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Please address correspondence to
Banco de Portugal, Economics and Research Department
Av. Almirante Reis 71, 1150-012 Lisboa, Portugal
T +351 213 130 000 | estudos@bportugal.pt

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Who's who in global value chains? A weighted network approach

João Amador
Banco de Portugal
Nova SBE

Sônia Cabral
Banco de Portugal

Rossana Mastrandrea
IMT School for Advanced Studies

Franco Ruzzenenti
Parthenope University of Naples

May 2017

Abstract
This paper represents global value chains (GVCs) as weighted networks of foreign value added in exports, which allows for the identification of the specific roles of countries and for the quantification of their relative importance over time. A major structural change occurred in the beginning of the century as GVCs steadily turned into global networks, amid an unprecedented growth of value-added flows and the rise of China as a major player. First-order network metrics highlight the vital but also distinct roles of Germany, the US, China and Japan in the international organisation of production. Germany is very relevant both as a user and as a supplier of foreign inputs, while the US acts mostly as a supplier of value added to other countries. Second-order properties of networks shed light on the complex architecture of GVCs, notably in terms of cyclical triangular relationships. Germany's GVCs mostly root in direct relationships, while Japanese ones typically involve more than two countries.

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Keywords: International trade, Global value chains, Network analysis, Fragmentation, Input-output tables.

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E-mail: jamador@bportugal.pt; scabral@bportugal.pt; rossmastrandrea@gmail.com; franco.ruzzenenti@uniparthenope.it

1. Introduction

The international fragmentation of production led to the emergence of global value chains (GVCs) and contributed to deepen the structural interdependence of the world economy (Baldwin 2013). In this context, important questions about the interconnections among countries arise, notably in relation to the impact and propagation of economic shocks (see Carvalho (2014) for a discussion). In particular, the significant role of specific countries in the functioning of GVCs can threaten the stability of the world trade system in case large shocks hit them.

In a growingly interconnected world, network analysis is a powerful tool to examine the international flows of value added and countries' positions in GVCs. Such analysis allows for studying the input-output relationship between any two countries in a structural way and not in isolation, i.e., taking into account the strong interdependence among all participants.

The so-called world trade web (WTW), where each country is a node and a bilateral trade flow defines an edge between two countries, has been extensively studied since the 2000s. In the area of econophysics, several aspects of the structural and topological properties of the WTW have been analysed by Serrano and Boguñá (2003), Garlaschelli and Loffredo (2005), Kali and Reyes (2007), Fagiolo *et al.* (2010), Reyes *et al.* (2010) and Fan *et al.* (2014), among others. The empirical trade literature has also applied network metrics to examine total world trade (e.g., De Benedictis and Tajoli (2011) and De Benedictis *et al.* (2014)) and trade in specific sectors (e.g., Akerman and Seim (2014) for arms trade and Amighini and Gorgoni (2014) for trade in auto parts and components).

Research on GVCs from a complex networks perspective is still scarce and can be divided into two main groups, according to the type of data used. Some studies apply network methods to disaggregated gross international trade statistics. Ferrarini (2013) quantifies and maps vertical trade using bilateral data on parts and components and network visualisation tools. More recently, Picciolo *et al.* (2017) examine cyclic paths of value in global trade and connect them to the evolution of oil prices. Other recent papers study linkages among countries obtained from global input-output matrices using network tools. Zhu *et al.* (2015) produce a detailed topological view of industry-level GVCs as global value trees for a large set of country-sector pairs, while Amador and Cabral (2016) examine the binary network of bilateral trade in value added and assess the role of goods and services as both inputs and outputs in GVCs.

We contribute to this literature by representing GVCs as a weighted directed network of value-added trade, with countries (nodes) linked by their value-added flows (edge weights). More specifically, we use the World Input-Output Database (WIOD) for the period 1995-2011 and compute the bilateral foreign value added in exports (FVAiX) to quantify the interactions among countries in GVCs.

To the best of our knowledge, this is the first application of weighted network analysis to flows of bilateral FVAiX at the country level, which allows for the identification of the specific roles of different countries within GVCs and for the quantification of their relative importance over time. Since the FVAiX network is complete, we start by examining its backbone structure, keeping for each country only its strongest user and supplier connections. We also study higher-order network properties that can shed light on the complex architecture of GVCs, notably in terms of cyclical triangular relationships, and on their structural evolution over time.

