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Networks of value added trade

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Abstract

Global Value Chains (GVCs) became the paradigm for the production of most goods and services around the world. Hence, interconnections among countries can no longer be adequately assessed through standard bilateral gross trade flows and new methods of analysis are needed. In this paper, we compute measures of network analysis and apply visualisation tools to value added trade flows in order to understand the nature and dynamics of GVCs. The paper uses data on the bilateral foreign value added in exports for the period 1995-2011 and, in each year, GVCs are represented as directed networks of nodes (countries) and edges (value added flows). The analysis is extended beyond total trade flows to discuss the distinct roles of goods and services in GVCs. Moreover, the differences between Germany, the US, China and Russia as major suppliers of value added in GVCs are also examined.

Keywords: International trade; Global value chains; Network analysis; Input-output tables;

JEL Codes: F12, F14, C67

Non-technical summary

In recent decades, the rise of Global Value Chains (GVCs) has dramatically changed the organisation of world production of goods and services, making a deep and lasting impact on international trade and investment patterns, as well as on labour and product markets. As GVCs spread worldwide, the concept of "country of origin" becomes increasingly difficult to apply, because a country may stand as a large exporter of a specific good without adding much value to it. Hence, the analysis of gross trade flows has to be complemented with the analysis of trade in value added, tracking down the original source country of the value added. Even if GVCs are a complex phenomenon, it is essential that policy-analysis takes on board their impacts on the quantification and interpretation of traditional trade and competitiveness indicators and on the forecasting of macroeconomic developments.

The expansion of GVCs has also strongly increased the economic interdependence between countries. In this context, since exports increasingly embody a sizeable share of foreign value added, important questions about the interconnections among countries arise, notably in relation to the impact and propagation of economic shocks. For example, the significant role of specific countries in the functioning of GVCs poses questions regarding the resilience of the world trade system if they are hit by large shocks. All these aspects have a bearing on monetary policy decisions.

The measurement of trade in value added, breaking down gross trade flows along sources and destinations of value added, has benefited from the recent availability of global input-output (I-O) matrices. One of the simplest measures of participation in GVCs is the use of imported inputs to produce goods that are afterwards exported, that is the "foreign value added content of exports". These foreign value added flows can be interpreted as the final result of complex linkages established between firms in different sectors and countries over time.

In spite of the intense research over the last decades, the mapping and measurement of GVCs is still incomplete and new research strands may bring further valuable results. Given the specific features of GVCs measured from global I-O matrices, network analysis is a useful tool to examine the international flows of value added and countries' position within GVCs. This type of analysis prompts the I-O relationship between any two countries not to be studied in isolation, focusing instead on its structural dimension, that is, taking into account the effect of all other participants in GVCs. In other words, network analysis assumes the interdependence of observations and explores the entire pattern of connections, instead of focusing on the isolated characteristics of each individual element.

The main goal of this paper is to provide a general picture of the characteristics and dynamics of GVCs from a complex network perspective, offering an economic interpretation of the results whenever possible. The paper uses data on the bilateral foreign value added in exports from the World Input-Output Database (WIOD) for the period 1995-2011. In each year, the GVC is represented as a directed network of nodes (countries) and edges (value added flows).

The analysis starts with the computation of several aggregate network metrics and the evolution of the key properties of the networks of foreign value added in total, goods and services exports is discussed. Next, we analyse in more detail the network of total foreign value added in exports and study the roles of goods and of services as both inputs and outputs in GVCs. The main differences between Germany, the US, China and Russia as major suppliers of foreign inputs embodied in the exports of other countries are also examined. Therefore, this paper offers an analysis of GVCs that is complementary to that of other papers also produced within the scope of the Competitiveness Research Network (CompNet) of the European System of Central Banks (ESCB), namely Amador et al. (2015), Benkovskis and Wörz (2015) and Nagengast and Stehrer (2016).

We find that large countries play a vital role and that the regional dimension of GVCs is still dominant, though it is progressively giving way to a more global network. The network of foreign value added in goods exports is denser than that of services exports, but some purely services-based GVCs are already visible. At country-level, Germany and the US maintain a robust participation in GVCs over the whole period, but with meaningful differences between them. Germany mostly bases its role as a major supplier of goods value added to be used in other countries' exports of goods, while the US supplies more services inputs to services exports. In addition, Germany also has some relevance as a client of value added to be embodied in German exports, while the US mostly acts as a supplier of value added to other countries. The rising importance of China as a supplier of value added is a clear result of the analysis. The emergence of China is mostly centred in the supply of goods inputs to the exports of goods of other countries.

The correct understanding of GVCs is crucial to predict shifts in their future dynamics, which, in turn, are important to forecast macroeconomic developments and to assess the role, if any, that policy can play in shaping this phenomenon. There is still substantial work to be done in the interplay between GVCs and network theory. A complex network approach that takes due account of the full set of linkages among countries and their positions in GVCs can contribute to a better assessment of how globalisation affects each national economy.

1 Introduction

Over the last decades, international trade has grown strongly and its pattern has changed significantly. International production sharing has always been part of international trade as countries import goods to be incorporated in their exports. However, the acceleration of technological progress, the reduction of transport and communication costs and the removal of political and economic barriers to trade greatly increased the opportunities for the international fragmentation of production, i.e., a paradigm where different countries specialise in particular stages of the production chain (see Amador and Cabral (2016) for a review). Such international fragmentation of production, which has led to the emergence of Global Value Chains (GVCs), poses challenges to policy-makers and it has contributed to deepen the structural interdependence of the world economy in the last decades. The organisation of global production networks is very complex and involves firms in manufacturing, logistics, transportation and other services, as well as customs agents and other public authorities across different countries.

The empirical analysis of GVCs has been focusing on the computation of indicators that break down gross trade flows along sources and destinations of value added, taking advantage of the recent availability of global input-output (I-O) matrices. One of the simplest indicators of participation in GVCs is the *foreign value added content of exports* (FVAiX), which measures the use of imported inputs to produce goods that are exported afterwards, as defined, for instance, in Foster-McGregor and Stehrer (2013) and Koopman et al. (2014). This I-O based measure of fragmentation focuses on the (direct and indirect) import content of exports, it captures cases where the production is carried out in at least two countries and the products cross at least twice the international borders and was initially formulated by Hummels et al. (2001), who labelled it "vertical specialisation".

This paper studies GVCs from a complex network perspective. The flows of value added in a GVC tend to occur in a sequential way with firms incorporating foreign value added as they embody intermediate goods in production that is subsequently exported for final consumption or integrated into other products or services.[1] Therefore, the path taken by each unit of value added in the world economy before it reaches the final consumer may be extremely complex and long. In conceptual terms, this path could be identified stepwise in the global I-O matrix, as implied in the notion of average propagation lengths of Dietzenbacher et al. (2005). However, given the structure of the matrix, the number of iterations would be

[1] See Baldwin and Lopez-Gonzalez (2015) for an overview of global patterns of supply-chain trade.

huge and the resulting network virtually impossible to visualise. Instead, economic theory has been focusing on the Leontief inverse matrix to capture the final impact of this iterative process. This is also the approach adopted in this paper: the network represents the final foreign value added flows after all stages of production have propagated through the world economy, and not individual flows in successive stages of the production chain.

International value added flows obtained from global I-O frameworks can be interpreted as the final outcome of complex linkages established between firms in different sectors and countries over time. Since exports increasingly embody a sizeable share of foreign value added, the interdependence between economies becomes even more relevant, notably in terms of the impact and propagation of economic shocks and the related co-movement across countries. In fact, the recent financial and economic crisis showed that GVCs affect the magnitude and international transmission of macroeconomic shocks. During this period, the collapse in global trade was severe, synchronised across the world, and particularly pronounced for trade in capital and intermediate goods. Several transmission mechanisms were at play but GVCs appear to have had a central role in the transmission of what was initially a demand shock in some markets affected by a sharp credit shortage.[2] The significant role of specific countries in the functioning of GVCs poses also serious questions regarding the resilience of the world trade system in case they are hit by large shocks. In this vein, Carvalho (2014) discusses the extension of the analysis of production networks to an open economy set-up to account for global supply chain networks.

The main goal of this paper is to provide a general picture of the nature and dynamics of GVCs from a complex network perspective, offering an economic interpretation of the results whenever possible. We base on the World Input-Output Database (WIOD) for the period 1995-2011 and examine the characteristics of the international flows of value added both analytically and graphically using tools of network analysis. The paper goes beyond total trade in order to asses the specific role played by goods and services as both inputs and outputs. Given the specific features of GVCs obtained from global I-O matrices, network analysis proves to be a useful tool to examine international flows of value added and countries' position within such chains. This type of analysis makes it possible to focuses on the structural dimension of an I-O relation between any two countries, i.e., taking into account the effect of all other participants in GVCs instead of taking it in isolation.

[2]Baldwin (2009) provides a useful discussion on the several causes of the great trade collapse, as well as on its consequences and prospects for the future of the global economy.

The paper is organised as follows. Section 2 discusses relevant literature on the network analysis of international trade flows. Section 3 briefly presents the methodology used to decompose value added in trade, the definition of the networks of foreign value added in exports and the database used. In section 4, the evolution of the networks of foreign value added in exports is examined through the computation of aggregate network metrics and using network visualisation tools, with a focus on the differences between goods and services. Finally, section 5 presents some concluding remarks.

2 Related literature on international trade networks

In order to study interconnections between agents, economic research has been making progressive use of network analysis tools. The appeal of network analysis to study economic relations comes from the ability to identify the full structure of interactions. Networks assume the interdependence of observations and explore the entire pattern of connections, instead of focusing on the isolated characteristics of each individual element. The research on networks has suggested several measures to examine analytically the large-scale statistical properties of graphs and summarise the main characteristics of a network as a whole.[3] Additionally, the visualisation of the network structure, using graphs that contain the architecture of nodes linked by edges, is a useful tool to facilitate the interpretation of complex inter-linkages, allowing also for the study of the properties of individual nodes within the network.

Economic research based on social network analysis already covers a wide set of issues, thus bridging the two disciplines.[4] In the area of econophysics, a number of articles have focused on the empirical analysis of international trade interactions from the perspective of complex networks. In the so-called World Trade Web (WTW) or International Trade Network (ITN), each country is a node and the bilateral trade flow between two countries defines an edge between them. Several aspects of the structural and topological properties of the WTW in its undirected/directed and binary/weighted forms are studied by Serrano and Boguñá (2003), Garlaschelli and Loffredo (2004*a*, 2005), Serrano et al. (2007), Kali and Reyes (2007), Bhattacharya et al. (2007), Fagiolo et al. (2009, 2010), Reyes et al. (2010) and Fan et al. (2014), among others. The binary WTW was found to display a scale-free degree distribution, where some countries, often called hubs, present many more connections than others. This network

[3] There is a vast interdisciplinary literature on the different measures and statistics for characterising network structures, which we do not attempt to survey here. The textbooks by Wasserman and Faust (1994) and Newman (2010) provide an extensive review of the essential methods used for the network analysis.

