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Sectoral interlinkages in global value chains: Spillovers and network effects

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Abstract

This paper studies the role of global input-output linkages in transmitting economic disturbances in the international economy. Our empirical results suggest that these sectoral spillovers are both statistically significant and of economic importance. We also provide evidence that it is not the interlinkages *per se* that matter for the international transmission but rather the presence of global hub sectors that are either large suppliers or purchasers of other sectors' inputs. When the links between these sectors and the rest of the global value chain are severed, the spillovers diminish strongly and eventually become statistically insignificant. This highlights the importance of the structure of the network for enabling spillovers and the prominent role played by hub sectors in the global economy.

JEL Classification E30, E32, F44, F62

Keywords input-output linkages, networks, spillovers, global value chains.

Non-technical summary

Decades of rapid globalisation have turned national production structures into complex global value chains. In these international networks, firms purchase inputs from suppliers, add value and sell them onward to other firms or final consumers. These value chains are intricate and involve companies across various sectors in different countries.

We show that the structure of global input-output linkages matters for how economic disturbances are transmitted through sectors in the world economy. Our empirical estimates suggest that a 1% change in real value added in the global value chain translates into around 0.3 percentage point impact on the real value added of a sector, on average. These effects are robust to the inclusion of various controls, such as other country-sector-specific determinants of real value added, movements in aggregate economic activity in the national economy, global factors (commodity prices and global interest rates) and unobserved common factors.

This paper also provides evidence that it is not the production linkages *per se* that cause the spillovers. Instead, they are largely driven by a few global hub sectors that link otherwise unrelated sectors together. In our dataset, the top 10 upstream sectors barely changed between 1997 and 2009 and comprise primarily "renting of machinery and equipment and other business activities" (which apart from renting comprise of research and development and computer related activities) and raw materials (chemicals, mining and metals) in the United States, Germany and Russia. Downstream in the value chain, sectors in China have risen to prominence. From not even entering the top 20 in 1997, the construction, basic metals and electrical and optical equipment sectors in China occupy the top 10 ranking in 2009.

When we sever the links between the top global hub sectors and the rest of the value chain spillovers are considerably reduced and eventually become statistically insignificant. This highlights the importance of the structure of the global network for generating spillovers and the prominent role played by hub sectors in the global economy. Our results thus add to the growing empirical literature on the quantitative importance of global input-output linkages for movements in aggregate activity.

1 Introduction

National economies are made up of complex production networks. Firms purchase inputs from upstream suppliers, add value, and sell intermediate inputs to other downstream firms that add value before the product or service is sold for final consumption. Decades of rapid globalisation have turned national production networks into global value chains that involve firms in different countries and across many different sectors (Baldwin, 2006; 2016). The structure of international production networks matters. As a recent strand of research has shown, shocks to individual firms or sectors that propagate through production linkages can be one explanation for the origins of aggregate movements in economic activity (Long and Plosser, 1983; Horvath, 1998, 2000; Foerster, Sarte and Watson, 2011; Jones, 2011 and Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi, 2012).

While a sector's contribution to total value added is the purely accounting reason for why some sectors might have a disproportionately large impact on economic activity in the aggregate, it is not the only factor that makes them a - in the network jargon - "critical node". Their potential for propagating shocks depend both on the degree to which they are supplying or purchasing inputs to/from other sectors and how they shorten the distance between sectors that do not otherwise trade directly (Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi, 2012; Carvalho, 2014 and Pesaran and Yang, 2016). As is argued by this literature, and as we emphasise in the rest of this paper, the network structure of global production, and in particular the presence of global hub sectors, is one important explanation for why and how economic activity spills over through sectors and across countries.

These insights have profound implications for today interconnected world. Could the rather spontaneous organisation of firms into global value chains be a candidate for the transmission of economic disturbances throughout the world economy and help explain why business cycles across countries are increasingly synchronised (Frankel and Rose, 1998; Burstein, Kurz and Tesar, 2008 and di Giovanni and Levchenko, 2010)?

To shed light on these questions, we draw on, and contribute to, two strands of the literature: (i) the role of input-output linkages and production networks for transmitting economic activity across sectors in different countries and (ii), the emergence of global value chains in international trade and the role of cross-border production for synchronising activity across countries. We make use of global input-output data from the publicly-available World Input-Output Database. These tables contain entries for 35 sectors in 40 countries annually, over 17 years (from 1995 to 2011) and cover around 85% of world GDP[1].

In order to test for real value added spillovers across sectors in the global economy, we specify a non-linear panel data model following Kapetanios, Mitchell and Shin (2014). The model allow us to estimate upstream and downstream network effects from a group of endogenously determined sectors in the (global) value chain and for controlling for other observed and unobserved causes of a sector's real value added, as well as other determinants. Through our threshold estimation we are also able to determine which are the sectors driving the transmission across countries ("hub" sectors).

Our results confirm that trade in global value chains and in particular global hub sectors has made international production tightly interconnected over time. Empirical estimates from our econometric model suggest that a 1% change in real value added in the global value chain of a sector translates into around 0.3% impact on a sector, on average.

The primary reason for the spillovers is, according to our results, the presence of global hub sectors that either act as large suppliers of inputs from - or users of - inputs of many others. The hubs in the global network have changed over time, primarily downstream in the value chain. Here, we can in particular observe the increasing importance of China in our data. From not even entering the top 20 of the most important sectors in 1997, three Chinese sectors (construction, electrical and optical equipment and basic and fabricated metals) appear in the top 10 in 2009. Upstream in the value chain, our model suggests that the 10 most important sectors have remained broadly stable between 1997-09 and are dominated by "renting of machinery and equipment and other business activities", which includes R&D and computer activities, raw materials, chemicals and finance in the United States, Germany and Russia.

To illustrate the importance of these hubs for generating spillovers, we perform a counter-factual exercise where the links between the hubs and the rest of the global production network are severed. Once we have severed the linkages one by one, the effects through the global value chains diminish rapidly. Specifically, when the links between the top 15 hubs (three upstream and 12 downstream sectors) and the rest of the global value

[1] Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R. and de Vries, G. J. (2015), An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. Review of International Economics, 23: 575-605. doi:10.1111/roie.12178

chain have been removed, the spillovers become statistically insignificant. This indicates that global hub sectors have a key role to play in synchronising sectoral economic activity within and across countries and provides empirical evidence for the theoretical analysis outlined by Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi (2012). Moreover, akin to Acemoglu, Akcigit and Kerr (2015), we also assess the direction of two exogenous shocks ("upstream" or "downstream" in the global value chain) and find evidence of backward propagation of a demand shock.

The rest of this paper is organised as follows: Section 2 starts with a brief description of the literature related to this paper. Section 3 presents the main data sources and some stylized facts about the global input-output network. Section 4 introduces the empirical specification and Section 5 presents the empirical estimates of real value added spillovers and shock transmission in global value chains as well as illustrating some post-regression evidence supporting the importance of hubs. Section 6 provides some concluding remarks and avenues for future research.

2 Related literature

This paper is related to two different strands of the literature: (i) the role of input-output linkages for economic activity across sectors and (ii) the emergence of global value chains in international trade and the role of cross-border production for synchronising activity across countries. In the following, we will provide a brief overview of this literature.

