PRELIMINARY VERSION

Benefitting from GVC participation: the role of network centrality

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Abstract

This paper explores the evolution of GVCs from 1995 to 2018 to assess the changes that have taken place during the last decades. Using OECD ICIO data and indicators from the OECD's TiVA database, we apply network techniques and graph theory to characterize the structure of the GVC network. We are interested in comparing the network at different moments in time to assess how its structure has evolved over the period of analysis, and which countries -and how- participate in the network. To do so, we compute centrality metrics to identify countries' position within these global production networks. Additionally, we also examine if countries benefit from GVC participation using a network analysis approach. We conduct panel regressions to assess if changes in network centrality have an impact on countries' upgrading in GVCs. Our results suggest that centrality plays an important role: according to our preferred estimation, a 1 percentage point increase in eigen centrality leads to an increase in the rate of growth of domestic value added embodied in exports of 0.6 percentage points.

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1. Introduction

Global value chains (GVC) have become a dominant feature of the economic landscape in the past decades. The ICT revolution, the reduction in transport costs and the increase in trade liberalization made it possible to split production processes across borders and to take advantage of lower labour costs in emerging countries. As a result, countries increasingly rely on imported inputs to produce their exports, leading to a complex configuration of GVCs.

However, since the Great Recession, the pace of globalization has slowed down compared to previous decades, as some of the factors that fueled the emergence of GVCs have reversed. Besides, recent events such as the COVID-19 pandemic and the war in Ukraine have caused severe disruptions in supply chains, raising concerns about the risks of this complex organization of production and trade. The above-mentioned events may lead to a reorganization of supply chains, but despite that, the world does not seem to have entered a phase of de-globalisation (Antràs 2020), and a significant amount of global trade is still organized around GVCs (World Bank, 2020).

This paper explores the evolution of GVCs from 1995 to 2018 to assess the changes that have taken place during the last decades. We use the foreign value-added content embodied in countries' gross exports, as defined in Koopman, Wang and Wei (2014), to assess countries' participation in GVCs. We can analyse it from a double perspective, since countries can be buyers of intermediate inputs that will be used in the production of their exports (*backward participation*), but we can also identify the suppliers of those inputs; that is, countries whose exports of intermediate inputs will be embodied in the exports of other countries (*forward participation*).

In the context of complex interactions among countries, network analysis appears as a suitable approach to examine the evolution of international flows of value added and countries' positions in GVCs. This approach has proved very useful to analyze the input-output relationship between any pair of countries in a structural manner and not as an isolated phenomenon, since it gives rich information about the interdependence amongst all participants in the network.

Hence, using OECD ICIO data and indicators from the OECD's TiVA database, we apply network techniques and graph theory to characterize the structure of the GVC network. We are interested in comparing the network at different moments in time to assess how its structure has evolved over the period of analysis, and which countries -and how- participate in the network.

To do so, we compute different metrics to identify countries' position within these global production networks and their roles. The matrix of foreign value added trade flows (FVA) is a directed weighted network, where we can distinguish between *providers* and *recipients* of FVA and thus, assess the role of countries as suppliers and buyers of FVA. The weights of the network are given by the shares of FVA in total world flows of FVA.

Additionally, we also examine if countries benefit from GVC participation. Several studies claim that GVC integration enhances productivity growth and promotes economic development (Kummritz et al. 2017, Constantinescu et al. 2019, Pahl and Timmer, 2020, among others). There are several channels through which GVCs can foster productivity, as outlined by Criscuolo and Timmis (2017): aside from the benefits from specialization, firms have access to a large variety of cheaper or higher quality inputs, which embody foreign technology; firms also have access to larger markets and the interaction with other firms may contribute to knowledge spillovers.

In this paper, we go a step further and analyse the impact of countries' centrality in the network on their economic performance in GVCs. Our aim is to determine if it is just GVC participation what matters -measured with the most commonly used indicators of *backward* and *forward* participation- or if the position in the network, as measured by the eigen centrality, is also relevant. Our results suggest that countries' performance in GVCs is positively correlated with network centrality. Hence, the position of countries in global supply chains, and not just GVC participation, matters.

We contribute to the growing literature that focuses on GVCs from a network approach (Cerina et al. 2015, Santoni & Taglioni 2015; Taglioni & Winkler 2016, Amador & Cabral 2017, Amador et al. 2018, Crioscuolo & Timmis 2018, Blázquez et al. 2020, among others). Compared to previous papers, we take advantage of the new edition of the OECD TiVA database to extend the analysis until 2018. Ideally, we would like to analyse the impact of two recent major events that heavily hit economies all over the world and also had a major impact on GVCs: the COVID-19 pandemic and the war in Ukraine. However, due to the complexity in the elaboration of inter-country input-output tables (ICIO), the last year available in the TiVA database is 2018.

The paper is organised as follows: Section 2 describes the methodology and the data used. Section 3 addresses the evolution of the network over the period of analysis and examines the participation in the GVC network of the main players -both as users and suppliers of FVA- as well as their centrality in the network. Section 4 focuses on the empirical analysis and finally, Section 5 concludes.

2. Methodology and data

In this section we describe the indicator that will be used in this paper to measure countries' participation in GVCs, as well as the tools of network analysis that will be applied.

2.1. Foreign value added in exports

With the emergence of GVCs, countries increasingly rely on imported inputs to produce their exports. The use of imported inputs in exports generates a disconnection between the value added generated in the exporting country and its gross exports, since exports are produced using a combination of domestic and foreign value added. The availability of global input-output tables, which represent bilateral flows of intermediate and final goods and services, allows us to trace back the value added generated in the production of a given good or service, making it possible to identify the sources of value added.

The value-added content of gross exports can be obtained using the Leontief inverse matrix (Leontief, 1936). The fundamental equation of the input–output framework can be written as

$$x = (I - A)^{-1}y, \qquad (1)$$

where $(I - A)^{-1}$ is the Leontief inverse matrix. This matrix shows the total input requirements (both direct and indirect) to produce a unit of output. Multiplying it by the final demand vector (y) reflects the output needed to satisfy the final demand absorbed in country j.

The equation in (1) can be rewritten as $\boldsymbol{X} = \boldsymbol{BY}$. With *N* countries and *S* sectors, matrix **X** on the left-hand side of the equation is the gross output decomposition matrix, which gives the breakdown of gross output in each producing country-sector by country-sector of destination**.** Matrix **B** is the Leontief inverse or total requirement matrix, which gives the amount of gross output in producing country *i* needed to satisfy a one-unit increase in final demand in destination country *j*. The final demand matrix **Y** shows the final goods produced in *i* and consumed in *j*.

The domestic value added generated in a country's gross output can be obtained by pre-multiplying the value-added coefficient matrix ($\hat{\mathbf{V}}$) with the gross output decomposition matrix **X.** The value-added coefficient matrix $\hat{\mathbf{V}}$ is a diagonal matrix which contains the direct value added coefficients (the share of domestic value added in country *i'*s gross output) on the main diagonal and zeros elsewhere.

