



# Patterns of variability in the structure of global value chains: a network analysis

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## Abstract

Global Value Chains (GVCs) are a feature of the organization of production in many sectors and countries and they deeply affect international trade patterns. How far the separation of production stages—generating increasingly widespread GVCs—can go, is currently a matter of debate. The main focus of this paper is to investigate GVCs at the country-industry level by modelling them through the construction of a specific network and using network analysis tools. In particular, the aim is to propose a network-based measure of GVCs length to assess whether the structure of GVCs has stretched or shrank over time. Analyzing the evolution of these structures is important to better understand the role played by countries in the production chain, with implications also for their fragility or resilience in presence of external shocks. Our measure allows to consider differently shaped GVCs, and the results show that there are relevant differences among sectors and countries in terms of the evolution of GVCs, especially considering direct or indirect links. Overall, we find a general stability over time of GVCs, confirming the importance of the “relational approach” in GVCs. But the shifts in the geographical patterns of the connections also support the view that firms organizing this complex form of production are ready to grasp better opportunities when they appear in the global markets.

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## 1 Introduction

Global Value Chains (GVCs) appear today as a characteristic feature of the organization of production in many sectors and countries and, after years of expansion, they deeply affect international trade patterns. How far this separation of production stages, generating increasingly widespread GVCs, can go, is currently a matter of debate, especially observing a partial slowdown of this “second great unbundling” [as it is named by Baldwin (2006)] in the last years and months, following hard international economic shocks (Miroudot, 2020).

The increasing relevance of GVCs in international trade has been widely emphasized in a large number of recent studies.<sup>1</sup> While providing a number of fundamental conceptual and empirical insights into their organization, these studies develop the analysis of the GVCs structures at the world level in terms of weight of trade carried, value added generated and relevance of involved countries. But, as the existing literature shows, measuring the *global length* of GVCs is not straightforward, because of limitations on the data available, and because of the multidimensionality of GVCs. Yet, the extension of GVCs is an important feature to assess their evolution over time, and understanding whether the GVCs’ reach has been increasing or reducing can provide insights for example on the range of spillovers on participating countries (Pahl and Timmer, 2019).

The aim of this paper is to propose a measure of GVCs’ length based on network analysis, that takes into account the fact that often GVCs are much more complex structures than chains and simply counting the number of steps from final demand might not provide a suitable measure. Following Antrás (2020), we adopt here a broad definition of GVCs, considering them as the result of production processes stretching across multiple countries, a series of stages required to produce a good or a service to be sold to consumers, with each stage adding value and with at least two stages taking place in different countries. This broad definition is consistent with various configurations and different structures of GVCs (Yeung and Coe, 2015), including “spider-like” or “snake-like” structures (Baldwin and Venables, 2013), as well as additional mixed structures, and it allows to analyze GVCs using data on international trade across countries jointly with inter-country input–output tables. In fact, regardless of the specific GVC shape, such an international organization of production is responsible for the occurrence of multiple trade exchanges among countries, shaping countries’ trade patterns.

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<sup>1</sup> Overviews on the role and expansion of GVCs are provided by Timmer et al. (2012, 2015), Johnson and Noguera (2012), Baldwin and Lopez-Gonzalez (2013), World Trade Organization (2017), The World Bank (2020), while a survey of the GVCs literature is conducted by Amador and Cabral (2016). A comprehensive analysis of the state of the art in the study of GVCs is provided by Antrás and Chor (2021).

In the paper we apply this network-based measure to investigate changes in GVCs, and in particular, to assess whether the structure and length of GVCs in some representative industries has changed over time. We focus on what Baldwin (2013) calls “geographic unbundling” rather than “functional unbundling”. The latter, in fact, would require much more detailed data at the firm level, unfortunately available only for a small number of countries and sectors. But understanding the geographical evolution of these structures is important to better understand the role played by countries in the production chain—with implications for example for the degree of competition along the GVC (e.g. McNerney et al. (2022))—as well as their fragility or resilience in presence of external shocks (Brakman and van Marrewijk, 2019).

## 2 Global value chains’ structures and length

GVCs can take very different shapes and structures according to the characteristics of the goods being produced, the countries involved and firms’ specific choices, so that there is no standard length or configuration of these production organizations. The importance of the structure of GVCs has been already emphasized in the early literature developed in the late 1990s studying the diffusion of international fragmentation of production that generated GVCs. Starting from Gereffi (1999), the relevance of the different organizational forms of production chains for upgrading is acknowledged, and Deardorff (2001b) shows that the equilibrium and the gains from trade related to the fragmentation of a production process across different countries depend crucially on the characteristics of the new production structure. In Arndt and Kierzkowski (2001), many contributions highlight the importance of the specific pattern of fragmentation and the role of services in shaping the structure of production processes. More recently, the impact the GVCs’ structures on the diffusion of innovation is highlighted in Lee and Gereffi (2021). Yet, tools to describe the structure of GVCs and measure their length are scarce. Most measures of length for GVCs proposed in the literature count steps in the chain: for example, Antràs et al. (2012) refer to the number of steps to go from a certain intermediate product to a final good, using U.S. disaggregated input–output tables with many sectors, and thus managed to be very detailed in the description of trade. Regrettably, highly disaggregated input–output tables are not available for most countries, and using I-O tables of a given country for others presents serious limitations and distortions. Additionally, this type of measure assumes a “snake-like” shape of GVCs that is not always applicable.<sup>2</sup>

In a recent influential paper, Antràs and de Gortari (2020) develop a new model to describe the structure of GVCs in terms of number of stages and their geographical location, following the optimization choices of a firm organizing such a process, or the choice of consumers that will prefer the finished good with the lower price. Differences in technology and factors’ costs across countries affect the marginal

<sup>2</sup> Wang et al. (2017) criticize these measures for being unsuitable for this type of study.

production cost of each stage. In the model, the optimal location of production of a given stage in a GVC is not only a function of the marginal cost at which that stage can be produced in a given country, but because of transportation costs, it is also shaped by the proximity of that location to the precedent and the subsequent desired locations of production. Given these characteristics, GVCs will be different and will differently involve countries, therefore having varied shapes and lengths.<sup>3</sup> When bringing their model to the data, the authors argue that the length of the sequentiality of production cannot be properly identified using World Input–Output Tables (WIOT), because bilateral trade flows in such dataset are too aggregated to provide an appropriate representation of many highly articulated supply chains, and they resort to using the variation in the data to find the model’s parameters conditional on a given length.

It is certainly true that the level of aggregation in the WIOT is generally too high to provide sufficient details on the functional unbundling of the production process. This type of analysis would require firm level data, to consider the specific inputs requested, imported and exported along the process. Unfortunately, detailed datasets at firm level are available only for a few countries and cannot be used to provide a general picture. Our aim here is to undertake a macroanalysis of the evolution of GVCs, focusing on the changes in their geographical extension and ramification. Following the vast empirical literature that analyses GVCs at the country level [see for example Johnson (2018), Timmer et al. (2021), Borin et al. (2021), Giunta et al. (2022)], we also rely on WIOT data that, even if missing the detailed decomposition of the production processes, allows to consider comprehensively the world production linkages. We propose to measure GVCs applying a measure based on network topology, that considers these organization of production not necessarily as a sequence of steps (a “chain”) but as a network, with multiple links that take different shapes.<sup>4</sup> This allows to further exploit the available variability in the WIOT to obtain a more fitting size of “Global Value Networks” (GVNs) and assess their evolution.

We are not the first to apply network topology to the analysis of GVCs. De Backer and Miroudot (2013) explored some structural properties of GVCs through the use of networks, and Zhu et al. (2015) built a network from the World Input Output Database (WIOD), producing a detailed topological view of the industry-level GVCs. Network analysis is used by Piccardi et al. (2017) and Riccaboni and Zhu (2018) to determine the relevance of GVCs in trade flows among countries applying

<sup>3</sup> This result is in line with the early literature cited above, underlying the role of services connecting the various parts of the production process and the importance of having lower direct production costs to overcome the additional “linking” costs [Deardorff (2001a), Jones and Kierzkowski (2001)], as well as with de Gortari (2019), showing that the structure and organization of GVCs can be different for different products and countries combinations and it cannot be assumed that the same input/country mix is always used.

<sup>4</sup> Carvalho (2014) shows the role of network analysis applied to input–output tables to better understand the performance of an economic system and how production networks can be mapped into a basic general equilibrium setting. As underlined also by Johnson (2018), input–output data are consistent not only with sequentiality in production, but also with more varied production arrangements.

community detection techniques.<sup>5</sup> Centrality in networks has also been used to identify the role of countries in GVCs. Cingolani et al. (2017) adopt a network-based perspective on international trade data and propose a three-faceted measure of centrality that captures countries' distinct roles at the upstream, midstream, and downstream stages of the international production process. Criscuolo and Timmis (2018) use centrality metrics to reflect the changing structure of Global Value Chains (GVCs), contrasting central hubs and peripheral countries and sectors, and examine how these changes impact the productivity of firms participating to GVCs.

