentation, but serves a different purpose. The same is true for measures of domestic value added in exports highlighted in Koopman et al. (2012). Los and Timmer (2018) provide an integrated discussion of the different classes of (bilateral) trade measures in value added terms.

Related research is focused on quantifying the position of individual industries along production chains, in particular the degree of upstreamness or downstreamness. This literature is aimed at characterising the position of a firm, industry or country relative to final users. A recent review is provided by Antràs and Chor (2019). Our measures capture a characteristic of the chain as a whole, not of an individual industry or country. As such it bears resemblance to measures of the "length" of chains introduced by Dietzenbacher and Romero (2007) and to chain measures proposed in Fally (2012), Antràs et al. (2012) and Fally and Hillberry (2018). It also relates to the cross-country distribution of value added within chains as studied in Los et al. (2015). The SCF ratio is different as it specifically singles out the flows of goods in a chain that cross borders. In addition, the SCF ratio is based on changes in volumes while previous measures are based on changes in nominal values, confounding price and volume effects. As such we view our SCF ratio as a complement to the wider set of measures, speaking to a different aspect of cross-border production fragmentation.

[5] This is simple to see for the offshoring measure as cost shares are typically below one, except for special circumstances (e.g. storing inventory). Koopman et al. (2012) showed that the import content of exports is equal to gross exports minus domestic value added in exports, and hence also bound by one as value added is normally not larger than output. See Los and Timmer (2018) for a more general discussion.

3 Data: World Input–Output Tables at Constant Prices

To apply the new measures, we have developed a new set of input–output tables at previous year prices. This data is publicly available at http://www.wiod.org/database/wiots_pyp16. It is based on deflation of an annual time-series of nominal world input–output tables from the 2016 release of the World Input–Output Database (WIOD). This release covers 43 countries and a consolidated estimate for the remaining non-covered part of the world economy, called the "rest of the world" region (Timmer et al. 2015, 2016). The countries included in WIOD are all twenty-eight members of the European Union (as of July 1, 2013) and fifteen other major economies: Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Norway, Russia, South Korea, Switzerland, Taiwan, Turkey and the USA. It should be noted that we will not be able to cover all trade flows in the world. We cover 91% of global imports in our analysis and the remaining 9% is trade between countries in the rest-of-the-world region. More specifically, in 2014, 54% of global imports consisted of trade between the WIOD countries, 21% were imports by WIOD countries from rest-of-the-world and 16% were rest-of-the-world imports from WIOD countries, according to UN COMTRADE (reconciled data version) for 2014. Imports are measured in free-on-board (fob) prices. The 2016 release includes data on 56 product groups, mainly at the 2-digit ISIC revision 4 level, together covering the entire economy.

For the particular purpose of this study we collected price statistics to deflate the world input–output tables to exclude the effects of differential price changes. Price deflators at the elementary level have been constructed on the basis of deflators for final demand and gross output taken from national accounts statistics for detailed industries in each country. A variant of the procedure proposed by Dietzenbacher and Hoen (1998) has been used to balance the tables for each year. We use a Laspeyres deflation procedure that ensures that supply equals demand for each product in current prices as well as in prices of the previous year, which is crucial for our accounting framework. Price deflators for industry value added and gross output have been taken from the WIOD Socio-Economic Accounts 2016, available at http://www.wiod.org/database/seas16. Deflators for the final demand categories were based on data from the United Nations (UN) National Accounts (at https://unstats.un.org/unsd/snaama). The online appendix provides additional details on the data deflation procedure.

It should be noted that the presented measurement framework puts high demands on the data, requiring international input–output tables at current as well as at constant prices. Yet, this data is not part of a standard program in the international statistical system. International IO tables are available from the OECD TiVA (at oe.cd/tiva), but only in nominal terms and typically with a considerable lag. We hope that future data developments will also be able to make better use of firm-level data, in particular to allow for heterogeneity in the use of imported intermediate inputs between exporting and non-exporting firms in an industry (Koopman et al. 2012; De Gortari 2019; Bems and Kikkawa 2020).

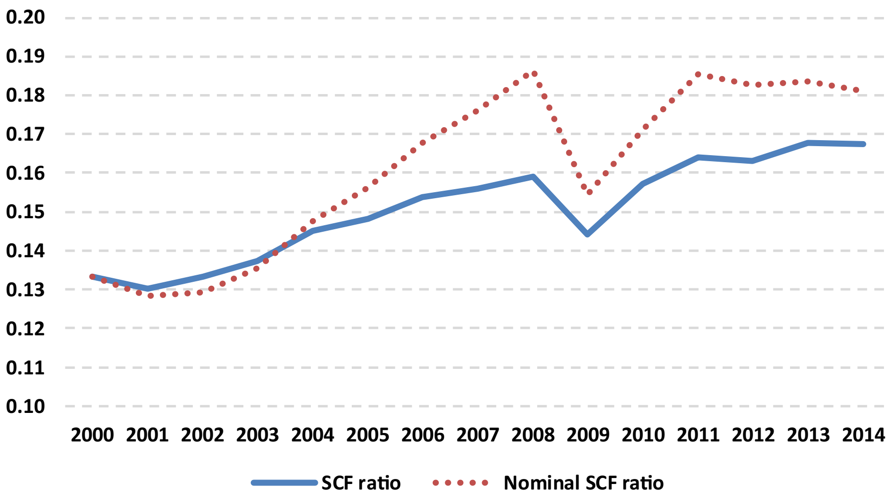

Fig. 2 Supply chain fragmentation (all goods and services). *Note*: The supply chain fragmentation (SCF) ratio is given in Eq. (6) in constant prices of the year 2000. The nominal alternative is in current year prices. Aggregation from supply chains of 56 product groups (goods and services) finalised in 43 countries using shares in global final output as weights

4 Supply Chain Fragmentation: Empirical Results

In this section, we present two main findings on trends in supply chain fragmentation during the period from 2000 to 2014, which are the first and last year in the WIOD 2016 release. First, we track the aggregate SCF ratio and find continuing fragmentation in the period after the great trade collapse in 2008–2009, albeit at a slower pace than before. We show how use of a non-deflated (nominal) measure can be misleading, as it would suggest de-fragmentation after 2010. Second, we analyse fragmentation in disaggregated supply chains of 56 product groups and find various cases in which production fragmentation for services is higher than for goods.

