

Measuring Exposure to Risk in Global Value Chains

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Abstract

How exposed are countries and sectors to GVC risks? GVC participation matters for answering this question. Standard approaches either overstate the degree of backward integration or underestimate the involvement of some industries, especially services, in Global Value Chain (GVC) activity. To correct these biases, this paper proposes a novel comprehensive method to measure GVC participation using Inter-Country Input-Output (ICIO) linkages in both trade and output and shows that these improvements in

methodology matter from a macroeconomic perspective. GVC integration, as measured by the indicators, decreases the exposure to domestic shocks and increases that to global shocks. The paper also finds that exposure to shocks is complex: in most countries and sectors, output is simultaneously exposed to supply and demand shocks. This two-sided exposure suggests that disruptions may not be easily managed by unilateral policy attempts at forcing a reorganization of buyers-seller relationships.

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1 Introduction

Since the original contributions on conceptualizing vertical integration (Hummels et al 2001) and measuring countries' value added in gross trade (Koopman et al. 2014), there has been a rapidly expanding demand for measures of GVC participation that offer a macro-view of the phenomenon. The current debate on how GVCs affect countries and industries resilience to shocks has led to a revival of interest for such measures. This paper responds to this demand. It is the first to propose a comprehensive method to measure GVC participation at the country-sector level using Inter-Country Input-Output (ICIO) linkages in both trade and output and to develop the relative measures from all the main sources of ICIO data. The paper also shows that such measures are empirically relevant, most notably to assess exposure of countries and sectors to GVC-related demand and supply shocks.

The basic building block of the methodology proposed for measuring GVC participation is a computational device proposed initially by Borin and Mancini (2015, 2019) and discussed in the survey by Antràs and Chor (2021). Specifically, this computational device consists in identifying traditional trade (or non-GVC trade) as gross trade flows that cross just one border. Flows that cross more than one border are considered GVC-related, instead. The current paper also applies the rationale originally developed for trade flows to measuring GVC-related output. By identifying the portion of both output and trade that are related to GVC activities, the paper points out the important biases that originate from neglecting the producer perspective in favor of the exporter perspective.

An additional original contribution of the methodological approach of this paper is to break down the measures of GVC-related trade and output in three additive terms, i.e. a backward component corresponding to the activities at the beginning of the chain, a forward component corresponding to the activities at the end of the chain, and an intermediate component – *two-sided* – for all activities encompassing both sourcing and selling intermediates. All measures proposed present two desirable features: i) they are bounded between 0 and 1, facilitating comparisons across different data points; and ii) they are additive at any level of aggregation/disaggregation of trade flows, thus data can be summed up and partitioned at any level along both the geographical and the sectoral dimension. In so doing, the methodology and indicators proposed by this paper offer a summary and yet comprehensive system of measures on countries and sectors engagement in GVC activities.

The empirical analysis of the paper brings new insights to a rapidly growing academic literature that investigates how shocks propagate along production networks. This literature concludes that many factors, including the nature of the shock (Carvalho and Tahbaz-Salehi, 2019), the position in GVCs (Ferrari, 2021), the level of substitutability of inputs (Barrot and Sauvagnat 2016; Baqaee and Farhi 2019), and many more concur to determine to which extent countries and sectors are exposed to shocks through their participation to national and global supply networks. The evidence produced in this paper shows that there is a high degree of interdependence in GVC participation and as a result, disentangling the various factors may not be an easy feat. It finds that deeper GVC integration, as measured by the indicators, decreases the exposure to domestic shocks and to shocks related to traditional trade. But it increases that to global shocks. Exposure to global shocks has the following characteristics. Higher forward (backward) participation in GVCs is associated with a larger exposure to demand (supply) shocks originating downstream (upstream) the production chain. In addition, the empirical analysis confirms that countries and sectors more engaged in the intermediate stages of GVCs and that are characterized by two-sided GVC linkages, are exposed to both demand and supply shocks.

Future research may want to investigate some interesting policy and research implications of such interdependence. First, the paper findings on the importance of two-sided exposure suggest that disruptions may not be easily managed by unilateral policy attempts at forcing a reorganization of buyers-seller relationships. Second, the findings of the paper point to the need to assess exposure to foreign (GVC-related) shocks not in isolation, but relative to exposure to domestic (non-GVC related) shocks, since GVC participation mediates both types of shocks. Finally, the paper offers tools to broaden the assessment of countries and sectors exposure to risks originating from shallower forms of international engagement (traditional trade) and from more geographically concentrated cross-border production (regional value chains).

The remainder of the paper is structured as follows. Section 2 discusses how to quantify exposure to risk using country-sector measures of GVC participation. Section 3 describes the methodology of decomposing GVC-related trade participation in three measures: pure backward participation, pure forward participation, and two-sided or mixed participation. Section 4 generalizes these results beyond trade, i.e. GVC-related value-added, GVC-related final goods production, and GVC-related output. Section 5 shows that our proposed decomposition matters empirically, showing the measures applied to country-wide, sector-specific examples. Section 6 discusses the empirical relevance of the indicators developed in earlier sections and uses them to detect exposure to domestic and imported shocks. Finally Section 7 concludes. Annex A illustrates the notation and provides some basic accounting relationships used in the paper. Finally, Annex B illustrates how to retrieve the broad set of measures discussed in the paper and made available on the World Integrated Trade Solutions (WITS) platform.

2 Quantifying Exposure

Policy interest in Global Value Chains (GVCs) has had a revival as of recent. In the past, the interest was due to GVCs' ability to boost productivity, technology upgrading, and employment in participating countries. Now policy and politics worry that too much interdependence may be a problem, notably because it may magnify and propagate shocks across national borders.

Measuring exposure to risk requires assessing the extent to which countries and sectors participate to GVCs. However, how to measure this phenomenon is still the object of academic debate. The main challenge lies in measuring where value is added in a GVC, where it comes from, and where it flows to. Ideally, data that trace firm-to-firm transactions both within and across countries should be used, since it is not countries or industries that engage in value chain production but rather firms. Using a firm-level approach to GVC participation however is severely constrained by data availability (Bems and Kikkawa, 2021; Kee and Tang, 2016).¹

Given the difficulties in using a firm-level approach to measuring many important aspects of GVC participation, a large body of work has focused on combining information from customs offices

¹According to Bems and Kikkawa (2021) only one country in the world - Belgium - allows to obtain comparable data on firm-level trade and the complementary census information on firm-to-firm domestic transactions needed for a fully-fledged measurement of GVC participation. It is equally hard to disentangle the foreign input content of a firm's exports from the foreign content of overall production (Kee and Tang, 2016 attempted to do so using processing trade in China). Even when a firm is identified as an exporter of intermediate inputs (instead of final goods), it is almost impossible to establish whether those inputs are fully absorbed in the importing country or whether they are reexported to third markets by the importing firms after having added value to them. Finally, without linking customs data across countries, it is very hard to establish the nature of the GVC link.

with national input-output tables.² Despite their limitations,³ such global input-output databases can be used to devise ways of measuring the extent to which production processes have globalized in recent years, how countries and sectors participate in GVCs, and several features of GVC linkages consistent with what Antràs (2020) calls *the broad view of GVC participation*.⁴

Building on global input-output tables, a sufficient condition for considering trade as GVC-related is that it crosses at least two borders (Hummels et al. 2001; Borin and Mancini, 2015; Antràs, 2020). This can be seen as the sum of two natural measures of cross-border linkages, i.e. *backward GVC participation* and *forward GVC participation*, which broadly speaking trace how much imports are embedded in a country’s exports and how much of a country’s own production is absorbed by demand from the global markets. According to the definition, all what is bought from abroad and exported constitutes a backward linkage and all what is exported for consumption in third markets is a forward linkage. The concepts of backward and forward participation are important, since exposure to foreign economic forces depends on the absolute and relative importance of forward and backward linkages in GVCs.⁵

However, the standard practice of assuming that the distinction between *backward participation* and *forward participation* fully characterizes engagement in GVCs leads to overstate the degree of backward integration. This is apparent from Figure 1, which shows that following standard measurement approaches, backward linkages are systematically higher than forward linkages, and - what is worse - forward and backward participation do not balance out at global level. Since there is no reason grounded in theory predicting that backward integration can be systematically larger than forward integration, and since at the global level the two need to balance out, for the same reason that world imports are equal to world exports, we conclude that standard approaches mis-characterize the relative importance of backward versus forward GVC linkages.