We find that, even if the regional dimension of GVCs is still dominant, value-added trade networks became more global, complex and strongly connected over time. This structural change took place in the beginning of the century, amid an unprecedented growth of value-added trade flows.

Large countries, namely Germany, the US, China, Japan, and Russia, play vital but distinct roles in the international organisation of production. The rise of China as a major player after 2001 is remarkable. The country emerged first as a user of foreign inputs but gradually became an important supplier of value added to other countries: in 2011, the relevance of China as a user and as a supplier of FVAiX is similar. Germany and the US maintain a robust participation in GVCs over the period, notwithstanding the decline of the US as a supplier after 2000. In addition, these countries play different roles in GVCs: Germany is important as supplier but is also very relevant 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' exports.

The paper is organised as follows. Section 2 briefly presents the methodology used to compute FVAiX, the definition of the weighted networks and the database used. In section 3, we extract the backbone of the FVAiX networks in 1995 and 2001, identifying five major players in GVCs (Germany, the US, China, Japan and Russia). In section 4, these countries are examined in more detail through the computation of first- and second-order network metrics over time. Finally, section 5 presents some concluding remarks.

2. Data and methods

The analysis of this paper 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 input-output (I-O) table. The database covers 27 European countries and 13 other major world economies from 1995 to 2011.[1] Timmer *et al.* (2015) describe in detail the content of this database and illustrate its potential to examine different aspects of the international

1. The list of countries is included in Appendix A.

fragmentation of production. All value added decompositions in this paper were made using the R package decompr (Quast and Kummritz 2015).

2.1. Foreign value added in exports

This section describes the methodology of computation of the bilateral foreign value added content of gross exports (FVAiX), which is the measure used to asses the interactions among countries in GVCs. This measure of fragmentation based on I-O tables focuses on the (direct and indirect) import content of exports and was introduced by Hummels *et al.* (2001) as "vertical specialisation". This concept results from the fact that domestic and foreign value added are combined to produce exports, which may be embodied as intermediates in other products or consumed as final goods and services. The calculation of this measure for all countries implies allocating the value added that is internationally traded to each producer along the GVC, thus requiring world I-O tables with information on bilateral flows of intermediate and final goods and services. In fact, the recent availability of global I-O matrices has led to several methodological contributions on detailed metrics of value-added trade (e.g., Johnson and Noguera (2012) and Koopman *et al.* (2014)).

Next, we follow closely Amador and Cabral (2016) for a simple presentation of the FVAiX. This indicator is based on the Leontief inverse matrix to capture the final foreign value-added flows embodied in exports after all stages of production have been concluded. The global Leontief inverse matrix is denoted as $L = (I - A)^{-1}$, with dimension $SN \times SN$, where S stands for the number of sectors and N for the number of countries, I is the identity matrix and A is the $SN \times SN$ 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 take into account both the direct and all indirect rounds of consecutive effects due to the interdependence of sectors and countries in production.

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

The FVAiX^{ij} provides the value added directly and indirectly created in the country from which intermediates are imported (source country i) for production of exports of country j. It is computed by pre-multiplying the Leontief inverse by the vector of value-added coefficients of country i, and post-multiplying by the vector of exports of country j. In other words, the FVAiX^{ij} basically takes the off-diagonal blocks of the global Leontief inverse for country j, pre-multiplies by country i value-added coefficients and post-multiplies by the vector of country j exports. Formally, this is written as:

$$\text{FVAiX}^{ij} = v^i L e^j \tag{1}$$

The total foreign value added embodied in exports of country j is obtained by summing over all partner countries, i.e., $\text{FVAiX}^j = \sum_{i \neq j} \text{FVAiX}^{ij}$.

2.2. The FVAiX network

The construction of a network requires the identification of a set of nodes and a criterion for the interactions between them, which defines the edges and the respective weights. The nodes in the weighted network of value-added trade are the 40 individual countries that are present in the WIOD ($N = 40$).

The edges are defined by the size of bilateral value-added trade flows among countries, as shown in equation 1. More precisely, a link of weight f_{ij} is defined by the total value added from source country i that is embodied in exports of country j. $F_t = [f_{ij}(t)]$ is the $N \times N$ weighted adjacency matrix at time t, with $t = 1995, ..., 2011$, which fully describes the evolution of the weighted networks of FVAiX over time.

The existence of a clear interpretation for the orientation of the edges, i.e., directed from supplier to user of value added, makes this network directed. In each year, the FVAiX network is fully connected. The formal definition of all network methods used is given in Appendix B and the textbooks by Wasserman and Faust (1994) and Newman (2010) provide an extensive review of the essential methods of network analysis.