Figure 2 shows the time-series of the SCF ratio aggregated from supply chains of 56 product groups. The ratio shows a clear upward trend in the early 2000s until the onset of the 2008/2009 global financial crisis. The drop in 2009 appears to have been a short-run phenomenon. This is partly a reflection of sizeable inventory adjustments with unusually low purchases of intermediate inputs (Alessandria et al. 2010; Bems et al. 2013). In 2010, the ratio was almost back at the 2008 level and continued to rise, albeit at a slower pace than before the crisis. This finding resonates well with recent findings of a modest increase in import protection arising from temporary trade barriers of antidumping, countervailing duties and safeguards in the wake of the Great Recession as documented in Bown (2018). In particular, he finds that temporary trade barriers tended to be shifted away from imports of final goods towards imports of intermediate inputs. This is likely to have dampened cross-border supply chain trade.

Figure 2 also shows the development of the SCF ratio calculated in nominal terms. This measure is much less data intensive, as it does not require deflators, yet

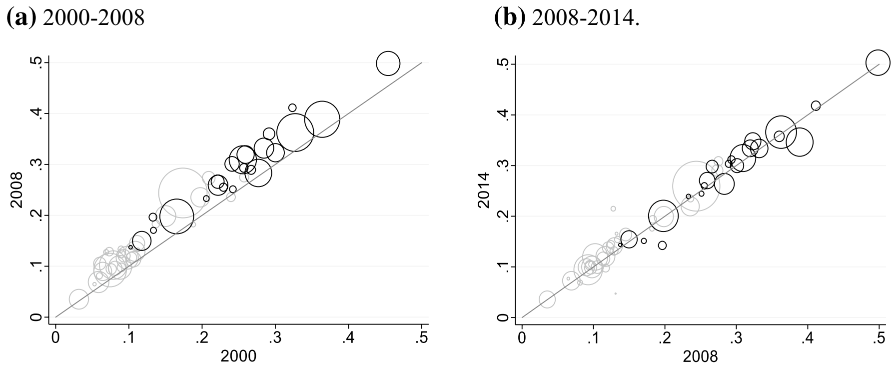

Fig. 3 Supply chain fragmentation ratios (56 goods and services). *Note*: Supply chain fragmentation ratios for 56 goods and services (weighted across countries of finalisation). Black circles are goods (agricultural, mining and manufactures goods) and grey circles are services. The size of a bubble is proportional to the share of a supply chain in overall intermediate imports in 2000 (panel a) and in 2008 (panel b). Solid lines are 45 degree lines. SCF ratios with year 2000 as base year, taken from Appendix Table 3

can be misleading as it confounds price changes with real fragmentation. We find indeed that the nominal fragmentation measure is much more volatile than the volume measure. This echoes findings in Haugh et al. (2016) and Gaulier et al. (2019), which show that movements in global trade volumes may differ widely from movements in nominal values.[6] In particular, we find that fragmentation is slowly increasing after 2009, while the nominal alternative is declining. Sole consideration of the latter could falsely suggest a period of overall de-fragmentation in supply chains in this period. In fact, the nominal trend is the combined effect of a continuing real fragmentation trend with on average declining prices of upstream goods and services relative to final products. This underlines the importance of using input–output tables at constant prices to analyse trends in fragmentation.

It is important to note that the SCF measures are possibly prone to aggregation biases in the underlying input–output data (Bems et al. 2010). Ideally, these measures are built up from firm-level information including domestic and international transactions (De Gortari 2019; Bems and Kikkawa 2020). In the online Appendix we provide a robustness check, using an alternative set of input–output tables from the OECD-WTO TiVa database. The TiVA database and the WIOD are based on similar sources and construction philosophy (see Tukker and Dietzenbacher 2013). A major difference is that the TiVa database contains tables with separate rows and columns for production in export processing zones (EPZ) and production in non-EPZ for China and Mexico. This is useful information given the higher import and export intensity of EPZ production compared to non-EPZ (Koopman et al 2012). Unfortunately, TiVA only contains data in current prices so we cannot compare volume measures. Reassuringly, we find that the trend in the nominal ratio based

[6] For example, crude oil prices rose from 28 US$ per barrel in 2000 to 94$ in 2008, dropped and then peaked again in 2012 at 109$.

on OECD TiVa is almost identical to the trend based on WIOD data (see online Appendix).

Facilitated by the detail in the 2016 release of the WIOD, we are also able to analyse fragmentation in more detailed supply chains of 56 product groups finalised in 43 countries. We aggregate across the countries of finalisation and present SCF ratios for 56 products in Fig. 3. The left panel compares SCF ratios in 2000 and 2008, while the right panel compares ratios in 2008 and 2014. We find that the aggregate fragmentation trend from Fig. 2 is reflected at the more detailed product level. The left panel shows widespread fragmentation during the period 2000–2008 with observations for almost all products above the 45 degrees line. Fragmentation was much slower in the period after, with SCF ratios for many products remaining more or less constant. There are some noteworthy cases of de-fragmentation as the SCF index declined for these product groups. These include Electronic products (C26) and Wearing apparel (C13–15). This is strongly related to the increased ability of China, the major producer of these final goods, to substitute imports of sophisticated intermediates by domestically produced inputs (Kee and Tang 2016). This is discussed further in Sect. 5.

Another, arguably surprising, finding is that we do not find a sharp demarcation between the fragmentation of supply chains of goods (black circles in Fig. 3) and of services (grey circles). We find that the most import-intensive supply chains in 2014 are those of refined petroleum (final output from ISIC rev. 4 industry code C19), followed by supply chains of basic metals (C24), motor vehicles (C29), electronic products (C26), electrical equipment (C27) and machinery (C28).[7] As expected, supply chains of many services are barely internationally fragmented. Yet, this is not true for all services. Appendix Table 3 shows that the import-intensities of the supply chains of water and air transportation services (H50 and H51), construction (F), electricity (D35) and other professional services (M74–75) are even higher than for manufactured food (C10–12). For example, the high import-intensity of supply chains for construction services is driven by heavy reliance on imports of raw materials not only by the construction industry itself but also by its suppliers.