2.1 Production networks and spillovers

Starting with the seminal work of Long and Plosser (1983), a growing literature on the role of sectoral input-output linkages for movements in aggregate activity has emerged (Horvath, 1998, 2000; Foerster, Sarte and Watson, 2011; Jones, 2011 and Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi, 2012). Their findings suggest that idiosyncratic microeconomic shocks that propagate through firm or sectoral interlinkages within an economy could help explain the origins of aggregate fluctuations. Specifically, Horvath (1998) showed that as much as four fifths of volatility in United States real GDP could be due to independent shocks to various economic sectors, while Foerster, Sarte and Watson (2011), estimates that idiosyncratic sectoral shocks explain about half of the variability in industrial production in the United States after the mid-1980s. Similarly, Atalay (2014) find that around two thirds of variability in aggregate output could be due to sector-specific shocks that spread through input-output linkages, in a model where incomplete substitutability among inputs is assumed. Moreover, Carvalho (2014) argues that, in particular, the presence of large sectoral hubs in production networks facilitates the propagation of shocks of otherwise localised disturbances. Not only do these hubs have direct connections with many other sectors through supply and use relationships, they also bring otherwise unrelated sectors "closer" to each other in a network sense.

Empirical evidence on how economic disturbances transmit across input-output linkages is sparser, but recent strides have been made, in particular by Saito, Nirei and Carvalho (2014), di Giovanni, Levchenko and Mejean (2014), Acemoglu, Akcigit and Kerr (2015) and across countries by Boehm, Flaaen, Pandalai-Nayar, (2014).

These empirical findings are somewhat in contrast to much of the standard macroeconomic literature, starting with Lucas (1977). There, it is argued that idiosyncratic shocks to individual firms or sectors will have very little - if any - impact on economic activity in the aggregate. When the economy is disaggregated enough, the argument goes, a shock to one sector will be broadly offset by a shock of the opposite sign to another sector and in the aggregate, these idiosyncratic sector shocks will tend to "average out". However, as Gabaix (2011) showed, when an economy's firm-size distribution is "fat-tailed", idiosyncratic shocks to very large firms may not be negated by shocks of the opposite sign to smaller firms and could thus translate into macroeconomic fluctuations. Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi (2012) expanded on this idea, and showed that not only does the firm-size distribution matter, but also the structure of the input-output network.

For example, if the economy consists of n number of sectors that do not sell or buy intermediate inputs from each other (Figure 1), Lucas diversification argument will hold as n increases and any idiosyncratic shock to one sector will be broadly offset by a shock of the opposite sign to other sectors. Similarly, in an equally dependent network where each sector is symmetrically selling and purchasing inputs from all other sectors, the diversification argument will also hold as n increases. However, if the economy is more similar to the third type of network (a so-called star-network) where one sector is disproportionately a large supplier (or purchaser) of inputs to all other sectors, shocks may not average out, even if n increases. This theoretical reasoning is crucial for the analysis in this paper and we will dedicate Section 3 to present some empirical facts about the presence of sectoral hubs in the global input-output network.

2.2 Global value chains and co-movements in business cycles

Although national production links are important, the build-up of global production networks following decades of continuous globalisation has increased the interaction among sectors across countries. Baldwin (2006) characterised this transformation of international trade over time as two unbundlings. This first enabled the spatial separation of production from consumption, as transportation costs fell. The second unbundling gave rise to what we today call trade in global value chains and permitted the scattering of production stages across countries due to the sharp fall in communication and coordination costs[2].

If links between sectors could affect aggregate activity in a particular country, could it be that trade between sectors in global value chains also helps to explain the increasing synchronisation of business cycles across countries, as documented by Frankel and Rose (1998)? As standard international business cycle models have been unable to account for these empirical findings, this has given rise to what Kose and Yi (2006) dubbed the "trade co-movement puzzle". Both Burstein, Kurz and Tesar (2008) and di Giovanni and Levchenko (2010) provides insights into this puzzle by documenting higher business cycle correlations among pairs of sectors that use each other as intermediate inputs, suggesting that "production sharing" is one significant part in explaining the puzzle.[3] Moreover, di Giovanni, Levchenko and Méjean (2014) show that business cycle shocks transmit through direct trade and indirect linkages by large multinational firms. In the absence of those linkages, average business cycle correlations fall significantly and emphasise the role played by fragmented production for explaining synchronisation of economic activity across countries.

2.3 The contribution of this paper

This paper adds to the empirical evidence of sectoral input-output spillovers in (global) production networks. Previous empirical work that has assessed the importance of input-output linkages has focused mainly on national input-output links, usually at one point in time (see for example Acemoglu, Akcigit and Kerr, 2015). We improve on this literature

[2]For an explanation of why firms organise in global value chains, see for instance Antràs and Chor (2013)

[3]Others, for example Imbs (2004) argued that co-movement in business cycles could simply be a reflection of the fact that country-pairs that trade with each other are simply similar in other ways and thus subject to common shocks.

in two respects: first, we do not only take into account national production structures, but truly global interlinkages with data from the World Input-Output tables[4]. This is important as production is not only a national matter in the age of global value chains. Second, we allow for the structure of the network to vary over time, in order to account for structural changes in the global economy such as the growing importance of trade in services and the rise of China in trade.

Moreover, our econometric strategy allows us to endogenously determine the most relevant sectors in the global input-output network, the so-called hubs. In this setting, only the sectors above a certain threshold enter into the function determining spillovers on other sectors. With this information, we can pinpoint the globally most important sectors (those which most often enter the function of all other sectors) both as upstream suppliers and downstream users. Once identified, we conduct a counterfactual exercise where the links between these sectors and the other sectors in the network are severed, one by one. This enables us to test whether or not the structure of the network is instrumental for transmitting economic activity, as proposed by Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi (2012). Moreover and in a similar vein to Acemoglu, Akcigit and Kerr (2015), we also test the magnitude and direction of two exogenous shocks, one to demand (government spending) and one to supply (TFP). This exercise illustrates the direction of shock propagation in the network (upstream and downstream).

3 Data and stylised facts

3.1 Data sources

In the rest of this paper, we use a sectoral dataset constructed from the publicly available World Input Output Database (WIOD). These global input-output tables contain annual information for 35 sectors, comprising primary, durable and nondurable manufacturing as well as services sectors, including financial intermediation. The tables are available for 40 countries, of which a majority is in the European Union, but also include countries in North America, South America and Asia, as well as the rest of the world (constructed as one economy) from 1995 to 2011. Therefore, for each year a full country-sector input-output matrix of the dimension 1435×1435 is available and allows for the analysis of

[4] Global input-output tables have also been used by Auer, Levchenko and Sauré (2017) who investigate inflation spillovers through input linkages.

supply and use relationships between a sector in a specific country and all other sectors in the country as well as all sectors in the 39 other countries.[5]

These tables are accompanied by Socio-Economic Accounts which contain country-sector panel data on employment (number of workers, compensation and share of labour in high, medium and low skilled occupations), capital stocks, gross output and value added at current (until 2011) and constant prices (until 2009).[6]

The two data-sets form the basis for the network-based measures constructed in the following and enable the complete mapping of supply and use relationships in the global economy, which will be taken advantage of in Section 4. For further computational details, the reader is referred to Appendix B.