[4] See Jackson (2014) for a discussion on how networks can help to model and understand economic behaviours.

is also characterised by a relatively high level of clustering (i.e., high probability that two trade partners of a country are themselves connected) and by a disassortative mixing (i.e., countries with many trade partners tend to be linked with countries with few partners), suggesting a hierarchical structure with strong heterogeneity among countries.

The conventional empirical international trade literature has also applied network metrics to examine the characteristics of world trade. The evolution of the binary WTW over time is studied by De Benedictis and Tajoli (2011). They find an increase of trade integration at the world level, but with a high level of heterogeneity among countries, and a significant role for trade policy in shaping the network. In the same vein, De Benedictis et al. (2014) describe the topology of the WTW in its binary and weighted versions by calculating and discussing a number of network statistics. Other authors have used network analysis to examine how trade in specific sectors has evolved over time. Akerman and Seim (2014) study the global arms trade network from 1950 to 2007 and conclude that it became more dense, clustered and decentralised over time. Amighini and Gorgoni (2014) use network analysis to study the trade in auto parts and components and find that the rise of emerging economies as suppliers led to a structural change in the international organisation of auto production.

Some recent papers study GVCs from a complex network perspective. Cerina et al. (2015) examine the total world input-output network (WION) as a directed and weighted network of country-sector pairs and compute several local and global network metrics over time. They find a strong rise in cross-country connectivity over time, as countries increasingly participate in GVCs. Using community detection techniques, they detect an important European community led by Germany and document also the rising importance of China. Zhu et al. (2015) produce a detailed topological view of industry-level GVCs as global value trees for a large set of pairs country-sector and compute a measure of industry importance based on them. In a different vein, Ferrarini (2013) uses international trade data on products classified as parts and components to quantify vertical trade among countries. The author uses network visualisation tools to map the resulting global network of vertical trade, highlighting the rise of China and the importance of the automotive and electronics sectors in GVCs.

As in this paper, Cerina et al. (2015) and Zhu et al. (2015) use the World Input-Output Database (WIOD) for the period 1995-2011, but the networks analysed are distinct. Firstly, the measures of participation in GVCs considered are different: they examine the total value added in final demand and our paper studies the foreign value added in exports. Secondly, they aim at the entire set of country-sector linkages, i.e., the nodes are the individual sectors in each country, while we focus on the geographical linkages. Finally, they examine the entire set of value added flows among each country-sector pair, including flows of domestic value added in final demand. Instead, as we use the foreign value added in exports, all value added flows within a given country are eliminated from the analysis.

3 Methodology and data

3.1 Foreign value added in exports

This section briefly reviews the methodology underlying the computation of the measure used to asses the participation in GVCs - the foreign value added content in a country's gross exports (FVAiX). The concept of trade in value added links with the fact that both domestic and foreign value added are combined to produce exports, which may be latter embodied in other products or consumed as final goods and services. Nowadays, imports of intermediate products to be embodied in exports are a very important part of the production process, thus gross exports tend to be much larger than their domestic value added component. In addition, the domestic value added included in exports can circulate in the global economy embodied in intermediate products used along the production chain and, in this process, part of it can even return to the domestic economy.

In this context, the measurement of trade in value added implies allocating the value added along the GVC to each producer, thus requiring world I-O tables with information on all bilateral flows of intermediate and final goods and services. The availability of global I-O matrices, where country-sector pairs of inputs are disentangled along country-sector pairs of outputs, has led to several methodological contributions on metrics of trade in value added, i.e., new proxies of participation in GVCs. Several recent articles generalise the concept of "vertical specialisation" of Hummels et al. (2001) and capture different dimensions of international flows of value added. The initial contributions were those of Daudin et al. (2011), Johnson and Noguera (2012) and Koopman et al. (2014). The FVAiX is part of this last generation of indicators and it can be computed at a detailed breakdown level.

Next, we follow closely Amador et al. (2015) for a simple presentation of the FVAiX. The most intuitive way to introduce this indicator is to start by defining the domestic value added in exports (DVAiX).

The global Leontief inverse matrix is denoted as $L=(I-A)^{-1}$, with dimension $NC\times NC$, where N stands for the number of sectors and C for the number of countries, and where I is the identity matrix and A is the $NC\times NC$ global I-O matrix. The Leontief inverse matrix is the sum of a converging infinite geometric series with common ratio A, that is, $[I-A]^{-1}=\left[I+A+A^2+A^3+\cdots+A^x\right]$, when $x\to\infty$. The elements of the Leontief inverse matrix are often termed as output multipliers, as they capture the total impact of a change in final demand, taking into account both the direct as well as all indirect rounds of consecutive effects arising from the interdependence of sectors in production.

The vector of value added coefficients, i.e., value added created per unit of gross output in country r, is denoted by v^r. This $1\times NC$ vector contains the value added coefficients for country r and zeros otherwise. Further, exports of country r are written in the vector e^r, which is of dimension $NC\times 1$ and reports the exports as positive elements and zeros otherwise.

The DVAiX^r takes the on-diagonal block in the Leontief inverse for country r, pre-multiplies by the value added coefficients in each sector and post-multiplies by the values of exports, that is:

$$\text{DVAiX}^r = v^r L^{rr} e^r \tag{1}$$

The FVAiX^{sr} provides the value added directly and indirectly created in the country from which intermediates are imported (source country s) for production of exports of country r and is calculated in a similar way. It implies pre-multiplying the Leontief inverse by the vector containing the value added coefficients for country s and zeros otherwise, denoted as v^s, and post-multiplying by the vector of exports of country r. In other words, the FVAiX^{sr} basically takes the off-diagonal blocks of the global Leontief inverse for country r, pre-multiplies by country s value added coefficients and post-multiplies by the vector of country r' exports. Formally, this is written as:

$$\text{FVAiX}^{sr} = v^s L^{sr} e^r \tag{2}$$

Summing up over all partner countries, the total foreign value added embodied in exports of country r is obtained as:

$$\text{FVAiX}^r = \sum_{s,s\neq r} v^s L^{sr} e^r \tag{3}$$

Adding the domestic and the foreign value added in exports, as presented in equations 1 and 3, provides the value of total exports of country r in gross terms:

$$\mathrm{X}^r = \mathrm{DVAiX}^r + \mathrm{FVAiX}^r \tag{4}$$

All value added decompositions computed in this paper were made using the R package decompr (Quast and Kummritz, 2015). The analysis is based on the World Input-Output Database (WIOD), which links national supply and use tables with bilateral trade data in goods and services to produce a global I-O table. This database covers 27 European countries and 13 other major world economies and comprises 35 industries, corresponding to a broad NACE classification. The description of the sectors and countries available in the WIOD is included in Appendix A. The sample period starts in 1995 and ends in 2011. Timmer et al. (2015) describe in detail the contents of this database and illustrate its potential to examine different aspects of the international fragmentation of production.

3.2 Defining the networks

The construction of a network requires the identification of a set of nodes or vertices and a criterion for the interactions between them, which define the edges. In this paper, the nodes are the 40 individual countries that are present in the WIOD ($N = 40$). The criterion for the existence of an edge is set to reflect the importance of a source country s as a supplier of value added for the production of the exports of country r. For the purpose of defining what is an important supplier of value added in exports, a threshold is set to obtain an incomplete adjacency matrix. The choice of the threshold is made in such a way that the resulting network is simple enough to interpret and visualise, while capturing the relevant interrelations between nodes, i.e., the main features of GVCs that are active around the world. The foreign value added threshold was set at 1 percent of total gross exports of the user country, resulting in a coverage of more than 65 percent of total foreign value added flows in every year.[5]

The existence of a clear interpretation for the orientation of the edge, i.e., directed from a country whose value added share in another country's exports is larger than the threshold,

[5] Alternative threshold percentages were tested and the main features of the networks remained qualitatively unchanged for similar values. Significant differences are only detected with threshold values above 4 percent of total gross exports of the user country, where less than 30 percent of total foreign value added flows are considered. All detailed results are available from the authors upon request.

makes this network *directed*. More precisely:

$$\overrightarrow{a_{sr}} = \begin{cases} 1 & if \quad \dfrac{\text{FVAiX}^{sr}}{\text{X}^{r}} > 0.01 \quad \text{for each country } s \neq r = 1,2\ldots N \\ \\ 0 & otherwise \end{cases} \tag{5}$$

where $AM = [a_{sr}]$ is the $N \times N$ connectivity or adjacency matrix.

The analysis in this paper disregards the strength of the edges identified, i.e., the values of the foreign value added shares in exports. Hence, we will only use the binary information contained in the data (*unweighted* network) and focus on the extensive margin of value added trade among countries. The option to perform a binary analysis based on two main arguments. Firstly, as far as we know, this is the first application of network analysis to foreign value added in exports at the country level, thus a binary analysis seemed the natural way to start. Secondly, a major research question in this paper is the identification of the main users and suppliers of foreign value added in exports. Setting the threshold, as in equation 5, focuses on the importance of the phenomenon relatively to the size of the user country. Hence, small countries do not necessarily disappear from the analysis. Even if the level of their trade in value added is small compared to the world total, their imports of value added can represent a large share of gross exports in case they are deeply engaged in GVCs. A weighted network analysis of foreign value added in exports, using the levels of value added flows between countries as weights, constitutes a distinct and complementary work that can answer different economic questions.

A very simple but powerful notion in network analysis is the degree of a node. This is simply the number of connections or edges that it has with all other nodes. If the network is directed, every node has two different degrees: outdegree and indegree. The outdegree is the number of outgoing edges and the indegree is the number of incoming edges, that is:

$$d_s^{out} = \sum_{r=1}^{N} \overrightarrow{a_{sr}} \qquad \text{and} \qquad d_s^{in} = \sum_{r=1}^{N} \overrightarrow{a_{rs}}$$

Therefore, the edges pointing towards a country identify its main suppliers and, conversely, the edges originating from a country reveal its importance as supplier in GVCs.

The analysis in this paper is extended beyond the total value added trade network with a view to discussing the distinct roles of goods and services in GVCs. Although it would be possible to examine the interrelations within all 35 sectors available in the WIOD, we focus the analysis on these two broad sectors as they tend to reflect major technological differences. We start by defining the networks of total foreign value added in exports of goods and of services. For each broad sector (goods or services), the edges in the network are set by pairs of countries where the supplier's total value added share in the user country's exports of the selected sector is above the threshold. Hence, the reading of the sectoral networks must always take into account that the importance of foreign suppliers of value added is set relative to the user countries' gross exports of goods or of services. In the same way, we define the individual networks that result from considering the foreign value added that is originated in the each of these two broad sectors and is embodied in either exports of goods or of services.