These studies confirm that applying network analysis to GVCs allows to obtain additional information on their structures and on countries' and firms' position. But so far, network analysis has not been applied to measure the overall extension of GVCs. This is precisely what we aim to do, investigating the GVCs at the industry-level by modeling them through the construction of a specific network. We analyze the topological properties of GVCs crossing different industries and sectors in order to produce a given final product. From a complex networks perspective, we map World Input–Output tables (WIOT) into Global Value Networks (GVNs), that are specific networks related to target sectors. We will study some sectors by analyzing the associated GVN, discussing its global and local properties and its evolution over time, considering in particular how widespread the GVNs are and if they changed over time in this respect. The construction of the GVN takes place by moving backward a number of steps from the sector under observation, following the edges modeling the supply of intermediate products. In addition, different methods of filtering the importance of edges will be applied in order to obtain streamlined networks that retain all the useful information. This type of analysis allows to provide a more complete picture of GVCs or GVNs for given products at the world level, and to show the remarkable stability over time of this organization of production.

### 3 Measuring distances on global value networks: shortest path and communicability

In order to introduce the indicators used in the analysis of GVCs, in this section we recall a few basic notions of network theory and we define and discuss the properties of the two measures of node-to-node distance that will be used throughout this paper, namely *shortest path distance* and *communicability*.<sup>6</sup>

A network (or graph) is a pair  $G = (V, E)$ , where  $V$  is the set of *nodes* and  $E$  is the set of *edges*. We denote by  $N = |V|$  and  $L = |E|$ , respectively, the number of nodes and edges. The network structure is fully described by the  $N \times N$  *adjacency matrix*  $A$ , whose entry  $a_{ij} = 1$  if the edge  $i \rightarrow j$  exists, and  $a_{ij} = 0$  otherwise.

<sup>5</sup> Communities in a network are dense clusters of nodes which are tightly coupled to each other inside the group and loosely coupled to the rest of the nodes in the network. Community detection can apply different methodologies and plays a key role in understanding the functionality of complex networks [Fortunato and Hric (2016), Piccardi and Tajoli (2012)].

<sup>6</sup> For a detailed introduction to network theory, see e.g. Newman (2010), Barabasi (2016), Latora et al. (2017).

A graph is *undirected* if the existence of edge  $i \rightarrow j$  implies the existence of  $j \rightarrow i$  (then  $A$  is a symmetric matrix), *directed* otherwise. In an undirected network, the *degree*  $k_i = \sum_j a_{ij}$  is the number of edges connected to node  $i$ , that is the number of neighboring nodes. In a directed network, we define the *indegree*  $k_i^{in} = \sum_j a_{ji}$  (resp. *outdegree*  $k_i^{out} = \sum_j a_{ij}$ ) as the number of incoming (resp. outgoing) edges, and the total degree as  $k_i^{tot} = k_i^{in} + k_i^{out}$ .

A graph is *weighted* if a real number, the weight  $w_{ij} > 0$ , is assigned to each edge  $i \rightarrow j$ , *unweighted* if all edges have the same weight (set to 1 without loss of generality). In the weighted case, both the network structure and the weights are summarized in the *weighted adjacency matrix*  $W$ , where  $w_{ij} > 0$  if the edge  $i \rightarrow j$  exists, and  $w_{ij} = 0$  otherwise.

GVNs are directed (the edge  $i \rightarrow j$  represents the contribution of sector  $i$  to sector  $j$ ) and weighted ( $w_{ij}$  is the amount of such a contribution—see Sect. 3.4 for details). In order to measure the extension, or length, of a GVN, we need a notion of node-to-node distance. Many such notions are available in network science: here we briefly review the simplest one, *shortest path distance*, and highlight its drawbacks with respect to our framework. Then we introduce the *communicability distance*, which better fits the properties of our GVN model.

### 3.1 Shortest path distance

A *walk* of length  $n$  is a sequence of (not necessarily distinct) nodes  $v_0, v_1, \dots, v_n$  such that, for each  $k = 0, 1, \dots, n - 1$ , the edge  $v_k \rightarrow v_{k+1}$  exists. A *path* is a walk where all nodes are distinct. Two nodes  $i, j$  are *connected* if there exists a path from  $i$  to  $j$  and a path from  $j$  to  $i$ . A path connecting  $i$  to  $j$  is a *shortest path* if its length—measured in number of edges—is minimal among all the paths from  $i$  to  $j$ . The *shortest path distance*  $d_{ij}$  is the length of a shortest path connecting  $i$  and  $j$ ; it only takes integer values, by definition. When the network is connected (i.e. all pairs  $i, j$  are connected) we can define the *average distance* as

$$d = \frac{1}{N(N-1)} \sum_{\substack{i,j \\ i \neq j}} d_{ij} \quad (1)$$

It is a global property of the network, representing how far, on average, two nodes are from each other. The shortest path distance, despite its simplicity, is not the best tool for analyzing GVNs because of a few limitations. Firstly, in common with many real-world situations, the connection between nodes does not only take place along the shortest path, but through all possible routes connecting the nodes, possibly with different intensities. The number of such routes can be very large in practice, thus a notion of distance different than the shortest path could be appropriate, because the shortest path alone could be scarcely representative of the whole structure of a network. In terms of economic organization of GVCs, these considerations are relevant

because the shortest connections between production phases are not necessarily the only existing ones or the most efficient. For example, especially in geographical terms, there can be multiple connections between one phase and the upstream or downstream ones in order to diversify suppliers or destination markets. Secondly, shortest path distance does not naturally consider edge weights, which are instead crucial in our case.<sup>7</sup>

### 3.2 Communicability

To cope with the above mentioned drawbacks, we introduce a new notion of node-to-node distance. The *communicability*  $G_{ij}$  between nodes  $i, j$  takes into account all walks of any length  $k$  starting at node  $i$  and ending at  $j$ , with the weight  $1/k!$  giving higher weight to shorter walks (Estrada and Hatano, 2008):

$$G_{ij} = \sum_{k=0}^{\infty} \frac{(A^k)_{ij}}{k!} = (e^A)_{ij}. \tag{2}$$

We recall that  $(A^k)_{ij}$  gives the number of walks of length  $k$  starting at node  $i$  and ending at  $j$ .

The *total network communicability*, a global measure characterizing the whole network, is defined as the sum of all node-to-node communicabilities  $G_{ij}$  (Benzi and Klymko, 2013):

$$TC = \sum_{i,j=1}^N G_{ij}. \tag{3}$$

This quantity has been empirically shown to provide an effective measure of how the information flows along the network and how well connected a network is [(see for example Estrada et al. (2012) and Bartesaghi et al. (2022)]. In a weighted network, the communicability is similarly defined from the weighted adjacency matrix:

$$G_{ij} = \sum_{k=0}^{\infty} \frac{(W^k)_{ij}}{k!} = (e^W)_{ij}, \tag{4}$$

and the total network communicability is accordingly defined as in Eq. (3).

Also in economic terms, distance is one possible proxy of accessibility of a market or a supplier, but certainly not the only one, or the most appropriate in some situations. If existing edges measure the presence of economic transactions between nodes, as it is in the GVN's studied here, the network structure and network communicability can be associated to the facility of access and the degree of competition in

<sup>7</sup> The possible logical connection between the optimization problem of finding the cost-minimizing path of a GVC and the minimal distance Hamiltonian path problem in graph theory is reminded also by Antràs and Chor (2021). But the authors also acknowledge that this problem requires picking an optimal sequencing out of the many possible permutations of countries in the value chain, rising issues in finding an efficient solution to the problem.