The result is the value-added production matrix $\hat{\mathbf{V}}\mathbf{BY}$, of dimensions SN x N. The elements on the main diagonal represent the domestic value added absorbed at home; the elements outside the diagonal correspond to a country's production of value added that is absorbed abroad, i.e. value added exports.

Therefore, total value-added exports of country i can be expressed as[3]:

$$VAinX_i = \sum_{j \neq i}^{N} V_i X_{ij}$$

Value added exports are the exports produced in country of origin i which are absorbed in country of destination j. This concept is defined in Johnson and Noguera (2012), where the authors propose the ratio of value added to gross exports (VAX ratio) as a measure of the value added content of gross exports and the intensity of production sharing.

As mentioned before, a country's gross exports are produced using a combination of domestic and foreign sources of value added. Domestic value added in exports (DVAinXj) is defined as:

$$DVAinX_j = V_j B_{jj} E_j$$

The counterpart of DVAinX is the foreign value added in exports (FVAinXj), which is defined as:

$$FVAinX_j = \sum_{i \neq j}^{N} V_i B_{ij} E_j$$

In the absence of firm-level data, the study of countries' involvement in GVC has relied on international input-output tables (IIOT). In the last years, several initiatives have developed ambitious databases (WIOD, OECD's TiVA, and EORA) which combine national input-output tables with international trade data. Despite their limitations[4], the IIOT have been widely used to analyse countries' participation in GVCs.

[3] We omit the subindex for the sector to simplify the notation. Besides, our analysis is conducted at the country-level.

[4] Their main limitations arise from the aggregation level and the use of strong assumptions that are needed to construct these tables. IIOT are defined at the sector-level; hence, sectors are broadly defined. Second, some assumptions are needed to elaborate the IIOTs, such as the import proportionality assumption –which assumes that firms use the same amount of imported intermediate inputs for domestic and foreign production-. Besides, because of the complexity in their elaboration, these tables are not as up to date as conventional trade data.

Our analysis is based on the data from the OECD's TiVA database (2021 edition), which provides indicators for 66 countries and an estimate for the "rest of the world" (see Table A.1 in the Appendix). The data is available for the period 1995-2018, which allows us to study the evolution of GVCs over a long-time span, covering different subperiods and events: a period of intensification of GVC links (1995-2008), the decline following the Great Recession and the *great trade collapse* - a term coined by Richard Baldwin to refer to the "sudden, severe and synchronised collapse" in world trade in late 2008 (Baldwin 2009)-, and the evolution in the aftermath of these events.

2.2. Defining the network

We want to examine the bilateral flows of foreign value-added embodied in countries' gross exports. To do so, we follow common practice in the literature and scale the network, so that the linkages reflect the shares of FVA in gross exports over the world's total flows of FVA embodied in gross exports, instead of absolute values. Besides, by using shares the flows are deflated, and we can compare the network at different moments in time.

In our analysis, the nodes are the 67 economies included in the TiVA database, and the edges are the flows of foreign value added embodied in gross exports. The shares are denoted by w_{ij} and are measured as:

$$w_{ij} = \frac{FVA_i inX_j}{\sum_i \sum_{i \neq j} FVA_i inX_j}$$

Table 1 shows a simplified representation of the network we are considering. We obtain an input-output table for each year, which records the flows of foreign value added in exports over the world's total flows of foreign value added (w_{ij}) for any pair of connected economies. For instance, the element w_{12} in the first row shows the foreign value added from country 1 embodied in the gross exports of country 2 as a share of world's total flows of foreign value added.

Since the network is directed, we can interpret the flows of FVAinX from two different perspectives: outgoing edges or forward links, and incoming edges or backward links. The rows in Table 1 identify the destination countries (buyers) of each source country (suppliers), whereas the columns can be read as the users of source countries' value added.

Table 1. Simplified representation of the *FVAinX* network

Data on w_{ij}		**Destination country *j***					
		Country 1	**Country 2**	**Country 3**	**…**	**Country *N***	**Total**
Origin country *i* (source of value added)	**Country 1**	0	w_{12}	w_{13}	[…]	w_{1N}	$\sum w_{1j}$
	Country 2	w_{21}	0	w_{23}	[…]	w_{2N}	$\sum w_{2j}$
	Country 3	w_{31}	w_{32}	0	[…]	w_{3N}	$\sum w_{3j}$
	…	[…]	[…]	[…]	0	[…]	[…]
	Country *N*	w_{N1}	w_{N2}	w_{N3}	[…]	0	$\sum w_{Nj}$
	Total	$\sum w_{i1}$	$\sum w_{i2}$	$\sum w_{i3}$	[…]	$\sum w_{iN}$	$\sum w_{NN}$

Source: own elaboration

Our aim is to analyse the network from two complementary perspectives. First, we will study the characteristics of the binary matrix, that is, a matrix that takes the values 0 or 1 depending on the existence of a flow of FVA between nodes. The elements of this matrix will be a_{ij}, where $a_{ij} = 1$ indicates that two countries are connected and have a network tie based on the presence of a flow of FVA, that is, $w_{ij} > 0$. The element a_{ij} will be zero if $w_{ij} = 0$, that is, the countries are not connected by an exchange of FVA. Additionally, since we are considering the value of the linkages among countries, and not just the existence of a link between them, our network is directed. Hence, we will examine the weighted network, where links are given by w_{ij}.

It is important to notice that the network we are considering is complete with closed ties: every country in our sample trades with each other. Thus, to consider only relevant flows of foreign valued added embodied in gross exports, a threshold should be set. We define a country-specific threshold and only consider the flows that contribute to at least 1% of the foreign value-added content the user country. In this way, we keep the main suppliers of FVA for each user country. Besides, with this threshold, we cover from 87% to 88% of world's total flows of FVA during the period 1995-2018.

We apply this threshold to compute the first-order indicators based on the binary matrix. Otherwise, since all countries are connected to each other, all of them would have the same number of connections (indegree and outdegree), and the structural measures of the network would collapse to one (in the case of transitivity or density, for instance) or zero. Besides, for clarity we also apply this threshold to the graphical representation of the network. Nonetheless, we do not consider this threshold when we examine the weighted network. The reason for doing so is that we prefer to take the raw data as given, and the use of shares of FVA in the weighted matrix reflect the intensity of connections between country pairs and allow to compute network metrics without applying a threshold. However, we check that results in the empirical approach conducted in Section 4 are consistent with the use of this threshold.

Regarding the computation of network metrics, package Igraph in R is used to study the whole network structural properties.[5]

3. The evolution of the network

3.1. Network structure

Table 2 presents the evolution of a selection of aggregate metrics of the binary matrix for the years 1995, 2008, 2011, and 2018. We select those indicators that appear to make sense for informing about the network structure.

Table 2. Structural indicators of the *FVAinX* network. 1995, 2008, 2011 and 2018.