3.2 Network structure of the global economy

As argued by Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi (2012), the structure of production networks matters for if - and how - shocks propagate and if they could lead to aggregate fluctuations. To illustrate the network structure of the global economy, we provide some stylised facts and show that the data in the World Input-Output tables are indeed characterised by some large sectoral hubs.

We compute the weighted degree defined as $d^i = \sum_{j=1}^{N} w_{ij}$, that is the sum of all weights of all links attached to a sector i for each country-sector pair in the network (see also Carvalho, 2014 and Cerina, Zhu, Chessa and Riccaboni, 2015). This measure captures sector i's connectivity through (binary) supply and use relationships but also the strength of these relationships (the monetary value). In other words, it assigns a larger value to sectors supplying/purchasing inputs of many other sectors in the network, while it assigns a value equal to zero if there are no interlinkages. If the global production network was fairly equally distributed (recall the middle illustration in Figure 1) the measure would simply yield a horizontal line across all sectors. If the network is characterised by hubs and more similar to a star network as in Figure 1, we would expect to see a left-skew in the distribution of sectors, meaning that a small number of sectors have relatively strong input supplying/purchasing relationships with many other sectors in the network.

Figure 2 shows the weighted degree across all country-sectors in 2009. Given the level

[5] www.wiod.org

[6] For the construction of the World Input-Output tables, see Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M. and De Vries, G., 2013. The construction of world input-output tables in the WIOD project. Economic Systems Research, 25(1), pp.71-98.

of aggregation in the World Input-Output tables, very few sectors have no connection whatsoever to other sectors (the ones that do, are largely private households with employed persons). The average weighted total degree across sectors is 0.9 and around that value we find for example pulp and paper in Italy and France, electricity gas and water supply in the UK, and chemicals and chemical products in Canada.

Above the 95th percentile of the weighted degree, we find large input supplying/purchasing sectors such as financial intermediation in the United States and the United Kingdom, renting of machinery and equipment and other business activities in the United States, France and Italy and mining and quarrying in Russia as well as wholesale trade in the United States and China.

One could argue that the weighted degree is simply a reflection of a sector's share of global value added. If so, could movements in these disproportionately large sectors be the purely accounting reason as to why sectoral activity might impact aggregate activity? While there is some correlation between a sector's contribution to global value added and its total degree, it is not the full story (Figure 3). For example, about 22% of sectors above the 95th percentile in terms of total degree have very low shares of global value added (less than 0.01%). These sectors are typically mining and quarrying activities in Europe, Russia and Asia and renting of machinery and equipment and other business activities in Western and Eastern Europe.

Another way of documenting the presence of hub sectors is to plot the evolution of the "distance" between any pair of sectors over time[7]. Distance measures the shortest path between any two sectors in the network, that is, how many times inputs from one sector are sold in order to reach another sector. If the network is characterised by hubs, distance should be lower than in the absence of them. One could think of an economy which has one large hub sector (similar to the star network in Figure 1) and another network which is less integrated. In the star network, each sector is only one trade away from each other through the hub. In less integrated networks, inputs from one sector travel further so the network distance is larger.

The blue line in Figure 4 (left-hand panel) shows the average distance across pairs of domestic sectors with foreign sectors in the World Input-Output tables. It is evident that network distance has fallen since the 2000s, albeit with a short disruption and a slowdown following the Great Recession. If we focus on sectors in specific countries, we can see

[7] Here, the shortest path is computed with the Dijkstra algorithm.

that their distance to other countries have generally become smaller over time. This is particularly noticeable for China, whereas the declines in the United States and Germany have been more gradual. Sectors in Germany have on average had lower distance to foreign sectors during the whole period, highlighting the relative openness of the German economy.

What would be the implications of the increasing presence of hubs in the network? Since they shorten the distance between otherwise unrelated sectors, we would expect correlation of economic activity between sectors on average to be higher as distance falls (Carvalho, 2014). To illustrate this point, we compute average pairwise correlations of sectoral real value added growth over 1995-2009 for all country-sectors and across various distances up- and downstream in global network in Figure 4 (right-hand panel).

Indeed, economic activity between two sectors correlates more strongly when distance is lower. This is important, because we argue that not only do hubs cause spillovers because they are large suppliers or purchasers of inputs, but they also shorten the distance between otherwise unconnected sectors. This could also help explain why activity across sectors co-moves within a country, but also across countries, even without the presence of aggregate shocks. Another interesting question is whether we can observe a co-movement in the gross output growth of sectors driven by network interdependence.

The Moran's I statistic provides a measure of correlation of a variable of interest through network relations and is defined as:

$$I = \frac{n}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j w_{ij}(y_i - \bar{y})(y_j - \bar{y})}{\sum_i (y_i - \bar{y})^2}$$

When we test the hypothesis of no network interdependence (I = 0), we find that for almost all the years in the sample we strongly reject the null hypothesis, meaning that we find evidence for positive network interdependence of gross output growth (Table 1). In sum, the network structure of the data in the World Input-Output tables seems to be characterised by sectoral hubs, and over time there has been a clear evolution towards tighter economic integration globally, even though most supply chains have clear regional characteristics (WTO 2013). Now, the relevant question is whether we can statistically establish an economically significant relationship between activity within a given sector and activity in its global value chain.

4 Methodology

To investigate how sectoral real value added spills over in global value chains, we utilise an econometric non-linear panel data model proposed by Kapetanios, Mitchell and Shin (2014). In this model, the current economic activity of a sector in a country, say sector i, is determined by sector i's past activity and a weighted average of the past economic activity of a group of sectors involved in its (global) value chain. In addition, we also consider network distance of other sectors from sector i. In this setting, more weight is attributed to sectors which have a higher share of value added in sector i's production and have a shorter distance to sector i in the World Input Output network. In the production of a car, for example, we would attribute more weight to the sector producing tires in the finished car's reference group, not only because the tires contribute to the finished car's total value added but also because the tires industry directly sells intermediate inputs to the car industry. Consider the following model specification:

$$y_{it} = \eta_t + \rho^{lag} y_{i,t-1} + \rho^{up} \tilde{y}^{up}_{i,t-1} + \rho^{down} \tilde{y}^{down}_{i,t-1} \tag{1}$$

where y_{it} is activity in a sector i at time t, $\tilde{y}^{up}$ is the upstream value added of other sectors defined by:

$$\tilde{y}^{up}_{i,t-1} = \sum_{j \neq i} 1(w^{up}_{ij,t-1} \geq r^{up}) w^{up}_{ij,t-1} y_{j,t-1} \tag{2}$$

$y^{down}_{i,t-1}$ is the downstream value added of other sectors defined by:

$$\tilde{y}^{down}_{i,t-1} = \sum_{j \neq i} 1(w^{down}_{ij,t-1} \geq r^{down}) w^{down}_{ij,t-1} y_{j,t-1} \tag{3}$$

In the weights' definition, we take both value added contribution and distance into account:

$$w^{up}_{ij,t} = \frac{VA_{j \to i,t}}{VA_{* \to i,t}} \times \frac{1}{d^{up}_{ij,t}} \tag{4}$$

$$w^{down}_{ij,t} = \frac{VA_{i \to j,t}}{VA_{i \to *,t}} \times \frac{1}{d^{down}_{ij,t}} \tag{5}$$

where VA is value added contribution to total output, i.e. the value added provided by a sector to another sector's total production, and d is the shortest distance between two sectors. Through the Leontief insight, we are able to trace the gross output used in all intermediate stages of production. Therefore, VA in (4) and (5) takes into consideration not only the direct connection via each sector's production chain, but also second and higher order interconnections to other sectors via direct trading partners.[8] The inclusion of both the value added share of a sector's total purchases (4) or sales (5) and the distance metric intends to achieve that the first component captures an importance of other sectors in sector i's production process and the second component captures the effective trading relationship between the sector i and other sectors. As we have shown previously, network distance is important because, apart from the value added contribution, whether sector j is directly trading with sector i or through some intermediate steps involving other sectors is relevant to degree in which activity in the two sectors correlate.[9] Table 5 in the appendix shows that the upstream and downstream measures do indeed capture different relations among sectors.