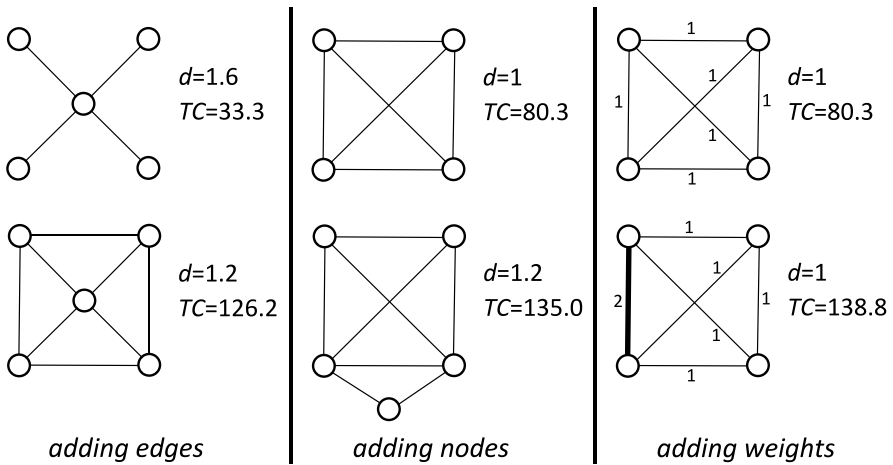
a given country market. How smooth is the movement within the network from one node to another and how many paths exist connecting different nodes, is an indicator of the relative openness of the market in a given country, and how exposed are exporters toward that market to the competition of other countries. With respect to GVN, communicability allows to measure how articulated and extended the international production process is, and whether the number of connected countries/industries (i.e. nodes) changes over time, as well as the relative weights of the connecting links.

### 3.3 Comparing shortest path and communicability

Figure 1 exemplifies the effect on the average distance  $d$  and on the total communicability  $TC$  of specific network perturbations. Generally speaking, in a network with a fixed number of nodes, adding edges implies creating new walks and paths, so that  $d$  will decrease and  $TC$  will increase. On the other hand, connecting new nodes to the existing network will increase  $d$ , since paths become longer on average, but will also typically increase  $TC$ , because of the increased number of walks. These network properties are interestingly related to a number of economic features. For example, the increase in the number of connections, generating a decrease in  $d$  and higher communicability [see the first panel of Fig. 1], implies an increase of potential competition in that market, similar to the effect shown for a region becoming less peripheral in economic geography models. The connection of new nodes to the network (i.e. the entrance of new countries in the market) by increasing  $d$  might increase the average transportation cost, but it expands the market size (i.e. higher  $TC$ ), with ambiguous effects on the final prices. At the same time, the possibility that an economic event or policy in a given country is transmitted to some extent to another country grows with the growth of connections and  $TC$ . Finally, increasing weights (i.e. the economic relevance of trade between countries) will not modify  $d$ , provided the structure is unchanged, but will increase  $TC$  according to Eq. (4). In Sect. 3.4, we will exploit these observations to understand the patterns of evolution of global value networks over the years.

Figure 2 provides a more detailed description of the two node-to-node distance measures, by comparing their distributions on two paradigmatic network models [e.g. Barabasi (2016)]: an Erdős-Rényi network, which is created in a purely random manner by connecting all node pairs with a given probability, thus yielding a network where all nodes are statistically equivalent and have similar degree; and a Barabási-Albert network, which is created by incrementally adding one node at a time and connecting it preferentially to the nodes already with large degree, eventually giving rise to a network where a majority of small-medium degree nodes coexists with a few nodes (called “hubs”) with a disproportionate number of connections. We know from many previous studies on the world trade network that in reality the connections between countries are not generated in a random manner [e.g. De Benedictis et al. (2014)].





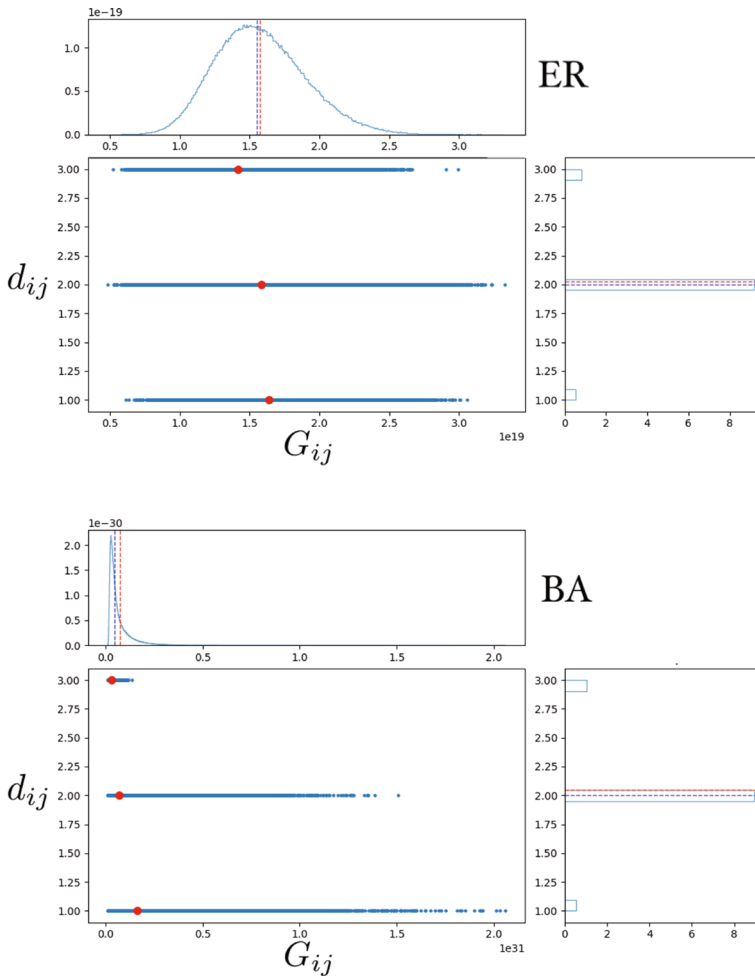
**Fig. 1** An illustration of the effect of network perturbations on the average distance  $d$  and on the total communicability  $TC$

From Fig. 2 we observe that, for both network models, a node pair separated by a smaller shortest path has, on average, higher communicability, a pretty obvious result. The distribution of communicabilities is quite interesting: in the Erdős-Rényi network it resembles a normal-like distribution. The great diversification of values reflects the many possible paths between two nodes. On the contrary, in the Barabási-Albert network the distribution tends to collapse toward zero, revealing the scarcity of possible paths for the totality of node pairs.

In economic terms, if existing links measure the presence of economic transactions between nodes, as it is in the GVN<sub>s</sub> studied here, the network structure and network communicability can be associated to the degree of competition in a given market. How easy it is to move within the network from one node to another and how many paths exist connecting different nodes is an indicator of the relative openness of the market in a given country, and how exposed are exporters toward that market to the competition of other countries. In line with this interpretation, the findings of Criscuolo and Timmis (2018) suggest that the high number of connections of the most central nodes (countries or firms) is correlated with the higher productivity of a given node.

### 3.4 Building sectoral global value networks (GVNs)

The World Input–Output Tables (WIOT) provide yearly data on the exchanges between supplying and using industries within countries and between countries, and therefore have been often used in the literature to obtain evidence on the evolution of GVCs. In this work, we used the WIOT available in the OECD TiVA ISIC Rev.3 database (<https://www.oecd.org/sti/ind/input-outputtables.htm>), providing data from 2005 to 2015 for 69 countries and 36 industries (listed in Appendix A). From now



**Fig. 2** Shortest path distance vs. communicability in a Erdős-Rényi (ER, above) and in a Barabási-Albert (BA, below) network with  $N = 1000$  nodes and average degree  $k_{avg} = 50$ . For both networks, the central panel is a scatter plot where each (blue) dot corresponds to a node pair  $(i, j)$ , and the  $(x, y)$ -coordinates are the communicability  $G_{ij}$  and the shortest path distance  $d_{ij}$ ; the red dots highlight the average communicability for fixed value of the shortest path distance. The top and right panels display the frequency distribution (density) of  $G_{ij}$  (top) and  $d_{ij}$  (right) over the network (mean value in red, median in blue)

on, for brevity a country-industry pair will be denoted by *sector*. We focus, for each year, on the intermediate transactions matrix  $Z = [z_{ij}]$ , whose entry  $z_{ij}$  is the amount (million USD) of the supply from sector  $i$  to sector  $j$ , and on the gross output vector  $X = [x_j]$  [see Miller and Blair (2009) and Timmer et al. (2012) for more details].