	1995	2008	2011	2018
Network Size	67	67	67	67
Diameter	4	4	5	5
Average Path Lenght	1.717	1.884	1.959	1.871
Transitivity	0.593	0.609	0.620	0.619
Edge	1291	1315	1337	1309
Dyad	4422	4422	4422	4422
Density	0.292	0.297	0.302	0.296
Reciprocity	0.393	0.423	0.428	0.431

[5] Igraph is a library and R package for network analysis. More information on: https://igraph.org/r/pdf/latest/igraph.pdf

Table 2 (*cont*). Structural indicators of the *FVAinX* network. 1995, 2008, 2011 and 2018.

Degree Centralization	0.434	0.398	0.401	0.384
Indegree Centralization	0.147	0.081	0.092	0.098
Outdegree Centralization	0.708	0.703	0.698	0.704

At first glance, the visualization and the main descriptive statistics in Table 2 reveal interesting insights. Firstly, the proportion of possible relationships in the network that are actually present is given by the density metric. It is a measure of network connectivity whose values range between 0 and 1, where the value of 1 corresponds to a scenario where all potential relationships are active in the network. The density of the network is around 0.30 in all years, that is, 30% of all possible ties are activated out of 4,422 potential relationships (67 user countries of FVA x 66 source countries of value added)[6].

Additionally, the average path length, which is the average number of steps along the shortest paths for all possible pairs of nodes, captures the efficiency of a network. The minimum average path length reached was 1.7171 in 1995. The reciprocity index is a measure of the likelihood of vertices in a directed network to be mutually linked. In 2018, there is a moderate probability of finding mutual links (40%). Reciprocity captures a basic way of interaction between suppliers and recipients of FVA.

Centralization, as measured by degree centrality, extends the concept of density, as it inspects if the network is organized around particular nodes. In our case, the index has decreased over the period of analysis from 0.43 to 0.38. The closer is this index to 0, the more decentralized and scattered is the network. Thus, the figures point to a more decentralized network, which is consistent with the integration of countries in GVCs, as pointed out in Amador & Cabral 2017.

On the other hand, our network is directed. Indegree centrality is a count of the number of ties directed to the node, which reflects the number of suppliers of FVA for a given country. Outdegree centrality is the number of ties that the node directs to others, that is, the number of destination countries of each node. Countries with high indegree centrality are important users of FVA, since they embody foreign value added from many source countries. As we will see, relevant buyers may become network *authorities* (Hansen et al. 2010), whereas relevant suppliers may become *hubs*. Outdegree centrality captures the role of a country as a supplier of FVA. As shown in Table 2, outdegree centrality is quite stable around 0.7, whereas indegree centrality has decreased from 0.15 to around 0.1. This points to a diversification of providers of FVA, that is, on average *user* countries increasingly embody foreign value added from a larger number of *source* countries.

The value of the global clustering coefficient or transitivity is also not negligible and high, with an index of 0.619 in 2019. Together with the low diameter value, the indicators suggest a fluent connection in the network. In other words, there is a high probability that two trade partners of a country are themselves connected.

Figure 1 shows the evolution of a selection of structural indicators shown in Table 2 over the period of analysis. Except for degree centrality (panel a), the indicators show a moderate increase through the 1995-2018 period. The degree centrality (panel a) is one of the most basic and intuitive ways to measure centrality. It reflects the number of direct ties an actor holds with others in the network. The higher the degree, the more central the node is. The clear decreasing tendency

[6] Since we focus on the flows of foreign value added, the value of the link when country i=country j is zero (that linkage would correspond to domestic value added). Hence, loops are not considered in this network.

of the degree centrality over the years points to the fact that the GVC network has evolved towards a more decentralized structure.

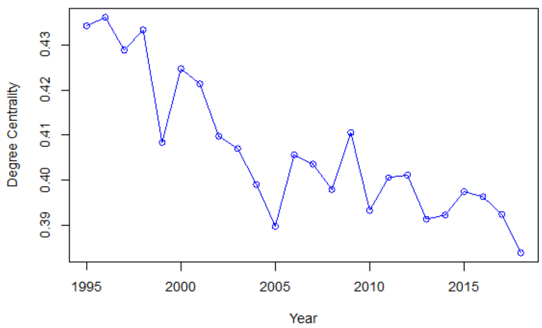
On the other hand, density (panel b) presents an increasing trajectory, which suggests that the connectivity of the network has improved over the years. Despite the peaks that can be observed, the value of density in 2018 is higher than at the beginning of the period. We observe an abrupt decrease (which is common to the indicators shown in panels c and d) between 2010-2011, which can be attributed to the impact of the *Great Recession*.

The average path length (panel c) also shows an increasing trend over the years. Shorter average path length is more desirable because it is often attributed to more efficient information transfer (Freeman et al. 1991). The average number of steps along the shortest paths between two nodes has grown since 1995.

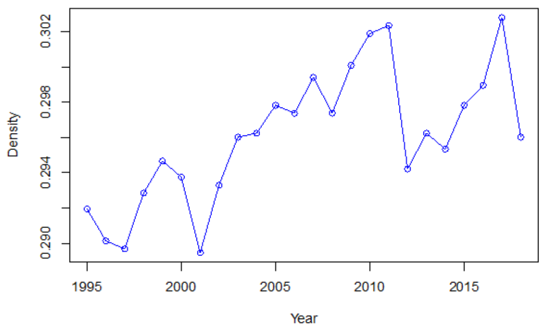
The transitivity (panel d) of a graph is a measure of the tendency of the nodes to cluster together. High transitivity means that the network contains communities or groups of nodes that are densely connected internally. Thus, the growth of this variable since 1995 points to the emergence or intensification of subnetworks. According to this, it is relevant to explore the clustering coefficient of nodes to study how well connected the neighborhood of the node is (PENDING).

Figure 1. Evolution of the structural indicators over the period 1995-2018

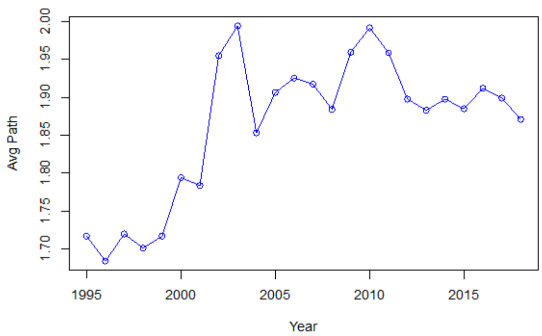
a) Degree centrality



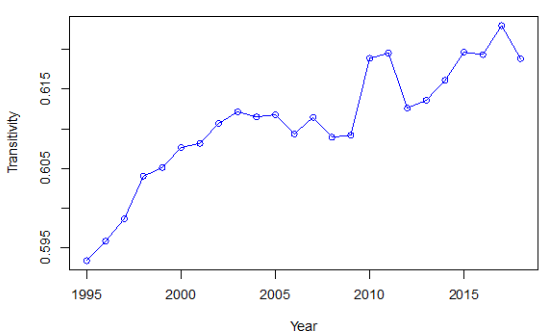
b) Density



c) Average path length



d) Transitivity



Source: Authors' calculation based on OECD's TiVA dabatase (2021)

Figure 2 shows the evolution of the structural network in 1995, 2008, 2011 and 2018. The size of the nodes reflects the *eigenvector centrality* for each country (Bonacich, 1991). The eigen centrality is a node-centrality indicator that, contrary to the degree centrality, which only takes into account the direct neighbors of each country, the eigenvector also considers the role of indirect links. In this type of centrality measure, the centrality of each actor is proportional to the sum of the centralities of those actors to whom he or she is connected. Intuitively, the nodes or actors that have a higher eigen centrality are connected to other nodes that are in turn very relevant. In contrast, nodes connected to other peripheral or less relevant nodes will have a low eigenvector centrality. Additionally, we add an attribute to the edges that connect the nodes, whose thickness reflect the share of FVA in gross exports over the world's total flows of FVA embodied in gross exports, as we previously explain above.