Characterizing linkages as either forward or backward also fails to capture an important empirical regularity: GVC participation encompasses many activities that are linked simultaneously backward and forward to entities abroad. These activities, which according to this paper’s estimates may account for up to two thirds of all GVC-related production, are known as I2E (import to export) in Baldwin and Lopez-Gonzales (2015). This paper shows that quantifying correctly these activities in the data is essential to a correct assessment of the exposure profile of countries and sectors. Accordingly, the paper proposes to use three distinct modes of participation: *pure forward participation* for the activities at the beginning of the value chain, *pure backward participation* for the activities at the end of the chain, and *two-sided or mixed participation* for activities neither at the beginning nor at the end of the chain. This is the first of two mis-measurements in standard approaches that this

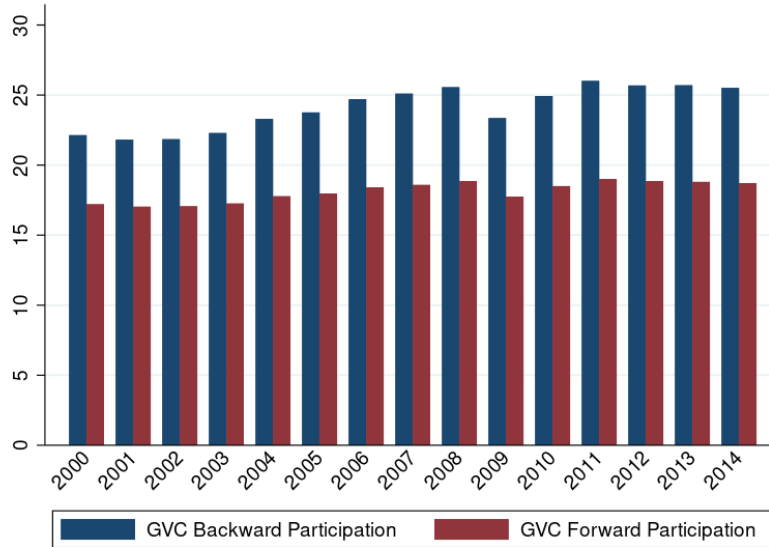
²The most widely used are the World Input-Output Database (WIOD; Timmer et al., 2015), a collaborative project led by researchers at the University of Groningen; the Trade in Value Added (TiVA) database compiled by the Organization for Economic Cooperation and Development (OECD); and the EORA global supply chain database (Lenzen et al., 2013), constructed by a team of researchers at the University of Sydney.

³Global input-output tables have two main limitations. First, because they rely on aggregated input-output data, the resulting sectoral disaggregation of GVC flows is coarse. They therefore miss a lot of GVC activity within the broadly defined sectors. For example, one can compute the origin of *fabricated metal products* in the production of *motor vehicles* in the United States but cannot infer where more specific components such as tires, car engines, or windshield wipers originate. Second, in constructing the tables, researchers are forced to impose strong assumptions to back out some bilateral intermediate input trade flows that cannot be readily read from either customs data or national IO tables, leading to statistically relevant aggregation biases (De Gortari, 2019; Bems and Kikkawa, 2021).

⁴In Antràs (2020), broad view of GVC participation a global value chain or GVC consists of a series of stages involved in producing a product or service that is sold to consumers, with each stage adding value, and with at least two stages being produced in different countries

⁵High exposure to forward linkages in GVCs increases the ability of the domestic economy to grow on the back of growing foreign demand, but it also increases the risk of external demand shocks. High exposure to backward linkages in GVCs allows a more efficient use of domestic resources, and easier access to foreign inputs, technology, and know-how, but it also increases the risk of imported supply shocks.

Figure 1: GVC Backward and Forward Participation at the global level (share of total trade)



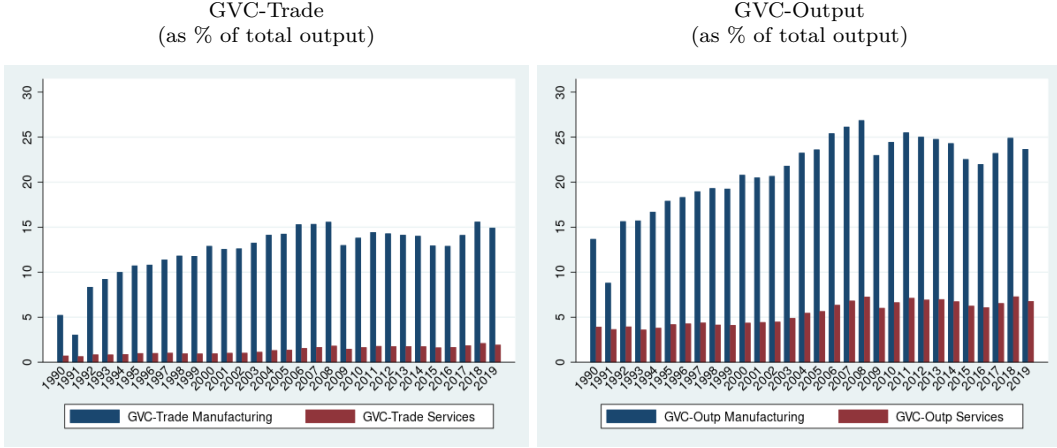
Source: own elaboration based on WIOD.

paper identifies and addresses.

A second improvement is also needed to characterise accurately exposure: measuring GVC participation as a proportion of output. Based on evidence in Section 5 of this paper, we can demonstrate that taking the viewpoint of the producing sector - and not only the one of the exporting sector - corrects another bias in standard measurement approaches: a systematic underestimation of some sectors' and countries' participation. More specifically, output-based measures allow to improve our understanding of GVC participation in two opposite cases. First, they allow to capture otherwise unobserved indirect participation, e.g. of those sectors and countries whose production feeds into GVCs despite a limited direct involvement in cross-border trade. This is the case for example of many professional services that are often supplied predominantly as inputs to manufacturing sectors that participate directly to GVCs. Failure to capture the full extent of their involvement in GVCs leads to underestimate severely also total services GVC participation (See Figure 2). Second, it allows to identify those cases in which a country's exposure to GVCs is limited because trade constitutes a small share of overall domestic output. This for example was the case of China at the beginning of the process of trade liberalization. In the late 1980s and early 1990s Chinese exporting firms, mainly located in Special Economic Zones where highly involved in global value chain production, but the bulk of the economic activity was still generally domestically oriented. Computing GVC participation relative to output on top of GVC participation relative to trade would have indicated that the domestic economy was relatively insulated from foreign shocks despite its export sector was heavily reliant on GVCs.