4 What can we learn from the networks of value added trade?

4.1 Aggregate network metrics

The research on complex networks has developed a rich set of quantitative metrics aimed at describing their main structural characteristics. Tracking such aggregate metrics over time can also shed light on the dynamics of the patterns of network formation. Figure 1 displays some of these macro measures for the networks of total foreign value added embodied in total, goods and services exports over time. Complementarily, Appendix B reports the values of these measures for all networks discussed along the paper. Overall, the results of the aggregate metrics are broadly similar for the cases of total and goods exports, while the measures computed for the network of total foreign value added in services exports show a distinct behaviour.

A very simple aggregate metric is the average degree of the network, which measures its average connectivity (panel a). From 1995 to 2011, there was an increase in the average degree, meaning that, on average, each country has a larger number of client/supplier relations. Therefore, over this period, the GVC network became more complex and strongly connected, as trade in intermediates among countries intensified. This result is much stronger for total trade and goods than for services networks.

The geodesic distance is the length of the shortest path between two nodes and the average geodesic distance or characteristic path length is simply its average over all nodes. It is a measure of how close nodes are to each other in a network and could be seen as a measure of economic integration. The average geodesic distances depicted in panel b) have relatively low values, similar to those of comparable random networks. In addition, a decreasing trend is visible for total and goods networks, in spite of a slight upturn during the global crisis, meaning that countries are becoming more integrated.

The prime node-specific network metrics are the centrality measures that aim at identifying the most important nodes in a network. Several definitions of centrality exist in the literature in line with the distinct meanings of importance of a node. As discussed in Jackson (2008), node centrality measures can be broadly categorised into four groups: degree (how connected a node is); closeness (how easily a node can reach other nodes); betweenness (how important a node is for connecting other nodes); and neighbours' characteristics (how important a node's neighbours are). In this latter class of centrality measures, the centrality of a node is recursively related to the centralities of the nodes it is connected to, i.e., a node's importance depends on how important its neighbours are. This category includes the measure of eigenvector centrality used herein, among others.

Centralisation is an aggregate metric that characterises how a network is centred around one or a few important nodes by examining the differences in centrality between the most central node in a network and all others. Higher levels of centralisation indicate a more concentrated network structure, dominated by one or a few very central nodes. In this sense, a very centralised network is less resilient to shocks because it can fail if such important nodes are not present. The centralisation measures of the three value added networks are very high but decreased over time, specially for total trade and goods networks (panel c). This means that node eigenvector centrality scores have become relatively closer over time.Therefore, while a set of major economies maintained their core positions in the network over the entire period, their influence has declined as other countries became also relevant players in GVCs.

With directed networks, it is also relevant to examine the extent to which ties are reciprocated, as a predominance of asymmetric relations points to a hierarchical structure. Panel d) of Figure 1 presents the measure of reciprocity of Garlaschelli and Loffredo (2004*b*), which computes the proportion of edges that are reciprocated, while accounting for the density of the network. Hence, this measure is appropriate to examine the evolution of reciprocity of a network with time-varying density. The services network shows an antireciprocal behaviour over the whole period, as the probability of occurring mutual links is smaller than in a random network. Total trade and goods networks are reciprocal networks in most periods but the values obtained are very low. However, for these two networks, there is some increase in the proportion of mutual connections in the last years. This increase in the percentage of two-way value added flows within the network suggests some deepening of GVCs with some countries acting both as important clients and suppliers of each other.

The pattern of connectivity among nodes of varying degrees also affects the interaction dynamics of the network. If the high-degree nodes in a network tend to be connected with other high-degree nodes, then the network is said to be assortative or to show assortative mixing. On the contrary, the network is said to be disassortative if the nodes with many connections tend to be attached to other nodes with few connections. Degree assortativity is a network-level measure which quantifies the tendency of nodes to link with nodes with similar degrees, i.e., it refers to the correlation between the degrees of adjacent nodes. Starting from the work of Serrano and Boguñá (2003), most empirical studies on international trade networks have found that they are characterised by a disassortative mixing, as highly connected countries tend to connect to poorly connected ones. The results obtained for the value added networks included in panel e) also show such a disassortative pattern. This feature reflects the existence of a few big and central countries that act as hubs and its economic interpretation can be linked with the discussion on core-periphery relationships.

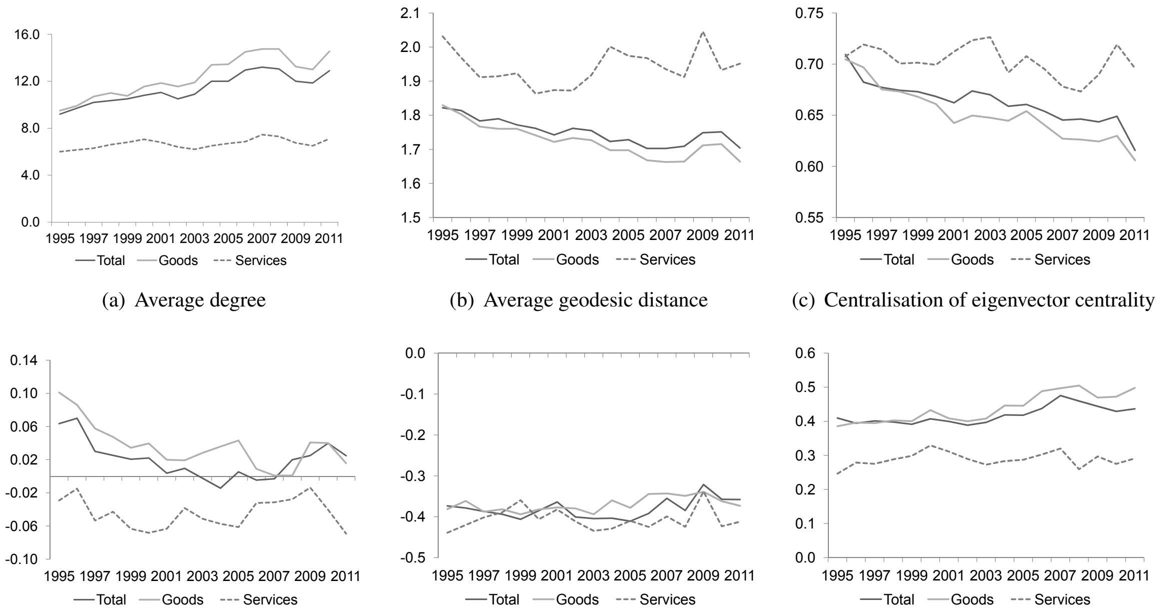
Another important feature of networks is how tightly clustered they are. There is a variety of concepts that measure how cohesive or closely knit a network is. The global clustering coefficient or weak transitivity is defined as the probability of two nodes being connected if they share a mutual neighbour and gives an overall indication of clustering in the whole network. For total trade and goods value added networks, there was a slight increase in the clustering coefficient until 2008 and some decline afterwards in the former (panel f). However, the clustering values are much higher than those corresponding to a random network of the same size, which suggests the presence of a hierarchical structure and a tendency of countries to group together around some influential players.[6] The values of the global clustering coefficient are always smaller in the value added network of services and its path is more stable over time.

In summary, the analysis of these aggregate metrics shows that the networks of foreign value added in exports are very centralised and asymmetric networks, where a few large economies act as hubs, thus, creating their areas of influence. Overall, these results are in line with those obtained from studies of the WTW in its binary form, which was found to have small-world properties (high clustering coefficient and low average geodesic distance) and a hierarchical

[6] We choose to represent the global clustering coefficient over time in panel f) of Figure 1 because it is less sensitive to the inclusion of low degree nodes than the average local clustering coefficient. In our case, the average local clustering coefficient is higher than the global clustering coefficient in all networks considered and both are higher than the clustering coefficient of an equivalent random network.

structure with a disassortative pattern.[7] Over time, value added trade networks became more complex and intensely connected and their hierarchical structure has been somewhat moderated with the entrance of new players and the establishment of new value added linkages among them.

Figure 1: Aggregate network metrics over time



(a) Average degree (b) Average geodesic distance (c) Centralisation of eigenvector centrality

(d) Reciprocity correlation (e) Degree assortativity (f) Global clustering coefficient

Notes: Network metrics were computed using the R packages statnet (Handcock et al., 2003) and igraph (Csardi and Nepusz, 2006). With the exception of the reciprocity correlation coefficient, all aggregate network measures were computed ignoring the directionality of the edges.

4.2 The network of total foreign value added trade

After describing the main topological features of the networks of foreign value added in exports in the previous section, the next sections will graphically represent those networks and calculate standard local network measures to detect and analyse the major users and suppliers of foreign value added over time. In fact, one of the primary methods of network analysis is the graphic visualisation of its structure, focusing on the characteristics of individual nodes within the network. Figure 2 displays the network representations of total foreign value added in total gross exports in 1995 and 2011.

[7] Small-world networks, according to Watts and Strogatz (1998), are a class of networks that are highly clustered, like regular networks, and have small characteristic path lengths, like random graphs. For a discussion of the small-world properties of a network, see Humphries and Gurney (2008) and Telesford et al. (2011).

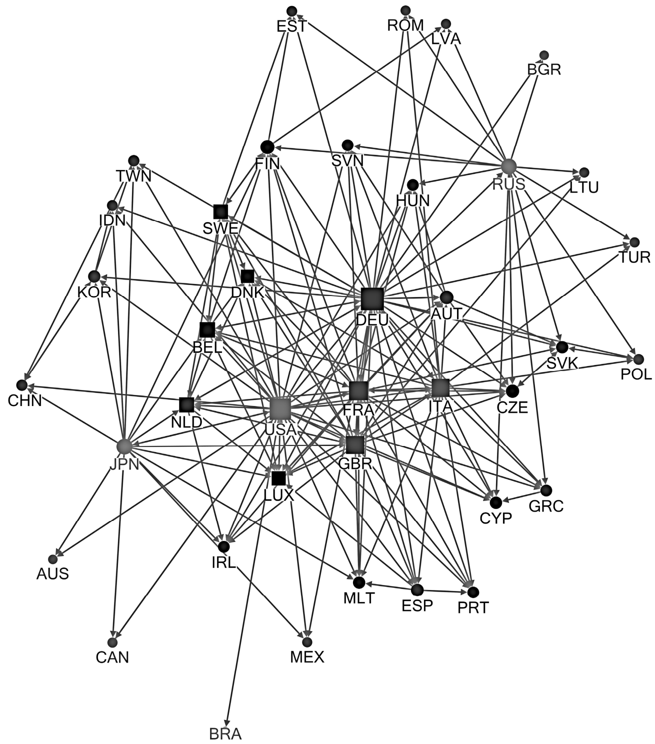
Each country is represented by a circle or a square, with arrows pointing from supplier to receiver of value added. Given the definition presented in equation 5, the scale of an economy interacts with its integration in GVCs to establish its importance within the network. In this setup, a force-directed layout algorithm is typically used to determine the location of the nodes in the network visualisation. All network graphs in this paper are based on the Harel-Koren fast multi-scale algorithm (Harel and Koren, 2002) and are drawn with the use of NodeXL (Hansen et al., 2010).[8] In all network graphs, the size of each node is proportional to its total degree (sum of indegree and outdegree) and the color of the node is mapped to its indegree, with darker shades indicating higher values. In addition, the shape of the vertices is related to its coreness. A *k-core* is a maximal subset of nodes such that each is connected to at least k others in the subset, that is, every node in the sub-graph has at least degree k. The core of maximum order is also called the main core. The nodes that belong to the main core are shaped as a square in the figures.