At first look, we can easily see that there are some countries with a high eigen centrality that remain at the center of the network for all the selected years. In 1995 (panel a), the countries at the core of the network were the United States, with important connections with Mexico and Canada, as shown by the thickness of the edges; a group of European countries (Germany, France, UK, Italy and the Netherlands) and Japan, which holds relevant ties with Taiwan.

In 2008, one of the most remarkable changes has to do with the position of China at the core of the network (panel b), which was a peripheral economy at the beginning of the period. The "rest of the world" (ROW), which represents an estimate of the countries not included in the database, has also moved from a peripheral position to the core of the network, suggesting that countries trade more and more with countries not included in the database, which is evidence of trade diversification from other sources and to other destination countries. The eigen centrality of Russia and Korea -as reflected by the size of the nodes- has also increased compared to 1995.

From 2008 onwards, we can also observe the configuration of the network around 3 main players: United States, China and Germany. This is consistent with the literature that emphasizes the regionalization of GVCs, with relevant networks organized around "Factory America", "Factory Asia" and "Factory Europe" (Baldwin and López-González, 2015). In 2018, the main nodes at the core of the network are still these three countries, together with ROW.

Figure 2. Network evolution, 1995, 2008, 2011 and 2018.

a) 1995 b) 2008

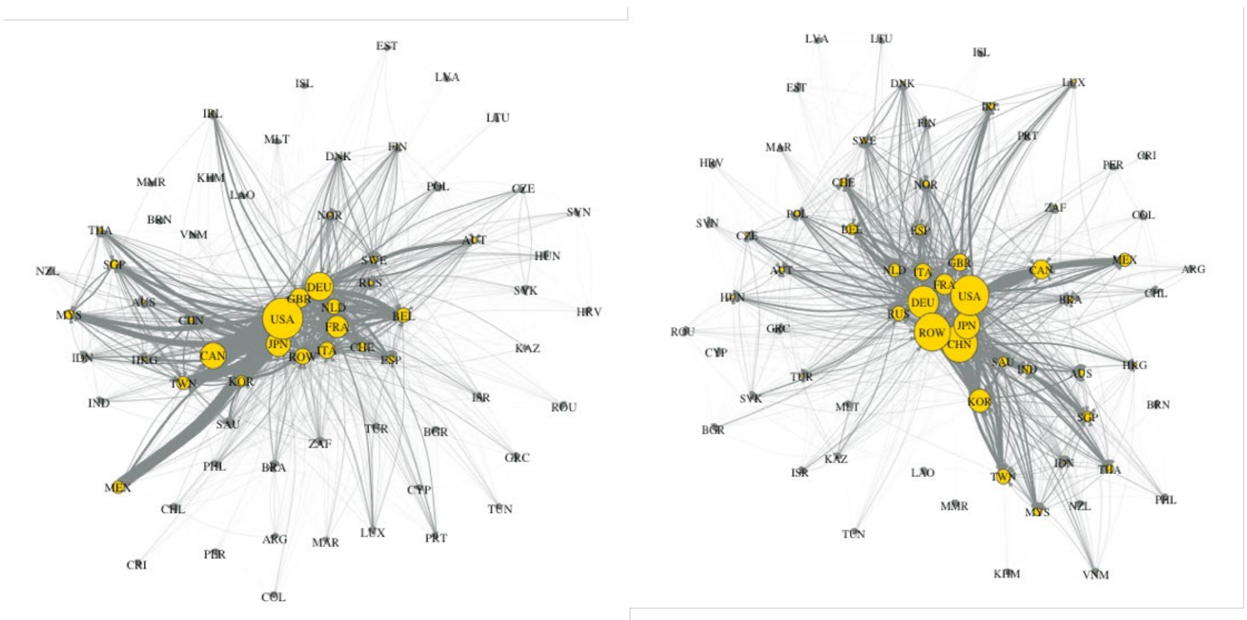
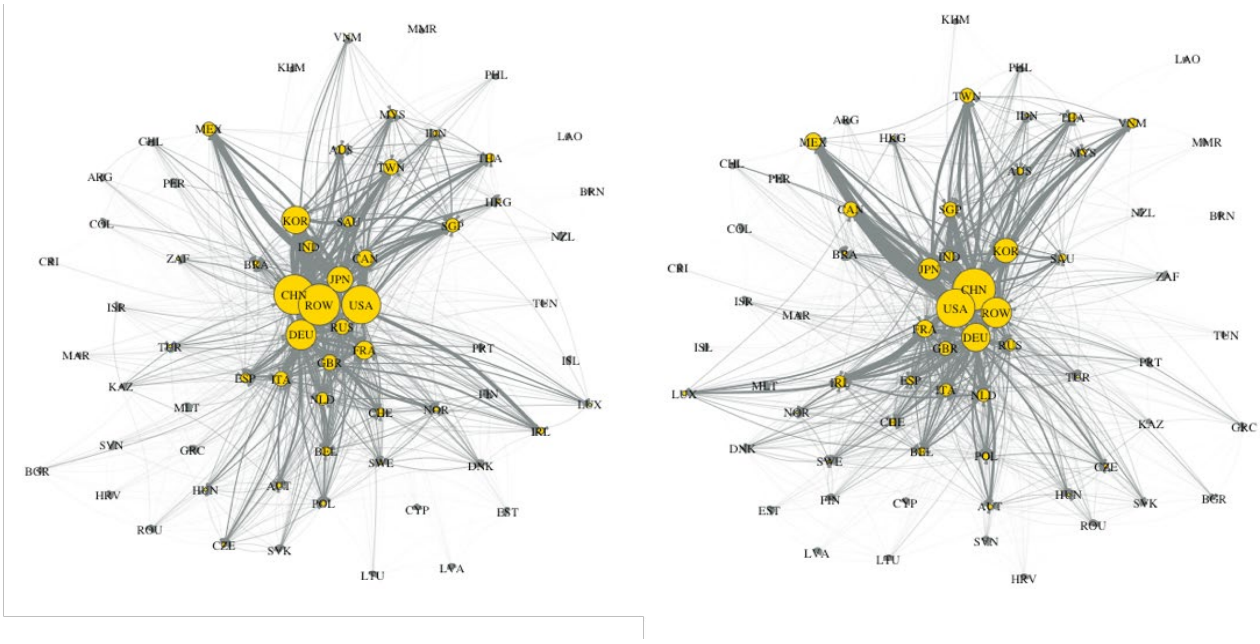


Figure 2 ***(cont)*****. Network evolution, 1995, 2008, 2011 and 2018.**

c) 2011 d) 2018



Source: Authors' calculations based on OECD-TiVA (2021 edition).