Section 3 and Section 4 below study systematically these measurement issues at the macro-level, using an accounting framework. As it is customary in the related literature, we propose a representation of GVC participation that uses global input-output data at the country-industry level of aggregation. Due to the nature of the data, our proposed framework remains subject to the limitations of homogeneity, proportionality and aggregation discussed by De Gortari (2019), Antràs and Chor (2021) and Bems and Kikkawa (2021) among others. The reader is warned however that

Figure 2: Exporter versus producer perspective in measuring GVC participation



Source: Our elaborations on data from EORA and ADB MRIO

such biases cannot be solved in most empirical work, given the unavailability of globally representative micro-data that trace firm-to-firm transactions both within and across countries.

3 GVC-related trade

In this section we take the view of an exporting sector, showing how to detect within any trade flow the amount of it that can be traced back to global value chains.

Consider a standard Inter-Country Input-Output (ICIO) model with G countries and N sectors. Appendix A gives an exhaustive definition of the notation and, for this reason, here we only mention that \mathbf{E}_{sr} is the $N \times 1$ vector of exports of country s to country r , \mathbf{X}_s is the $N \times 1$ vector of gross output produced by country s , \mathbf{Y}_{sr} is the $N \times 1$ vector of final goods and services produced by country s and absorbed in country r , \mathbf{A} is the $GN \times GN$ global matrix of input coefficients, \mathbf{B} is the global Leontief inverse matrix for the entire inter-country model, \mathbf{L} is the local Leontief inverse matrix, taking into account only the domestic chains, and \mathbf{V}_s is the $1 \times N$ vector that incorporates the value-added shares embedded in each unit of gross output produced by country s . Lastly, given a generic $1 \times N$ or $N \times 1$ vector \mathbf{W} , $\widehat{\mathbf{W}}$ is its $N \times N$ diagonal form.

It is convenient to start from the identification of the simplest form of trade between countries, by tracing the amount of value that crosses just once the border between the exporter and the importer. It consists of the value of final goods produced entirely at home and consumed abroad and of the value of the intermediate inputs that are (entirely) produced at home and used by the importing country to produce final goods for its internal market. In more formal terms, the simplest form of trade between country s and r is the Directly Absorbed Value-Added exports:

$$\mathbf{DAVAX}_{sr} = \widehat{\mathbf{V}}_s \widehat{\mathbf{L}}_{ss} \mathbf{Y}_{sr} + \widehat{\mathbf{V}}_s \widehat{\mathbf{L}}_{ss} \mathbf{A}_{sr} \mathbf{L}_{rr} \mathbf{Y}_{rr}, \quad (1)$$

The vector \mathbf{DAVAX}_{sr} identifies, for each country $s \in N$ sector of exports, the ‘traditional’ type of exports to country r , as opposed to the international shipments that take place under the global sharing of production (‘GVC-related trade’). In other words, the ‘GVC-related trade’ includes all the traded items that cross at least two international borders, i.e. that are re-exported at least

once before being absorbed in final demand. This can be considered as a sufficient condition for an exported good to be part of an international production network.⁶

The ‘GVC-related trade’ can be measured simply by excluding from country s gross exports to country r the domestic value-added exported by each sector n that is absorbed directly by country r , i.e. the bilateral partner (\mathbf{DAVAX}_{sr}):

$$\mathbf{GVC}_{sr} = \mathbf{E}_{sr} - \mathbf{DAVAX}_{sr}. \quad (2)$$

This GVC indicator presents two desirable features: *i*) once divided by exports, i.e. $\mathbf{GVC}_{sr} \oslash \mathbf{E}_{sr}$, it is bounded between 0 and 1, since it traces within the trade flow the share of it related to GVC activity; *ii*) it is additive at any level of aggregation/disaggregation of trade flows; thus, data can be summed at any level – total country exports/world exports/world sector exports/country groups and so on – in order to obtain the proper GVC participation measures at the desired level of aggregation. For instance, the GVC share of the total exports of country s , for each sector n , will be

$$\mathbf{GVCX}_s = \sum_{r \neq s}^G \mathbf{GVC}_{sr} \oslash \sum_{r \neq s}^G \mathbf{E}_{sr}, \quad (3)$$

while at the world level we have:

$$\mathbf{GVCX}_{world} = \sum_s^G \sum_{r \neq s}^G \mathbf{GVC}_{sr} \oslash \sum_s^G \sum_{r \neq s}^G \mathbf{E}_{sr}. \quad (4)$$

Total GVC-related trade for any country s is obtained summing across the exports of each sector n , as

$$GVCX_s = \frac{\sum_{r \neq s}^G \mathbf{u}_N \mathbf{GVC}_{sr}}{\sum_s^G \sum_{r \neq s}^G \mathbf{u}_N \mathbf{E}_{sr}}. \quad (5)$$

where \mathbf{u}_N is the $1 \times N$ unit row vector.

In the same way, world trade related to GVC is

$$GVCX = \frac{\sum_s^G \sum_{r \neq s}^G \mathbf{u}_N \mathbf{GVC}_{sr}}{\sum_s^G \sum_{r \neq s}^G \mathbf{u}_N \mathbf{E}_{sr}}. \quad (6)$$

It should be noted that the overall GVC participation encompasses three different types of GVC linkages, i.e. purely forward, purely backward, and intermediate ones. In fact, a sector of export n might be engaged in GVC activities at the end of the chain, relying on imported inputs to export goods and services that are not further re-exported by the partner (pure backward participation). Alternatively, it might participate closer to the origin of the chain, exporting value-added that has been generated within the domestic chains – without any border crossing – to partners which, in turn, re-exports it to other markets (pure forward participation). Finally, the sector might be located in a more central position of the chain, therefore using imported inputs to produce its own exports,

⁶In principle, also value-added produced in completion stages of the production process, even if it crosses only one border, should be labeled as GVC. However, this part cannot be singled out using standard ICIO tables and, indeed, it is not considered by any other measure of GVC trade in the literature.

⁷This broad definition is completely in line with Borin and Mancini (2017, 2019). However its sub-components differ. More specifically, here the pure forward participation corresponds to what they label as forward participation. Instead, the sum of pure backward and two-sided participation equals their backward participation. See below for further discussion.

further re-exported by the partner (two-sided participation).

In the rest of the section, we provide a precise measure of the share of exports related to ‘pure forward’, ‘two-sided’ and ‘pure backward’ linkages.