In general, larger countries tend to have bigger nodes and to locate in the centre of the network, mostly because they are important suppliers of value added. Smaller economies tend to locate in the outer layers of the network. These countries are usually placed in intermediate stages of the GVC and act as clients of other countries either at the beginning of the chain (e.g. focused on R&D and engineering or raw materials) or at the final stages (as assemblers). In addition, some small countries have the darkest nodes in the graph as they use value added from several sources, signalling also a strong integration in the network.

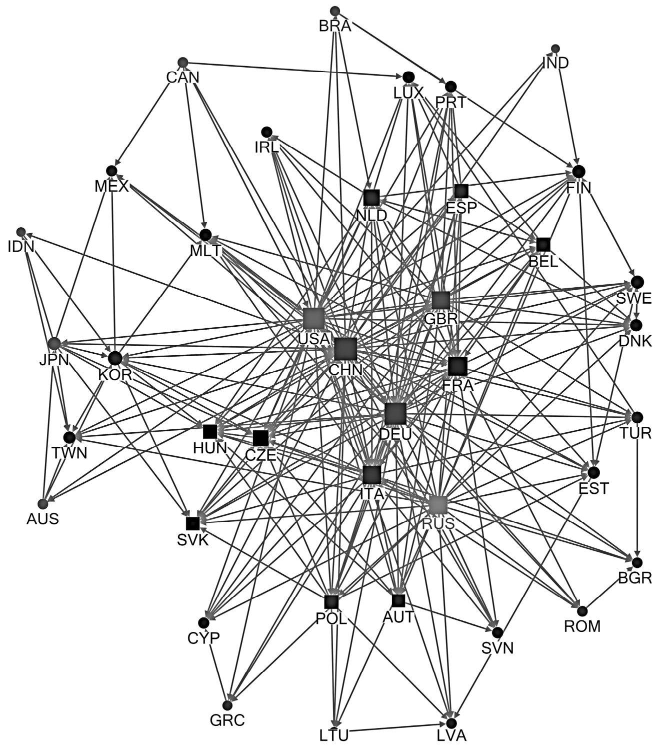
The increase in the density of the network from 1995 to 2011, due to a larger number of edges linking the 40 countries in the database, stands out in Figure 2. The flows of foreign value added embodied in gross exports became larger, increasing the number of cases where the threshold is surpassed and the respective edges are represented. The position of the nodes takes into consideration their relative importance in the network. In 1995, the countries standing in the main core are the large European countries, like Germany, France and the UK, as well as the US. Secondary relations are seen in Asia, centred in Japan as a supplier and linking countries like China, Korea and Taiwan. Other secondary edges locate in Central and Eastern Europe, with Russia supplying value added to several other countries in the region.

[8]Other layout algorithms were tried, like the Fruchterman-Reingold force-directed algorithm (Fruchterman and Reingold, 1991), without substantial differences in the visualisation of the networks.

Figure 2: Network graphs of total foreign value added in exports - 1995 and 2011



(a) 1995



(b) 2011

Notes: The networks are directed and the arrows that represent the edges point towards countries whose exports embody more than 1 percent of value added from the source country. The size of each node is proportional to its total degree (sum of indegree and outdegree) and the color of the node is mapped to its indegree, with darker shades indicating higher values. The nodes that belong to the *k-core* of maximum order are shaped as a square. The network graphs are based on the Harel-Koren fast multi-scale algorithm and are drawn with the use of NodeXL (see Hansen et al. (2010) for details).

In 2011, the network is denser than in 1995 and China joins the inner core, while Germany and the US maintain their central positions. A more subtle difference between these two central countries, Germany and the US, is visible when the shade of the nodes is considered. Even if their nodes are almost of the same size (i.e., similar total degree), the node of Germany is darker than that of the US in both periods. This means that the role of the US is mostly that of a supplier of foreign value added to other countries, while Germany also has some relevance as a client of value added to be embodied in German exports (i.e., higher indegree). Finally, Russia became a member of the main core and gained importance in the network as a supplier of other countries. This is evident from its squared, bigger but still light-shaded node in 2011, which mostly reflects Russia's role as a major exporter of energy products. These facts are in line with the conclusions of other authors that highlight the progressive transformation of GVCs, evolving from a regional dimension into a truly global network, i.e., the emergence of the so-called "factory world" (see Los et al. (2015) for a discussion).

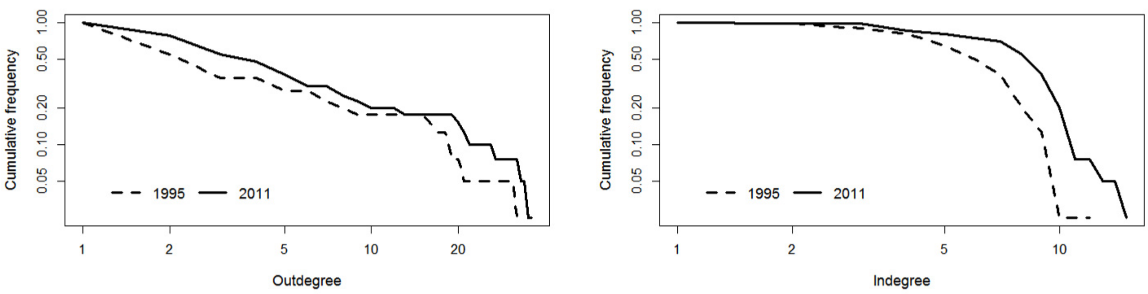
4.2.1 Degree distribution

The examination of the degree distribution provides additional insights about the structure of a network. In contrast to a random network, in most real world networks the large majority of nodes has a relatively small degree, while a few nodes have very large degrees. Hence, the degrees of the nodes in most networks are highly right-skewed and their distribution has a long right tail of values that are much higher than the mean. Figure 3 shows the outdegree and indegree marginal cumulative distributions of the networks of total foreign value added in exports for 1995 and 2011. The cumulative outdegree (indegree) distribution P_k gives the percentage of nodes that have an outdegree (indegree) larger than or equal to k, i.e, the probability that the outdegree (indegree) of a node is greater or equal than k.

The visual inspection of these distributions confirms that they are markedly right-skewed and became more polarised over time, i.e., with more density concentrating around extreme values as the complexity of the network increases. The marginal outdegree distribution is particularly right-skewed as large countries tend to dominate the supply of foreign value added into other countries' exports. For instance, in 1995, 45 percent of the nodes had a null outdegree but that percentage declined to 22.5 percent in 2011, pointing to a deepening of GVCs over time. Another signal of the increase in the complexity of the network is the rise in the percentage of nodes with more outdegrees. In 1995, 17.5 percent of the nodes had outdegree ≥ 8 and in 2011 that percentage increased to 22.5 percent. In addition, in 2011, 10 percent of the nodes (i.e., 4 countries) had an outdegree ≥ 25. The countries that emerged as the largest input suppliers to the world economy were China, the US, Germany and Russia, with at least 25 other countries using their value added in the production of exports in a percentage larger than 1.

The same broad features are visible from the marginal indegree distributions, though not so markedly, as the distributions are less right-skewed than in the outdegree case. That is, the asymmetry among countries in terms of the number of different sources of foreign inputs embodied in exports is smaller than in the supply side where a small number of countries stand as major suppliers in GVCs. The fact that GVCs became more complex over time is also visible in the increase in the percentage of countries whose exports incorporate foreign value added from many sources. In 1995, 12.5 percent of the nodes had an indegree ≥ 8 and that percentage increased to 37.5 in 2011.

Figure 3: Outdegree and indegree marginal cumulative distributions - 1995 and 2011



(a) Outdegree (b) Indegree

Notes: The x-axis gives the outdegree (indegree) of each country in a log scale. The y-axis, also in log scale, gives the probability of finding a country with outdegree (indegree) $\geq x$, that is, the empirical cumulative distribution P_x.

4.2.2 Degree centrality

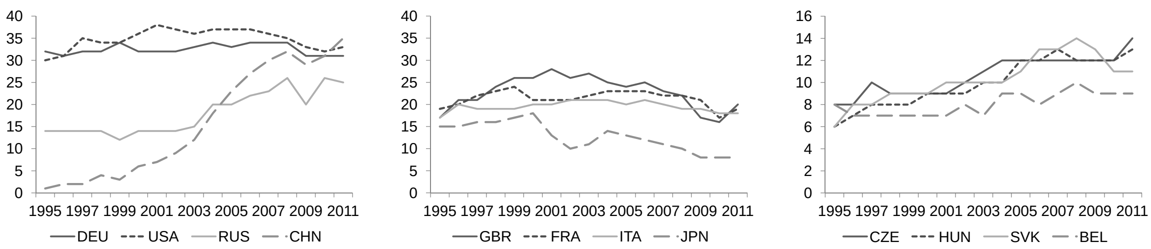
Centrality indicators are used to determine how important nodes are in a network. Node degree, which is also designated as degree centrality, is the simplest form of centrality. Despite its simplicity, the indegree and outdegree of the various countries in these networks allow for the identification of the most important users and suppliers of foreign value added in exports in each period. Recall that the international flows of value added were computed using the Leontief inverse matrix and, hence, reflect the final static equilibrium after all stages of production have propagated through the world economy.

Figure 4 displays the evolution of indegree and outdegree centralities for the main countries in the GVC network from 1995 to 2011 and underlines some of the major features observable in the networks of value added trade described above. The values of the indegree and outdegree centralities of each country in 2011 are presented in Appendix C.

The most important suppliers of value added throughout the entire period are the US and Germany, countries whose value added is regularly used in the exports of more than 30 other countries. Panel a) of Figure 4 also shows a sharp rise in the outdegree of China since the beginning of the 2000s, accelerating after 2003 and standing as the most important supplier in 2011. In this year, 35 other countries are identified as using Chinese value added in their exports above the defined threshold. Moreover, the role of Russia as a supplier of value added in world GVCs has also slowly increased since the mid 2000s. Panel b) focuses on other relevant economies, which seem to have lost some of their relative importance as suppliers in the network. The reduction in the outdegree of Japan is clear, while the UK shows an upturn in the latest years of the period, though not compensating the decline that took place after the beginning of the 2000s.

A complementary analysis bases on the identification of the countries that import value added from many sources to embody in their exports. Panel c) of Figure 4 identifies smaller European countries that stand as the most important receivers of foreign value added in the GVC network, i.e., countries with high indegree. The Czech Republic, Hungary and Slovakia progressively increased their importance as clients of foreign value added to be incorporated in exports, which confirms their important role in the intermediate stages of European production chains. Although less markedly, the same evolution is visible for Belgium.