3.2. Top players

In this section we focus on a selection of countries and examine their participation in the GVC network over time. To do so, we analyse the role of these countries as users and suppliers of FVA using different types of measures. All the indicators shown in this Section are computed based on the weighted matrix; that is, the matrix that considers the value of the flows of FVA across countries.[7]

First, we explore the total amount of foreign value-added that each exporting country embodies from all its provider countries (as a percentage of world's total flows of FVA). This measure reflects the *in-strength* of a node and reveals the role of a country as a *buyer* of FVA. We also look at the value of the outgoing connections of a node and compute the total amount of value-added that it sells to all destination countries to be embodied in their exports (as a percentage of world's total flows of FVA). This measure is the *out-strength* of a node. Countries with the highest *out-strength* are the main suppliers of FVA in the network.

Figure 3 shows the top buyers and suppliers of FVA, as reflected by their in-strength and out-strength respectively (panels a and b). We have divided the countries in 2 panels for each indicator for a better visualization. The main buyers of FVA in 2018 are China, which concentrates 8.6% of total flows of FVA, and Germany (7.3%). Korea, United States, Singapore, France, Mexico and the Netherlands are also among the top buyers. Each of these countries absorb more than 3% of total FVA flows.

[7] Contrary to the analysis in Section 3.1, which is based on the information provided by the binary matrix, we do not apply any thresholds and consider all the FVA flows across countries.

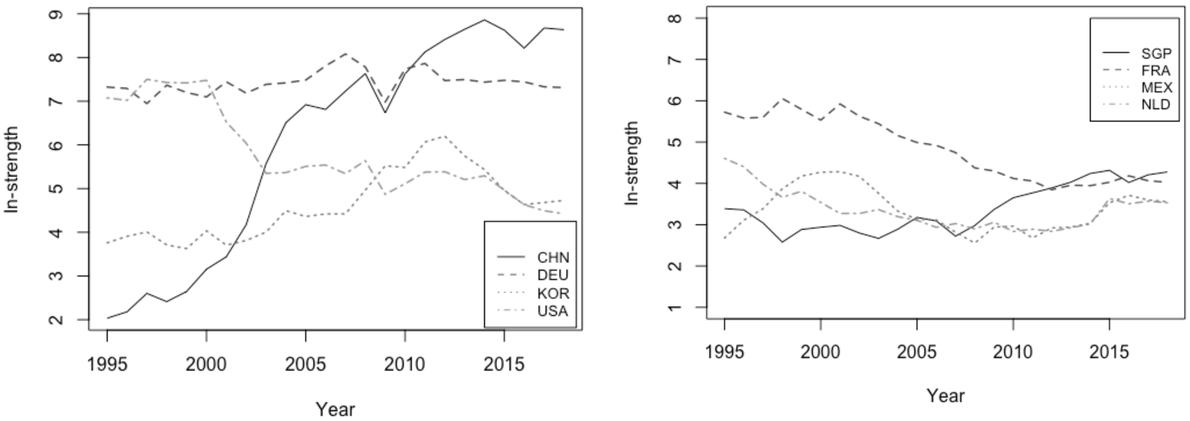
The extraordinary growth of China can be seen in the left panel of Figure 3 (a): in 1995, the amount of FVA that China was buying from the other countries was around 2% of total world flows. Its role as a key buyer accelerated after 2001, coinciding with its entry in the World Trade Organization (WTO).

Panel b) in Figure 3 identifies the main suppliers of FVA. United States holds the leading role, although its importance in 2018 has decreased with respect to 1995, from 15.3% to 12.2%. Again, the trajectory of China is remarkable: from providing a 1.6% of total FVA in 1995, it has reached 9.7%. Germany also has an important role as a supplier (7.5%), followed by Japan, whose out-strength has decreased from 10.5% in 1995 to 4.8% in 2018.

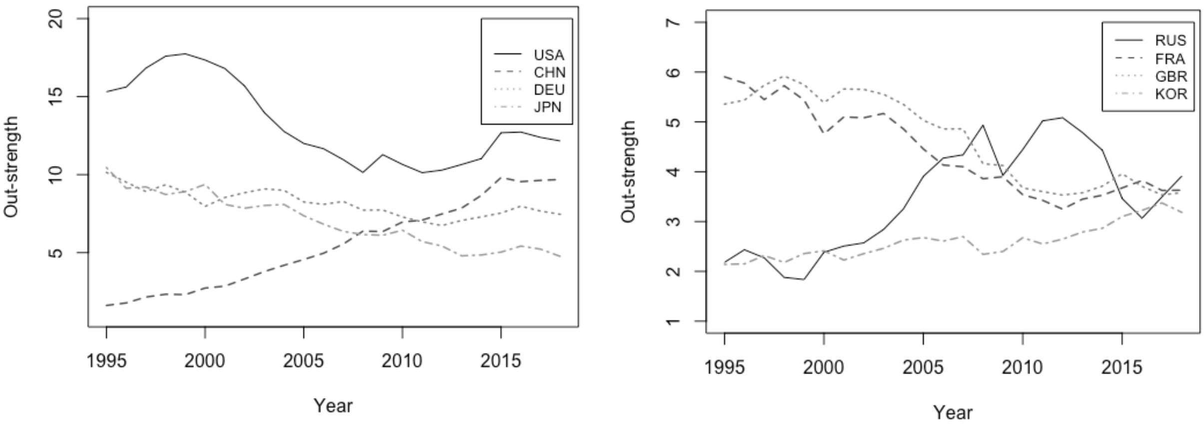
France and UK are among the top suppliers of FVA, with each concentrating more than 3% of total FVA flows, although their importance has declined during this period. On the contrary, Russia emerges as an important player. Its role as a supplier of FVA is related to its specialization in natural resources. Korea also appears to be an important provider of FVA, with an increasing share of total FVA flows.

Figure 3. In-strength and out-strength. Selected countries, 1995-2018

a) In-strength



b) Out-strength



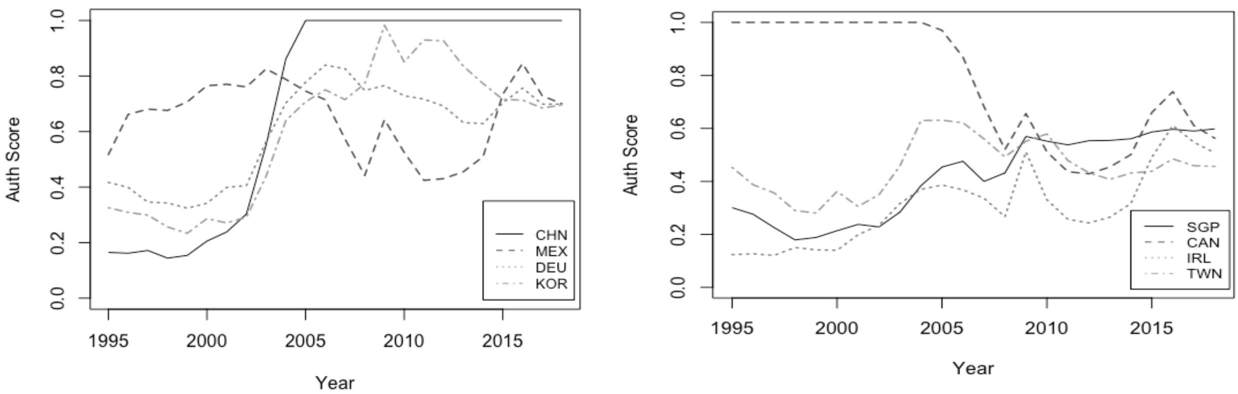
Source: Authors' calculations based on OECD-TiVA (2021 edition).