3. The backbone of the FVAiX network

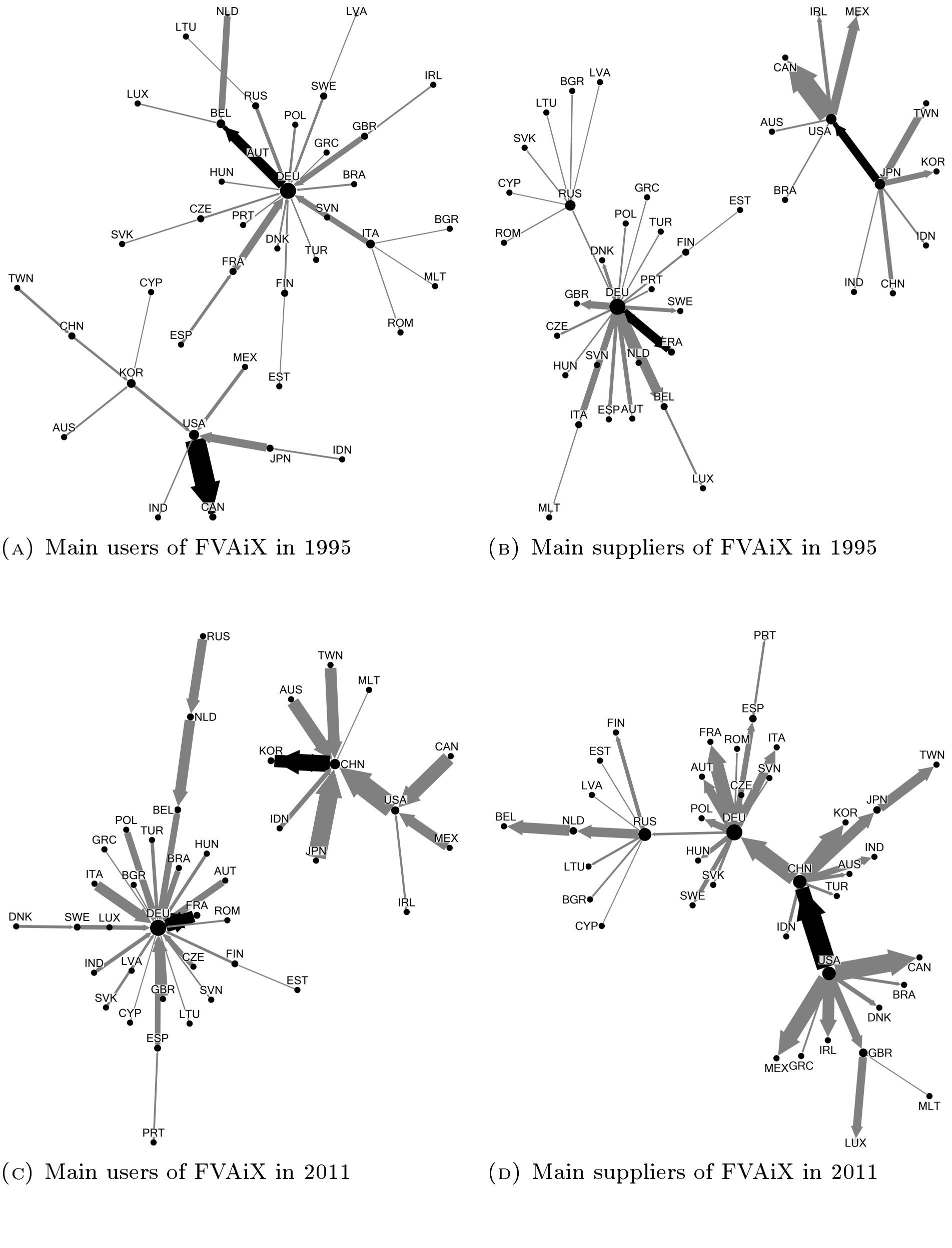
This section examines the skeleton of the FVAiX network by graphically representing the strongest connections among countries (Figure 1). Starting from the complete weighted FVAiX network in each year, two new sub-graphs are built by keeping, for each country, the maximum incoming (its main supplier) and the maximum outgoing (its main receiver) links.