Figure 4: Main suppliers and users of foreign value added in exports over time



(a) Outdegree centrality (b) Outdegree centrality (c) Indegree centrality

Notes: The outdegree centrality of a country reflects its relevance as a supplier of foreign value added in exports, while the indegree centrality signals its importance as a user of foreign value added in exports.

4.3 The networks of goods and services foreign value added trade

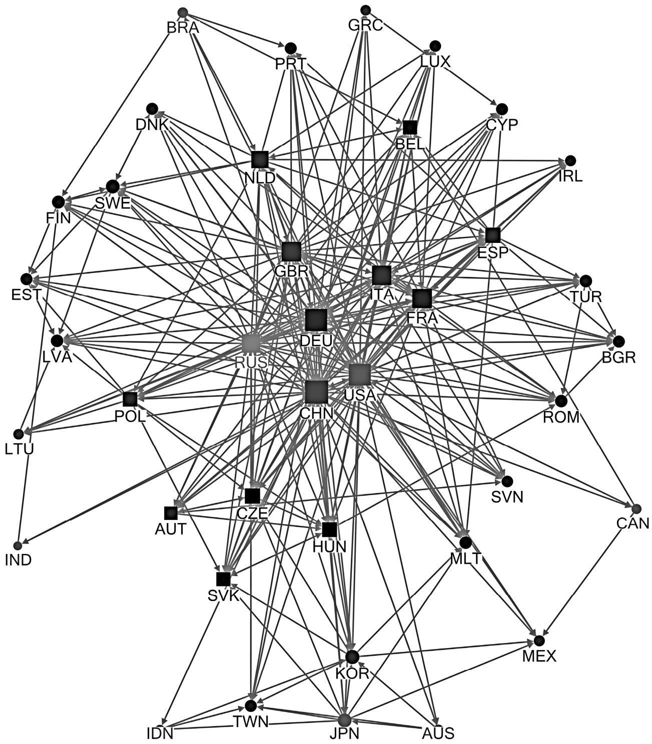
One important dimension of the networks of foreign value added in exports relates to the role of different sectors in the organisation of GVCs. Technology, as defined by the structure of I-O tables, imposes a relation between specific sectors, thereby affecting the linkages in production networks. In addition, choices of firms regarding the international organisation of the production process also crucially shape the linkages between countries that act as suppliers and users of different types of value added. To study the roles of goods and of services as both inputs and outputs on foreign value added trade networks, this section graphs these networks and computes simple local network metrics to identify and examine the main users and suppliers of foreign value added of goods and of services embodied in exports of goods and of services. The values of the indegree and outdegree centralities of each country in 2011 for all of these networks are included in Appendix C and support several of the inferences made in this section.

4.3.1 Goods and services as outputs

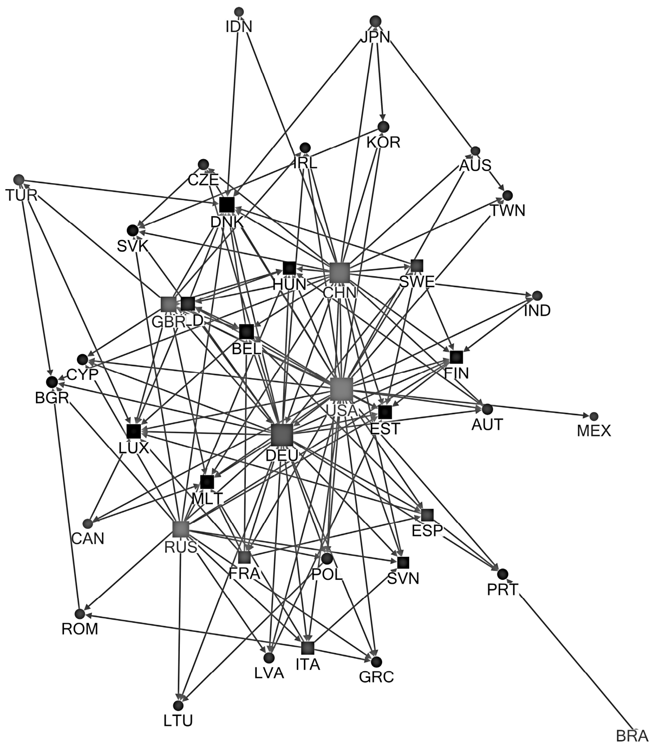
Figure 5 represents the networks of total foreign value added in exports of goods and of services in 2011. It is clear from the visualisation of these networks that GVCs are more developed and integrated in goods than in services, i.e., there are more edges among countries in the former case. In line with the analysis of section 4.1, the representation of the goods exports network in 2011 strongly resembles that of foreign value added in total exports. In both networks, China, the US and Germany belong to the main core and stand as the 3 top suppliers of foreign value added, respectively. This inference is also supported by the fact that the order of the main k-core is very similar in both networks. In addition, German exports of goods also use foreign value added from more sources than those of the other two main suppliers. The main users of foreign value added in goods exports are again the Czech Republic, Hungary and Slovakia.

As for the services exports network in 2011, the US stands out as the main supplier of foreign value added to be embodied in the services exports of other countries, followed by Germany and then China. Moreover, these three countries are less important as users of foreign value added in their services exports than in their goods exports. In 2011, the country whose services exports use value added from more sources is Denmark, with an indegree of 11.

Figure 5: Network graphs of total foreign value added in exports of goods and of services



(a) Exports of goods 2011



(b) Exports of services 2011

Notes: The networks are directed and the arrows that represent the edges point towards countries whose exports embody more than 1 percent of value added from the source country. The size of each node is proportional to its total degree (sum of indegree and outdegree) and the color of the node is mapped to its indegree, with darker shades indicating higher values. The nodes that belong to the *k-core* of maximum order are shaped as a square. The network graphs are based on the Harel-Koren fast multi-scale algorithm and are drawn with the use of NodeXL (see Hansen et al. (2010) for details).

Overall, the analysis so far conveys the message that GVCs presently play a stronger role in goods than in services. As previously mentioned, the distinct shapes of the goods and services networks depicted in Figure 5 reflect not only the technological differences implicit in the global I-O matrix but also the differences in the organisation of GVCs. Therefore, it could be argued that the liberalisation of services trade and the increased demand for services around the world will drive the expansion of GVCs towards more foreign value added of services being embodied in exports of goods or of services. In order to shed some light on these issues, the roles of goods and of services both as inputs and as outputs in GVCs are explicitly considered in the next subsection.

4.3.2 Goods and services as inputs and outputs

The four panels in Figure 6 present the combined roles of goods and of services as both inputs and outputs on value added trade networks in 2011. The comparison of panels a) and b) makes it clear that foreign value added of goods is mostly used in GVCs that lead to exports of goods. The network of foreign value added of goods used in exports of services is the least dense of the four networks considered: its average degree is less than half of the other networks considered and around a fifth of the value obtained for the network of goods foreign value added in goods exports. This is not surprising as classical GVCs relate to trade of parts and components to be embodied in different stages of the manufacturing process, while goods tend to be embodied in services typically as energy sources.

The comparison of panels c) and d) reveals that foreign inputs of services are embodied both in exports of goods and of services. This result is in line with other studies that highlight the importance of services in GVCs (see, for instance, Amiti and Wei (2005) for a description of the main world trends in outsourcing of services and Francois et al. (2015) for an analysis of the value added trade linkages between services and goods). In fact, the efficient operation of GVCs involves significant inputs of services, like logistics, transportation and other business services, and depends on the availability of the adequate services at low cost.

A complementary reading of panels a) and c) states that foreign value added in goods exports comes both from goods and from services inputs, while foreign value added embodied in services exports originates mostly from services inputs (comparison of panels b) and d)). In recent decades, the sharp progress in information and communication technologies and the strong fall in telecommunication costs have enhanced the development of GVCs within the services sector. The network displayed in panel d) confirms the existence of these purely services-based GVCs.

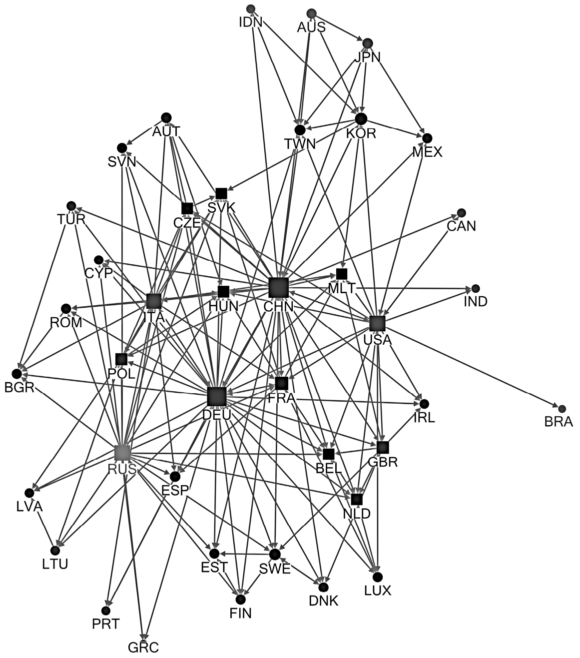
It is interesting to assess whether countries that stand as the main users of foreign value added are the same in the four panels of Figure 6. There are important differences in countries' indegrees that relate with their distinct roles in GVCs (see Appendix C). In 2011, the main users of goods foreign value added embodied in exports of goods are Hungary and Slovakia with indegrees of 8. These two Central-Eastern European countries are engaged in classical goods GVCs that have been documented in the literature. In this respect, Kaminski and Ng (2005) offer a detailed analysis of the integration of Central European countries in global, mostly EU-based, networks of production and distribution. In addition, goods exports of Belgium, Taiwan and Malta incorporate goods inputs from 7 other countries. In the sparser network of foreign goods inputs to services exports, the largest indegrees are just 4 for Malta and 3 for Denmark.

Regarding services inputs to goods exports, Belgium and Malta include value added from 6 other countries in their exports, while the number for Finland, Luxembourg, Ireland and Hungary is equal to 5. Finally, in the network of services foreign value added in services exports, the two main users in 2011 are Luxembourg and Denmark, embodying foreign inputs from many more sources than the other countries (indegrees of 9 and 8, respectively). Luxembourg and Denmark participate in services GVCs mostly through the use of foreign financial services and transport and other business activities on the production of their significant exports of services. The next group of countries presents indegrees equal to 4 and is composed by the Netherlands, Belgium, Ireland, Estonia and Hungary.