The pure forward participation is simply the difference between the entire domestic value-added that is exported ($\widehat{\mathbf{V}_s \mathbf{L}_{ss} \mathbf{E}_{sr}}$) and the one that is directly absorbed by the importer,⁸ i.e. the \mathbf{DAVAX}_{sr}

$$\mathbf{GVC}PureForw_{sr} = \widehat{\mathbf{V}_s \mathbf{L}_{ss} \mathbf{E}_{sr}} - \mathbf{DAVAX}_{sr}. \quad (7)$$

The rest of the GVC-related trade is given by the sum of the *pure* backward participation and the *intermediate* participation. This is what Hummels et al. (2001) call vertical specialization, i.e. the import content of exports

$$\sum_{t \neq s}^G \widehat{\mathbf{u}_N \mathbf{A}_{ts} \mathbf{L}_{ss} \mathbf{E}_{sr}}. \quad (8)$$

The total import content of exports might be broken down into two very different terms, namely the import content of country s ’s exports *absorbed by the importing country r* and the import content of country s ’ exports *re-exported by r* . The former measures ‘pure’ backward participation, since the chain ends just after the exporting activity. The latter, instead, traces the GVC activities that are more in an intermediate position, as goods and services are further re-exported beyond the bilateral partner, i.e. *two-sided* participation.¹¹

Operationally, we first express bilateral exports \mathbf{E}_{sr} as the sum of exports of final goods and intermediates that are absorbed by the partner without crossing any other border and intermediates that are further re-exported by the partner,

$$\mathbf{E}_{sr} = (\mathbf{Y}_{sr} + \mathbf{A}_{sr} \mathbf{L}_{rr} \mathbf{Y}_{rr}) + \left(\mathbf{A}_{sr} \mathbf{L}_{rr} \sum_{j \neq r}^G \mathbf{E}_{rj} \right). \quad (9)$$

⁸It should be noted that Borin and Mancini (2017, 2019) label what here is defined as pure forward participation simply as forward. In fact, in this paper we refine their classification considering a broader sufficient condition to define the *total* forward participation, i.e. the supply of intermediate inputs for foreign exporters. In turn, the necessary condition to have a *pure* forward participation is that intermediate inputs for foreign exporters have to originate in the domestic economy, as in equation (7).

⁹For some empirical application, it could be convenient to trace also the market where the value-added is ultimately absorbed, following Borin and Mancini (2019):

$$\mathbf{GVC}PureForw_{sr} = \widehat{\mathbf{V}_s \mathbf{L}_{ss} \mathbf{A}_{sr} \mathbf{L}_{rr}} \left(\sum_{j \neq r}^G \mathbf{Y}_{rj} + \sum_{j \neq r}^G \mathbf{A}_{rj} \sum_k^G \sum_{l \neq s}^G \mathbf{B}_{jk} \mathbf{Y}_{kl} \right).$$

¹⁰Borin and Mancini (2019) show that Hummels et al. (2001) import content of exports might be expressed in a more convenient way to trace also the origin of the imported inputs. In this way, import content of exports is given by the sum of the entire foreign content in a country’s exports and the domestic double counting, i.e. the domestic inputs that are first exported and then imported again by the country to produce other exports

$$\widehat{\mathbf{V}_s \mathbf{L}_{ss} \sum_{j \neq s}^G \mathbf{A}_{sj} \mathbf{B}_{js} \mathbf{E}_{sr}} + \sum_{t \neq s}^G \widehat{\mathbf{V}_t \mathbf{B}_{ts} \mathbf{E}_{sr}}.$$

¹¹Borin and Mancini (2017, 2019) consider the entire import content of export as a measure of GVC backward participation. In fact, a sufficient condition to define backward participation is the use of imported intermediates to produce exports. In this work we refine this definition, adding a necessary condition for *pure* backward participation, i.e. the use of imported intermediates to produce exports to *final destinations*. In other terms, we label as *two-sided* participation the imported intermediates used to produce exports that are further re-exported. While it would be correct to account them in the engagement in backward activities, as in Borin and Mancini (2017, 2019), it is true that they also meets the sufficient condition to be considered as forward participation, i.e. the supply of intermediates for foreign exporters.

Then, we substitute this result back in in the import content of exports (8). Pure backward participation is given by the imported inputs embedded in the exports to final markets¹²

$$\mathbf{GVCPureBack}_{sr} = \sum_{t \neq s}^G \overline{\mathbf{u}_N \mathbf{A}_{ts} \mathbf{L}_{ss}} (\mathbf{Y}_{sr} + \mathbf{A}_{sr} \mathbf{L}_{rr} \mathbf{Y}_{rr}). \quad (11)$$

Instead, two-sided participation is given by the imported inputs embedded in the re-exports of the bilateral partner¹³

$$\mathbf{GVCTwoSide}_{sr} = \sum_{t \neq s}^G \overline{\mathbf{u}_N \mathbf{A}_{ts} \mathbf{L}_{ss}} \left(\mathbf{A}_{sr} \mathbf{L}_{rr} \sum_{j \neq r}^G \mathbf{E}_{rj} \right). \quad (13)$$

Since $\mathbf{GVCPureBack}_{sr}$ traces backward linkages up to country s 's exports to the final market, it mirrors $\mathbf{GVCPureForw}_{sr}$, which measures forward linkages on-wards from the origin of the chain, i.e. country s itself. Instead, the intermediate participation meets the sufficient condition that define a *broad* measure of backward participation – since it encompasses the use of imported inputs for the country's exports – and also a *broad* measure of forward participation – as it also encompasses the exports of inputs that are further re-exported by the bilateral partner. However, it does not meet the necessary condition for *pure* backward participation – use of imported inputs for the country's exports *to final markets* – nor the one for *pure* forward participation – exports of inputs *produced with domestic value-added* that are further re-exported by the bilateral partner. Depending on the empirical application, it could be useful to consider broad measures of participation instead of pure ones. These are precisely defined by the sufficient conditions highlighted above, and can be computed simply aggregating the intermediate mode of participation to one of the two pure modes.

Finally, the GVC-related trade within the export flow from s to r for any sector n might be expressed as the sum of these three components:

$$\mathbf{GVC}_{sr} = \mathbf{GVCPureForw}_{sr} + \mathbf{GVCPureBack}_{sr} + \mathbf{GVCTwoSide}_{sr}. \quad (14)$$

The forward, backward and two-sided participation might also be computed for any level of aggregation, as for the overall indicator of 'GVC-related trade' (see equations 3 to 6).

¹²The country of origin of the imported inputs might be traced separating foreign content from domestic double counting,

$$\begin{aligned} \mathbf{GVCPureBack}_{sr} = & \mathbf{V}_s \mathbf{L}_{ss} \sum_{j \neq s}^G \overline{\mathbf{A}_{sj} \mathbf{B}_{js}} (\mathbf{Y}_{sr} + \mathbf{A}_{sr} \mathbf{L}_{rr} \mathbf{Y}_{rr}) \\ & + \sum_{t \neq s}^G \overline{\mathbf{V}_t \mathbf{B}_{ts}} (\mathbf{Y}_{sr} + \mathbf{A}_{sr} \mathbf{L}_{rr} \mathbf{Y}_{rr}). \end{aligned} \quad (10)$$

¹³As for the pure forward and pure backward participation, the country of origin of the imported inputs and the country of final absorption might be traced as

$$\begin{aligned} \mathbf{GVCTwoSide}_{sr} = & \mathbf{V}_s \mathbf{L}_{ss} \sum_{j \neq s}^G \overline{\mathbf{A}_{sj} \mathbf{B}_{js}} \left[\mathbf{A}_{sr} \mathbf{L}_{rr} \sum_{j \neq r}^G \left(\mathbf{Y}_{rj} + \mathbf{A}_{rj} \sum_k^G \sum_{l \neq s}^G \mathbf{B}_{jk} \mathbf{Y}_{kl} \right) \right] \\ & + \sum_{t \neq s}^G \overline{\mathbf{V}_t \mathbf{B}_{ts}} \left[\mathbf{A}_{sr} \mathbf{L}_{rr} \sum_{j \neq r}^G \left(\mathbf{Y}_{rj} + \mathbf{A}_{rj} \sum_k^G \sum_{l \neq s}^G \mathbf{B}_{jk} \mathbf{Y}_{kl} \right) \right], \end{aligned} \quad (12)$$