The measures presented in Figure 3 are closely related to the concepts of hubs and authorities. In a directed network, the nodes with a high hub score are those that point to many nodes that have in turn high authority scores. On the other hand, the authorities are the nodes that are connected to many nodes with high hub scores. Hence, we should expect countries with a high out-strength to have high hub scores, whereas authorities should have a high in-strength. This is the case: out-strength and hub measures are strongly correlated in our sample (94%), as well as countries' authority scores and in-strength (88.8%). Table A2 in the Appendix shows the data for all the countries in our sample.

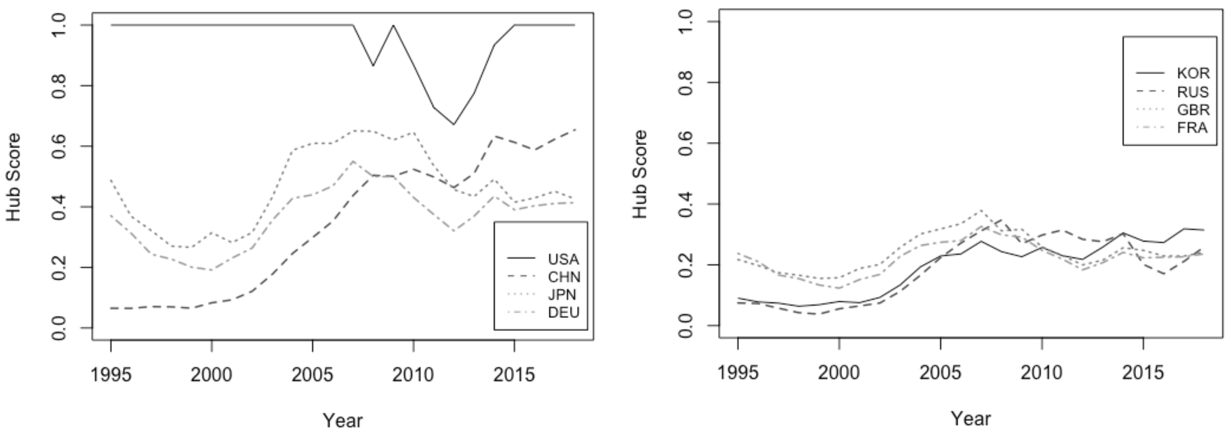
Figure 4 shows the countries with the highest authority and hub scores (panels a and b, respectively). The value of these indexes ranges from 0 to 1. China is the country with the highest authority in the network. Its score has remarkably increased since 2001. Mexico, Germany and Korea, despite their diverging evolution, have similar scores in 2018. Singapore, Canada, Ireland and Taiwan are also relevant authorities in the network. Many of these countries are also among the ones with the highest in-strength, as shown in Figure 3 (panel a). This is consistent with what has been mentioned before: countries' authority scores and in-strength are strongly correlated.

Figure 4. Authorities and hubs and. Selected countries, 1995-2018

a) Authorities



b) Hubs

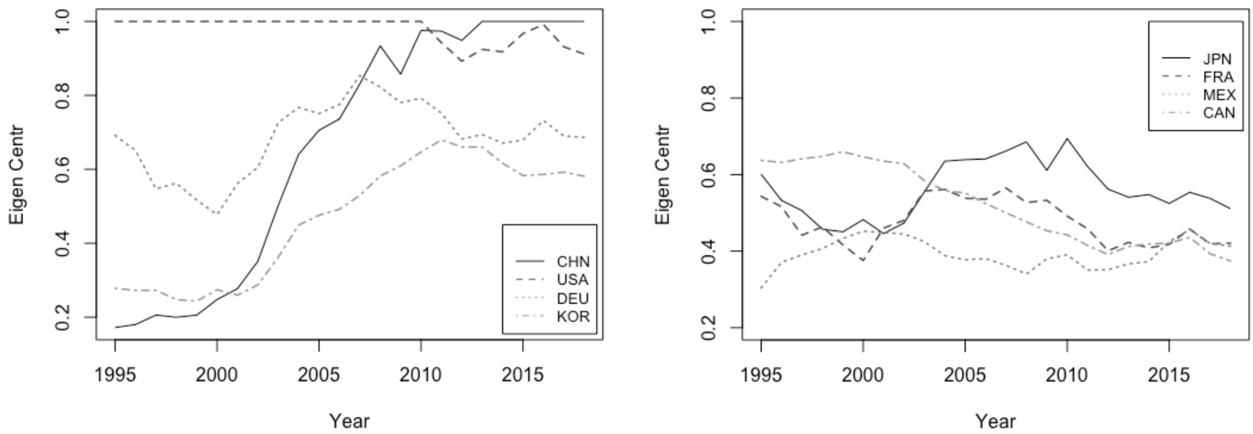


Source: Authors' calculations based on OECD-TiVA (2021 edition).

United States is the country with the highest hub score, followed by China, Japan and Germany. Being a hub implies that these countries are important suppliers of relevant buyers (the authorities). Other important hubs are Korea, Russia, United Kingdom and France. These countries are also the ones with the highest out-strength (see Figure 3, panel b).

Finally, in Figure 5 we focus on countries' eigen centrality, which is the variable of interest in the econometric analysis conducted in Section 4. The value of this index ranges from 0 to 1. As we can see in the left panel of Figure 5, United States had the highest -and the maximum- eigen centrality until 2010. From 2010 onwards, China took the lead in this indicator, whose eigen centrality skyrocketed from less than 0.2 in 1995 to 1 in 2018. Other relevant countries are Germany and Korea, which also became a significant central country in 2018, starting from low levels in 1995. Japan, France, Mexico and Canada are also among the countries with the highest eigen centrality, although the value of the eigenvector for these countries in 2018 has decreased compared to 1995 or is only moderately higher.

Figure 5. Eigen centrality. Selected countries, 1995-2018



Source: Authors' calculations based on OECD-TiVA (2021 edition).

4. The empirical model

After having examined the configuration of the network of foreign value-added trade flows and its evolution over time, we proceed with the empirical analysis of the impact of centrality in countries' performance in GVCs.

There are different alternatives to measure countries' upgrading in GVCs. We choose the growth of domestic value added embodied in gross exports at the country-level, which is one of the most used measures of upgrading. Our hypothesis is that benefiting from GVCs may stem from position within them and not just participation.