Our aim is to extract, from the WIOT, the GVN of a given *target sector* in a given year, namely the network representing its GVC in that year.<sup>8</sup> In such a network, each sector (a given industry in a given country) is a node, an edge from node  $i$  to node  $j$  means that sector  $i$  contributes to sector  $j$  by providing inputs and adding value, and the weight  $w_{ij} > 0$  associated to the edge is the amount of such a contribution. The GVN is built by starting from the target sector and then by proceeding backward by adding *levels*: the first level contains all sectors directly contributing to the target; the second level all sectors directly contributing to the first level (but not to the target), etc.. Clearly, by increasing the number of levels the GVN tends to progressively include most WIOT sectors and thus it becomes loosely descriptive of the target sector. After extensive analysis, and also taking into account the related computational requirements, we decided to truncate the GVN at the third level, as this appeared as the best trade-off between the meaningful representation of a specific GVN and the useful level of details.<sup>9</sup>

We must notice that the term GVN was originally used by Zhu et al. (2015) in a similar context but with a different technical meaning. In their work, Zhu et al. (2015) first map WIOT into a *Global Value Network* using value-added contributions and the Leontief Inverse Matrix. Then, they start from target sectors and use a modified “breadth first search” and an edge weight threshold to associate a *Global Value Tree* to each sector. In our approach, the network is directly defined by trade data, and the graph associated to each sector is not constrained to be a tree, thus allowing a more flexible description. Despite the above technical differences, we decided to use the same term GVN as it is well suited to a network describing a global value chain.

The global trade value tends to increase over the years because of rising trade flows and inflation. Since we are only interested in structural changes of the GVN, in order to make years comparable we normalized the matrix  $Z$  by the value of total output: more precisely, we multiplied all entries of  $Z$  by  $10^7 / \sum_j x_j$ .<sup>10</sup> Additionally, to compare different sectors, we have to deal with the fact that they can have very different total exchanges. For this reason, when constructing the GVN for a given target sector, we further normalize data for the total trade in that sector: in particular, we further multiplied all entries of  $Z$  by  $10^5 / x_j$ , if  $j$  is the target sector. In this way we can compare the production chain of, say, a German car with a US one, avoiding that differences in country’s size reflected in production distort the picture.

We performed the GVN construction with three different methods, based on alternative filtering strategies:

<sup>8</sup> As mentioned, Antràs and de Gortari (2020) as well as Adarov and Stehrer (2021) underline that GVCs in different industries and involving different countries have specific characteristics. This supports our choice to build industry and country specific networks.

<sup>9</sup> Results obtained with different levels of cut-offs are available from the authors upon request.

<sup>10</sup> The  $10^7$  scaling factor, as the  $10^5$  below, is introduced just to obtain more manageable numbers.

1. *Sector contribution* After defining the target node  $j$ , all edges  $i \rightarrow j$  directed to  $j$  are included in the network, provided their weight is sufficiently large, i.e. a given share of total output,  $w_{ij} > \alpha x_j$ , where  $x_j$ , as pointed out above, is the gross output of the target sector.  $\alpha = 0.003$  has been set after many trials as a trade off between computational speed and number of included sectors. Then the same procedure is repeated treating all the existent nodes as the target one, up to the third level. In summary, this method includes all edges with non negligible weight and all sectors connected to them, that is the substantive part of the production network.
2. *Total incoming weight* After defining the target node  $j$ , all edges  $i \rightarrow j$  directed to  $j$  are considered and sorted in descending order by their weight  $w_{ij}$ . Then, we start from the largest weights and we include the corresponding edges in the network, until we reach a prescribed cumulative fraction  $\gamma$  of  $x_j$  (we set  $\gamma = 0.8$ ). Then the same procedure is repeated treating all the existent nodes as the target one, up to the third level. In summary, this method aims at selecting the most important contributions for every sector: differently from the previous method, we look globally at the total incoming weight of a node rather than at the individual weights of the contributions.
3. *Backbone extraction* After defining the target node  $j$ , the edge  $i \rightarrow j$  is included in the network if the following two inequalities are met:

$$\left(1 - \frac{w_{ij}}{s_j^{\text{in}}}\right)^{k_j^{\text{in}}-1} < \alpha_{\text{in}}, \quad \left(1 - \frac{w_{ij}}{s_i^{\text{out}}}\right)^{k_i^{\text{out}}-1} < \alpha_{\text{out}}, \quad (5)$$

where  $w_{ij}$  is the weight of the edge  $i \rightarrow j$ ,  $k_j^{\text{in}}$  (resp.  $k_i^{\text{out}}$ ) is the number of incoming (resp. outgoing) edges of node  $j$  (resp.  $i$ ),  $s_j^{\text{in}}$  (resp.  $s_i^{\text{out}}$ ) is the total weight of the incoming (resp. outgoing) edges of  $j$  (resp.  $i$ ), and  $\alpha_{\text{in}}$ ,  $\alpha_{\text{out}}$  are threshold parameters (we set  $\alpha_{\text{in}} = \alpha_{\text{out}} = 0.1$ ). Then the same procedure is repeated treating all the existent nodes as the target one, up to the third level. This method includes in the network only those edges which, based on their weight but also on the features of the two nodes they connect, are statistically significant according to a specific criterion [see Serrano et al. (2007, 2009) for details].

A careful analysis of the GVN's obtained with the three above methods revealed a strong similarity among them, in all case studies. Thus, for brevity, in the remainder we will only present the results obtained with the first method (*Sector contribution*).

Since the main issue we want to address is measuring the length of GVN's and assessing whether global value chains have been expanding or shrinking in past years, the sort of questions we want to answer are: For a given sector (i.e. a country/industry pair), has the GVN increased its size over time? For a given industry, has the GVN different size in different countries or, more in general, has the GVN of different countries evolved with different patterns over time? This obviously requires some definition of what the *size* of a network means: to have a broad picture, we will simultaneously investigate the behavior of a few features associated to a GVN, namely: the number of nodes and the number of edges, which reflect the number of

sectors involved and thus the complexity of the GVN; the total weight and the average weight per edge, which are representative of the overall importance of the target sector and of its fragmentation along the GVC; and the total communicability  $TC$  (Eq. 3) which, as discussed in Sect. 3.2, aims at providing a global quantification of the size (or length) of the GVC.

In addition, in order to grasp the geographical dimension of GVNs, we introduce a *geointegrated weight*  $v_{ij}$  which, for the edge  $i \rightarrow j$ , is the product of the value of the flow  $w_{ij}$  and of the geographical distance  $g_{ij}$  between the countries<sup>11</sup> associated to sectors  $(i, j)$ . The rationale is to weight the distance that all components of a GVC have to travel before being assembled into the final product, not only their quantity. For example, if Germany would buy half of the components from China to build a car and France would get the same half from Bulgaria, we would say—*ceteris paribus*—that the size of the production chain of German cars is larger than that of French cars. Or, if France would buy 1% of components from China, and Germany 50%, again we would say that the size of the German production chain is larger than that of the French one.<sup>12</sup>

## 4 Case studies and results

In this section we analyze the time evolution of the GVNs of a few selected sectors, with the main goal of contrasting the different features of the GVCs of the same industries in different countries. Each case is illustrated by a number of figures plotting the time series (2005-2015) of the following quantities, for each level of the GVN:

- *Total weight*, i.e. total value of the flow (not normalized by total output),
- *Average weight per edge* (not normalized by total output),
- *Number of nodes* (i.e. sectors) or *number of edges* of the GVN,
- *Average geointegrated weight* (i.e. flow value  $\times$  geographical distance) *per edge*,
- *Total network communicability*, based on the geointegrated weights.

We also plot the GVN structure of the most recent year available (2015) or, in a few cases, of the first (2005) and last (2015) year, with node size proportional to the total in/out weight and edge size to the weight. For readability, the network plots are limited to two levels, nodes are labeled only at the first level, and only edges with large weights are drawn (cut-off  $\alpha = 0.01$ , see method 1 in the previous section).

<sup>11</sup> The distance  $g_{ij}$  between two countries (in kilometers) is computed from the geographical coordinates of the capital towns. When two sectors refers to the same country the distance is set to 1.

<sup>12</sup> The distance  $g_{ij}$  between two countries can be measured in many different ways, not only using geographical distance, and the literature has not reached a consensus on which is the most appropriate indicator, see for example Brun et al. (2005). Our methodology is flexible in this respect, and different measures can be used to weight distance. We chose the simplest and more direct one, as aiming to measure GVCs' length, this appeared as the most intuitive.