This panel model allows us to control for observed and unobserved common factors which could cause activity growth in a sector, but that is not driven by spillovers through production linkages. Therefore, the estimated spillover coefficient will just pick up the influence of the global value chain on activity of sector i. In the regression, we also include a $k \times 1$ vector of sector, country or global variables, $x_{i,t}$, a full set of year effects η_t and the error term has the form:

$$\varepsilon_{it} = \lambda' \mathbf{f}_t + u_{it}$$

where f_t is the $f \times 1$ vector of unobserved common factors modelled as in Pesaran (2006), i.e. with the cross-sectional averages of the dependent variable and the regressors and u_{it} is an *iid* error process.

Apart from better controlling for observed and unobserved factors driving fluctuations in economic activity, another interesting novelty of this approach is that it allows for the endogenous determination of the most important sectors in the global network (the so called hubs). The threshold search identifies the parameters r^{up} and r^{down} which are then

[8] Algebraically, $VA_{j \to i,t}$ is an entry of the matrix $VA_t = v_t L_t GO_t$ where v_t is a $(NC * NI \times NC * NI)$ diagonal matrix with value added vector on the diagonal, L_t is the Leontief matrix $(NC * NI \times NC * NI)$ and GO_t is a $(NC * NI \times NC * NI)$ diagonal matrix with gross output on the diagonal. NC is the total number of countries and NI is the total number of sectors. The Leontief matrix is computed as $L_t = (I - A_t)^{(-1)}$, with the dimension $(NC * NI \times NC * NI)$, where I is the identity matrix and A_t is the $(NC * NI \times NC * NI)$ technical coefficient matrix, that is the use of intermediate goods in the production of one unit of output and it is computed from the global input-output matrix Z_t as $A_t = Z_t GO_t^{(-1)}$.

[9] We also estimated the model with weights not adjusted by the distance variable. The model delivers similar results, however it has a higher sum of squared errors.

used to choose which sectors are included in (2) and (3).[10] These hubs will be identified in a regression context as those sectors entering most often into the endogenously determined group of relevant sectors across all sectors in the global network.

The threshold obtained from the grid search minimises the sum of squared errors, and thus ensure that the final model best fits the data. In a network sense, our approach identifies the significant edges ("links") between nodes. This makes it possible to draw up ex-post a rank of sectors for each year, according to their prominence in the global production network. It is worth noting that we identify the hubs as those sectors with the highest weights for the partners and we evaluate the importance of a sector with its connectedness (number of links). After all, by using only a sector's degree as measure of its importance a sector may appear important just because it provides a very high share of inputs to a few sectors even when it is not linked to many other sectors.

5 Results

In order to empirically estimate real value added spillovers through a sector's global value chain, we utilise our econometric model described in Section 4. We also discuss the results and provide some post-estimation details.

5.1 Estimates of the spillovers

We consider log-changes of the variables involved in the estimation, in order to address stationarity concerns regarding macroeconomic time series and also attenuate Nickell's bias[11]. The results from the regressions are reported in Table 2. The baseline regression only includes a lagged dependent variable and the past economic activity of upstream and downstream sectors' in the global value chain. As a robustness-check of the results, we also add other determinants such as time dummies and country and sector-level controls. Specifically, the regressions include country aggregate real value added, sector-level employment and global factors such as prices of agricultural products, metals and fuels as well as global interest rates. We also run regressions including capital stocks for the sample

[10] The threshold parameters are determined with a grid search over several percentile values of $w_{ij,t}^{up}$ and $w_{ij,t}^{down}$. (r^{up}, r^{down}) is the combination minimizing the model's sum of squared errors as in Hansen (1999).

[11] Nickell's bias (1981) occurs in dynamic panel data with fixed effects and is particularly severe when the number of cross-sectional units is considerably greater than the number of time observations.

1997-2007, which also verifies the consistency of the results for the pre-crisis period.[12]

The spillovers through the global value chain are significant and the magnitudes are notably relevant. The addition of control variables reduces the fairly large coefficients but does not compromise their significance. A 1% change in real value added in the global network translates into an impact of slightly above 0.3%[13] to a sector's real value added growth, on average. This means that aggregate effects do play a role in driving aggregate fluctuations, but they are not the only source and economic activity is also affected by sector-level production linkages.

5.2 Hubs in the global value chain

With the estimates derived from equation (1) and in particular the threshold parameters r^{up} and r^{down}[14] we are now able to determine, for each year, the sectors entering the reference group of each sector i in the sample. This enables us to identify upstream and downstream hubs in the global production network as those sectors entering the highest number of times in other sectors' upstream and downstream groups, respectively. Table 3 shows the rankings of sectors derived from the regressions that produced the results in Table 2 for 1997 and 2009. Looking at the upstream ranking, the top sectors are active in "renting of machinery and equipment and other business activities" (which includes R&D and computer activities) and raw materials (chemical, mining, metals) in the United States, Germany and Russia. This result is fairly intuitive and we expect such sectors to be located upstream as they provide primary inputs (both R&D and raw materials) to the production processes of many other sectors. This ranking changed little over time. As regards sectors situated downstream the production network, the ranking is dominated by manufacturing (cars, machinery and electrical and optical equipment), construction and government activities (in the United States).

Interestingly, in the top 10 downstream ranking we can observe the rise to prominence of some Chinese sectors at the expenses of those in the United States in recent years: three sectors in the United States have been replaced by three Chinese sectors, highlighting the growing importance of China in global value chains. The regression including sector level

[12]Tables 7 and 8 in Appendix A report the standardized and non-standardized results for the regression including the capital variable for the sample 1997-2007.

[13]The estimate refers to coefficients obtained from the regression with non-standardized variables (see Table 6 in the Appendix).

[14]The reader can refer to footnote 10 for details about the threshold determination.

capital stocks delivers the same ranking.

5.3 Estimates of spillovers stemming from two hub sectors

Another illustrative result of sectoral spillovers can be constructed by using the estimated coefficients ρ^{up} and ρ^{down} and the weights assigned to each sector pair i, j. In Table 4, we consider changes in real value added in one upstream and one downstream sector and their impact on all other sectors in the production network, stemming from all supply and use relations. We consider the top 1 upstream sector in 2009, German "renting of machinery and equipment and other business activities". A 1% change in real value added in this sector would affect 321 other sectors (almost a fourth of all sectors in our data) and the spillovers to other sectors would amount to 1.14%. About half of this impact is on other sectors in Germany, and slightly less than half is transmitted to other sectors in the euro area. The remainder (almost 16%) affect sectors in other parts of the world. Interestingly, the spillovers amplify through the production network.