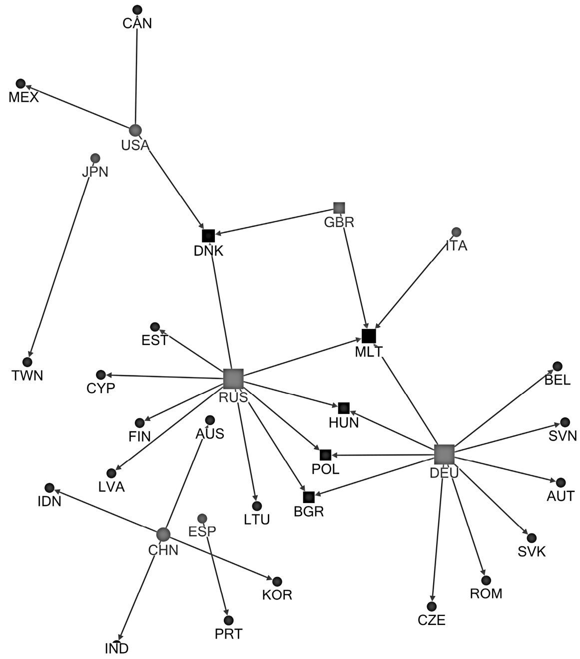
The main four suppliers of foreign value added in the networks of Figure 6 are Germany, the US, China and Russia, with the exception of the UK, which is the third most important supplier of services inputs to exports of services in 2011 (panel d). Even if the countries that act as hubs in these GVCs are the same, their ranking is not the same in the four networks.

The main suppliers of goods value added to exports of goods are China and Germany, with outdegrees of 31 and 28, respectively, in 2011. The number of countries whose goods exports use goods value added from Russia and the US is much smaller (19 and 17, respectively). Regarding the sparser network of goods inputs to services exports, the maximum outdegrees are, as expected, much lower. The main suppliers are Russia and Germany with outdegrees of 10, while China and the US have outdegrees of 4 and 3, respectively.

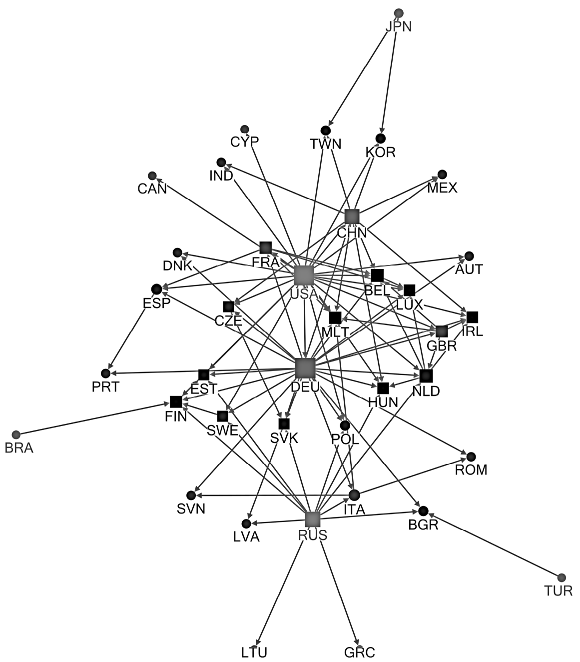
Figure 6: Network graphs of goods and services foreign value added in goods and services exports in 2011



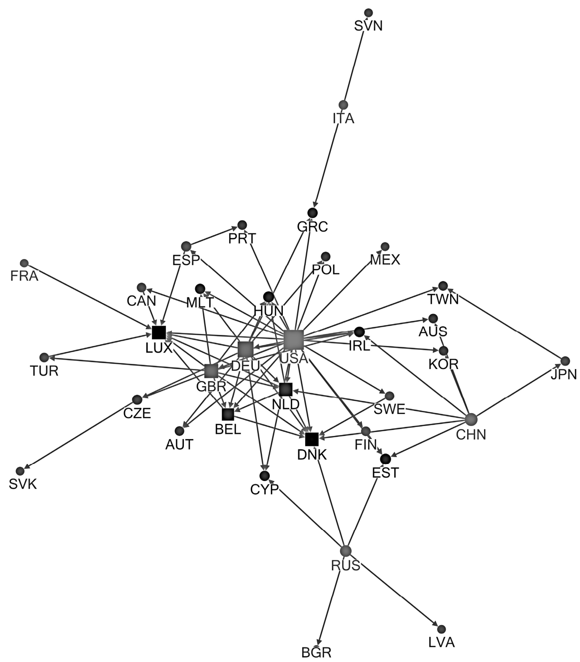
(a) Goods inputs to goods exports



(b) Goods inputs to services exports



(c) Services inputs to goods exports



(d) Services inputs to services exports

Notes: The networks are directed and the arrows that represent the edges point towards countries whose exports embody more than 1 percent of value added from the source country. The size of each node is proportional to its total degree (sum of indegree and outdegree) and the color of the node is mapped to its indegree, with darker shades indicating higher values. The nodes that belong to the *k-core* of maximum order are shaped as a square. The network graphs are based on the Harel-Koren fast multi-scale algorithm and are drawn with the use of NodeXL (see Hansen et al. (2010) for details).

The two main suppliers of services foreign value added are the same in the case of exports of goods and of services: the US and Germany. However, there is a substantial difference in the relative magnitude of their outdegrees in the two networks depicted in panels c) and d). In the services inputs to goods exports network, the two countries have similar outdegrees (24 for the US and 23 for Germany), while, in the services inputs to services exports, the outdegree of the US doubles that of Germany (24 and 12, respectively). These differences point to distinct roles played by two of the largest economies on today's geographically dispersed production and the next subsection tries to examine them in more detail.

4.3.3 Comparing Germany, the US, China and Russia as suppliers of value added

A complementary analysis to that performed with Figure 6 is to adopt the perspective of the four main suppliers of foreign value added in exports and assess the relevance of each of the goods and services I-O relationships for their outdegrees, i.e., which supply linkages are dominant in terms of their role as hubs on GVCs between 1995 and 2011. Considering each of the four detailed goods and services networks of Figure 6, the evolution of the values of the outdegree centralities of Germany, the US, China and Russia over time is presented in Figure 7.[9]

The outdegree centralities of Germany from 1995 to 2011 in the four detailed networks are displayed in panel a) of Figure 7. The first point to notice is the absence of a major trend in the relative importance of each network, which suggests that Germany established its role in GVCs before 1995. This role is mostly based on the supply of goods value added to be used in other countries' exports of goods. The supply of services inputs to be incorporated in exports of goods of other countries is also relevant.

For the US, there is also no major trend in the relative importance of either goods or services as inputs embodied in exports of goods or of services by other countries, signalling a mature GVC participation. Nevertheless, there are some interesting differences relatively to Germany. Although there is a relevant role for goods value added as an input of other countries' exports of goods, the US supplies more services value added for services exports.

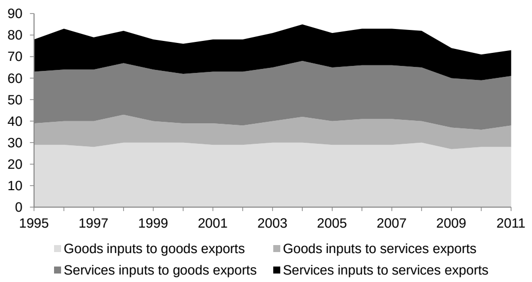
[9] For each country, the sum of the outdegrees obtained in each of the four panels of Figure 6, considering goods and services both as inputs and as outputs, does not match the outdegrees of the total network represented in Figure 2. On the one hand, it is possible that a supplier identified in Figure 2 provides both goods and services value added to be embodied in another country's exports of goods and/or services above the threshold. In the partial networks, these edges are shown separately and each outdegree is counted, while in the total network of Figure 2 they correspond to just one outdegree. On the other hand, in the partial networks the set of inputs is restricted to goods or to services, making it harder that their isolated value added represents a share of gross exports (of goods and/or services) of the user country above the defined threshold.

Such key role of US services inputs in services exports of other countries points to a type of participation in GVCs that is distinct from that of Germany.

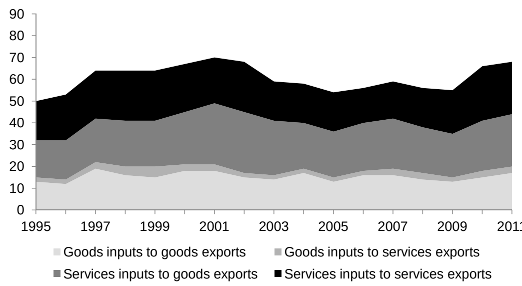
The path of China's outdegree centralities along goods and services dimensions is described in panel c) of Figure 7. As expected, the striking element is the sharp increase in the number of outgoing edges after the beginning of the 2000s. The emergence of China as a major world supplier of value added is mostly centred in goods inputs to goods exports. However, in the latest years, there was also some increase in the number of countries using Chinese services value added in their exports of both goods and services.

As for the case of Russia, there is no clear trend in the relative importance of each network in this period but there is some volatility in the values of the outdegree centralities across time. This volatility reflects the changes in the price of energy goods, which constitute an important element of Russian value added used in other countries' exports. In any case, Russia's role as world supplier of value added mostly relates with goods inputs to goods exports.

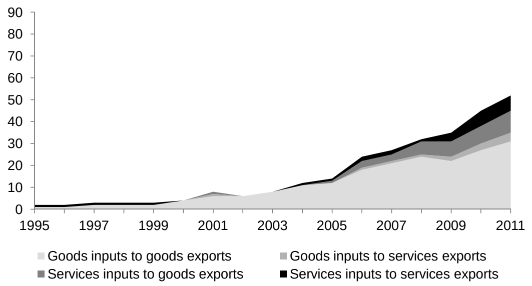
Figure 7: Main four suppliers of foreign value added in exports over time - goods and services



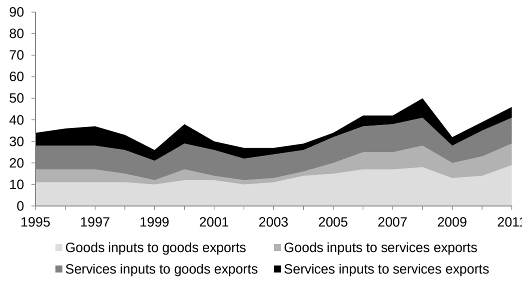
(a) Germany



(b) United States



(c) China



(d) Russia

Notes: In each panel, the values of outdegree centralities of the country are those obtained in each of the four networks of subsection 4.3.2, considering goods and services both as inputs and as outputs.

5 Final remarks

Global Value Chains (GVCs) have deeply changed the paradigm of world production and cannot be perfectly understood under the classical concept of comparative advantages applied to broad sectors and countries. Instead, GVCs are mostly about combining value added from different sources. Their effects span over multiple dimensions, namely trade flows, productivity and labour market developments. GVCs also have significant policy implications, changing the way policy-makers interpret trade policies, exchange rate fluctuations and external competitiveness. The correct understanding of the nature and dynamics of GVCs is crucial to reap the benefits from international trade and to assess the role, if any, that economic policy can play in shaping their evolution.