5 A New Accounting Framework for the Global Trade Elasticity

What is the impact of changes in supply chain fragmentation on the global trade elasticity? And how big is this effect relative to the impact of changes in the mix of final demand? The second goal of this paper is to decompose the global trade elasticity, explicitly accounting for both changes in fragmentation and final demand. To do so, we extend the multi-country input–output framework introduced by Bems

[7] The SCF ratio is generally higher for products from industries where upstream inputs account for larger shares of value added of the final product. For example, crude oil makes up a sizeable share of the value of refined petroleum. Moreover, it can only be drilled in a limited number of countries, while refineries are widespread across the world. The supply chain of refined petroleum thus entails more cross-border trade than most other goods. Put otherwise, the petroleum chains are more fragmented, as indicated by the high SCF ratio.

et al. (2010, 2011), BJY henceforth. BJY linked changes in trade flows to changes in the final demand of countries. Importantly, they assumed a fixed input–output structure over time, effectively ruling out the impact of changes in production fragmentation. This is appropriate for the analysis of trade volume changes over short periods, such as the 2008–2009 period analysed by BJY. But substitution of intermediate inputs will occur in the longer run as a response to relative price movements, changes in trade policies as well as technological advances. In our framework we will explicitly account for changes in fragmentation relying on time-series information about global input–output structures. By holding supply chain structures constant we trace the effects of asymmetric shocks in final demand on global trade as in BJY. These include what we will call "final product trade effects" and "between supply chain effects". Additionally, by holding the demand mix constant, we trace the effects of changes in supply chain fragmentation on global trade which we call "within supply chain effects".

Let M be the sum of imports by all countries in the world in nominal terms. It consists of imports of final goods (M^{Fin}) and of intermediate goods (M^{Int}) such that $M = M^{Fin} + M^{Int}$. Then volume growth in imports is given by

$$\widehat{M} = \frac{M^{Fin}}{M}\widehat{M^{Fin}} + \frac{M^{Int}}{M}\widehat{M^{Int}}. \tag{7}$$

The weights are given by the (begin-of-period) shares of final and intermediate goods in global imports.[8] The elasticity of imports with respect to global GDP (ε) is then given by $\widehat{M}/\widehat{F}$, and using (7) we can write

$$\varepsilon = \frac{M^{Fin}}{M}\varepsilon^{Fin} + \frac{M^{Int}}{M}\varepsilon^{Int}, \tag{8}$$

where $\varepsilon^{Fin} = \widehat{M^{Fin}}/\widehat{F}$ is the elasticity of final imports to global GDP, and similarly $\varepsilon^{Int} = \widehat{M^{Int}}/\widehat{F}$ is the elasticity of intermediate imports to global GDP. Equation (8) shows that the global trade elasticity can be written as a weighted sum of these partial elasticities.

We develop an expression for the elasticity of intermediates trade to single out the role of fragmentation. Remember that the volume change in global intermediate imports, $\widehat{M^{Int}}$, is given by $\sum_{(s,i)} w^{Int}_{(s,i)}\widehat{m^{Int}}(s,i)$, with $m^{Int}_{(s,i)}$ the aggregate imports in the supply chain of *(s,i)*. The latter can be derived using $f(s,i)$, the final output of (s,i), and $\theta(s,i)$, the nominal SCF ratio as by our definition $m^{Int}_{(s,i)} = \theta(s,i) \times f(s,i)$. This can be rewritten in volume changes as $\widehat{m^{Int}}(s,i) = \widehat{\theta}(s,i) + \widehat{f}(s,i)$. Substituting this result, we can write the volume change in intermediate imports as

[8] Equation (7) holds exactly in discrete time for arbitrary period lengths, as long as all aggregate volume changes are measured by Laspeyres indices built up from the elementary level (that is, the lowest level for which data is available, in this case flows of intermediates between country-industries required for the production of a particular final output). We maintain this convention throughout the analysis. We suppress the time subscript for expositional ease, bringing it back when the final decomposition has been derived.

$$\widehat{M^{Int}} = \sum_{(s,i)} \left[w^{Int}_{(s,i)} \hat{\theta}(s,i) \right] + \sum_{(s,i)} \left[w^{Int}_{(s,i)} \hat{f}(s,i) \right], \tag{9}$$

with weights $w^{Int}_{(s,i)} = m^{Int}_{(s,i)} / M^{Int}$, the imports in the supply chain of (s,i) as a share of global imports of intermediates. The elasticity of intermediate imports to global GDP is then given by dividing (9) by $\hat{F}$ such that

$$\varepsilon^{Int} = \sum_{(s,i)} w^{Int}_{(s,i)} \left[\frac{\hat{\theta}(s,i)}{\hat{F}} \right] + \sum_{(s,i)} w^{Int}_{(s,i)} \left[\frac{\hat{f}(s,i)}{\hat{F}} \right]. \tag{10}$$

Equation (10) shows that an increase in the intermediate import elasticity can be driven by an increase in international fragmentation *within* supply chains, as reflected in $\hat{\theta}(s,i)$, as well as by shifts in demand *between* the output of the chains, as reflected by differential growth in $\hat{f}(s,i)$. We will show below that both effects can be sizeable. This provides a strong caveat against the practice of simply inferring global fragmentation trends from the share of intermediates in total trade, as done in e.g. Baldwin and Lopez-Gonzalez (2015), Haugh et al. (2016) and Gaulier et al. (2019).