In 1995, the networks of both users and suppliers are characterised by two main blocks centred around the US and Germany (panels a and b). Hence, the strong I-O linkages are mostly visible at the regional level, with the US exerting its influence on the value added traded in the Asian region. Within each component, important secondary relations are also visible on the supply-side: in Asia, centred in Japan as a supplier and linking countries like China, Korea and Taiwan; in Central and Eastern Europe, with Russia as the main supplier of value added to several other countries in the region.

As GVCs expanded and reshaped the international organisation of production, the network architecture became more complex and intensely connected. Substantial changes occurred in the FVAiX network, with new countries emerging as relevant players. In 2011, the backbone clearly identifies the three major blocks described in Baldwin and Lopez-Gonzalez (2015): "Factory Europe", "Factory North-America" and "Factory Asia", with Germany, the US and China as hub suppliers in their respective regions. Within "Factory Europe", the role of Russia on the supply-side, identified as a secondary relation in 1995, is one of the characteristics that remains in 2011.

Even if the relevance of regional linkages cannot be neglected, the evolution of the backbone of main suppliers from 1995 to 2011 also illustrates the increasingly global nature of GVCs. A single giant-component emerges, with China acting as the main supplier of value added to both Germany and the US, thus bridging the two formerly separated blocks. This result corroborates recent evidence on the progressive transition from regional production systems to a truly global organisation of production, leading to the emergence of the so-called "Factory World" (Los *et al.* 2015).

Reciprocal linkages in the backbone of the FVAiX networks represent countries that are the main users (suppliers) of the value added of each other, pointing to intense back and forth transactions and to a common participation in production chains. The edges representing flows that are reciprocated are black-shaded in Figure 1. Another indication of the profound transformations that occurred in world trade is the fact that all reciprocal relations in 1995 and 2011 are distinct. For instance, on the supply side (panels b and d), China and the US are the main suppliers of value added to each others' exports in 2011, while in 1995 that feature was shared by the US and Japan. On the using side (panels a and c), a significant reciprocal linkage emerged between Germany and France, which stand as the main value-added receivers of each other in 2011. The close relation between China and Korea in production and trade networks in East Asia is also evident in panel c.



(A) Main users of FVAiX in 1995

(B) Main suppliers of FVAiX in 1995

(C) Main users of FVAiX in 2011

(D) Main suppliers of FVAiX in 2011

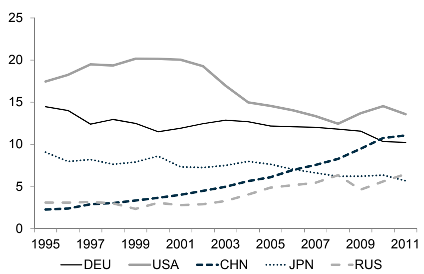
FIGURE 1: The backbone of the FVAiX networks in 1995 and 2011

Notes: The networks are directed and the arrows that represent the edges are oriented from supplier to receiver. The edge width is proportional to the its weight and the edges representing flows that are reciprocated are black-shaded. In each panel, the size of each node is proportional to its share as user/supplier of value added in the respective backbone. The network graphs 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).

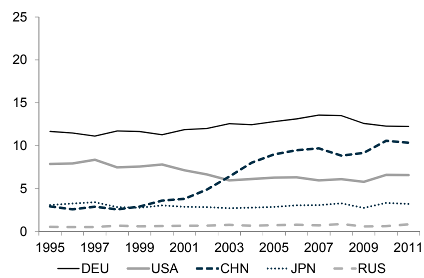
4. Top players in GVCs

This section focuses on five countries (Germany, the US, China, Japan, and Russia), whose relevance in GVCs has been pinpointed in the previous section. Two centrality measures are used: the total value of connections of a node (strength) and the Kleinberg (1999) centrality based on the concepts of hub and authority. An authority is a country using value added from several large hub countries; a hub is a country supplying value added to several high authority countries.

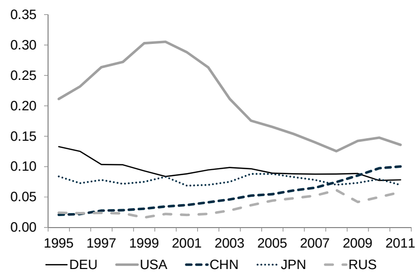
The rise of China as a major participant in GVCs is clearly visible in all panels of Figure 2. After its accession to the World Trade Organisation (WTO) in 2001, China's role as an assembly centre soared and this country quickly caught up with Germany as user of FVAiX. Chinese importance as a supplier did not accelerate around 2001, though it was equally impressive over the whole period. In the last two years, only the US prevails over China as supplier of