For the downstream impacts we utilise a sector which has become prominent as a final assembler in many global value chains during the 2000s, namely China's electrical and optical equipment sector.[15] According to our estimates, a 1% change to real value added in this sector would have impact on 13% of all sectors in the data and would cause real value added spillovers of 0.47 percentage points. It is interesting to note that almost two thirds of the effect concern sectors in other countries than China.[16]

5.4 Spillovers in the absence of hub sectors

The importance of the sectoral hubs in the global network can be illustrated when the input-output relations between them and the rest of the global value chain are severed. This counter-factual exercise has two interesting features: first, if the hubs are instrumental in transmitting economic disturbances we would expect to see falling size of the estimated coefficients on the up- and downstream spillovers as hubs are gradually removed. Second, we would expect the spillovers to become statistically insignificant when enough top hub sectors are removed. We utilise the full rankings of sectors derived in Table 3 to first identify the hubs and then re-estimate equation (1) when the ties for these sectors are

[15] See for example, Lu (2015).

[16] The estimated spillover effects for the model with sector-level capital stocks and the 1997-2007 sample are reported in Table 9 in Appendix A.

severed, one at a time. This is done by setting the weight in (4) and (5) equal to zero first for the top one hub sector, then the top two, then three, and so on. The process continues until the estimated spillovers through the global value chain are statistically insignificant.

These recursive estimates reveal the importance of the global hub sectors for real value added spillovers (Figure 5). When the top five upstream and downstream global sectors are cancelled (ten in total), spillovers through the global value chain fall by almost a fifth. When the top three upstream and the 12 downstream global sectors are removed, spillovers through the global value chain become statistically insignificant and this highlights the importance of large global hubs in transmitting economic activity across sectors in different countries.

5.5 Transmission of sectoral shocks

Following Acemoglu, Akcigit and Kerr (2015), we also test the direction of two plausibly exogenous shocks. We consider one demand shock (government spending) and one supply shock (to total factor productivity). According to a theoretical setup in which production and preferences is Cobb-Douglas, supply shocks should propagate from upstream sectors to those downward in the supply chain, as downstream sectors are reliant on inputs from sectors further up the value chain. A demand shock on the other hand should propagate from downstream sectors to upstream ones, as their sales of inputs are directly tied to the demand for the final product. Here, it is also interesting to compare the impact through the global value chain with the "own" impact on the sector. Our demand shock is represented by changes in all government sectors' expenditure weighted by the share of sales of each sector i to the government, whereas the TFP shocks are lagged changes of estimated four-factor total factor productivity.

The results reported in the last two columns of Table 2 provide support to the upward propagation of demand shocks (government spending), whereas results for supply (TFP) shocks are inconclusive. However, we should remark that the supply shock regression utilises a smaller sample because of lack of data for TFP, both cross-sectionally and time wise.

6 Conclusions

As we have shown in this paper, the global economy is a network of complex input-output linkages characterised by large sectoral hubs. Our findings confirm the statistical and economic significance of these links for transmitting economic activity across sectors in the global economy. Our estimates suggest that a 1% change in economic activity in a sector's global value chain translates into around 0.3 percentage points impact on the activity of the sector, on average. We also provide evidence that it is not input-output linkages *per se* that cause the spillovers, but rather the presence of large hub sectors in the global economy that tie otherwise unrelated sectors together. In the absence of these sectors, spillovers through the global value chain become significantly reduced. This highlights their importance in synchronising economic activity across the global economy.

When assessing the transmission of sectoral shocks in the global network, we can confirm that demand shocks propagate upwards through the global value chain whereas results for supply shocks (TFP) are ambiguous. The effect stemming from these shocks through the value chain are fairly large, whereas the "own" impact is small and sometimes insignificant. This suggests that exogenous shocks only have a moderate direct impact on a sector, whereas the impact transmits and propagates through the global value chains, via the hub sectors.

We therefore add to the growing empirical literature (Saito, Nirei and Carvalho, 2014; di Giovanni, Levchenko and Mejean, 2014; Acemoglu, Akcigit and Kerr, 2015; Boehm, Flaaen, Pandalai-Nayar, 2014 and Auer, Levchenko and Sauré, 2017) on the importance of input-output linkages for movements in aggregate activity. The findings also stress the importance for policy makers not to only focus on aggregate - or global - shocks when considering cross-country spillovers, but also to take into account international production linkages. Moreover, we can confirm that the network structure of global production matters for how economic shocks might transmit through the presence of hub sectors, as suggested by Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi (2012) and Carvalho (2014).

Some caveats to the results in this paper should be highlighted. First, an obvious pitfall is that our data is not "granular" enough to make valid statements about the sector-level transmission of economic shocks. Ideally, we would like to test the hypothesis of firm-level spillovers in global value chains and their impact on aggregate activity. However, firm-level data is scarce and firm-level input-output data even more so. While not perfect, analysis on less aggregated input-output tables for the United States, as in Acemoglu, Akcigit and Kerr (2015) still find robust results with more finely disaggregated sectors.

In addition, our empirical model does not capture substitution of suppliers in the face of large disruptions, especially within sectors, which is one valid critique to input-output tables in general. While valid, the few studies that have attempted to estimate substitution effects between firms find that they are fairly small at least in the short term (see for example, Boehm, Flaaen, Pandalai-Nayar, 2014).

An interesting avenue for future research would be to estimate substitution effects in the longer run and investigate the speed of substitution with non-linear effects. In addition, firm-level evidence on the transmission of economic activity through complete global input-output networks (as in the World Input-Output database) and the identification of global "hub" firms could yield a better understanding of cross-country spillovers driven by granular shocks.

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Tables and Figures

Table 1: **Moran I's statistics**

year	Moran I	z-score	p-value
1996	0.088	27.27	0.000
1997	0.136	41.96	0.000
1998	0.202	62.21	0.000
1999	0.165	53.15	0.000
2000	0.099	31.94	0.000
2001	0.070	25.77	0.000
2002	0.068	22.66	0.000
2003	0.076	26.71	0.000
2004	0.052	18.04	0.000
2005	0.002	1.52	0.064
2006	0.003	4.46	0.000
2007	0.092	35.70	0.000
2008	0.002	2.97	0.002
2009	0.004	2.26	0.012
2010	0.137	50.07	0.000
2011	0.082	31.50	0.000

Notes: For each year, the table reports Moran I statistics (second column) and the test for the hypothesis H_0: no network interdependence (third and fourth columns). For details on hypothesis testing, the reader can refer to Moran (1950).