Next, we develop an expression for changes in the global import elasticity of final goods, ε^{Fin}. To incorporate trade in final products, we need to identify not only the country where a product is finalised, but also the country to which it is sold. Let $f(s,i)(j)$ be the final goods produced in industry s in country i and purchased by country j. Then we can write global trade in final goods as $M^{Fin} = \sum_{(s,i)(j)} \left[f(s,i)(j) - f(s,i)(i) \right]$ and growth in M^{Fin} as

$$\widehat{M^{Fin}} = \sum_{(s,i)(j)} w^{Fin}_{(s,i)(j)} \hat{f}(s,i)(j), \tag{11}$$

with weights $w^{Fin}_{(s,i)(j)} = f(s,i)(j)/M^{Fin}$ if $(i \neq j)$ and zero otherwise. Dividing by growth in global GDP gives

$$\varepsilon^{Fin} = \sum_{(s,i)(j)} w^{Fin}_{(s,i)(j)} \left[\frac{\hat{f}(s,i)(j)}{\hat{F}} \right]. \tag{12}$$

We can now derive a decomposition of the import elasticity of global GDP. Substituting the expressions for the partial elasticities from (12) and (10) into (8), we get, after some rearranging and re-introducing time subscripts:

$$
\begin{aligned}
\varepsilon_{(0,t)} &= 1 && \text{unitary elasticity} \\
&+ \sum_{(s,i)} \tilde{w}^{Int}_{(s,i),0} \left[\frac{\hat{\theta}(s,i)_{(0,t)}}{\hat{F}_{(0,t)}} \right] && \text{within chain} \\
&+ \sum_{(s,i)} \tilde{w}^{Int}_{(s,i),0} \left[\frac{\hat{f}(s,i)_{(0,t)} - \hat{F}_{(0,t)}}{\hat{F}_{(0,t)}} \right] && \text{between chain} \\
&+ \sum_{(s,i)(j)} \tilde{w}^{Fin}_{(s,i)(j),0} \left[\frac{\hat{f}(s,i)(j)_{(0,t)} - \hat{F}_{(0,t)}}{\hat{F}_{(0,t)}} \right] && \text{final trade}
\end{aligned} \tag{13}
$$

with $\tilde{w}^{Int}_{(s,i)} = m^{Int}_{(s,i)}/M$, the imports of intermediates in the supply chain of good (s,i) as a share of all global imports (of intermediates and final products), and $\tilde{w}^{Fin}_{(s,i)(j)} = f(s,i)(j)/M$, the share of final good (s,i) in global imports when $(i \neq j)$ and zero otherwise.[9] We add 1 to the right hand side to focus on the deviations from unitary elasticity in which case imports grow at the same rate as global GDP.

In our framework, deviations from a unitary import elasticity can arise from three main sources, each with a straightforward interpretation. The first element on the right-hand side in Eq. (13) captures the effects of *within supply chain fragmentation*. Everything else equal, the trade elasticity increases if production for some goods becomes more fragmented over time: $\widehat{\theta}(s,i) > 0$. Conversely, it declines if de-fragmentation is observed for some goods, $\widehat{\theta}(s,i) < 0$. For example, reshoring of stages would show up as de-fragmentation in the analysis.[10] The second element indicates that the elasticity will be higher than unity if final demand rises relatively more for products of which the production process is more internationally fragmented. We refer to this as the *between supply chain effect*. For example, we show in Appendix Table 3 that the production of cars induces more imports per unit of output than the production of food, such that a shift in global demand towards cars will increase the global trade elasticity. The last element accounts for the *final product trade effect*. The global trade elasticity might decrease when the mix of demand shifts to final goods that are produced at home. This effect arises when demand increases for products that generally rely more heavily on domestic production (such as health care services) and/or because there is a shift in production location from abroad to home within a product category (such as the recent increase in domestic tourism due to the COVID pandemic).[11]

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[9] Remember that both weights are expressed as a share in global imports and add up to one such that $\widehat{F}$ is equal to $\sum_{(s,i)} \tilde{w}^{Int}_{(s,i)} \hat{F} + \sum_{(s,i),j} \tilde{w}^{Int}_{(s,i),j} \hat{F}$.

[10] But de-fragmentation comprises a wider class of phenomena, e.g. it might also be due to imports being substituted by domestic production that did not take place in the country before.

[11] Empirically, these two effects could be distinguished in the decomposition of equation (13) by splitting the final product trade effect term into a within product effect, using $\widehat{f}(s,i)(j)_{(0,t)} - \widehat{f}(s,i)_{(0,t)}$, and a between product effect, using $\widehat{f}(s,i)_{(0,t)} - \widehat{F}_{(0,t)}$, as these sum to $\widehat{f}(s,i)(j)_{(0,t)} - \widehat{F}_{(0,t)}$.

The decomposition in Eq. (13) improves the framework introduced by BJY. By holding supply chain structures constant we trace the trade effects of changes in final demand mix, as in BJY. Additionally, we can trace effects of changes in fragmentation by holding the demand mix constant. With fragmentation incorporated, our decomposition exactly matches the actual trade data and there is no residual left as in BJY. It is also useful to note that our procedure of relating imports to final demand categories is a logical extension of the innovation in the estimation of import demand models introduced by Bussière et al. (2013) and used extensively in Aslam et al. (2018). In the standard setup of these demand models, imports by a country are related to this country's GDP. Bussière et al. (2013) adjusted the GDP of countries to account for differences in import-intensity across demand components, using information from national input–output tables. We extend this line of reasoning and link final demand to all imported products along the supply chain, by the consuming country as well as by all other countries. In fact, our decomposition result formalises the intuition stated in Aslam et al. (2018, footnote 8). We show mathematically under what conditions the decomposition of world trade is exact. In fact, we show that it holds not only for nominal levels of imports, but also for volume growth rates provided that the Laspeyres volume index is used properly.