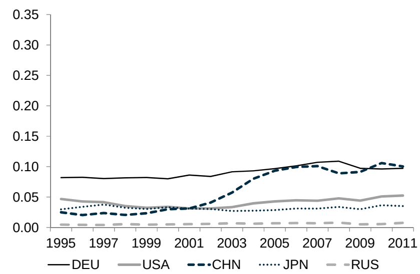
(A) Out-strength centrality



(B) In-strength centrality



(C) Hub centrality (out)



(D) Authority centrality (in)

Figure 2: Centrality measures

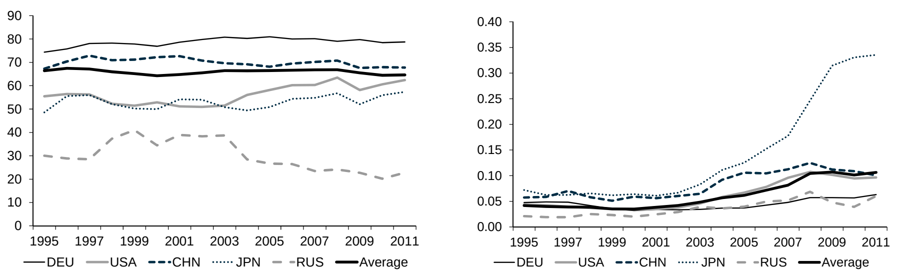
Notes: The out-strength and the hub centralities of a country reflect its relevance as a supplier in the FVAiX network, while the in-strength and the authority centralities signal its importance as a user of foreign value added in exports. Formal definitions are provided in Appendix B.

value added to be incorporated in other countries' exports. This fact confirms the recent evidence on the upgrading of Chinese exports (Ito and Vézina 2016) and contradicts the belief that products made in China have little Chinese value added.

There is a meaningful difference between the roles of Germany and the US in GVCs: the US acts mostly as a supplier, while Germany is also an important user of FVAiX. In fact, the strong reliance of the German manufacturing industry on foreign inputs has even led some authors to refer to it as a "bazaar effect" (Sinn 2006). Moreover, their hub centrality differs more than their out-strength, indicating that, not only the US supplies more than Germany, but also supplies to relatively more important users. The dynamics of their centrality measures are also different. Germany broadly maintained its central position in the network, in particular as a user, while the importance of the US as a supplier strongly declined since 2000.

In directed networks, it is also relevant to examine the extent to which ties are reciprocated (Squartini *et al.* 2013). The network of FVAiX is highly reciprocated as the average of bilaterally balanced flows, i.e., those that are mutually exchanged, stands around 65 per cent of total flows with no clear trend from 1995 to 2011 (Figure 3, panel a). Germany consistently presents the highest reciprocity amongst top players, while Russia stays in the last position in the reciprocity ranks because it acts largely as a supplier, especially of energy products, and its relevance as a user of FVAiX is negligible.

Another important feature of real-world networks is how tightly clustered they are, reflecting the tendency of two nodes being connected if they share a neighbour. Panel b) of Figure 3 displays the clustering coefficient proposed by Mcassey and Bijma (2015) for complete weighted directed networks in terms of cyclic triangles, i.e., triplets of nodes strongly connected by edges clockwise



(A) Reciprocity

(B) Clustering coefficient (cyclic triangles)

Figure 3: Reciprocity and clustering coefficient

Notes: Reciprocity is the share of flows that are mutually exchanged. Clustering coefficient measures the interconnectivity among nodes. Formal definitions are provided in Appendix B.

(or counter-clockwise) oriented. The clustering coefficient of the top players is relatively stable up to the turn of the century, it increases in the early 2000s and flattens after 2008. This pattern reflects the entrance of new players in GVCs and the inherent creation of value-added linkages among all participants. The results for Germany and, mostly, Japan are worth mentioning. Germany records small increases in the clustering coefficient, signalling that its GVCs root in direct relationships. Conversely, the increase in the Japan's coefficient is particularly striking. It mirrors the role of Japanese affiliates in East Asian production networks (Kimura 2006 and Urata 2014), which typically involve more than two countries, thus increasing the prevalence of cyclical triangles.

Until 2001, there is a strong positive correlation between the in-strength of a node and its clustering coefficient, meaning that the most important users of FVAiX were most likely to be involved in clusters (Figure 4). Afterwards, this nexus fades, which indicates that the average increase in the clustering coefficient is only marginally explained by direct relations in the network. Overall, this fact suggests that second-order properties are important to understand key organisational features of GVCs, such as the combination of intra-firm and arm's-length transactions, which lead to links between several countries.