To test this hypothesis, we regress the centrality measure we have computed in the previous section (eigenvector centrality) on the growth of domestic value-added in exports. Our model also includes as control variables the initial level of GDP per capita to account for the country's level of development, initial value-added, initial exports and export openness.

Our baseline specification is shown in Equation (2):

$$\frac{1}{T}ln\frac{DOMVAX_j^t}{DOMVAX_j^0} = \beta_0 + \beta_1\frac{1}{T}ln\frac{eigencent_j^t}{eigencent_j^0} + \beta_2 X_j^0 + \alpha_j^t + u_j^t, \tag{2}$$

where the dependent variable, $\frac{1}{T}ln(DOMVAX_j^t/DOMVAX_j^0)$, is the annual average growth of the domestic value added embodied in country j gross exports. $\frac{1}{T}ln(\ eigencent_j^t/\ eigencent_j^0)$ is the annual average change in the eigen centrality based on the weighted matrix, and X_j^0 is a vector of controls at the country level (initial domestic value-added embodied in exports, country's GDP, export openness, capital intensity and human capital) whose values correspond to the beginning of each subperiod. α_j^t captures time fixed effects and u_j^t denotes the error term.

The dependent variable and the eigen centrality have been calculated using OECD's TiVA database. Capital intensity is calculated as capital stock per worker and human capital per worker is based on the average years of schooling from Barro and Lee (2013). These two measures - capital intensity and human capital-, together with GDP, have been obtained from the Penn World Table (version 10.0). Export openness has been obtained from the World Bank's World Development Indicators (WDI) database. The correlation matrix can be found in the Appendix (Table A3).

We estimate equation (2) using a fixed effects model. We have considered different subperiods: 1995-2000, 2000-2005, 2005-2008, 2008-2013, 2013-2018. All the subperiods have a 5-year length except the period from 2005-2008. We preferred to separate the period 2008-2013 from the others to control for the impact of the trade collapse in 2008-2009 and the recovery in the aftermath of the Great Recession. The different number of years included in each subperiod is not an issue since the growth rates are calculated as annual averages.

Table 2 shows the results of our econometric approach. Column (1) is the unconditional regression of changes in eigen centrality on the growth of domestic value added in exports. The coefficient is significant at the 1% level, which suggests that holding a central position in the GVC network is positively related to countries' upgrading in GVC in terms of being able to generate more domestic value added in exports.

Column (2) is our preferred specification since it includes all the relevant control variables. Still, changes in eigen centrality are positively correlated with countries' upgrading in GVCs. The coefficient, although slightly lower than in col. (1), is significant at the 1% level. Our results imply that a 1 percentage point increase in eigen centrality would lead to an increase of 0.6 percentage points in the growth of domestic value added embodied in exports.

Real GDP –which controls for country size-, export openness and capital intensity have positive coefficients and are significant at least at the 5% level. Initial domestic value added in exports is negatively correlated with the dependent variable, which implies that countries with lower levels of DVAinX have more opportunities to increase it. Human capital is positive but not statistically significant.

Columns (3) and (4) run the same specification than in (2) but splitting the full sample according to countries' level of development. Col. (3) only includes high-income countries whereas col. (4) considers all the other countries (low, lower-middle and upper-middle income). Changes in eigen centrality appear to be positive and statistically significant in both cases, although the coefficient is higher for high income countries.

Table 2. The impact of network centrality on domestic value added in exports. 1995-2018.

	Dependent variable: Growth in domestic value added in exports			
	(1)	(2)	(3)	(4)
	Full sample		High income countries	Lower and middle-income countries
log DVAinX		-0.041***	-0.045***	-0.054***
		(0.013)	(0.016)	(0.017)
Growth in eigen centrality	0.663***	0.618***	0.609***	0.572***
	(0.042)	(0.046)	(0.064)	(0.059)
log real GDP		0.049**	0.042*	0.043
		(0.019)	(0.022)	(0.036)
Export Openness		0.001***	0.001**	0.001**
		(0.000)	(0.000)	(0.000)
Human Capital		0.017	-0.003	0.004
		(0.024)	(0.039)	(0.051)
log Capital Intensity		0.029**	0.011	0.032*
		(0.013)	(0.020)	(0.018)
Constant	0.063***	-0.556***	-0.156	-0.362
	(0.003)	(0.187)	(0.270)	(0.392)
Observations	325	316	168	148
R^2	0.884	0.906	0.899	0.917
Number of country	65	64	42	37

Significance levels: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.
Notes: Results from estimating equation (x) using panel data and fixed effects. All regressions include time dummies. The dependent variable is the annual average growth rate of the domestic value added content in exports over the periods 1995-2000, 2000-2005, 2005-2008, 2008-2013 and 2013-2018.
All level variables are in natural logarithms and their values correspond to the beginning of each subperiod. Columns (1) and (2) consider the full country sample, whereas column (3) estimates the equation (x) only for high-income countries and column (4) for low, lower-middle, and upper-middle countries.

5. Conclusions

This paper has addressed the evolution of the GVC network over the period 1995-2018. Our approach has relied on network techniques and graph theory to analyse the structural network of flows of foreign value added embodied in countries' gross exports. Together with the description of the evolution of the network, our aim has been to determine if centrality in this network is positively correlated with upgrading in GVCs.

The structural indicators of the GVC network suggest that the network of value-added trade flows is getting more decentralized over time, which is consistent with the emergence of new players and the participation of more countries in GVCs. However, despite this growing diversification of participants in the exchange of value-added trade flows, there are some top players in the network which are becoming more important, as measured by their eigen centrality.

The most central countries in the network at the end of the period were United States, Germany and China, which was not a significant player in 1995, but it skyrocketed positions until it reached the core of the network, becoming a very relevant player. The configuration of the network around these three main nodes seems to confirm the regionalization patterns in GVCs, with large amounts of FVA been exchanged around these three countries, which play a leading role in their respective regions.

The clustering indicator or transitivity, together with the *hub* and *authority scores,* marks an evident path towards the formation of subnetworks. The process of grouping together is mainly based on some similarity measure that make countries to be closer to each other. Thus, identifying those patterns might help to gain insights about the clusters' characteristics and nature. Therefore, that facts suggest a line to explore in our following steps in this work.

The econometric approach conducted in this paper explores the link between centrality in GVCs and countries' upgrading. To test our research question, we opted for a directed network with weighted edges that reflect the importance of connections between country pairs. We find that centrality plays an important role in boosting the growth of domestic value added embodied in exports: a 1 percentage point increase in eigen centrality leads to an increase of 0.6 percentage points in the growth of domestic value added embodied in exports. The results hold for countries at different levels of development, although the coefficient is slightly higher for higher-income countries.

This result opens doors to different considerations for future research. It might be interesting to explore the implications of spatial distance as a node attribute, since it might play a crucial role in the formation of links and *clusters*. Other elements of the network structure, member attributes and relational attributes might be determinant in the incidence of ties. Thus, a further step can lead us to use methodologies that give more importance to other social and relational aspects that can explain the GVC network, for example, Exponential Random Graphs Models (ERGM).