Furthermore, at the aggregate level, i.e. summing across exporters s , importers r and sectors n , the ‘GVC pure backward-related trade’ is equal to the ‘GVC pure forward-related trade’:

$$\sum_{s,r \neq s}^G \mathbf{u}_N \mathbf{GVC} \text{PureBack}_{sr} = \sum_{s,r \neq s}^G \mathbf{u}_N \mathbf{GVC} \text{PureForw}_{sr}. \quad (15)$$

Lastly, a natural measure of the type of participation in GVC at any level of aggregation can be straightforwardly obtained as the difference between pure forward and pure backward participation divided by the overall GVC participation. For instance, for each n exporting sector within the trade flow from s to r :

$$\mathbf{P}_{sr} = (\mathbf{GVC} \text{PureForw}_{sr} - \mathbf{GVC} \text{PureBack}_{sr}) \oslash \mathbf{GVC}_{sr}. \quad (16)$$

The vector \mathbf{P}_{sr} measures the ‘forwardness’ of country s exports to country r , for each sector, and each of its elements is bounded between -1 and 1. At the country-level, i.e. summing across sectors and bilateral partners, we have:

$$P_s = \frac{\sum_{r \neq s}^G \mathbf{u}_N \mathbf{GVC} \text{PureForw}_{sr} - \sum_{r \neq s}^G \mathbf{u}_N \mathbf{GVC} \text{PureBack}_{sr}}{\sum_{r \neq s}^G \mathbf{u}_N \mathbf{GVC}_{sr}}. \quad (17)$$

At the global level, P is equal to zero, given the relation in equation (15):

$$\sum_s^G P_s = 0. \quad (18)$$

Thus, any index different from zero at any level of aggregation might be interpreted as a deviation from the world aggregate average.

3.1 Comparison with other indices of GVC-trade participation

The GVC-related trade indicator proposed above is not the first measure based on ICIO tables that has been developed to gauge the relevance of GVCs in international shipments. The ‘vertical specialization’ index (\mathbf{VS}) of Hummels et al. (2001), measuring the import content of country’s exports, is probably one of the first and most popular of these measures:

$$\mathbf{VS}_{sr} = \mathbf{u}_N \sum_{t \neq s}^G \mathbf{A}_{ts} (\mathbf{I} - \mathbf{A}_{ss})^{-1} \mathbf{E}_{sr} \oslash \mathbf{E}_{sr}. \quad (19)$$

However, as pointed out by the authors themselves, it is a partial measure of participation in global value chains, as also shown in Figure 3, where \mathbf{VS}_{sr} , computed at the global level, lies well below the total GVC-trade. Indeed, it can be shown that Hummels et al.’s (2001) vertical specialization \mathbf{VS}_{sr} corresponds precisely to the sum of pure backward and two-sided GVC participation as reported in equations (11) and (13). In addition, equations (10) and (12) generalize the \mathbf{VS}_{sr} indicator, providing information both on the very origin of the value and on its final destination.

In order to take forward linkages into account, Hummels et al. (2001) also suggest considering the exports of intermediate products that are later further processed and re-exported (they

label it **VS1**). However, they do not propose a precise formulation of this measure, since it can be implemented only in a fully-fledged ICIO framework that was not available at the time of writing. Thus, the ‘forward’ component of GVC-trade in equation (7) can be considered as the first *correct* implementation of the **VS1** indicator suggested by Hummels et al. (2001).

Therefore, our overall GVC-trade indicator can be seen as the implementation and generalization of Hummels et al. (2001) insights:

$$\mathbf{GVC}_{sr} = \underbrace{\mathbf{GVC}PureForw_{sr}}_{\mathbf{VS1}_{sr}} + \underbrace{\mathbf{GVC}PureBack_{sr} + \mathbf{GVC}TwoSide_{sr}}_{\mathbf{VS}_{sr}}. \quad (20)$$

Notably, at the country level, $\mathbf{GVC}PureForw_s$ differs from the version of the $\mathbf{VS1}_s$ index proposed by Koopman et al. (2014) – and recently reported also by Aslam et al. (2017) – since they compute it by aggregating the content of a country’s production embedded in other countries’ exports (i.e. $\mathbf{V}_s \sum_{r \neq s} \mathbf{B}_{sr} \mathbf{E}_{r*}$). While the $\mathbf{GVC}PureForw$ index is a portion of country s ’s exports (like **VS**), this does not necessarily hold true for the measure proposed by Koopman et al. (2014). Suppose, for instance, that a certain intermediate component exported by country s later undergoes other processing phases in different countries; the original component will be double-counted several times in the summation of country s ’s content in other countries’ exports. The discrepancy between the original value of goods exported by s and the related amount that enters in Koopman et al.’s (2014) indicator increases with the relative ‘upstreamness’ of country s ’s production. This is a feature that refers to the relative positioning of a country in GVCs and that has been specifically addressed in the literature through proper tools.¹⁴ Moreover, this positioning does not directly influence the VS indicator which is commonly used as the ‘backward’-participation counterpart of the $VS1$ indicator proposed by Koopman et al. (2014).¹⁵ Conversely, the $\mathbf{GVC}PureForw$ of equation (7) measures the share of a country’s exports related to forward GVC linkages in a way that is consistent with how the $\mathbf{GVC}PureBack$ (i.e. **VS**) measures the portion that is related to backward GVC connections.

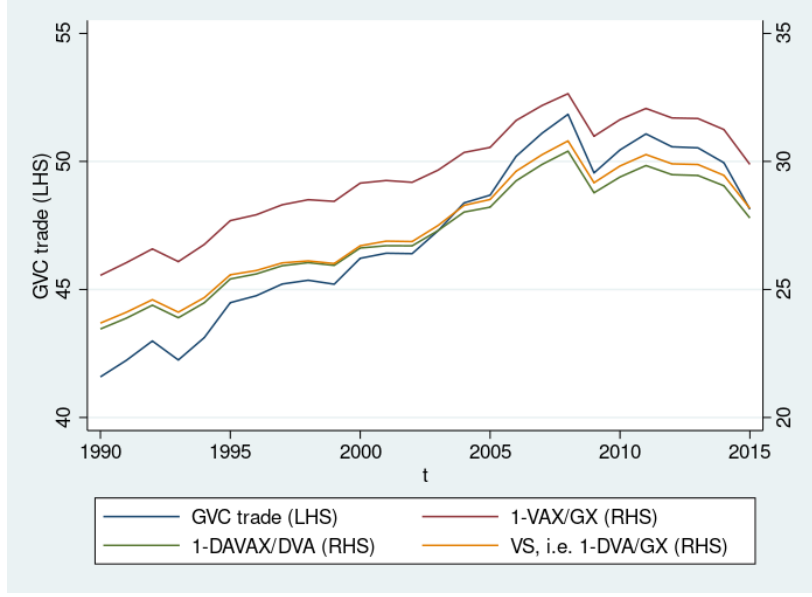
Finally, other studies have measured a country’s GVC-trade participation by identifying the export components that are later re-exported by the direct importer, as we propose here (see, among others, Rahman and Zhao, 2013; Cappariello and Felettigh, 2015; Ahmed et al., 2017; Altomonte et al., 2018). However, these contributions rely on the decomposition of gross exports of Koopman et al. (2014) or, alternatively, on that of Wang et al. (2013). The problem, discussed in detail in Borin and Mancini (2019), is that these methodologies do not properly allocate countries’ exports between the share that is directly absorbed by importers and the one that is re-exported abroad. Thus, the resulting measures of GVC participation are also imprecise.