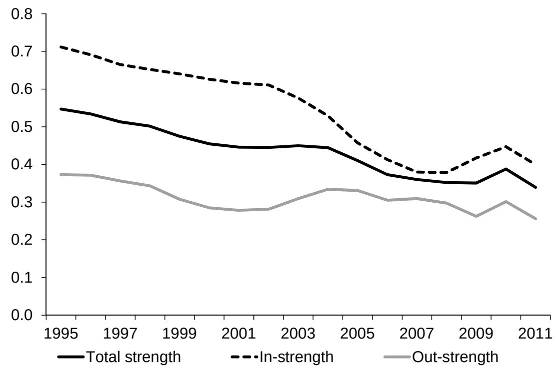


FIGURE 4: Correlation between clustering and strength

Notes: Linear correlations measured by the Pearson correlation coefficient. The out-strength of a country reflect its relevance as a supplier in the FVAiX network, while the in-strength signals its importance as a user of foreign value added in exports. Clustering coefficient measures the interconnectivity among nodes. Formal definitions are provided in Appendix B.

5. Conclusion

We use complex network metrics to illustrate the profound transformations that occurred in international trade and production from 1995 to 2011. The paper is based on the World Input-Output Database (WIOD) and studies the evolution of global value chains (GVCs) from a network perspective. More specifically, we focus on the concept of foreign value added in exports (FVAiX) and, in each year, the GVC is represented as a weighted directed network of countries (nodes) and value added flows between them (edges). These weighted networks of FVAiX enable us to represent quantitatively processes and flows in GVCs, taking into account both the extensive and intensive margins of value-added trade, and to identify the main players in GVCs over time.

We find that the fundamental structure of GVCs is still organised around major regional blocks, with Germany, the US and China acting as hub suppliers in their respective regions. Nonetheless, over time, GVCs became more global and the networks turned more complex and strongly connected. The change in the architecture of the network of FVAiX highlights the rising importance of China since 2000, which developed into the largest supplier of value added after the US.

Furthermore, we identify the distinct roles played by Germany and the US in GVCs: Germany is very relevant both as a user and as a supplier of foreign inputs, while the US acts mostly as a supplier of value added to other countries. Our results emphasise that second-order properties of the network can shed light on complex organisational features of GVCs and inherent multi-country linkages. Indeed, Germany's GVCs are mostly based on direct relationships, while Japanese ones typically include more than two countries.

The mapping and measurement of GVCs is still incomplete and the use of tools of network analysis can bring valuable insights. The potential of a network perspective to understand the structure and organisation of world production is large and still greatly unexplored. A complex network approach, which 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 to identify the appropriate policies in that environment. Our findings can be seen as a contribution to further research on the application of network methods for studying GVCs.

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

ISO alpha-3 code	Country name
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

Appendix B: Network metrics

Let $G = (N, L)$ be a network with a set of N nodes and L links. It is fully characterised by its binary and weighted adjacency matrices: $A \equiv (a_{ij})_{1\leq i,j\leq N}$ and $W \equiv (w_{ij})_{1\leq i,j\leq N}$. In its simplest binary form, $a_{ij} = 1$ if there is a link from node i to node j and $a_{ij} = 0$ if not. Analogously, the weighted adjacency matrix is defined such that the entry w_{ij} is equal to the weight of the link between i and j. In a directed network, the links are oriented from node i to node j, so that $a_{ij} \neq a_{ji}$ and $w_{ij} \neq w_{ji}$. By convention, the origin of the directed edge (node i) are the rows, and the recipients of the edges (node j) are the columns of the adjacency matrices.

B.1. The backbone

The network of foreign value-added exports is fully connected, directed and weighted. A link of weight f_{ij} is defined by the value added from source country i that is embodied in exports of country j, thus it is oriented from the supplier to the receiver of the value added. $F = [f_{ij}(t)]$ is the $N \times N$ weighted adjacency matrix at time t, with $t = 1995, ..., 2011$ and $N = 40$, which fully describes the evolution of the weighted directed network of foreign value added in exports over time.

Given a graph, a subset of its edges obtained by removing some of the original links represents a sub-graph. A backbone reduction aims at preserving only the most relevant part of a network. The resulting sub-graph can also be conveniently used for visualisation purposes. The procedure has been applied in several research fields with distinct algorithms and the results can differ substantially from network to network. Recently, Mastrandrea *et al.* (2017) use a maximum spanning tree approach similar to the one of this paper to analyse the human functional brain network.