The expansion of GVCs requires new tools for evaluating the linkages among countries, which can no longer be adequately appraised by bilateral gross trade flows. This paper makes use of standard tools of network analysis to examine the evolution of value added trade linkages between countries in the period 1995-2011. More specifically, we focus on the concept of foreign value added in exports and the GVC is represented as a directed network of nodes (countries) and edges (value added flows between them). Initially, several aggregate network metrics are computed and the evolution of the key structural properties of the networks of foreign value added in total, goods and services exports are discussed. The analysis continues by examining in more detail the network of total foreign value added in exports and is extended afterwards to study the roles of goods and of services as both inputs and outputs in GVCs. The main differences between Germany, the US, China and Russia as major suppliers of foreign inputs embodied in the exports of other countries are also examined.

As the empirical research on the international fragmentation of production expands, the analysis of the networks of foreign value added in exports stands as an important complementary tool. Therefore, this paper offers an analysis of GVCs that integrates with that of other papers also produced within the scope of the Competitiveness Research Network (CompNet) of the European System of Central Banks (ESCB), namely Amador et al. (2015), Benkovskis and Wörz (2015) and Nagengast and Stehrer (2016).

Not surprisingly, several results of our network analysis of foreign value added in exports confirm the findings of previous studies. The evolution of the value added networks over time is consistent with the growing fragmentation of production and deepening of GVCs.

Larger countries play a vital role and the regional dimension of GVCs is still dominant, though it is progressively giving way to a more global network. The network of foreign value added in goods exports is denser than that of services exports. We also find evidence of the important role of services inputs for exports of goods and some purely services-based GVCs are visible.

At country-level, Germany and the US maintain a robust participation in GVCs over the whole period, but with meaningful differences between them. Germany is a major supplier of goods inputs to be used in other countries' exports of goods, while the US supplies more services value added to services exports. In addition, Germany also has some relevance as a client of value added to be embodied in German exports, while the US acts mostly as a supplier of value added to other countries. The rising importance of China as a supplier of value added is impressive and chiefly reflects the supply of foreign inputs of goods. Russia is an important supplier of goods inputs to goods exports, mainly due to its role as major source country for energy products.

The analysis of aggregate network metrics reveals that GVCs are very centralised and asymmetric networks, with a few large economies acting as hubs. These networks are also characterised by small-world properties, showing a hierarchical structure with a disassortative pattern. Over time, with the integration of new countries in GVCs, the networks of value added trade became denser, more complex and intensely connected. However, all in all, there is still room to expand and deepen the networks of value added trade in the global economy, both through the stronger integration of peripheral economies and the development of linkages in the services sector.

In spite of intense research over the last decades, the mapping and measurement of GVCs is still incomplete and the use of tools of network analysis may bring valuable results. In fact, the relevance of network analysis to understand the structure and organisation of world production is large and the existing research is still in its infancy. A complex network approach that takes into account the full set of connections among countries and their positions in GVCs can contribute to a better assessment of how globalisation affects each national economy and of which policies are appropriate in that environment.

Network analysis and its metrics can help to capture the heterogeneity of the firms, sectors and/or countries participating in GVCs, accounting for their direct and indirect linkages, and to explore the complexity of the whole structure of interactions. As discussed in Carvalho (2014), a network perspective of general production linkages offers important insights on the propagation of shocks and on the origins of aggregate fluctuations. An extension of this literature that takes account of value added trade flows can be extremely useful to examine the international transmission of shocks and the synchronisation of business cycles across countries. The development of models of global supply chains that incorporate the rich set of measures in network theory is a promising avenue for future research.

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Appendices

A Sectoral and geographical breakdown of the database

Sectoral breakdown in the World Input-Output Database (WIOD) (35 sectors)

ISIC rev.3 code	Industry name
AtB	Agriculture, hunting, forestry and fishing
C	Mining and quarrying
15t16	Food, beverages and tobacco
17t18	Textiles and textile products
19	Leather, leather products and footwear
20	Wood and products of wood and cork
21t22	Pulp, paper, printing and publishing
23	Coke, refined petroleum and nuclear fuel
24	Chemicals and chemical products
25	Rubber and plastics
26	Other non-metallic mineral
27t28	Basic metals and fabricated metal
29	Machinery, not elsewhere classified
30t33	Electrical and optical equipment
34t35	Transport equipment
36t37	Manufacturing, not elsewhere classified; recycling
E	Electricity, gas and water supply
F	Construction
50	Sale and repair of motor vehicles and motorcycles; retail sale of fuel
51	Wholesale trade, except of motor vehicles and motorcycles
52	Retail trade and repair, except of motor vehicles and motorcycles
H	Hotels and restaurants
60	Inland transport
61	Water transport
62	Air transport
63	Other supporting transport activities
64	Post and telecommunications
J	Financial intermediation
70	Real estate activities
71t74	Renting of machinery & equipment and other business activities
L	Public administration and defence; compulsory social security
M	Education
N	Health and social work
O	Other community, social and personal services
P	Private households with employed persons

Notes: Throughout this paper, the goods aggregate includes ISIC rev. 3 industry codes from AtB to F and the services aggregate includes ISIC rev. 3 codes between 50 and P.

Geographical breakdown in the World Input-Output Database (WIOD) (40 countries)

ISO alpha-3 codes	Country names
AUS	Australia
AUT	Austria
BEL	Belgium
BGR	Bulgaria
BRA	Brazil
CAN	Canada
CHN	China
CYP	Cyprus
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GBR	United Kingdom
GRC	Greece
HUN	Hungary
IND	India
IDN	Indonesia
IRL	Ireland
ITA	Italy
JPN	Japan
KOR	South Korea
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MEX	Mexico
MLT	Malta
NLD	The Netherlands
POL	Poland
PRT	Portugal
ROM	Romania
RUS	Russia
SVK	Slovak Republic
SVN	Slovenia
SWE	Sweden
TUR	Turkey
TWN	Taiwan
USA	United States

B Aggregate network metrics from 1995 to 2011

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Network of total foreign value added in exports (T)																	
Number of non-isolated nodes	39	39	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Number of unique edges	184	194	204	207	210	216	221	210	218	240	240	259	264	261	240	237	258
Average degree	9.2	9.7	10.2	10.4	10.5	10.8	11.1	10.5	10.9	12.0	12.0	13.0	13.2	13.1	12.0	11.9	12.9
Average geodesic distance	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.8	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.7
Centralisation of eigenvector centrality	0.71	0.68	0.68	0.67	0.67	0.67	0.66	0.67	0.67	0.66	0.66	0.65	0.65	0.65	0.64	0.65	0.62
Reciprocity correlation	0.06	0.07	0.03	0.03	0.02	0.02	0.00	0.01	0.00	-0.01	0.01	0.00	0.00	0.02	0.03	0.04	0.02
Degree assortativity	-0.37	-0.38	-0.39	-0.39	-0.41	-0.39	-0.36	-0.4	-0.4	-0.4	-0.41	-0.39	-0.36	-0.38	-0.32	-0.36	-0.36
Global clustering coefficient	0.41	0.39	0.40	0.40	0.39	0.41	0.40	0.39	0.40	0.42	0.42	0.44	0.48	0.46	0.44	0.43	0.44
Order of the main k-core	8	8	7	8	8	8	8	8	8	8	9	10	10	10	9	9	10
Network of total foreign value added in goods exports (G)																	
Number of non-isolated nodes	40	39	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Number of unique edges	190	198	214	220	215	231	237	231	238	268	269	290	295	295	265	260	291
Average degree	9.5	9.9	10.7	11.0	10.8	11.6	11.9	11.6	11.9	13.4	13.5	14.5	14.8	14.8	13.3	13.0	14.6
Average geodesic distance	1.8	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Centralisation of eigenvector centrality	0.70	0.70	0.68	0.67	0.67	0.66	0.64	0.65	0.65	0.64	0.65	0.64	0.63	0.63	0.62	0.63	0.61
Reciprocity correlation	0.10	0.09	0.06	0.05	0.03	0.04	0.02	0.02	0.03	0.04	0.04	0.01	0.00	0.00	0.04	0.04	0.02
Degree assortativity	-0.38	-0.36	-0.39	-0.38	-0.39	-0.38	-0.38	-0.38	-0.39	-0.36	-0.38	-0.34	-0.34	-0.35	-0.34	-0.36	-0.37
Global clustering coefficient	0.39	0.40	0.39	0.40	0.40	0.43	0.41	0.40	0.41	0.45	0.45	0.49	0.50	0.50	0.47	0.47	0.50
Order of the main k-core	8	8	8	8	8	8	8	7	8	9	10	11	10	11	10	10	11
Network of total foreign value added in services exports (S)																	
Number of non-isolated nodes	38	38	37	37	38	37	37	37	38	38	39	39	39	39	39	39	40
Number of unique edges	120	123	126	132	136	141	136	128	124	130	134	137	149	146	135	130	142
Average degree	6.0	6.2	6.3	6.6	6.8	7.1	6.8	6.4	6.2	6.5	6.7	6.9	7.5	7.3	6.8	6.5	7.1
Average geodesic distance	2.0	2.0	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.0	2.0	2.0	1.9	1.9	2.0	1.9	2.0
Centralisation of eigenvector centrality	0.71	0.72	0.71	0.70	0.70	0.70	0.71	0.72	0.73	0.69	0.71	0.70	0.68	0.67	0.69	0.72	0.70
Reciprocity correlation	-0.03	-0.01	-0.05	-0.04	-0.06	-0.07	-0.06	-0.04	-0.05	-0.06	-0.06	-0.03	-0.03	-0.03	-0.01	-0.04	-0.07
Degree assortativity	-0.44	-0.42	-0.4	-0.39	-0.36	-0.41	-0.38	-0.41	-0.43	-0.43	-0.41	-0.42	-0.4	-0.42	-0.34	-0.42	-0.41
Global clustering coefficient	0.25	0.28	0.28	0.29	0.30	0.33	0.31	0.29	0.27	0.28	0.29	0.30	0.32	0.26	0.30	0.27	0.29
Order of the main k-core	5	6	5	6	6	6	5	6	6	5	5	5	6	5	6	5	5