Table 2: **Regression results**

	baseline	**unobs.factors + controls**	**unobs. factors + controls + global bc**	**government (demand) shock**	**TFP (supply) shock**
lag	0.138***	-0.037***	-0.036***	-0.036***	0.058**
	(0.013)	(0.013)	(0.013)	(0.013)	(0.028)
upstream	0.156 ***	0.046***	0.049***	0.002	0.002
	(0.015)	(0.017)	(0.017)	(0.013)	(0.015)
downstream	0.059***	0.028**	0.027**	0.020**	0.003
	(0.013)	(0.013)	(0.013)	(0.009)	(0.015)
own				0.009	-0.034*
				(0.008)	(0.023)
country		0.134***	0.114***	0.198***	0.060**
		(0.023)	(0.023)	(0.013)	(0.031)
employment		0.238***	0.236***	0.239***	0.206***
		(0.008)	(0.008)	(0.008)	(0.015)
agriculture			- 0.024*		
			(0.014)		
fuel			-0.028*		
			(0.016)		
metal			0.011		
			(0.024)		
interest rate			-0.005		
			(0.014)		
year effects	n	y	n	y	y
obs.	17511	17511	17511	17511	4950

Notes: $***p < 0.01$, $**p < 0.05$, $*p < 0.1$
The table reports estimated coefficients from regression (1) where the dependent variable y_{it} is the log difference of value added. The average of the dependent variables is considered as common factor in the error term. To make it possible to compare coefficients, variables are standardized and the coefficient reported measure the effect of a one standard deviation change of the independent variables. Standard errors are reported in brackets.

Table 3: **Ranking of sectors in the production network - real value added**

Top sectors according to number of presences in other sectors' function

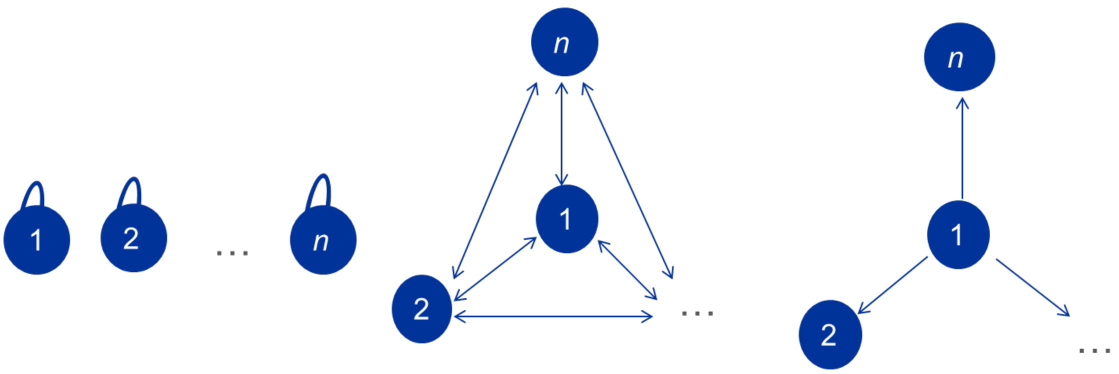
upstream 1997	**upstream 2009**	**downstream 1997**	**downstream 2009**
USA - renting of m&eq and other business activities	DEU - renting of m&eq and other business activities	DEU - transport equipment	DEU - transport equipment
DEU - renting of m&eq and other business activities	USA - renting of m&eq and other business activities	USA - transport equipment	CHN - electrical and optical equipment
RUS - inland transport	RUS - mining and quarrying	DEU - construction	CHN - basic metals and fabricated metal
DEU - basic metals and fabricated metal	GBR - renting of m&eq and other business activities	USA - public admin and defence; compulsory social security	USA - public admin and defence; compulsory social security
RUS - mining and quarrying	DEU - basic metals and fabricated metal	USA - construction	DEU - construction
RUS - wholesale trade and commission trade, except of motor vehicles and motorcycles	USA - financial intermediation	DEU - machinery, nec	DEU - machinery, nec
DEU - chemicals and chemical	FRA - renting of m&eq and other business activities	USA - electrical and optical equipment	CHN - construction
RUS - coke, refined petroleum and nuclear fuel	RUS - wholesale trade and commission trade, except of motor vehicles and motorcycles	DEU - basic metals and fabricated metal	DEU - basic metals and fabricated metal
USA - financial intermediation	NLD - renting of m&eq and other business activities	USA - basic metals and fabricated metal	FRA - transport equipment
USA - wholesale trade and commission trade, except of motor vehicles and motorcycles	DEU - chemicals and chemical	JPN - construction	USA - transport equipment

Table 4: **Change in value added of important hub sectors**
1% change to value added growth

	Upstream	Downstream
Origin of the change	Germany: Renting of machinery and equipment and other business activities	China: Electronics and optical equipment
number of sectors affected	321	172
sum of impact across affected sectors	1.14	0.47
of which is locally:	0.56	0.19
of which is in the euro area:	0.40	0.07
of which is cross-country:	0.18	0.21

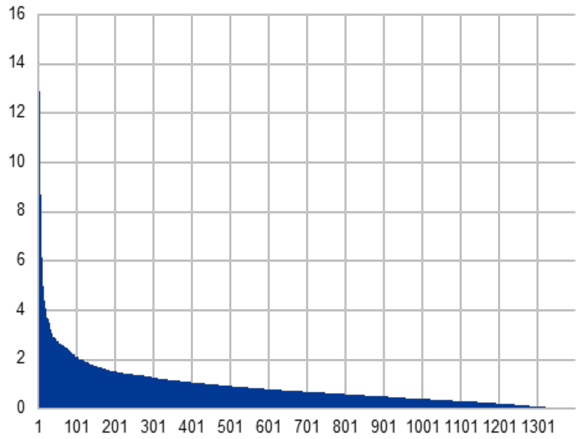
Notes: The impact of sector j reported in the columns on each other sector i is computed as $\rho^* w^*_{ij,t}$ and the overall impact as $\rho^* \sum_{j \neq i} 1(w^*_{ij,t} \geq r^*) w^*_{ij,t}$ with local (same country) and cross-country effects calculated by considering the affected sectors. * stands for "up" and "down".

Figure 1: Stylised network representations



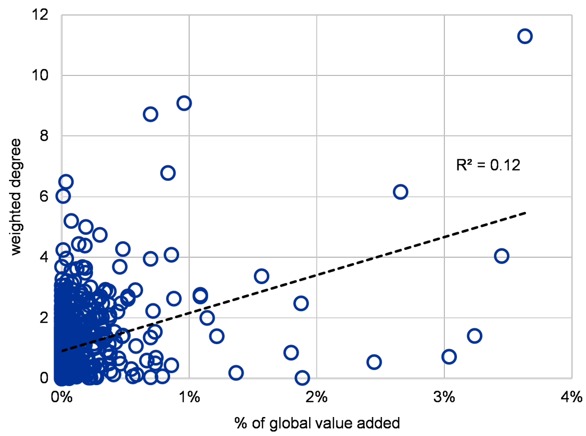
Source: Acemoglu, Carvalho, Ozdaglar and Tahbaz-Salehi (2012) "The Network Origins of Aggregate Fluctuations"

Figure 2: The weighted degree distribution across sectors



Note: The figure shows the sum over all the weights of the network in which a sector and is a direct and indirect input-supplying or purchasing sector in 2009. Sources: WIOD and authors' calculations.