Our accounting framework is versatile and can be easily extended to perform alternative decompositions along other dimensions of the data. This is because the Laspeyres index is consistent in aggregation: an index based on direct aggregation of elements is equal to an index derived in a two-step procedure first aggregating elements into sub-groups and then aggregating across sub-groups. For example, it is possible to zoom in on the trade effects of changes in final demand structures, such as a shift from consumption to investment. Let $f_{con}(s,i)$ be global consumption demand for output from (s,i) and $f_{inv}(s,i)$ global investment demand, such that $f_{con}(s,i)+ f_{inv}(s,i) = f(s,i)$. Then we can decompose the between supply chain effect into

$$\begin{aligned} &\sum_{(s,i)} \frac{f_{con}(s,i),0}{f(s,i),0} \tilde{w}^{Int}_{(s,i),0} \left[\frac{\hat{f}(s,i)_{(0,t)} - \hat{F}_{(0,t)}}{\hat{F}_{(0,t)}} \right] && \text{consumption} \\ &+ \sum_{(s,i)} \frac{f_{inv}(s,i),0}{f(s,i),0} \tilde{w}^{Int}_{(s,i),0} \left[\frac{\hat{f}(s,i)_{(0,t)} - \hat{F}_{(0,t)}}{\hat{F}_{(0,t)}} \right] && \text{investment} \end{aligned} \tag{14}$$

Likewise, one can decompose the final product trade effect. This can also be done for more detailed groups of products, such as durables and non-durables.

Using the same logic, one might also account for the role of particular countries for changes in global trade elasticity. Suppose one is interested in the trade effects related to increasing final production in a country C. The effect on global trade in final products is measured by setting weights $\tilde{w}^{Fin}_{(s,i)(j)}$ in Eq. (13) to zero when $i \neq C$ (and when $i{=}j$). The between supply chain effect and the within supply chain effect are measured by setting weights $\tilde{w}^{Int}_{(s,i)}$ in Eq. (13) to zero when $i \neq C$. We provide illustrative examples of these extensions in the next section.

Table 1 Decomposition of global trade elasticity

	2000–2007 (1)	2007–2011 (2)	2011–2014 (3)	Change (3)–(1)
(1) Unitary elasticity	1	1	1	0
(2) Within supply chain fragmentation effect	0.44	0.53	0.05	−0.39
(3) Between supply chain effect	0.19	0.04	0.04	−0.15
(3a) *Consumption products*	*0.06*	*0.01*	*0.00*	*−0.06*
(3b) *Investment products*	*0.12*	*0.03*	*0.03*	*−0.09*
(4) Final product trade effect	0.54	0.07	−0.06	−0.60
(4a) *Consumption products*	*0.31*	*−0.02*	*0.23*	*−0.08*
(4b) *Investment products*	*0.23*	*0.09*	*−0.29*	*−0.51*
(5) Import elasticity of global GDP	2.16	1.63	1.03	−1.14

Calculated according to Eqs. (13) and (14) using begin-of-period weights. Contributions may not add due to rounding.

6 Accounting for the Global Trade Elasticity: Empirical Results

We study developments in the period from the year 2000 to 2014. Constantinescu et al. (2020) showed that this period is characterised by a falling trend in global trade growth, which was a combination of declining world GDP growth and a declining trade elasticity. We compare the trade elasticity in the period before and the period after the great trade collapse and rebound. The global import elasticity declined from 2.16 in the period before (2000–2007) to 1.03 in the period after (2011–2014).[12] Results of the decompositions according to Eq. (13) are shown in Table 1 featuring the contributions of the four elements of the decomposition in the rows. The contributions add up to the elasticity as actually measured in the data, given in the last row.[13] We use Eq. (14) to further decompose the effects of growth in consumption (final consumption demand by households and governments) and growth in investment (public and private gross fixed capital formation).[14]

We find that the effects of changes in supply chain fragmentation are quantitatively important. The second row in Table 1 shows that it added 0.44 points to the

[12] Additional analysis (not reported) shows that the findings are (qualitatively) not sensitive to the inclusion of the year 2010 in the last period, or of 2008 in the first period.

[13] We use begin-of-period weights for each period in order to have an exact (exhaustive) additive decomposition. A small number of supply chains have zero, or even negative, final output in one or more years due to inventory changes. Non-positive values cannot be handled in Laspeyres aggregation and have hence been left out in the empirical exercise. The overall effect in the aggregate decomposition is negligible.

[14] We measure final demand as the sum of final consumption by households (WIOD category CONS_h), final consumption by non-profit organisations serving households (CONS_np), gross fixed capital formation (GFCF), changes in inventories (INVEN) and final consumption by government (CONS_g) across all countries. The number of non-positive trade flows increased because of this detailing of the final demand flows and these had to be dropped. As a result, the decomposition of the final output and final demand mixes was not exact and we allocated the (small) residual proportionally to C and I.

Table 2 Decomposition of global trade elasticity and the role of China

	2000–2007 (1)	2007–2011 (2)	2011–2014 (3)	Change (3)–(1)
(1) Unitary elasticity	1	1	1	0
(2) Within supply chain fragmentation effect	0.44	0.53	0.05	−0.39
(2a) *of chains ending in China*	*0.07*	*−0.10*	*−0.14*	*−0.21*
(2b) *of chains ending in other countries*	*0.37*	*0.63*	*0.20*	*−0.18*
(3) Between supply chain effect	0.19	0.04	0.04	−0.15
(3a) *of chains ending in China*	*0.17*	*0.41*	*0.16*	*0.00*
(3b) *of chains ending in other countries*	*0.02*	*−0.38*	*−0.13*	*−0.15*
(4) Final product trade effect	0.54	0.07	−0.06	−0.60
(4a) *of products finalised in China*	*0.30*	*0.13*	*0.06*	*−0.25*
(4b) *of products finalised in other countries*	*0.23*	*−0.06*	*−0.12*	*−0.35*
(5) Import elasticity of global GDP	2.16	1.63	1.03	−1.14

Calculated according to Eq. (13) using begin-of-period weights. Contribution of China calculated setting j = China, and contribution of other countries setting $j \neq$ China. Contributions may not add due to rounding.

global import elasticity during 2000–2007. Fragmentation of supply chains continued after the crisis, still pushing the trade elasticity above one, albeit at a much slower pace: 0.05 points during 2011–2014. This is congruent with our previous findings: it is the positive net effect of defragmentation in some supply chains after the crisis, and continuing fragmentation in many other supply chains, including those of services as shown in Sect. 3. Overall, the slowing pace of fragmentation implied that it no longer strongly boosted the global trade elasticity, but it cannot be solely credited for the major decline in the elasticity after the crisis.