The backbone structure is extracted from the complete FVAiX network by selecting for each country only its strongest supplier and user connections. Starting from the complete weighted network in a given year, two new sub-graphs are built: one uses only the maximum incoming link of each node (maximum value of each column of F), i.e., for each country the graph includes only its main supplier of foreign value added in exports; another uses only the maximum outgoing link of each country (maximum of each row of F), i.e., the graph includes only the main receiver of the value added of each country. Each new sub-graph has the same number of nodes and links ($N = 40$).

Figure 1 in the main text displays the network representations of the backbone of users and suppliers in 1995 and 2011. Each country is represented by a circle and the arrows that represent the edges are oriented from supplier to receiver of value added. The size of each node is proportional to its share as a user/supplier of value added in the respective backbone. The edge width is proportional to its weight (value-added flows). The edges representing flows that are reciprocated, i.e., countries that are the main users (suppliers) of the value added of each other are black-shaded. The network graphs 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).

B.2. Centrality measures

We define a node's out-strength (in-strength) as the sum of all its outgoing (incoming) link weights (Barrat *et al.* 2004). Then, it is normalised by the total weight of the network:

$$s_i^{out} = \frac{\sum_{j=1}^{N} w_{ij}}{\sum_{j=1}^{N} \sum_{i \neq j}^{N} w_{ij}} \tag{B.1}$$

$$s_i^{in} = \frac{\sum_{j=1}^{N} w_{ji}}{\sum_{j=1}^{N} \sum_{i \neq j}^{N} w_{ij}} \tag{B.2}$$

In directed networks, the hub and authority centralities are measures based on the centrality of nodes' neighbours and they are computed iteratively. Kleinberg (1999) was the first to introduce these concepts developing an algorithm called *hyperlink-induced topic search* (HITS). To each node i, it assigns a hub centrality y_i, defined to be proportional to the sum of the authority centralities of the vertices that it points to; and an authority centrality x_i, proportional to the sum of the hub centralities of the vertices that point to it:

$$y_i = \beta \sum_{j=1}^{N} w_{ij} x_j \tag{B.3}$$

$$x_i = \alpha \sum_{j=1}^{N} w_{ji} y_j \tag{B.4}$$

where β and α are constants. In the network of foreign value added in exports, a hub is a country that supplies a lot of value added to countries that are themselves important users and an authority is a country that uses largely value added from countries that are themselves important suppliers.

Hence, the out-strength and the hub centralities of a country reflect its relevance as a supplier of foreign value added to other countries' exports, while the in-strength and the authority centralities signal its importance as a user of foreign value added in its own exports.

B.3. Reciprocity

In a binary network, if there is a directed edge from node i to node j and a link in the opposite direction, we say that the link from i to j (and obviously from j to i) is reciprocated (Garlaschelli and Loffredo 2004). Network reciprocity is a global measure of directed networks counting the fraction of reciprocated edges (Newman *et al.* 2002). That is:

$$r^b \equiv \frac{L^{\leftrightarrow}}{L} \tag{B.5}$$

where $L = \sum_j \sum_{i \neq j} a_{ij}$ is the total number of links, $L^{\leftrightarrow} = \sum_j \sum_{i \neq j} a_{ij} a_{ji}$ is the total number of links pointing in both directions, and $a_{ij} = 1$ if there is a link from i to j and $a_{ij} = 0$ if not.

The definition of reciprocity for weighted networks involves the amount of reciprocated flows between any pair of nodes. If there exists a reciprocated link between nodes i and j, Squartini *et al.* (2013) define the reciprocated strength $s_i^{\leftrightarrow}$ of node i as:

$$s_i^{\leftrightarrow} \equiv \sum_{i \neq j} w_{ij}^{\leftrightarrow} = \sum_{i \neq j} w_{ji}^{\leftrightarrow} = \sum_{i \neq j} \min[w_{ij}, w_{ji}] \tag{B.6}$$

where $w_{ij}^{\leftrightarrow}$ is the reciprocated weight between i and j (the symmetric part).

For the network-wide level, Squartini *et al.* (2013) proposed the following global measure:

$$r \equiv \frac{W^{\leftrightarrow}}{W} = \frac{\sum_j \sum_{i \neq j} w_{ij}^{\leftrightarrow}}{\sum_j \sum_{i \neq j} w_{ij}} \tag{B.7}$$

where W is the total weight of the network and and $W^{\leftrightarrow}$ represents the total reciprocated weight.