In some cases the complement of the Johnson and Noguera (2012) value-added exports to gross exports ratio (**VAX**) has been interpreted as a measure of the share of trade involved in GVCs (see the red line in Figure 3). Although the change over time of this indicator tends to be closely related to the variation in international fragmentation of production —especially at the world level, see Johnson and Noguera (2017)— in level terms, it underestimates to a quite large extent the weight of GVCs in trade. As compared to the GVC-related trade index of equation (4), the underestimation is given by the difference between **VAX** and **DAVAX** divided by gross exports, as shown also in

¹⁴Indicators of relative upstreamness/downstreamness in GVCs have been proposed by Fally, 2012; Antràs et al., 2012; Wang et al., 2017, among others. See Antràs and Chor (2019) for a comprehensive discussion.

¹⁵The \mathbf{VS}_s index does not vary with the number of borders crossed by a certain item before being imported by country s . In other words, the relative ‘downstreamness’ of country s does not influence the \mathbf{VS}_s indicator in the same way as its relative ‘upstreamness’ influences the $\mathbf{VS1}_s$ indicator in the formulation of Koopman et al. (2014).

Figure 3: Comparison among different GVC measures.



Antràs and Chor (2021).¹⁶

3.2 Regional GVC-related trade

The total GVC-related trade as reported in equation (14) can be broken down to distinguish between intra-regional and extra-regional value chain participation. The same holds for its sub-components, i.e. pure forward, pure backward and two-sided participation in equations (7), (11) and (13).

Given a country s , member of a region K , intra-regional value-chain participation, $\mathbf{IRVC}_{s,K}$ for each exporting sector n is defined as the sum of the import content of inputs sourced directly from a regional member that are exported to final markets (pure backward) or to partners that re-exports it (two-sided), and domestic value-added re-exported by a regional member (pure forward). In formal terms,

$$\mathbf{IRVCPureBack}_{s,K} = \sum_{t \in K, t \neq s}^G \widehat{\mathbf{u}_N \mathbf{A}_{ts} \mathbf{L}_{ss}} \sum_{r \neq s}^G (\mathbf{Y}_{sr} + \mathbf{A}_{sr} \mathbf{L}_{rr} \mathbf{Y}_{rr}) \quad (21)$$

$$\mathbf{IRVCTwoSide}_{s,K} = \sum_{t \in K, t \neq s}^G \widehat{\mathbf{u}_N \mathbf{A}_{ts} \mathbf{L}_{ss}} \sum_{r \neq s}^G \left(\mathbf{A}_{sr} \mathbf{L}_{rr} \sum_{j \neq r}^G \mathbf{E}_{rj} \right). \quad (22)$$

$$\mathbf{IRVCPureForw}_{s,K} = \widehat{\mathbf{V}_s \mathbf{L}_{ss}} \sum_{r \in K, r \neq s}^G \mathbf{E}_{sr} - \sum_{r \in K, r \neq s}^G \mathbf{DAVAX}_{sr}, \quad (23)$$

Extra-regional value-chain participation with countries outside region K , $\mathbf{ERVC}_{s,K}$, is the difference between the total GVC participation and the intra-regional one:

$$\mathbf{ERVC}_{i_s, K} = \mathbf{GVC}_{i_s} - \mathbf{IRVC}_{i_s, K} \quad (24)$$

¹⁶This comes from the fact that only a subportion of \mathbf{VAX} is not GVC-related, and this is precisely the \mathbf{DAVAX} .

for $i = \text{PureForw}, \text{PureBack}, \text{Interm}$.

4 A more general view on GVC participation

In the previous section we showed how to precisely single out the amount of a sector's gross trade that stems from countries' participation in global production sharing. This allows to assess how import and export dynamics are driven by the evolution of GVCs. Nevertheless, in order to gauge the overall degree of involvement of a specific sector we cannot limit the analysis to trade flows. In some countries the exporting sectors might be deeply integrated in GVCs, but they might account only for a small fraction of the whole economic activity. It was the case, for instance, of China at the beginning of the opening up process in the late '80s and early '90s, when the exporting firms, mainly located in the Special Economic Zones, were highly involved in the international production chains, while the remaining part of the economic activity was still generally domestically oriented. Moreover, regarding the sectoral participation in GVCs, it is necessary to take into account that some industries might be indirectly but heavily involved in international production networks despite their limited export activity (e.g. often services are supplied as inputs to manufacturing sectors that directly participate to GVCs).

A more general assessment of the amount of productions of each sector that is related to GVCs is retrieved taking into account the entire supply chain in which a sector participates to, regardless of its involvement in export activities. Similarly as for the identification of GVC-related trade, we identify three salient moments that matters to define a supply chain, namely the contribution provided by a sector to the production stages at its very beginning, in an intermediate position, and at the very end of it.

Here the emphasis to define the mode of participation is on the sector of production, not on the sector of exports, as in Section 3. Therefore, the activities related to the creation of value-added that will be exported by any sector and then re-exported by the partner are the most purely forward ones, the very first link of a chain. Those related to the assembly of the final goods or services are instead the most purely backward related, as they represents the last link of a chain. Even final goods that are not exported fall into this case, if they are assembled using inputs that have previously crossed at least two borders. In between we find all the activities that encompass both buying and selling of inputs, therefore representing an intermediate type of participation, not purely forward nor backward but two-sided.

In the following sections we define three indices of GVC participation based on the framework provided above. In Section 4.1 we present the GVC-related value-added, a measure of purely forward engagement in GVC, traced in the sector of its origin. In Section 4.2 we compute the GVC-related final goods and services, a measure of purely backward participation, traced at the very end of the chain, in the sector of final completion. Finally, in Section 4.3 we provide a comprehensive breakdown of total output, showing how to trace not only GVC-related value-added and final goods and services – the origin and the end of the chain – but also a more central mode of participation, consisting of all the inputs that are bought and sold by a sector in the intermediate links of the global supply chain. It turns out that this intermediate mode of participation, overlooked by the literature, is by far the most relevant in the data.

4.1 GVC-related value-added

The portion of value-added related to GVC corresponds to value-added originated in a specific sector, exported directly or after further domestic processing stages, *and* re-exported by the bilateral partner. This mode of participation is purely forward, as goods and services are sold onwards from the origin. It is obtained subtracting from total value-added of a sector the portion that is never exported and the one that cross just one border, following Borin and Mancini (2015) and Wang et al. (2017), i.e.

$$\mathbf{GVC}_s^{VA} = \widehat{\mathbf{V}}_s \sum_{j,k}^G \mathbf{B}_{sj} \mathbf{Y}_{jk} - \widehat{\mathbf{V}}_s \mathbf{L}_{ss} \left[\mathbf{Y}_{ss} + \sum_{r \neq s}^G \mathbf{Y}_{sr} + \sum_{r \neq s}^G \mathbf{A}_{sr} \mathbf{L}_{rr} \mathbf{Y}_{rr} \right] \quad (25)$$

It should be noted that at the country level this is precisely the GVC-related trade forward participation in equation (7), since $\mathbf{V}_s \sum_{j,k}^G \mathbf{B}_{sj} \mathbf{Y}_{jk} - \mathbf{V}_s \mathbf{L}_{ss} \mathbf{Y}_{ss} = \mathbf{V}_s \mathbf{L}_{ss} \sum_{r \neq s}^G \mathbf{E}_{sr}$.¹⁷ Instead, at the sectoral level GVC-forward participation in exports and GVC-related value-added do differ. The former traces the engagement in GVC activities of a particular exporting sector, which might not be the origin of the value-added. Instead, the latter looks at the direct and *indirect* connections with international production networks of the sector that is the origin of the value-added and might not even export at all.