Changes in the mix of final demand also contributed to the decline in the global trade elasticity. First, increased imports of final products added in total 0.54 points to the global trade elasticity during 2000–2007 (row 4), indicating that the product mix of global demand continuously shifted from products that were finalised at home to products that were finalised abroad. This happened for final consumption goods as well as for investment goods, driving up the trade elasticity by 0.31 and 0.23 points, respectively. Second, these changes in the final demand mix also boosted trade in intermediates, as demand rose most rapidly for goods produced in supply chains that were relatively more fragmented. The associated flow of intermediates trade added 0.19 points to the global trade elasticity in 2000–2007 (see row 3). The great trade collapse in 2008 provided a watershed. Both the between supply chain effect and the final product trade effects dropped to a mere 0.04 and 0.07 points during 2007–2011 as final demand no longer shifted to products that were more intensive in trade. Column (3) shows that these effects did not rebound after the crisis, contributing only marginally positive or even negative during 2011–2014 (0.04 and −0.06 points). Declining final product trade, in particular investment goods, accounted for 0.60 points out of the 1.14 points reduction in the elasticity after the crisis (see last column). This

Table 3 Supply chain fragmentation ratio (θ) for 56 goods and services

Code	Final product name	θ (imports per unit of final output)			Imports in supply chain (share in global imports in %)		
		2000	2008	2014	2000	2008	2014
C19	Petroleum products	0.454	0.498	0.503	3.12	4.18	3.65
C24	Basic metals	0.323	0.411	0.418	0.31	0.57	0.51
C29	Motor vehicles	0.327	0.363	0.366	7.67	6.83	7.49
C22	Rubber and plastic products	0.291	0.360	0.358	0.74	0.71	0.63
C30	Other transport equipment	0.300	0.323	0.348	1.77	1.87	2.28
C26	Electronic products	0.364	0.389	0.346	6.99	5.19	4.29
C20	Chemical products	0.259	0.319	0.334	1.67	1.80	1.65
C27	Electrical equipment	0.284	0.332	0.334	2.14	2.19	2.08
C28	Machinery	0.256	0.309	0.315	4.19	4.71	4.20
C33	Repair of machinery	0.257	0.293	0.312	0.39	0.38	0.27
H50	*Water transport*	*0.257*	*0.275*	*0.309*	*0.47*	*0.55*	*0.43*
C17	Paper products	0.267	0.289	0.304	0.42	0.32	0.29
C25	Fabricated metal products	0.241	0.301	0.300	1.15	1.25	1.05
C21	Pharmaceuticals	0.221	0.266	0.298	0.94	1.03	1.03
H51	*Air transport*	*0.209*	*0.273*	*0.290*	*0.90*	*0.87*	*0.86*
C31–32	Furniture and other goods	0.222	0.259	0.270	2.17	1.71	1.44
C13–15	Wearing apparel	0.277	0.283	0.264	4.03	2.82	2.66
C23	Other mineral products	0.229	0.255	0.260	0.35	0.26	0.24
F	*Construction*	*0.174*	*0.244*	*0.259*	*13.27*	*16.05*	*17.06*
C16	Products of wood	0.242	0.251	0.244	0.25	0.16	0.17
C18	Printing products	0.206	0.233	0.239	0.18	0.12	0.12
E37–39	*Sewerage*	*0.239*	*0.236*	*0.235*	*0.43*	*0.30*	*0.24*
D35	*Electricity, gas, steam*	*0.198*	*0.235*	*0.220*	*2.00*	*2.36*	*2.21*
M74–75	*Other professional services*	*0.069*	*0.128*	*0.215*	*0.14*	*0.14*	*0.23*
C10–12	Food products	0.165	0.198	0.201	6.45	6.35	6.26
H49	*Land transport*	*0.150*	*0.199*	*0.199*	*2.32*	*2.63*	*2.76*
H52	*Warehousing*	*0.137*	*0.183*	*0.194*	*0.31*	*0.38*	*0.41*
E36	*Water supply*	*0.188*	*0.182*	*0.175*	*0.12*	*0.15*	*0.17*
H53	*Postal services*	*0.112*	*0.132*	*0.166*	*0.07*	*0.05*	*0.06*
G45	*Trade of vehicles*	*0.111*	*0.145*	*0.164*	*1.29*	*1.03*	*0.95*
A01	Crop and animals	0.118	0.150	0.154	1.93	1.90	1.81
M72	*Scientific research*	*0.089*	*0.134*	*0.154*	*0.20*	*0.25*	*0.48*
A03	Fishing products	0.134	0.171	0.151	0.19	0.17	0.18
M71	*Engineering services*	*0.089*	*0.124*	*0.144*	*0.35*	*0.41*	*0.40*
A02	Forestry products	0.102	0.137	0.143	0.07	0.07	0.07
B	Mining products	0.133	0.196	0.142	0.33	0.43	0.44
R_S	*Other services*	*0.109*	*0.129*	*0.141*	*2.15*	*1.82*	*2.06*
J62–63	*Information services*	*0.093*	*0.121*	*0.137*	*0.82*	*0.92*	*1.25*
M69–70	*Legal services*	*0.073*	*0.129*	*0.132*	*0.38*	*0.46*	*0.40*

Table 3 (continued)