Figure 3 panel a) in the main text depicts the values of the reciprocated strength for the main players, as well as the global measure for the network as whole from 1995 to 2011.

B.4. Clustering

In a binary network, the clustering coefficient of a node i is the ratio between the number of pairs of its neighbours that are connected and the total number of pairs of neighbours of i. In other words, it counts the number of closed triangles with respect to the total number of connected triples passing through node i (Watts and Strogatz 1998).

The extension of the clustering coefficient to the weighted case is not trivial. In fact, there are alternative definitions for the weighted clustering coefficient in undirected networks (Barrat *et al.* 2004, Saramäki *et al.* 2007, Kalna and Higham 2007) and for the directed case (Fagiolo 2007). Here, we consider the definition introduced recently by Mcassey and Bijma (2015) for complete networks.

In a weighted directed network, a node can be involved in triadic structures in one direction more than in another. Thus, for each node in a complete directed network there are eight possible triangles according to all combinations of link directions. Two of them are cyclic in the sense that links in the triangle have the same cyclic direction. One can define the clustering coefficient in terms of all triangles and in terms of the two cyclic triangles.

Mcassey and Bijma (2015) normalise the complete weighted adjacency matrix W so that the weights $w_{ij} \in [0, 1]$. The closer w_{ij} is to one, the more nodes i and j are considered strong neighbours, while the nearer w_{ij} is to zero the more these nodes are regarded as weak neighbours. Intuitively, the clustering coefficient for node i is large if the set of strong neighbours of i are themselves strong neighbours of each other; the clustering coefficient for node i is small if it has mostly weak neighbours.

A threshold t is introduced such that:

$$W_t = \{w_{ij} | w_{ij} \geq t\} \qquad \text{and} \qquad A_t = [1 | w_{ij} \geq t] \tag{B.8}$$

where W_t is the weighted adjacency matrix of the thresholded network and A_t is the corresponding binary adjacency matrix with entries a_{ij}^t.

Let $\gamma_i(t)$ denote the number of closed triangles passing through node i and let $\Gamma_i(t)$ denote the number of triangles (closed or not) passing through node i in the thresholded network:

$$\gamma_i(t) = \sum_{j \neq i} \sum_{k \neq i,j} \frac{(a_{ij}^t + a_{ji}^t)}{2} \frac{(a_{jk}^t + a_{kj}^t)}{2} \frac{(a_{ik}^t + a_{ki}^t)}{2} \tag{B.9}$$

$$\Gamma_i(t) = \sum_{j \neq i} \sum_{k \neq i,j} \frac{(a_{ij}^t + a_{ji}^t)}{2} \frac{(a_{ik}^t + a_{ki}^t)}{2} \tag{B.10}$$

The weighted clustering coefficient of node i in the weighted thresholded network represented by W_t is given by:

$$c_i^{all}(t) = \frac{\gamma_i}{\Gamma_i} \tag{B.11}$$

Then, the weighted clustering coefficient for each node considering all triangles in the complete weighted network represented by W is given by:

$$c_i^{all} = \int_0^1 c_i^{all}(t)dt \tag{B.12}$$

If we focus on cyclic triangles, we have:

$$c_i^{cyc}(t) = \frac{\sum_{j \neq i} \sum_{k \neq i,j} a_{ij}^t a_{jk}^t a_{ki}^t}{\sum_{j \neq i} \sum_{k \neq i,j} a_{ij}^t a_{ki}^t} \tag{B.13}$$

and the weighted clustering coefficient for node i in the complete network is given by:

$$c_i^{cyc} = \int_0^1 c_i^{cyc}(t)dt \tag{B.14}$$

For each typology, the global clustering coefficient of a network is simply the average of the clustering coefficient of all nodes.

Figure 3 panel b) in the main text depicts the values of the clustering coefficient computed for cyclic triangles for the main players, as well as the average for the network as whole from 1995 to 2011. The clustering indicator computed for all triangles presents a very similar pattern. The main difference between the two measures of clustering regards Russia, where the values are higher if all triangles are considered. This difference results from the fact that Russia is a large supplier of energy products in Europe but its importance as a user of foreign value added in exports is negligible. Hence, the edges pointing to Russia are mostly weak ties, leading to a coefficient based on cyclic paths that is smaller than the one considering all patterns of directed triangles.

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