At the country level, summing across the n sectors, the share of value-added related to GVC activities is

$$GVCX_s^{VA} = \frac{\mathbf{u}_N \mathbf{GVC}_s^{VA}}{\mathbf{u}_N \mathbf{VA}_s} = \frac{\mathbf{GVC}PureForw_s}{\mathbf{u}_N \mathbf{VA}_s}, \quad (26)$$

while at the world level

$$GVCX^{VA} = \frac{\mathbf{u}_N \sum_s^G \mathbf{GVC}_s^{VA}}{\mathbf{u}_N \sum_s^G \mathbf{VA}_s} = \frac{\mathbf{u}_N \sum_s^G \mathbf{GVC}PureForw_s}{\mathbf{u}_N \sum_s^G \mathbf{VA}_s}, \quad (27)$$

It should be noted that at the global level, while the overall GVC-related trade ($GVCX$ in equation 6) takes into account also the length and the complexity of the GVCs, GVC-related value-added does not. In fact, when the same item (i.e. value added component) is re-exported many times along the value chain by different countries, the GVC share of gross trade will automatically increase as compared to the non-GVC portion. Instead, the GVC-related value-added indicator is not directly affected by the fact that a certain item crosses just two or many borders.

4.2 GVC-related final goods production

Following the usual rationale, we consider as GVC-related those final goods and services productions that crossed at least two borders, as in Wang et al. (2017). This is traced in the sector that completes the final goods and services, as it is the very last link of a chain, purely backward integrated. Operationally, we need to subtract from total final goods production what is imported by the bilateral partner and absorbed in the domestic economy and what is produced only exploiting domestic value

¹⁷In other words, domestic value-added in exports, which is given by the GVC pure forward participation and the traditional trade, is equal to the total domestic value-added minus the domestic value-added in final goods that has never crossed a single border.

chains, before being absorbed by the domestic or foreign demand:

$$\mathbf{GVC}_s^Y = \sum_z^G \mathbf{Y}_{sz} - \sum_{j \neq s}^G \widehat{\mathbf{V}_j \mathbf{L}_{jj} \mathbf{A}_{js} \mathbf{L}_{ss}} \mathbf{Y}_{ss} - \widehat{\mathbf{V}_s \mathbf{L}_{ss}} \sum_z^G \mathbf{Y}_{sz} \quad (28)$$

Again, at the country level, summing across the n sectors, the share of final goods related to GVC activities is

$$\mathbf{GVCX}_s^Y = \frac{\mathbf{u}_N \mathbf{GVC}_s^Y}{\sum_z^G \mathbf{u}_N \mathbf{Y}_{sz}}, \quad (29)$$

while at the world level

$$\mathbf{GVCX}^Y = \frac{\mathbf{u}_N \sum_s^G \mathbf{GVC}_s^Y}{\mathbf{u}_N \sum_{s,z}^G \mathbf{Y}_{sz}}, \quad (30)$$

Obviously, at the global level, summing across countries and sectors, final goods production related to GVC is equal to the value-added related to GVC activities:

$$\sum_s^G \mathbf{u}_N \mathbf{GVC}_s^{VA} = \sum_s^G \mathbf{u}_N \mathbf{GVC}_s^Y. \quad (31)$$

In the next Section we show that this property can be exploited to obtain an index of the degree of relative participation in GVC-output.

4.3 GVC-related output

We now develop a more comprehensive framework to trace different modes of GVC participation within output, taking the view of a sector of production. We show that this encompasses the GVC activities traced in value-added and final goods, but also all the exchanges of inputs within the intermediates stages of production that are related to GVCs. This is crucial since GVC-related value-added and final goods provide just a partial representation of countries' and sectors' engagement in GVCs. The former looks only at purely forward linkages, traced in the very first link of a chain, i.e. the sector of origin of the value-added. The latter considers only purely backward linkages, measured in the very last link of a chain, i.e. the sector of completion of final goods and services. At the end of the section we will discuss the advantages of assessing GVC participation considering the entire chain.

Following the same rationale as in the case of GVC participation traced in trade flows we define as GVC-related the output of a sector that crosses more than one border.

First, we decompose the total output of a specific sector in terms of *i*) imported intermediates, *ii*) domestic intermediates and *iii*) value added:

$$\mathbf{X}_s = \sum_j^G \widehat{\mathbf{V}_j \mathbf{L}_{jj} \sum_{k \neq j}^G \mathbf{A}_{jk} \mathbf{B}_{ks}} \mathbf{X}_s + \widehat{\mathbf{V}_s \mathbf{L}_{ss} \mathbf{A}_{ss}} \mathbf{X}_s + \widehat{\mathbf{V}_s} \mathbf{X}_s \quad (32)$$

Then, we trace in each one of the terms above the share that is related to GVC activities, i.e. that crosses at least two borders.

Starting from imported inputs, we note that only those coming directly from the partner – bought by country s sector n directly from abroad or indirectly, from other domestic sectors after many processing stages within the domestic value chain – and not re-exported cannot be considered as related to GVC. The reason is that only these imported inputs cross just one border. The rest, directly or indirectly bought by the sector through domestic and foreign value chains, crosses at least two borders, either before the domestic absorption or considering also their re-export. Thus, GVC-related imported inputs is

$$\mathbf{GVC}_s^{ImpInp} = \sum_j^G \overbrace{\mathbf{V}_j \mathbf{L}_{jj} \sum_{k \neq j}^G \mathbf{A}_{jk} \mathbf{B}_{ks} \mathbf{X}_s} - \sum_{j \neq s}^G \overbrace{\mathbf{V}_j \mathbf{L}_{jj} \mathbf{A}_{js} \mathbf{L}_{ss} \mathbf{L}_{ss} \mathbf{Y}_{ss}} \quad (33)$$

It should be noted that the only portion of GVC imported inputs not sold to other sectors, i.e. at the end of the chain, is the one purchased by the sector of completion of the final good. Indeed, this is the only share of total output that is purely related to backward participation in GVC. In other words, it represents the very last link of a chain, since it encompasses *i*) the inputs that have crossed more than one border that are embedded in final goods and services produced in country s by the sector and absorbed in s itself; and *ii*) the inputs that have crossed one border and are embedded in final goods and services produced in s by the sector and exported by the same sector to the final market. Therefore, starting from (33), pure backward GVC related-output is obtained substituting final production to output in the two terms:

$$\mathbf{GVC}^{PureBack}_s^X = \sum_j^G \overbrace{\mathbf{V}_j \mathbf{L}_{jj} \sum_{k \neq j}^G \mathbf{A}_{jk} \mathbf{B}_{ks}} \sum_z^G \mathbf{Y}_{sz} - \sum_{j \neq s}^G \overbrace{\mathbf{V}_j \mathbf{L}_{jj} \mathbf{A}_{js} \mathbf{L}_{ss} \mathbf{Y}_{ss}} \quad (34)$$