Additionally, our analysis has been conducted at the country level. In a next step, we would like to consider the sectoral dimension as well to check the consistency of our results.

6. Appendix

Table A1. Country list

iso3	Country name	iso3	Country name
ARG	Argentina	LAO	Lao People’s Democratic Rep.
AUS	Australia	LVA	Latvia
AUT	Austria	LTU	Lithuania
BEL	Belgium	LUX	Luxembourg
BRA	Brazil	MYS	Malaysia
BRN	Brunei Darussalam	MLT	Malta
BGR	Bulgaria	MEX	Mexico
KHM	Cambodia	MAR	Morocco
CAN	Canada	MMR	Myanmar
CHL	Chile	NLD	Netherlands
CHN	China (People's Republic of)	NZL	New Zealand
TWN	Chinese Taipei	NOR	Norway
COL	Colombia	PER	Peru
CRI	Costa Rica	PHL	Philippines
HRV	Croatia	POL	Poland
CYP	Cyprus	PRT	Portugal
CZE	Czech Republic	ROU	Romania
DNK	Denmark	RUS	Russian Federation
EST	Estonia	SAU	Saudi Arabia
FIN	Finland	SGP	Singapore
FRA	France	SVK	Slovak Republic
DEU	Germany	SVN	Slovenia
GRC	Greece	ZAF	South Africa
HKG	Hong Kong, China	ESP	Spain
HUN	Hungary	SWE	Sweden
ISL	Iceland	CHE	Switzerland
IND	India	THA	Thailand
IDN	Indonesia	TUN	Tunisia
IRL	Ireland	TUR	Turkey
ISR	Israel	GBR	United Kingdom
ITA	Italy	USA	United States
JPN	Japan	VNM	Viet Nam
KAZ	Kazakhstan	ROW	Rest of the World
KOR	Korea		

Table A2. Eigen centrality, in-strength, out-strength, hubs and authorities. 2018

Country	Eigen centrality	In-strength	Out-strength	Hubs	Authorities
CHN	1.00	8.64	9.69	0.654	1.00
USA	0.91	4.42	12.16	1.000	0.41
ROW	0.72	3.19	9.44	0.726	0.35
DEU	0.69	7.31	7.46	0.414	0.70
KOR	0.58	4.73	3.18	0.314	0.70
JPN	0.51	3.21	4.76	0.426	0.39
FRA	0.42	4.03	3.63	0.236	0.45
MEX	0.41	3.55	1.04	0.078	0.70
CAN	0.37	2.67	1.57	0.120	0.56
SGP	0.37	4.28	1.37	0.098	0.60
TWN	0.36	3.08	1.62	0.170	0.46
GBR	0.34	2.65	3.58	0.241	0.31
NLD	0.33	3.53	2.41	0.159	0.42
ITA	0.31	3.05	2.62	0.168	0.33
IRL	0.30	3.45	1.19	0.079	0.51
RUS	0.27	0.90	3.91	0.259	0.12
IND	0.27	2.20	1.83	0.133	0.34
VNM	0.25	2.60	0.56	0.049	0.37
ESP	0.22	2.30	1.80	0.111	0.25
THA	0.22	2.34	0.85	0.068	0.32
BEL	0.21	2.36	1.49	0.099	0.24
CHE	0.19	1.79	1.39	0.102	0.21
SAU	0.19	0.23	2.58	0.219	0.03
AUS	0.18	0.67	1.89	0.176	0.09
POL	0.17	1.88	1.37	0.085	0.19
MYS	0.17	1.57	0.92	0.084	0.21
AUT	0.14	1.47	1.09	0.074	0.15
BRA	0.13	0.73	1.23	0.101	0.10
LUX	0.13	1.78	0.33	0.022	0.20
CZE	0.12	1.48	0.69	0.044	0.15
IDN	0.12	0.65	1.13	0.095	0.09
HKG	0.11	0.95	0.64	0.047	0.14
SWE	0.11	1.18	1.00	0.059	0.11
TUR	0.10	0.92	0.83	0.049	0.11
HUN	0.09	1.19	0.44	0.027	0.11
NOR	0.09	0.51	1.27	0.080	0.05
DNK	0.08	1.04	0.57	0.035	0.10
ZAF	0.07	0.47	0.50	0.041	0.07
PHL	0.06	0.50	0.43	0.039	0.07
SVK	0.06	0.84	0.33	0.019	0.08
CHL	0.06	0.25	0.54	0.049	0.04
FIN	0.05	0.58	0.48	0.030	0.06
PRT	0.05	0.63	0.33	0.021	0.06
ISR	0.05	0.41	0.39	0.029	0.05
ROU	0.04	0.43	0.41	0.026	0.04
KAZ	0.04	0.14	0.61	0.039	0.02

Table A2 (*cont*). Eigen centrality. in-strength. out-strength. hubs and authorities. 2018

Country	Eigen centrality	In-strength	Out-strength	Hubs	Authorities
GRC	0.04	0.46	0.24	0.015	0.06
PER	0.04	0.15	0.38	0.031	0.03
COL	0.03	0.13	0.24	0.018	0.02
ARG	0.02	0.16	0.26	0.017	0.02
MAR	0.02	0.28	0.14	0.009	0.03
SVN	0.02	0.27	0.15	0.008	0.03
BGR	0.02	0.30	0.14	0.008	0.03
NZL	0.02	0.17	0.14	0.011	0.02
MLT	0.01	0.21	0.03	0.002	0.02
LTU	0.01	0.19	0.13	0.006	0.02
TUN	0.01	0.13	0.06	0.004	0.02
MMR	0.01	0.08	0.08	0.007	0.01
KHM	0.01	0.09	0.04	0.003	0.01
EST	0.01	0.14	0.07	0.003	0.01
CRI	0.01	0.08	0.04	0.003	0.01
HRV	0.01	0.12	0.07	0.003	0.01
ISL	0.01	0.07	0.04	0.003	0.01
CYP	0.01	0.09	0.04	0.002	0.01
LVA	0.01	0.07	0.07	0.003	0.01
BRN	0.01	0.01	0.08	0.006	0.00
LAO	0.00	0.02	0.03	0.003	0.00

Note: Countries are ranked according to their eigen centrality. The values for the eigen centrality. hubs and authorities range from 0 to 1. In-strength and out-strength range from 0 to 100.

Table A3. Correlation matrix

	Growth in DVAinX	log DVAinX	Growth in weigencent	log real GDP	Export Openness	Human Capital	log Capital Intensity
log DVAinX	-0.26	1					
Growth in eigen cent	0.84	-0.24	1				
log real GDP	-0.10	0.91	-0.09	1			
Export Openness	-0.01	-0.11	-0.02	-0.36	1		
Human Capital	-0.16	0.40	-0.15	0.16	0.14	1	
log Capital Intensity	-0.26	0.36	-0.24	0.07	0.28	0.66	1

Note: DVAinX stands for domestic value added embodied in gross exports.

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