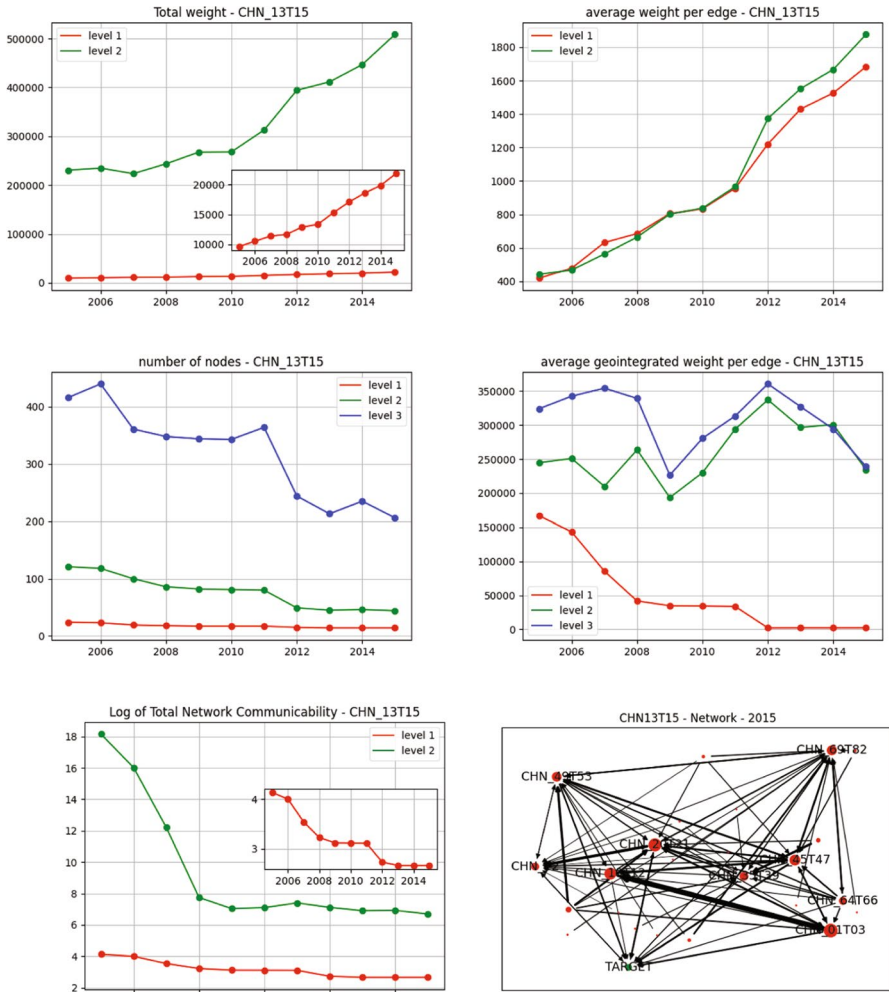
#### 4.1 Textiles, wearing apparel, leather and related products (D13T15): China (CHN) and Italy (ITA)

Figure 3 shows that, from 2005 to 2015, the Chinese textile sector remarkably decreased the number of sectors (*number of nodes*) with which it had significant exchanges. The *average geointegrated weight* of the direct contributors (level 1) experienced a sharp decline, with no foreign contributions since 2012. Also, the *total network communicability* indicates that China has dramatically reduced trade with distant countries not only at the first but even at the second level. On the other hand, if one observes the steady increase over the years of the value of the flow (*total weight* and *average weight per edge*), the conclusion is that the origin of previously evidenced patterns lies in an important variation in the geography of trade, which has become essentially domestic. We can infer that the GVC of China's textile industry from 2005 to 2015 has considerably reduced its size. This first result confirms what has been shown also in other studies using different techniques, that is the increasing domestic and regional organization of the Chinese production system in some sectors (Kee and Tang, 2016).

The Italian textile sector (Fig. 4) behaved very differently from the Chinese one: the *number of nodes* it trades with remained more or less constant, while the trade value (*total weight*) suffered a slight decrease. We can observe a small increasing trend in both *total network communicability* and *average geointegrated weight per edge*, which are due to a slight geographical enlargement of the set of supplier countries. Like China, also Italy gets most of its supplies from industries in the same country, but the largest foreign supplier is the Chinese textile sector, which has become increasingly important over the years. As evidenced by the figure, the Italian textile industry has experienced a decrease in trade value in absolute terms, and we can safely say that some of this trade has been swallowed up by the Chinese industry. In detail, the first level declined almost steadily, while the second level started to decline after the 2008 crisis. Overall, we can draw the conclusion that, from 2005 to 2015, the GVC of the Italian textile has slightly increased its size, basically because a geographically distant country such as China has become an increasingly important supplier. It is possible that after the trade collapse of 2009 and the recession in the following years, the Italian textile industry was forced to re-organize and find more competitive suppliers, expanding its links toward East Asia.

#### 4.2 Motor vehicles, trailers and semi-trailers (D29): Germany (DEU) and United States (USA)

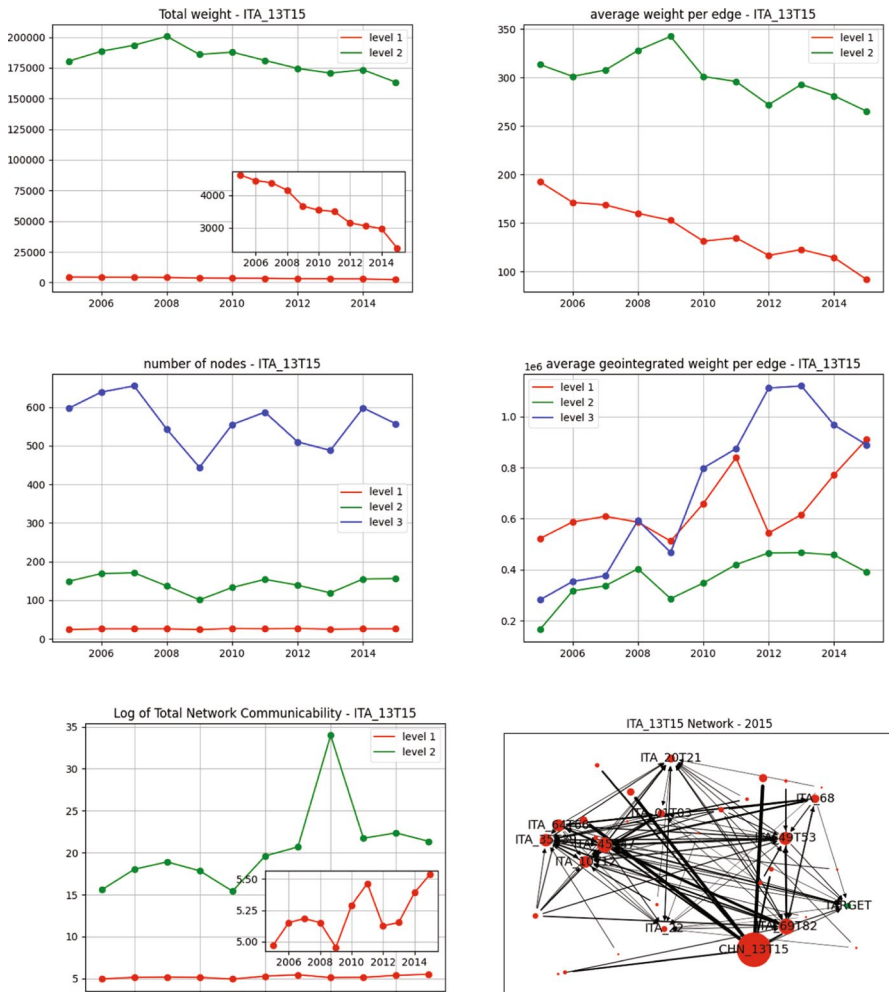
The German motor vehicle sector (Fig. 5) has kept an almost constant number of partner sectors over the years. However, we note that the plots of the *number of nodes*, *average geointegrated weight per edge*, and *total network communicability* show a decrease from 2006 to 2009 and then an increase until 2015. They suggest that the German automotive sector was trying to shorten its production chain but then the 2008 crisis forced it to expand it again. We also learn from the figure (*total weight* and *average weight per edge*) that the decline in the amount of the flow



**Fig. 3** China (CHN): Textiles, wearing apparel, leather and related products (D13T15)

started with the crisis of 2008. The network plot shows a prominence of domestic suppliers, with the exception of the Czech Republic automotive sector which has a considerable importance in the network. Overall, there is evidence of a change of gear in the German motor vehicles sector strategy: the GVC shortened until 2008 and then enlarged again.

Considering now the USA, it seems from Fig. 6 that the GVN of the motor vehicles sector has changed in specific ways over the years. The GVN has communicated better over the years, as we can see from the *total network communicability* pattern: as a matter of fact, it can be checked that the number of edges has increased for the second level, yielding an increase in network density. This seems to indicate that



**Fig. 4** Italy (ITA): Textiles, wearing apparel, leather and related products (D13T15)

the restructuring and re-organization of the motor industry included also a better organization of the foreign supply chains. It is worth remarking that, over the years, the partner countries have changed: Japan, Canada and Germany, which were relevant partners in 2005, have been replaced by the increasingly powerful Chinese electronics industry (see network plots). The automotive industry has undergone a large worldwide transformation in past years, and this has certainly brought about a reorganization of the supply chains. Another interesting insight is given by the total value of trade (*total weight*), where we note that, differently from other sectors, the US automotive industry reacted well to the crisis of 2008, indeed it was even able to revert the previous decreasing trend. This is a sector that received substantial



support from the U.S. government, but it seems also likely that the international reorganization was helpful in the recovery.