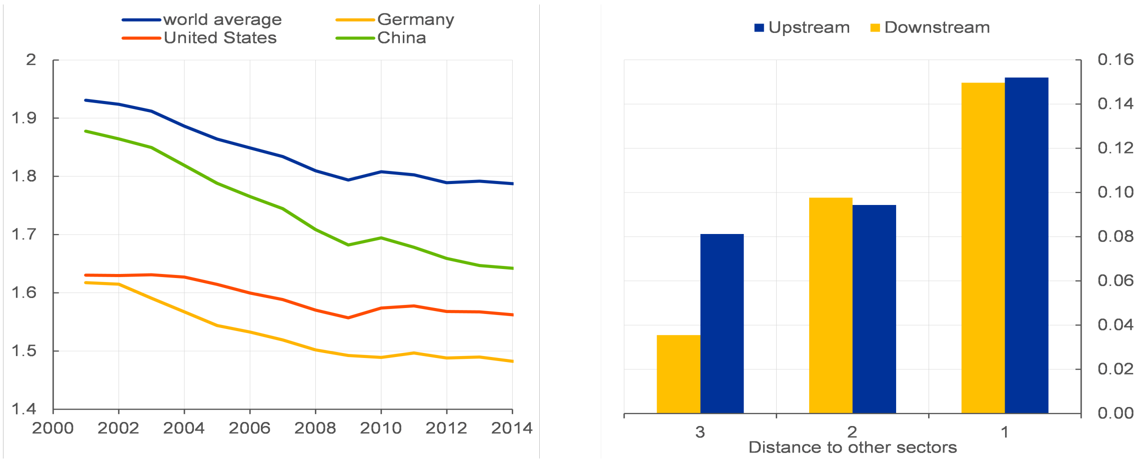
Figure 3: Weighted degree and global value added



Note: The Figure plots each country-sectors % share of global value added (x-axis) against the same sectors weighted degree (y-axis). Sources: see Figure 2.

Figure 4: Network distance and correlations across distance for upstream and downstream sectors

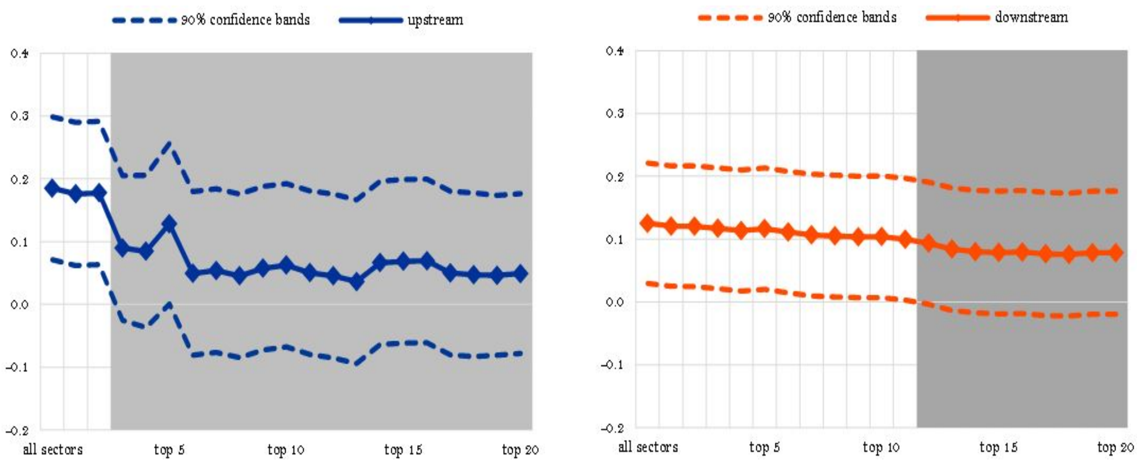
(left-hand panel: average distance, right-hand panel: correlation coefficient)



Note: The left-hand panel of Figure 4 shows the shortest path length (number of edges) between country pairs computed with the adjacency matrix assigning 1 if nonzero trade in intermediate between i and j, 0 otherwise from the respective Input-Output matrix. Transaction below 100,000$ have been considered as 0. The shortest path has been computed with the Dijkstra algorithm. For each country, average (upstream and downstream) distances from all country-sector linkages, excluding sectors in the own country, are reported. The right-hand panel shows the average (1996-2009) pairwise correlation between sectors' value added, at given distance to upstream and downstream sectors.
Sources: WIOD (2013 and 2016 release) and authors' calculations.

Figure 5: Value added spillovers without upstream and downstream hubs

(estimates of ρ^{up} and ρ^{down})



Note: The figures show the estimated coefficient from "upstream" (left-hand panel) and downstream (right-hand panel) in the second column of Table 6. "All sectors" is the exact entry in Table 6, whereas top 1 refer to estimates when the top 1 global sector is cancelled out, top 5 estimates without the top 5 global sectors and so on.
Sources: WIOD (2013 release) and authors' calculations.

Appendices

A Additional Results

Table 5: **Correlation between upstream and downstream weights**

year	simple weights corr.	year	dist corrected weights corr.
1995	0.32	1995	0.32
1996	0.32	1996	0.32
1997	0.32	1997	0.32
1998	0.32	1998	0.32
1999	0.32	1999	0.32
2000	0.31	2000	0.31
2001	0.32	2001	0.32
2002	0.32	2002	0.32
2003	0.32	2003	0.32
2004	0.32	2004	0.32
2005	0.32	2005	0.32
2006	0.31	2006	0.31
2007	0.31	2007	0.31
2008	0.31	2008	0.31
2009	0.32	2009	0.32

Notes: For each year, correlation between upstream (equation (4)) and downstream (equation (3)) weights have been computed. ŞSimple weightsŤ refers to the case in which $d^{up}_{ij,t}$ and $d^{down}_{ij,t}$ are equal to one for any ij.

Table 6: **Regression results - Full sample (1997-2009)**

	baseline	**unobs.factors + controls**	**unobs. factors + controls + global bc**	**government (demand) shock**	**TFP (supply) shock**
lag	0.027***	-0.033***	-0.032***	-0.033***	0.038*
	(0.012)	(0.012)	(0.012)	(0.012)	(0.021)
upstream	0.705***	0.185***	0.198***	0.307	0.001
	(0.050)	(0.069)	(0.069)	(1.671)	(0.007)
downstream	0.407***	0.125**	0.123**	1.330**	0.004
	(0.051)	(0.058)	(0.058)	(0.626)	(0.022)
own				0.060	-0.036*
				(0.054)	(0.024)
country		0.152***	0.129***	0.224***	0.099**
		(0.027)	(0.026)	(0.015)	(0.043)
employment		0.455***	0.453***	0.456***	0.457***
		(0.015)	(0.015)	(0.015)	(0.033)
agriculture			-0.056*		
			(0.032)		
fuel			-0.030*		
			(0.017)		
metal			0.011		
			(0.023)		
interest rate			-0.078		
			(0.226)		
year effects	n	y	n	y	y
obs.	17511	17511	17511	17511	4950

Notes: $***p < 0.01$, $**p < 0.05$, $*p < 0.1$
The table reports estimated coefficients from regression (1) where the dependent variable y_{it} is the log difference of value added. The average of the dependent variables is considered as common factor in the error term. Standard errors are reported in brackets.