Code	Final product name	θ (imports per unit of final output)			Imports in supply chain (share in global imports in %)		
		2000	2008	2014	2000	2008	2014
I	*Hotel and food services*	*0.098*	*0.117*	*0.121*	*2.76*	*2.58*	*2.59*
Q	*Human health services*	*0.079*	*0.102*	*0.120*	*4.34*	*4.52*	*5.23*
J61	*Telecommunications*	*0.106*	*0.114*	*0.116*	*1.27*	*1.19*	*1.26*
J59–60	*Broadcasting services*	*0.090*	*0.098*	*0.105*	*0.40*	*0.28*	*0.29*
N	*Administrative services*	*0.076*	*0.095*	*0.103*	*0.59*	*0.56*	*0.60*
G46	*Wholesale trade*	*0.088*	*0.098*	*0.100*	*3.00*	*3.00*	*2.81*
K65	*Insurance services*	*0.060*	*0.105*	*0.100*	*0.84*	*1.03*	*1.00*
P85	*Education*	*0.064*	*0.090*	*0.099*	*1.78*	*1.87*	*2.25*
K64	*Financial services*	*0.081*	*0.096*	*0.098*	*1.05*	*1.05*	*0.97*
J58	*Publishing services*	*0.104*	*0.117*	*0.098*	*0.60*	*0.39*	*0.26*
O84	*Public administration*	*0.074*	*0.093*	*0.094*	*6.02*	*5.82*	*5.56*
M73	*Advertising services*	*0.053*	*0.065*	*0.077*	*0.06*	*0.05*	*0.06*
G47	*Retail trade*	*0.059*	*0.069*	*0.073*	*2.40*	*2.21*	*2.38*
K66	*Auxiliary finance services*	*0.060*	*0.081*	*0.069*	*0.20*	*0.17*	*0.11*
T	*Services of households*	*0.111*	*0.131*	*0.047*	*0.01*	*0.01*	*0.00*
L68	*Real estate services*	*0.032*	*0.035*	*0.036*	*2.09*	*1.85*	*1.85*

Supply chain fragmentation ratios (θ) for 56 goods and services (weighted across countries of finalisation). This is the amount of imports in the supply chain of the good or service expressed per unit of final output, calculated according to Eq. (6). All ratios are expressed in constant prices of the year 2000. Imports in last three columns are given as shares in overall total of intermediate imports (at current prices) and add up to 100% in each column. Rows are sorted by θ in 2014, from high to low. Code column indicates the classification code of the industry producing the final product (based on ISIC rev. 4). Entries in rows for services are in italics.

reinforces the conclusion from Bems et al. (2013) that the product mix of final demand plays an important role in driving the global trade elasticity. We add our finding of the similar importance of changes in the pace of fragmentation in supply chain production.

The 2000s have been characterised by an increased concentration of final production stages, such as assembly activities, in China (Reyes-Heroles et al. 2020). We split the trade effects identified above into those related to final production in China, and those related to final production outside China.

Table 2 shows that shifts of final production stages to China and concomitant increase in imports of final goods from China added 0.30 points to the global trade elasticity in the pre-crisis period. But this effect petered out after the crisis, adding only 0.06 points during 2011–2014. Production relocation also fuelled trade in intermediates as Chinese supply chains were on average more fragmented than other supply chains in the world. Table 2 shows that the shift in global final demand towards output from Chinese chains added 0.17 points to the global trade elasticity before, and 0.16 points after. A major change, however, is observed regarding the pace of fragmentation within Chinese supply chains. Table 2 shows that fragmentation of Chinese supply chains contributed positively (0.07 points) before the crisis. Interestingly, the Chinese chains defragmented after the crisis (on average, weighted by final output), bringing the global elasticity down by 0.14 points. This reflects the increasing ability of China to substitute its imports of intermediates by domestics production, with local firms spanning more and more stages of production (Kee and Tang 2016; Chor et al. 2020). In contrast, there was continuing fragmentation of chains ending outside China, in total adding 0.37 points before the crisis, and 0.20 points after. This involved for example the integration of Eastern European countries into value chains in the European Union (Marin 2006). In conclusion, the rise of China as a final production location boosted the global trade elasticity before the crisis by 0.54 (0.07 + 0.17 + 0.30) points out of the 1.16 points (column 1). But this did not continue after the crisis, as Chinese chains became more self-sufficient and Chinese demand for domestically produced goods increased faster than its demand for imports, both intermediates and final.

7 Concluding Remarks

In this paper, we introduced a new measure of supply chain fragmentation which sums all imports by all countries that participate in the chain. We found that the pace of cross-border production fragmentation slowed down after 2008, in particular for supply chains of electronic goods and wearing apparel. Supply chains of services continued to fragment, also after 2008. We also argued that fragmentation trends need to be assessed on the basis of trade data in volume terms, and showed substantial confounding effects of differential price movements across intermediates. We used the new measure to account for changes in the trade elasticity of global GDP, extending the framework by Bems et al. (2010, 2011). We confirmed the important role of asymmetric demand shocks in the decline in trade elasticity after the 2008/2009 crisis (Aslam et al. 2018). In particular, we find that global demand shifted towards output of chains of investment goods and chains ending in China. This fuelled trade in final goods as well as in intermediates in the pre-crisis period, adding 0.72 points to the global trade elasticity during 2000–2007, but no longer afterwards. In addition, we found that the fragmentation of supply chains added 0.44 points to the global trade elasticity before the crisis, but only 0.05 points after. All in all, our findings suggest that demand mix changes and fragmentation trends both accounted for a sizeable part of the decline in the global trade elasticity. Our main conclusion and recommendation is that they should be analysed in conjunction for a better understanding of the dynamics in world trade.

As a final remark, we expect our approach to be a versatile tool in future analyses of global trade, including the impact of the current COVID-19 pandemic (WTO 2020). We showed that SCF ratios can be used to track fragmentation trends at a disaggregate industry level, and potentially also at a fine-grained product level, if data allow. This may be used to point towards potential vulnerabilities of global supply chains. For example, our data can be used to show that production of human health services fragmented internationally in the past decades (see Appendix Table 3), a trend that might be reversed in response to the pandemic. In addition, increased uncertainty may encourage firms to re-shore activity back to rich countries or more generally to shorten supply chains. But it may also stimulate a process of diversification, with industries sourcing a given input from multiple countries to alleviate the problem of excessive dependence on one country. These developments are likely to have persistent effects on the level of global trade, which can be traced in our accounting framework. Needless to say, our measurement framework is basically model-free. It provides a first exploration of the patterns in the data that may inform further study into the many structural and cyclical factors that determine the pace of global trade.