### 4.3 Chemicals and pharmaceutical products (D20T21): Japan (JAP) and Ireland (IRL)

The network of the Japanese chemical sector (Fig. 7) is dominated by the presence of a node with strong connections (JPN\_19, at the center of the network plot) which has gained importance over the years: it is the petroleum products sector, which strongly influences the behavior of the network from 2005 to 2015. The patterns of *average geointegrated weight per edge* and *total network communicability* highlight its influence on the network: the peak in 2008 and the decline in 2015 are compelling evidence of this. For what concerns the GVC structure, the network plot reveals that Japan has mostly kept its trade within its borders, so that the changes in the production chain are mostly due to the amount rather than the geography of trade. Overall, the amount of trade started to decline in 2008, and since 2012 this decline has become more pronounced (*total weight*).

The GVN of chemicals and pharmaceutical products of Ireland (Fig. 8) appears very different from the Japanese one. While Japan trade is mainly domestic, Ireland has many important foreign suppliers. The near tax-haven status of Ireland has increasingly attracted the financial and insurance sectors, heavily functional also to the capital-intensive chemical and pharmaceutical industries: remarkably, the first trade partner is the US business services sectors (see network plot). We can clearly see that, with first level partners, the amount of trade increased from 2005 to 2010, then decreased until 2012 and then increased again, both in terms of *total weight* and of *average weight per edge*. The behavior of the first level network in terms of *average geointegrated weight per edge* and *total network communicability* is similar, except for the last year, so we can conclude that the geography of the sectors that contribute directly to the target sector has remained pretty stable. The second level network behaves very differently from the first level one. The total amount of trade (*total weight*) has remained fairly stable, but the sudden drop in *total network communicability* reveals that the crisis of 2008 caused a reduction in trade with geographically distant countries—mainly attributable to the sharp decline in the US financial sectors – only slowly recovered in the following years. That is, after the 2008 crisis, Ireland chemical and pharmaceutical sector reduced the size of its GVC and then slowly widened it again.

### 4.4 Computer, electronic and optical products (D26): United States (USA) and China (CHN)

The comparison between US and China for the electronics sector resembles what above discussed between Italy and China for the textile sector: China has progressively expanded its role over time becoming a leader in this competitive sector.

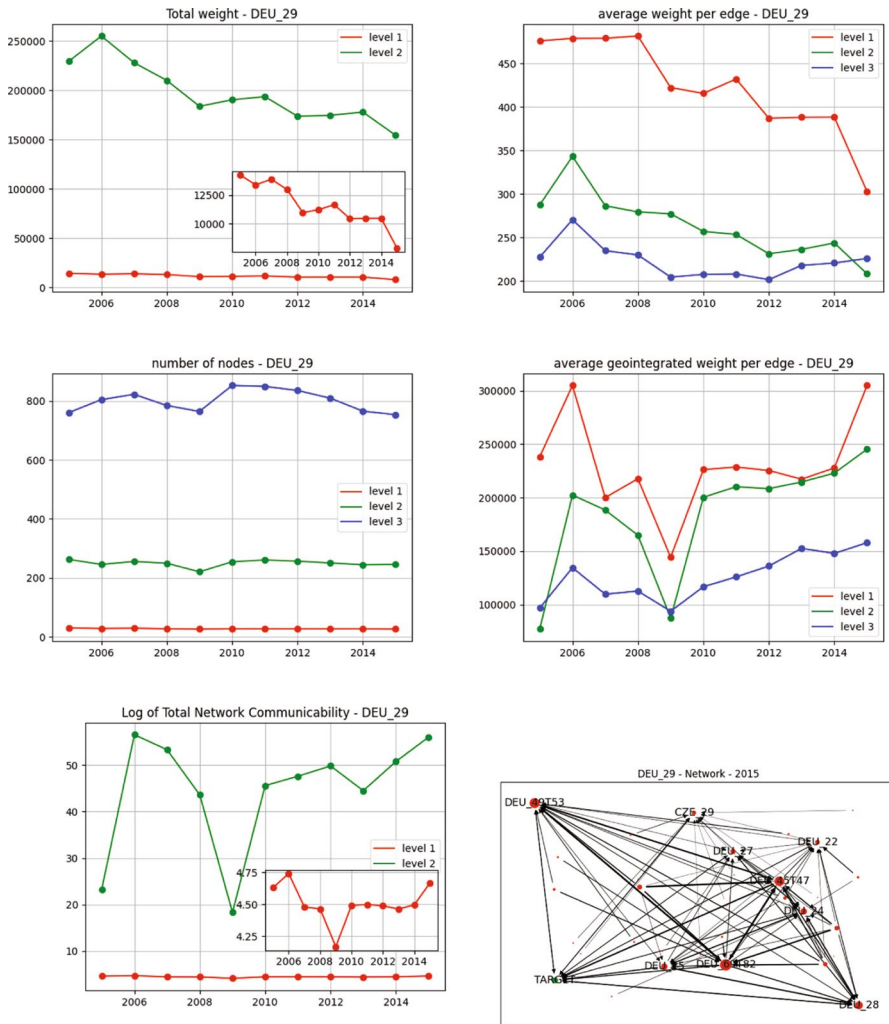


Fig. 5 Germany (DEU): Motor vehicles, trailers and semi-trailers (D29)

From 2005 to 2015, the US electronics sector is characterized by the reduction in both the *number of edges* and the *total weight* (Fig. 9). Specifically, the network plots put in evidence the transition from a mainly domestic trade to a tight connection to China as a major supplier. The patterns of *total network communicability* and *average geointegrated weight per edge* reveal that US started to significantly increase the trade with the Chinese electronic sector just after the crisis of 2008. Indeed, a significant growth in communicability and average geointegrated weight has been taking place since 2009, while the *total weight*, which does not take geography into account, continues its decline. We can conclude that since 2009 the GVC

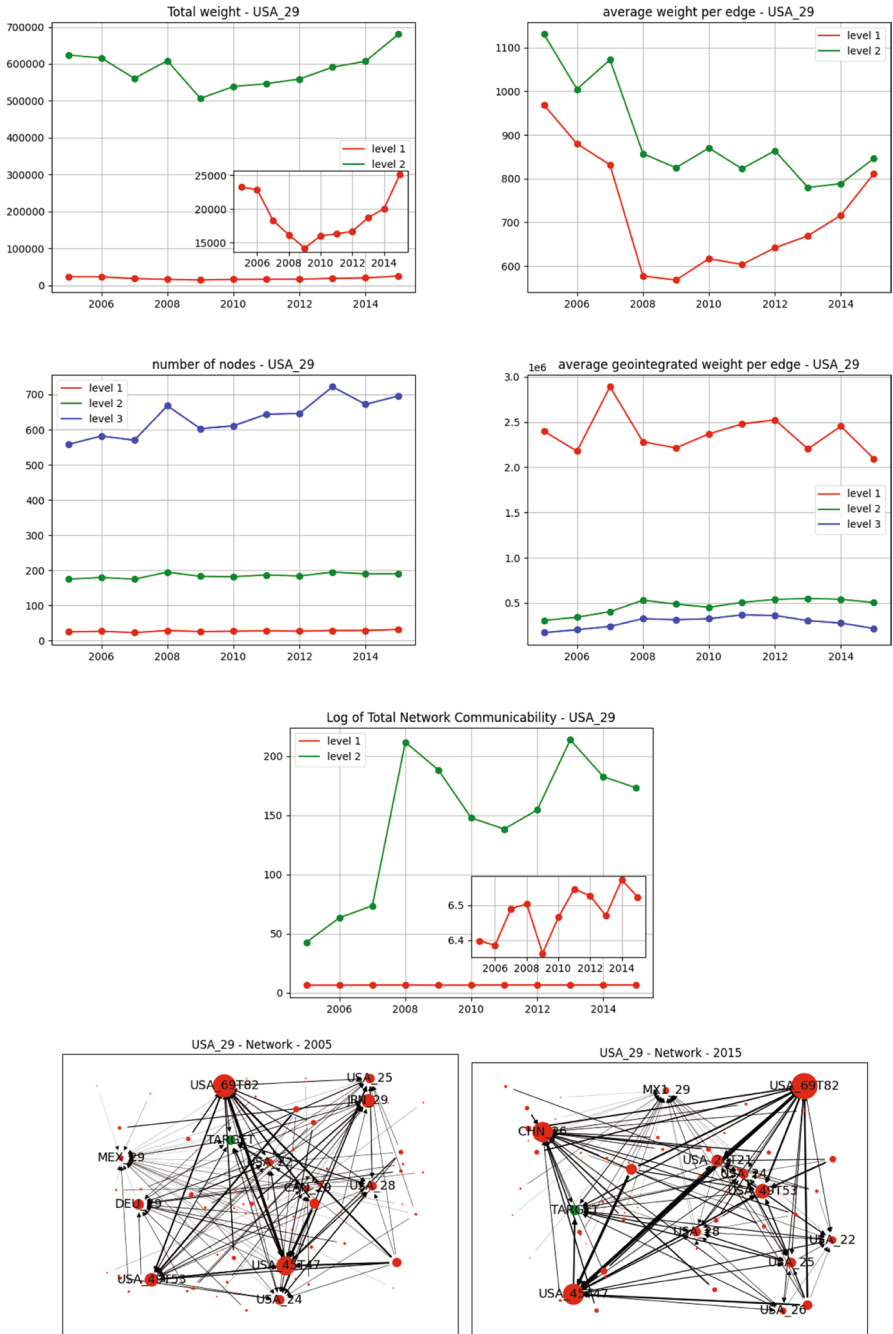


Fig. 6 United States (USA): Motor vehicles, trailers and semi-trailers (D29)