Notes: Network metrics were computed using the R packages statnet (Handcock et al., 2003) and igraph (Csardi and Nepusz, 2006). With the exception of the reciprocity correlation coefficient, all aggregate network measures were computed ignoring the directionality of the edges.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Network of goods foreign value added in goods exports (GG)																	
Number of non-isolated nodes	38	38	39	39	39	39	38	38	39	39	39	39	39	39	39	39	40
Number of unique edges	117	121	133	135	132	143	142	132	133	148	143	161	159	156	136	148	162
Average degree	5.9	6.1	6.7	6.8	6.6	7.2	7.1	6.6	6.7	7.4	7.2	8.1	8.0	7.8	6.8	7.4	8.1
Average geodesic distance	2.1	2.1	2.1	2.1	2.1	2.0	2.0	2.1	2.1	2.0	2.1	2.0	1.9	1.9	2.0	1.9	1.9
Centralisation of eigenvector centrality	0.76	0.77	0.75	0.75	0.76	0.75	0.75	0.76	0.76	0.73	0.73	0.71	0.71	0.73	0.70	0.74	0.70
Reciprocity correlation	0.05	0.08	0.09	0.07	0.07	0.05	0.02	0.04	0.04	0.04	0.07	0.05	0.04	0.03	0.02	0.00	0.02
Degree assortativity	-0.4	-0.3	-0.4	-0.4	-0.3	-0.4	-0.3	-0.3	-0.4	-0.3	-0.3	-0.4	-0.4	-0.3	-0.4	-0.3	-0.4
Global clustering coefficient	0.28	0.29	0.31	0.31	0.32	0.33	0.32	0.31	0.29	0.30	0.30	0.34	0.33	0.32	0.30	0.33	0.33
Order of the main k-core	5	5	5	5	5	5	5	5	5	6	6	7	6	6	5	6	6
Network of goods foreign value added in services exports (GS)																	
Number of non-isolated nodes	28	27	28	28	28	28	28	22	27	26	26	30	31	30	29	29	32
Number of unique edges	28	28	33	31	27	27	24	19	23	26	25	32	32	31	25	26	32
Average degree	1.4	1.4	1.7	1.6	1.4	1.4	1.2	1.0	1.2	1.3	1.3	1.6	1.6	1.6	1.3	1.3	1.6
Average geodesic distance	3.1	2.4	2.9	3.1	4.1	3.5	2.7	2.4	2.4	2.5	2.1	3.7	3.4	3.8	2.8	2.2	2.8
Centralisation of eigenvector centrality	0.91	0.90	0.89	0.90	0.92	0.91	0.93	0.93	0.93	0.91	0.91	0.89	0.88	0.86	0.90	0.88	0.85
Reciprocity correlation	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Degree assortativity	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	-0.4	-0.4	-0.4	-0.4	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5
Global clustering coefficient	0.08	0.07	0.05	0.03	0.04	0.00	0.05	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Order of the main k-core	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Network of services foreign value added in goods exports (SG)																	
Number of non-isolated nodes	35	35	35	36	35	38	38	38	36	37	37	37	37	37	36	38	38
Number of unique edges	78	77	84	87	83	92	98	96	96	99	95	97	101	99	89	89	93
Average degree	3.9	3.9	4.2	4.4	4.2	4.6	4.9	4.8	4.8	5.0	4.8	4.9	5.1	5.0	4.5	4.5	4.7
Average geodesic distance	2.3	2.2	2.1	2.1	2.1	2.2	2.1	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.2
Centralisation of eigenvector centrality	0.78	0.78	0.78	0.78	0.78	0.76	0.76	0.75	0.76	0.77	0.77	0.76	0.76	0.75	0.77	0.76	0.76
Reciprocity correlation	-0.03	-0.05	-0.03	-0.06	-0.06	-0.06	-0.07	-0.07	-0.04	-0.05	-0.04	-0.04	-0.05	-0.07	-0.04	-0.06	-0.06
Degree assortativity	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.5	-0.5
Global clustering coefficient	0.20	0.18	0.24	0.24	0.25	0.22	0.22	0.23	0.23	0.25	0.25	0.26	0.26	0.27	0.29	0.22	0.23
Order of the main k-core	4	4	5	5	4	4	4	5	5	5	5	5	5	5	5	4	4
Network of services foreign value added in services exports (SS)																	
Number of non-isolated nodes	34	35	35	36	34	34	33	33	32	34	33	34	35	36	35	35	35
Number of unique edges	75	82	82	86	81	83	79	76	68	78	76	79	82	81	77	71	73
Average degree	3.8	4.1	4.1	4.3	4.1	4.2	4.0	3.8	3.4	3.9	3.8	4.0	4.1	4.1	3.9	3.6	3.7
Average geodesic distance	2.4	2.2	2.3	2.3	2.2	2.3	2.3	2.2	2.4	2.4	2.4	2.4	2.5	2.5	2.4	2.4	2.4
Centralisation of eigenvector centrality	0.77	0.76	0.78	0.78	0.78	0.78	0.78	0.78	0.76	0.75	0.76	0.74	0.73	0.74	0.77	0.82	0.81
Reciprocity correlation	-0.02	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.02	-0.01	-0.03	-0.02	0.00	-0.03	-0.03	-0.02	-0.05	-0.05
Degree assortativity	-0.3	-0.5	-0.4	-0.4	-0.4	-0.4	-0.3	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	-0.4	-0.3	-0.4	-0.4
Global clustering coefficient	0.23	0.20	0.22	0.23	0.22	0.25	0.29	0.22	0.20	0.21	0.24	0.23	0.27	0.24	0.24	0.23	0.24
Order of the main k-core	5	5	5	4	4	4	5	5	4	4	4	4	5	4	4	5	5

Notes: Network metrics were computed using the R packages statnet (Handcock et al., 2003) and igraph (Csardi and Nepusz, 2006). With the exception of the reciprocity correlation coefficient, all aggregate network measures were computed ignoring the directionality of the edges.

C Outdegree and indegree centralities in 2011

		Outdegree centrality							Indegree centrality						
		T	G	S	GG	GS	SG	SS	T	G	S	GG	GS	SG	SS
AUS	Australia	4	4	0	4	0	0	0	2	2	2	1	1	0	2
AUT	Austria	3	4	1	2	0	0	0	8	8	3	4	1	2	2
BEL	Belgium	4	3	3	1	0	1	2	9	11	7	7	1	6	4
BGR	Bulgaria	0	0	0	0	0	0	0	6	9	5	5	2	3	1
BRA	Brazil	3	4	1	0	0	1	0	2	2	0	1	0	0	0
CAN	Canada	4	3	2	1	0	0	1	2	2	1	2	1	1	1
CHN	China	35	38	22	31	4	10	7	6	6	1	4	0	1	0
CYP	Cyprus	0	0	0	0	0	0	0	7	9	4	4	1	1	3
CZE	Czech Republic	3	3	1	2	0	1	1	14	14	3	6	1	3	2
DEU	Germany	31	31	25	28	10	23	12	6	9	3	4	0	1	1
DNK	Denmark	1	1	0	1	0	0	0	8	8	11	4	3	2	8
ESP	Spain	6	9	3	1	1	1	2	7	8	3	5	0	3	1
EST	Estonia	1	1	0	0	0	0	0	8	8	8	5	1	4	4
FIN	Finland	2	2	1	1	0	1	1	9	9	6	4	1	5	1
FRA	France	19	22	4	7	0	4	1	9	9	2	5	0	2	0
GBR	United Kingdom	20	24	11	6	2	4	8	5	7	1	4	0	2	1
GRC	Greece	1	1	0	1	0	0	0	4	5	4	2	0	1	3
HUN	Hungary	0	2	0	0	0	0	0	13	14	7	8	2	5	4
IND	India	2	2	1	2	0	0	0	2	2	1	1	1	0	0
IDN	Indonesia	1	1	1	0	0	0	0	2	2	2	2	1	2	0
IRL	Ireland	0	0	0	0	0	0	0	7	7	4	4	0	5	4
ITA	Italy	18	22	4	14	1	3	2	7	8	3	3	0	2	0
JPN	Japan	8	10	3	4	1	2	1	3	3	2	2	0	0	1
KOR	South Korea	7	7	2	5	0	0	0	7	7	3	5	1	3	2
LTU	Lithuania	1	1	0	1	0	0	0	4	5	3	3	1	1	0
LUX	Luxembourg	0	0	0	0	0	0	0	9	8	9	5	0	5	9
LVA	Latvia	0	0	1	0	0	0	0	6	10	3	4	1	2	1
MEX	Mexico	1	1	0	1	0	0	0	6	6	1	4	1	2	1
MLT	Malta	0	0	0	0	0	0	0	9	10	8	7	4	6	3
NLD	The Netherlands	11	15	4	3	0	4	4	8	8	5	5	0	4	4
POL	Poland	6	7	1	5	0	0	0	7	8	4	4	2	3	2
PRT	Portugal	0	0	0	0	0	0	0	8	9	4	3	1	2	2
ROM	Romania	1	1	1	1	0	0	0	5	9	2	4	1	2	0
RUS	Russia	25	27	14	19	10	12	5	0	0	0	0	0	0	0
SVK	Slovak Republic	1	2	0	0	0	0	0	11	12	5	8	1	4	1
SVN	Slovenia	0	0	0	0	0	0	0	7	8	5	5	1	2	1
SWE	Sweden	3	4	3	3	0	1	1	8	9	3	5	0	3	1
TUR	Turkey	2	2	3	1	0	1	1	6	8	1	3	0	0	1
TWN	Taiwan	1	1	0	0	0	0	0	8	8	3	7	1	3	2
USA	United States	33	36	30	17	3	24	24	3	4	0	3	0	0	0

Notes: The outdegree centrality of a country reflects its relevance as a supplier of foreign value added in exports, while the indegree centrality signals its importance as a user of foreign value added in exports. The columns correspond to the several networks of foreign value added in exports included in the paper, namely T stands for the network of total foreign value added in total exports (Figure 2 panel (b)); G and S stand for the networks of total foreign value added in exports of goods and of services, respectively (Figure 5); GG, GS SG and SS stand for the networks of foreign value added of goods in exports of goods, foreign value added of goods in exports of services, foreign value added of services in exports of goods, and foreign value added of services in exports of services, respectively (Figure 6). For each country, the sum of the outdegree (indegree) centrality values of the detailed networks do not add-up to the outdegrees (indegrees) of the total network (see footnote 9 in the main text.).

Competitiveness Research Network

This paper presents research conducted within the Competitiveness Research Network (CompNet). The network is composed of economists from the European System of Central Banks (ESCB) - i.e. the 29 national central banks of the European Union (EU) and the European Central Bank – a number of international organisations (World Bank, OECD, EU Commission) universities and think-tanks, as well as a number of non-European Central Banks (Argentina and Peru) and organisations (US International Trade Commission). The objective of CompNet is to develop a more consistent analytical framework for assessing competitiveness, one which allows for a better correspondence between determinants and outcomes. The research is carried out in three workstreams: 1) Aggregate Measures of Competitiveness; 2) Firm Level; 3) Global Value Chains CompNet is chaired by Filippo di Mauro (ECB). Workstream 1 is headed by Pavlos Karadeloglou (ECB) and Konstantins Benkovskis (Bank of Latvia); workstream 2 by Antoine Berthou (Banque de France) and Paloma Lopez-Garcia (ECB); workstream 3 by João Amador (Banco de Portugal) and Frauke Skudelny (ECB). Monika Herb (ECB) is responsible for the CompNet Secretariat. The refereeing process of CompNet papers is coordinated by a team composed of Filippo di Mauro (ECB), Konstantins Benkovskis (Bank of Latvia), João Amador (Banco de Portugal), Vincent Vicard (Banque de France) and Martina Lawless (Central Bank of Ireland). The paper is released in order to make the research of CompNet generally available, in preliminary form, to encourage comments and suggestions prior to final publication. The views expressed in the paper are the ones of the author(s) and do not necessarily reflect those of the ECB, the ESCB, and of other organisations associated with the Network.

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