Appendix: Computation of the Supply Chain Fragmentation (SCF) ratio

For ease of exposition we make use of matrix notation. Let **A** be a matrix of intermediate input requirements (per unit of industry output) with dimensions (C*NxCN*) where *C* is the number of countries and *N* is the number of industries in each of the countries. We are interested in the imports along the supply chain of a particular final product from industry *s* in country *i (s,i)*. Let **z** be a (*CN*x1) vector with element *(s,i)* set to one and zeros elsewhere. The last stage of production requires intermediate inputs from first-tier suppliers, given by $\mathbf{A}\bar{z}$ (*CN*x*CN*). $\bar{z}$ is a diagonal matrix, with the elements of **z** on the main diagonal. As we aim to measure import flows only, all domestic transaction flows are excluded by a suitably chosen "trade selection" matrix (**T**).[15] Imports sourced from foreign first-tier suppliers are thus contained in a $CN \times CN$ matrix $\mathbf{M}_z^{tier1} = \mathbf{T} \circ (\mathbf{A}\bar{z})$, where ○ refers to element-wise multiplication (the Hadamard product operation).

Production by the first-tier suppliers in turn requires intermediate inputs from second-tier suppliers, given by $\mathbf{A}(\overline{\mathbf{Az}})$. The imports from second-tier suppliers are then $\mathbf{M}_z^{tier2} = \mathbf{T} \circ \left(\mathbf{A}(\overline{\mathbf{Az}} \right)$. Note that this includes imports by country *s*, but can also include imports by other countries hosting first-tier suppliers. Continuing this line of reasoning for higher-tier suppliers, we can write $\mathbf{M}_z^{Int}$, the ($CN \times CN$) matrix with import flows needed for one unit of final output of (*s,i*) as an infinite series $\mathbf{M}_z^{tier1} + \mathbf{M}_z^{tier2} + \mathbf{M}_z^{tier3} + \ldots$. Substituting the expressions above, we find

$$\mathbf{M}_z^{Int} = \mathbf{T} \circ (\mathbf{A}\bar{z}) + \mathbf{T} \circ \left(\mathbf{A}\overline{\mathbf{Az}} \right) + \mathbf{T} \circ \left(\mathbf{A}\left(\overline{\mathbf{A}^2\mathbf{z}} \right) \right) + \mathbf{T} \circ \left(\mathbf{A}\left(\overline{\mathbf{A}^3\mathbf{z}} \right) \right) + \ldots, \quad (15)$$

which can be written as

[15] The *C* blocks of dimension *N*x*N* along the main diagonal of **T** are filled with zeros, while all other elements of **T** have value one. This multiplication implies that domestic transactions are set to zero, while cross-border transactions remain unaffected. If one would like to focus on imports between specific pairs of countries or industries, more elements of **T** should be set to zero.

$$\mathbf{M}_z^{Int} = \mathbf{T} \circ \{ \mathbf{A} \overline{[(\mathbf{I} - \mathbf{A})^{-1} \mathbf{z}]} \} \tag{16}$$

(16) follows from the well-known Taylor-series expansion of the Leontief inverse matrix.[16]

$\mathbf{M}_z^{Int}$ is the (*CNxCN*) matrix with the typical element $m_z^{Int}(t,j)(u,k)$ representing the value of cross-border flows of intermediates from *(t,j)* to *(u,k)* required for the production of final output of (*s*,*i*). The nominal fragmentation measure of the supply chain of (*s*,*i*) is given by the aggregate of intermediate imports in the supply chain, summing across all elements of this matrix:

$$\theta_z = 1' \mathbf{M}_z^{Int} 1 \tag{17}$$

where **1** is a (*CN*x1) summation vector consisting of ones and a prime indicates transposition.

Suitable adjustment of the **z** vector results in the derivation of the total imports related to the production of a particular amount of final products. For example, let $f(s,i)$ be the final output of industry *s* in country *i*. The aggregate of imports in the supply chain of (*s*,*i*) is then given by $\theta(s,i) \times f(s,i)$.

We introduce a subscript to indicate year *t* in order to track changes in θ over time. Let $\mathbf{A}_t$ be the nominal matrix of intermediate input requirements stated in current (year *t*) prices. And let $\mathbf{A}_{t+1}^{PYP}$ be the matrix for year *t + 1* at year *t* prices (also known as previous year prices, PYP). Using (16) we can now define the current price intermediate import matrix

$$\mathbf{M}_{z,t}^{Int} = \mathbf{T} \circ \{ \mathbf{A}_t \overline{[(\mathbf{I} - \mathbf{A}_t)^{-1} \mathbf{z}]} \} \tag{18}$$

And the intermediate import matrix of year *t+1* in year *t* prices

$$\mathbf{M}_{z,t+1}^{Int,PYP} = \mathbf{T} \circ \{ \mathbf{A}_{t+1}^{PYP} \overline{[(\mathbf{I} - \mathbf{A}_{t+1}^{PYP})^{-1} \mathbf{z}]} \} \tag{19}$$

Such that the change in the SCF ratio can be written as

$$\theta_{z,t+1}^{PYP} - \theta_{z,t} = 1' \mathbf{M}_{z,t+1}^{Int,PYP} 1 - 1' \mathbf{M}_{z,t}^{Int} 1 \tag{20}$$

Input–output tables at previous year prices have the desirable characteristic that the elements of the deflated columns and corresponding rows add up to the same value, or put otherwise, that the fundamental input–output equality is still valid. For longer periods, the ratio should therefore be chained to account for annual changes in the **M** matrix. For example, the change in the SCF ratio over the period $[t, t+2]$ is given by $\left(\theta_{z,t+2}^{PYP} - \theta_{z,t+1}\right) + \left(\theta_{z,t+1}^{PYP} - \theta_{z,t}\right)$. The additive property is also crucial for our decompositions to be exact. Making exact decompositions of the world trade

[16] See Miller and Blair (2009) for the mild conditions under which the summation converges. **I** stands for the *CN*x*CN* identity matrix.

elasticity as in (13) over longer than one year periods therefore requires the use weights in the initial year of the period (Table 3).

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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