**Fig. 7** Japan (JAP): Chemicals and pharmaceutical products (D20T21)

has expanded due to the increasing contribution of geographically distant countries (i.e. China) to the sector.

As we can see from Fig. 10, the network of Chinese electronics is predominantly made up of sectors from Asian countries, with a predominance of Chinese suppliers. As for the textile sector, China has increased its total amount of trade (*total weight*) over the years, and since 2011 such a growth has been more pronounced. However, the sharp decline in *total network communicability* confirms that China's electronics sector has significantly decreased trade with geographically distant countries, so that we can claim that the GVN has reduced its size over time.

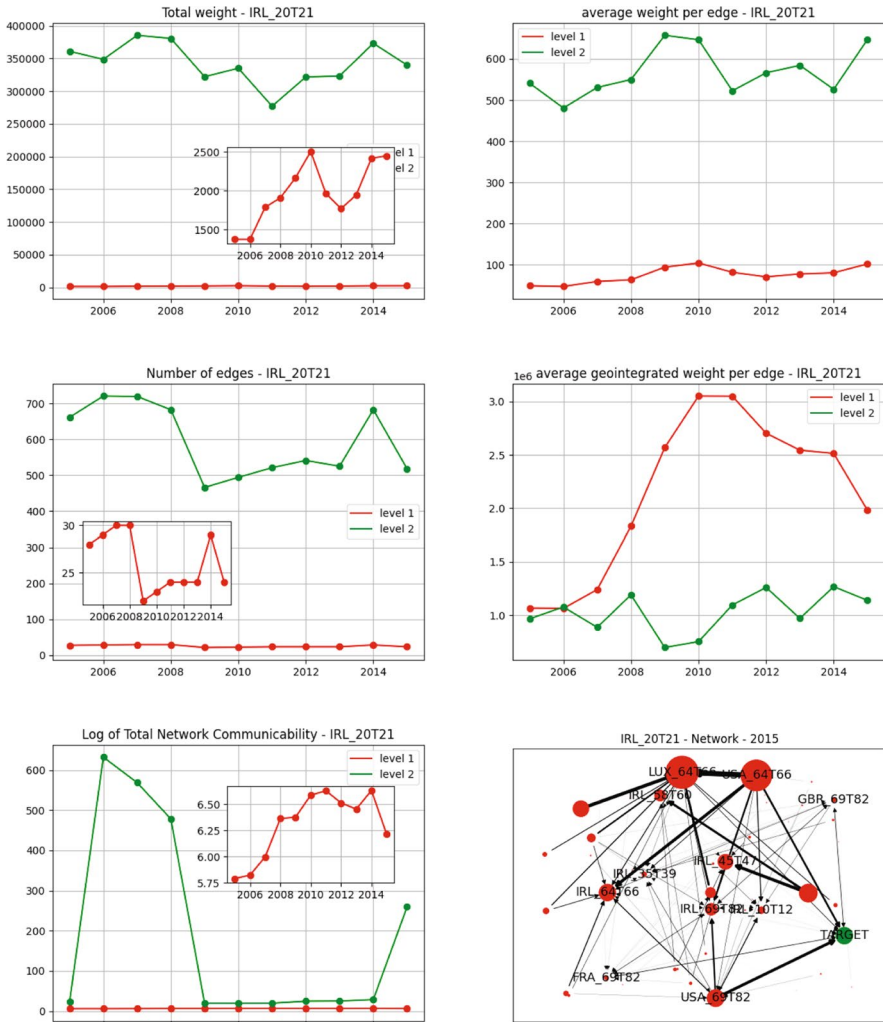


Fig. 8 Ireland (IRL): Chemicals and pharmaceutical products (D20T21)

### 5 Concluding remarks

Network analysis proves to be a very useful tool to better understand the structure and evolution of Global Value Chains, here characterized as Global Value Networks (GVNs). The evolution of GVNs displayed by the set of indicators used in this work, and especially the measures that aim to quantify the potential expansion or shrinkage of GVNs in the recent past, in many cases is in line with the existing knowledge based on stylized facts and anecdotal evidence, but a number of new results and information also emerge.

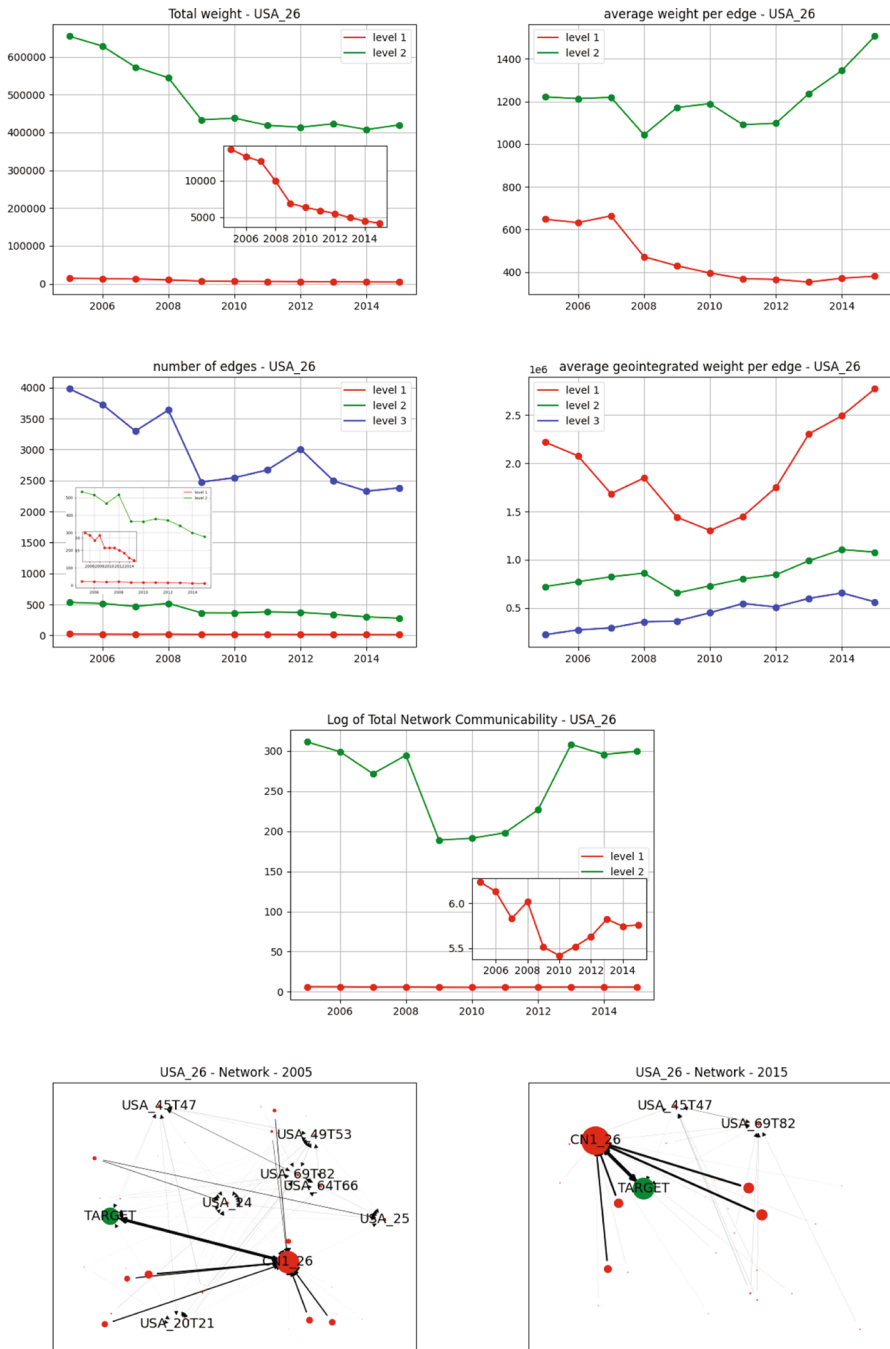


Fig. 9 United States (USA): Computer, electronic and optical products (D26)