Table 7: **Regression results - 1997-2007 sample - standardized coefficients**

	baseline	**unobs.factors + controls**	**unobs. factors + controls + global bc**	**government (demand) shock**	**TFP (supply) shock**
lag	0.121***	-0.068***	-0.067***	-0.067***	0.029
	(0.015)	(0.015)	(0.015)	(0.015)	(0.029)
upstream	0.201***	0.062***	0.065***	0.087***	0.002
	(0.016)	(0.019)	(0.019)	(0.016)	(0.015)
downstream	0.067***	0.037***	0.036**	0.013	0.002
	(0.014)	(0.014)	(0.014)	(0.013)	(0.015)
own				-0.002	-0.01
				(0.009)	(0.023)
country		0.104***	0.090***	0.188***	0.051*
		(0.026)	(0.026)	(0.015)	(0.031)
employment		0.176***	0.175	0.177***	0.182***
		(0.008)	(0.008)	(0.008)	(0.015)
capital		0.146***	0.145***	0.149***	0.092***
		(0.009)	(0.008)	(0.009)	(0.017)
agriculture			-0.027*		
			(0.015)		
fuel			-0.029*		
			(0.015)		
metal			0.022		
			(0.025)		
interest rate			-0.010		
			(0.017)		
year effects	n	y	n	y	y
obs.	14817	14817	14817	14817	4950

Notes: $***p < 0.01$, $**p < 0.05$, $*p < 0.1$
See notes to Table 6. To make it possible to compare coefficients, variables are standardized and the coefficient reported measure the effect of a one standard deviation change of the independent variables. Standard errors are reported in brackets.

Table 8: **Regression results - 1997-2007 sample - non-standardized coefficients**

	baseline	**unobs.factors + controls**	**unobs. factors + controls + global bc**	**government (demand) shock**	**TFP (supply) shock**
lag	0.119***	-0.062***	-0.062***	-0.062***	0.025
	(0.015)	(0.013)	(0.013)	(0.013)	(0.024)
upstream	0.662***	0.251***	0.262***	17.318***	0.001
	(0.052)	(0.075)	(0.075)	(3.190)	(0.007)
downstream	0.246***	0.165***	0.161**	1.282	0.003
	(0.052)	(0.064)	(0.064)	(1.250)	(0.022)
own				-0.027	-0.011
				(0.108)	(0.025)
country		0.118***	0.102***	0.213***	0.075*
		(0.029)	(0.029)	(0.017)	(0.045)
employment		0.375***	0.371***	0.376***	0.400***
		(0.018)	(0.018)	(0.018)	(0.034)
capital		0.454***	0.448***	0.461***	0.230***
		(0.026)	(0.026)	(0.026)	(0.042)
agriculture			-0.066*		
			(0.038)		
fuel			-0.034*		
			(0.018)		
metal			0.027		
			(0.031)		
interest rate			-0.209		
			(0.367)		
year effects	n	y	n	y	y
obs.	14817	14817	14817	14817	4950

Notes: $***p < 0.01$, $**p < 0.05$, $*p < 0.1$
See notes to Table 6. Standard errors are reported in brackets.

Table 9: **Change in value added of important hub sectors - 1997-2007 sample**

1% change to value added growth

	Upstream	Downstream
Origin of the change	Germany: Renting of machinery and equipment and other business activities	China: Electronics and optical equipment
number of sectors affected	305	154
sum of impact across affected sectors	1.39	0.53
of which is locally:	0.69	0.22
of which is in the euro area:	0.42	0.08
of which is cross-country:	0.28	0.23

Notes: The impact of sector j reported in the columns on each other sector i is computed as $\rho^* w^*_{ij,t}$ and the overall impact as $\rho^* \sum_{j \neq i} 1(w^*_{ij,t} \geq r^*) w^*_{ij,t}$ with local (same country) and cross-country effects calculated by considering the affected sectors. * stands for "up" and "down".

B Computational Details

For each $t = 1995, ..., 2009$

- NC - total number of countries

- NI - total number of sectors

- $n = NC \times NI$ total number of country-sectors

- Y - $(NC * NI \times 1)$ vector of country-sector real value added ($e.g.$ element y_i is the real value of German car industry). Nominal gross value added deflated with value added price index.

- Z - $n \times n$ global input-output matrix. Element z_{ij} is the amount of intermediate goods produced in sector i used in sector j's production. Reading the matrix along a column yields the intermediate goods produced in all sectors used in a particular sector. A particular row provides information on the intermediate goods from a particular sector to all global value chains in the world.

- GO - $n \times n$ diagonal matrix with sectors gross output on the diagonal

- $A = ZGO^{-1}$ $n \times n$ technical coefficient matrix

- $L = (I - A)^{-1}$ $n \times n$ Leontief matrix

- v - $n \times n$ diagonal matrix with value added vector on the diagonal. Value added vector contains sectors share of direct domestic value added in total output. This is equal to one minus the intermediate input share from all countries (including domestically produced intermediates).

- $VA = v\ L\ GO$ value added contribution matrix. Reading the matrix along the column, yields the value added produced in all sectors used in a particular sector. Each row provides information on the value added from a particular sector to all global value chains in the world.

$$
\begin{aligned}
VA &= vLGO \\
&= \begin{bmatrix} v_1 & 0 & \cdots & 0 \\ 0 & v_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ 0 & 0 & \cdots & v_n \end{bmatrix} \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1n} \\ L_{21} & L_{22} & \cdots & L_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ L_{n1} & L_{n2} & \cdots & L_{nn} \end{bmatrix} \begin{bmatrix} go_1 & 0 & \cdots & 0 \\ 0 & go_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ 0 & 0 & \cdots & go_n \end{bmatrix} \\
&= \begin{bmatrix} v_1 L_{11} go_1 & 0 & \cdots & 0 \\ 0 & v_2 L_{22} go_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ 0 & 0 & \cdots & v_n L_{nn} go_n \end{bmatrix}
\end{aligned}
$$

- $VA\_w = VA\ GO^{-1}$ weighted (by total output) value added contribution matrix

- $VA\_outdegree = \sum_{j=1,j\neq i}^{n} VA\_w_{ij}$ (row-sums of VA_w)

- $VA\_indegree = \sum_{i=1,i\neq j}^{n} VA\_w_{ij}$ (column-sums of VA_w)

- $VA\_totdegree = VA\_outdegree + VA\_indegree$

- Adj - nxn matrix with $Adj_{ij} = 1$ if $Z_{ij} \neq 0$ and $Adj_{ij} = 0$ if $Z_{ij} = 0$. Transaction below 100,000$ have been considered as 0.

- $Distance\_up$ - $n \times n$ matrix with distances from upstream sectors. Its element d_{ij} is the distance of sector i from the upstream sector j. Distance is computed from Adj, with the Dijkstra algorithm which finds the shortest path (number of edges) between two sectors (nodes).

- $Distance\_down$ - $n \times n$ matrix with distances from downstream sectors. Its element d_{ij} is the distance of sector i from the downstream sector j. It is the transposed of $Distance\_up$.

- W^u - upstream value added weight matrix. Each element w_{ij} is obtained as $w_{ij} = VA_{i\rightarrow j}/\sum_{i=1,i\neq j}^{n} VA_{i\rightarrow j}$ (value added contribution to j from i divided by total value added contribution from all sectors i - column sums)

- W^d - downstream value added weight matrix. Each element w_{ij} is obtained as $w_{ij} = VA_{i\rightarrow j}/\sum_{j=1,j\neq i}^{n} VA_{i\rightarrow j}$ (value added contribution from i to j divided by total value added contribution from i to all sectors j - row sums)

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