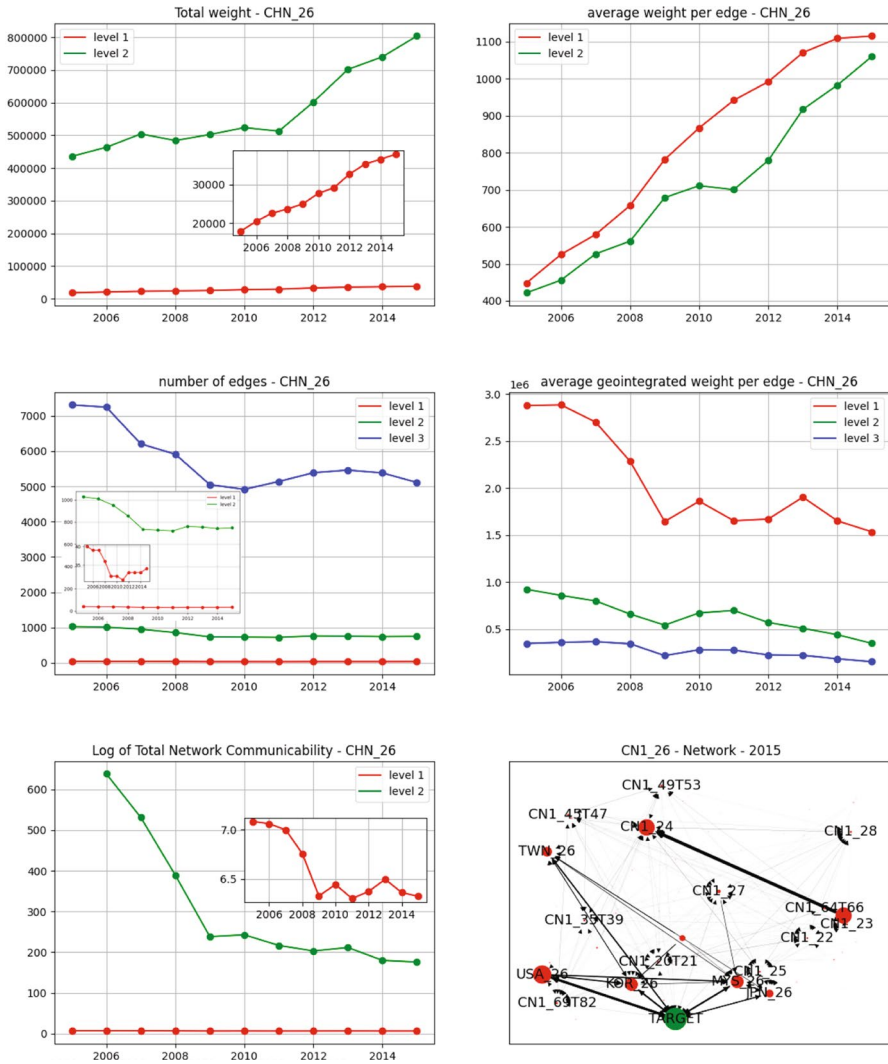


Fig. 10 China (CHN): Computer, electronic and optical products (D26)

It seems difficult to infer from the analysis a general trend in the evolution of GVN, as there are relevant differences among sectors and countries. Interestingly, our results display a different pattern in what we call ‘level 1’ and ‘level 2’ connections between industries and countries: total communicability at level 1 (as well as the number of edges) seems quite stable over time, but this is not the case for level 2. These differences show up also in the average geointegrated weight per edge, showing shifts in the geographical pattern of links. It is worth noticing that dissimilar evolutions of the trade patterns across countries and sectors have been observed in

the past decade also in other domains [see for example The World Bank (2020) or Tajoli et al. (2021)], raising fears of possible fractures and disconnections in the world trading system.

Even if a non-homogeneous and evolving picture emerges, our results do not suggest that radical shifts are in place. The general stability of GVN<sub>s</sub>, especially in the first level of connections, confirms the hypothesis of the importance of the “relational approach” in GVC<sub>s</sub> (Antrás, 2020; Antrás and Chor, 2021), as these relations are not immediately interchangeable. At the same time, the shifts in the geographical patterns of the links also support the view that firms organizing this complex form of production seek efficiency and they are ready to grasp better opportunities when they appear in the global markets.

Our dataset covers the period 2005–2015, allowing to witness turbulent changes in the world markets, including also the severe trade shock of 2009. Overall, the analysis confirms the high adaptability of GVC<sub>s</sub> to the changing world. We observe that indeed some of the analyzed GVN<sub>s</sub> display structural changes after 2010, adapting to a transformed scenario, often increasing their length and diversification. Similar transformations and adaptations can be expected also after the pandemic shock of 2020–2021: GVN<sub>s</sub> are likely to change again, but not to shrink or disappear, as all the evidence indicates that this phenomenon is here to stay.

## Appendix A Countries and industries in OECD TiVA database

### A.1 List of countries in the 2018 edition of the OECD TiVA database

*OECD Countries* AUS Australia—AUT Austria—BEL Belgium—CAN Canada—CHL Chile—CZE Czech Republic—DNK Denmark—EST Estonia—FIN Finland—FRA France—DEU Germany—GRC Greece—HUN Hungary—ISL Iceland—IRL Ireland—ISR Israel—ITA Italy—JPN Japan—KOR Korea—LVA Latvia—LTU Lithuania—LUX Luxembourg—MEX Mexico—NLD Netherlands—NZL New Zealand—NOR Norway—POL Poland—PRT Portugal—SVK Slovak Republic—SVN Slovenia—ESP Spain—SWE Sweden—CHE Switzerland—TUR Turkey—GBR United Kingdom—USA United States—MX1 Mexico, Activities excl. Global Manufacturing—MX2 Mexico, Global Manufacturing activities

*Non OECD Countries* ARG Argentina—BRA Brazil—BRN Brunei Darussalam—BGR Bulgaria—KHM Cambodia—CHN China (People’s Republic of)—COL Colombia—CRI Costa Rica—HRV Croatia—CYP Cyprus—IND India—IDN Indonesia—HKG Hong Kong, China—KAZ Kazakhstan—MYS Malaysia—MLT Malta—MAR Morocco—PER Peru—PHL Philippines—ROU Romania—RUS Russian Federation—SAU Saudi Arabia—SGP Singapore—ZAF South Africa—TWN Chinese Taipei—THA Thailand—TUN Tunisia—VNM Viet Nam—ROW Rest of the World—CN1 China, Activities excl. export processing—CN2 China, Export processing activities



## A.2 List of industries in the 2018 edition of the OECD TiVA database

D01T03 Agriculture, forestry and fishing—D05T06 Mining and extraction of energy producing products—D07T08 Mining and quarrying of non-energy producing products—D09 Mining support service activities—D10T12 Food products, beverages and tobacco—D13T15 Textiles, wearing apparel, leather and related products - D16 Wood and products of wood and cork—D17T18 Paper products and printing—D19 Coke and refined petroleum products—D20T21 Chemicals and pharmaceutical products—D22 Rubber and plastic products—D23 Other non-metallic mineral products—D24 Basic metals—D25 Fabricated metal products—D26 Computer, electronic and optical products—D27 Electrical equipment—D28 Machinery and equipment, nec —D29 Motor vehicles, trailers and semi-trailers—D30 Other transport equipment—D31T33 Other manufacturing; repair and installation of machinery and equipment—D35T39 Electricity, gas, water supply, sewerage, waste and remediation services—D41T43 Construction—D45T47 Wholesale and retail trade; repair of motor vehicles—D49T53 Transportation and storage—D55T56 Accommodation and food services—D58T60 Publishing, audiovisual and broadcasting activities—D61 Telecommunications—D62T63 IT and other information services—D64T66 Financial and insurance activities—D68 Real estate activities—D69T82 Other business sector services—D84 Public admin. and defense; compulsory social security—D85 Education—D86T88 Human health and social work—D90T96 Arts, entertainment, recreation and other service activities—D97T98 Private households with employed persons

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