Despite the different formulation, $\mathbf{GVC}^{PureBack}_s^X$ is equal to GVC-related final goods production, i.e. \mathbf{GVC}_s^Y reported in equation (28).¹⁸

Lastly, the part of GVC-related imported inputs that is not pure backward participation might be considered as an intermediate type of participation in GVCs, i.e. two-sided, as imported inputs are bought directly or indirectly by the sector (backward) but are sold to other sectors (forward):

$$\mathbf{GVC}^{TwoSide}_s^{ImpInp} = \mathbf{GVC}_s^{ImpInp} - \mathbf{GVC}^{PureBack}_s^X \quad (35)$$

The same strategy to compute GVC-related output might be applied to the second component, i.e. domestic inputs. These inputs originate in country s and are bought directly or indirectly through domestic chains by the sector ($\overbrace{\mathbf{V}_s \mathbf{L}_{ss} \mathbf{A}_{ss} \mathbf{X}_s}$). We can focus on just two sub-components of domestic inputs, namely domestic inputs sold to other countries by the sector ($\sum_{r \neq s}^G \mathbf{A}_{sr} \mathbf{X}_r$) and domestic inputs sold to other domestic sectors and embedded in exports later on ($\sum_{r \neq s}^G \mathbf{A}_{ss} \mathbf{L}_{ss} \mathbf{A}_{sr} \mathbf{X}_r$). To encompass GVC participation, we need to be sure that inputs are further re-exported by the bilateral partner, thus crossing at least two borders. This can be achieved substituting total gross output of country r , \mathbf{X}_r , with the total gross output of r that is re-exported, or, in other terms, not directly absorbed, $\mathbf{X}_r^{exp} = \mathbf{X}_r - \mathbf{L}_{rr} \mathbf{Y}_{rr}$. It should also be noted that GVC-related domestic inputs embraces both backward and forward inter-linkages. In fact, these inputs are bought within domestic chains (backward component) but also sold to other domestic sectors or directly exported

¹⁸Proof available upon request.

(forward component). Therefore, GVC-related domestic inputs represents an intermediate mode of GVC participation:

$$\mathbf{GVCTwoSide}_s^{DomInp} = \widehat{\mathbf{V}}_s \mathbf{L}_{ss} \mathbf{A}_{ss} \sum_{r \neq s}^G (\mathbf{A}_{sr} \mathbf{X}_r^{exp} + \mathbf{A}_{ss} \mathbf{L}_{ss} \mathbf{A}_{sr} \mathbf{X}_r^{exp}) \quad (36)$$

Finally, we consider the last component of output, i.e. value-added, and trace the part of it related to GVC following the same rationale applied to domestic inputs. The only difference is that the sector producing value-added identifies the very first link of a supply chains, i.e. it's actual origin. Thus, it might be considered as a measure of pure forward participation in GVCs:

$$\mathbf{GVCPureForw}_s^X = \widehat{\mathbf{V}}_s \sum_{r \neq s}^G (\mathbf{A}_{sr} \mathbf{X}_r^{exp} + \mathbf{A}_{ss} \mathbf{L}_{ss} \mathbf{A}_{sr} \mathbf{X}_r^{exp}). \quad (37)$$

Not surprisingly, despite the different formulation, GVC pure forward participation measured in output is equal to GVC-related value-added, i.e. \mathbf{GVC}_s^{VA} reported in equation (25).¹⁹

Summing up, as for the GVC-related trade presented in Section 3, GVC-related output can be broken down in three components: pure backward participation, i.e. imported inputs embedded by the sector in final goods; pure forward participation, i.e. value-added sold by the sector of origin abroad or domestically and incorporated in exports later on; domestic inputs and imported inputs not embedded in final goods, i.e. a two-sided type of GVC participation that is simultaneously backward and forward related, since it consists of inputs that are first bought and then sold by the sector:

$$\mathbf{GVC}_s^X = \mathbf{GVCPureBack}_s^X + \mathbf{GVCPureForw}_s^X + \mathbf{GVCTwoSide}_s^X \quad (38)$$

where $\mathbf{GVCTwoSide}_s^X = \mathbf{GVCTwoSide}_s^{ImpInp} + \mathbf{GVCTwoSide}_s^{DomInp}$.

As for the other indices of GVC participation, results at the country level, i.e. summing across the n sectors, might be obtained thanks to the additive property of these measures:

$$GVCX_s^X = \frac{\mathbf{u}_N \mathbf{GVC}_s^X}{\mathbf{u}_N \mathbf{X}_s}, \quad (39)$$

while at the world level

$$GVCX^X = \frac{\mathbf{u}_N \sum_s^G \mathbf{GVC}_s^X}{\mathbf{u}_N \sum_s^G \mathbf{X}_s}, \quad (40)$$

Analogously, \mathbf{GVC}_s^X sub-indices can be aggregated to national and global level:

$$GVCiX_s^X = \frac{\mathbf{u}_N \mathbf{GVC}_s^X}{\mathbf{u}_N \mathbf{X}_s}, \quad (41)$$

while at the world level

$$GVCiX^{VA} = \frac{\mathbf{u}_N \sum_s^G \mathbf{GVC}_s^X}{\mathbf{u}_N \sum_s^G \mathbf{X}_s}, \quad (42)$$

where $i = PureForw, TwoSide, PureBack$.

In addition, the value of output that never crosses a border, i.e. purely domestic, is obtained

¹⁹Proof available upon request.

as the sum of the domestic inputs and value-added that are not exported at all:

$$\mathbf{Dom}_s^X = \widehat{\mathbf{V}_s \mathbf{L}_{ss} \mathbf{A}_{ss} \mathbf{L}_{ss}} \mathbf{Y}_{ss} + \widehat{\mathbf{V}_s \mathbf{L}_{ss}} \mathbf{Y}_{ss}. \quad (43)$$

Finally, output related to traditional trade, i.e. crossing only one border before being absorbed by final demand, can be computed as:

$$\mathbf{Trad}_s^X = \mathbf{X}_s - \mathbf{Dom}_s^X - \mathbf{GVC}_s^X. \quad (44)$$

As for the indicator of ‘GVC-related trade’, at the global level, i.e. summing across all countries, the ‘GVC pure-backward-related output’ will be equal to the ‘GVC pure-forward-related output’:

$$\sum_s^G \mathbf{GVCPureForw}_s = \sum_s^G \mathbf{GVCPureBack}_s. \quad (45)$$

Therefore, a natural measure of the type of participation in output of countries and sectors in GVC can be straightforwardly obtained as

$$\mathbf{P}_s^X = (\mathbf{GVCPureForw}_s^X - \mathbf{GVCPureBack}_s^X) \oslash \mathbf{GVC}_s^X. \quad (46)$$

The vector \mathbf{P}_s^X measures the ‘forwardness’ of the n sectors in country s in terms of their total output, and is bounded between -1 and 1. At the country level, summing across the sectors, we have

$$P_s^X = \frac{\mathbf{u}_N \mathbf{GVCPureForw}_s - \mathbf{u}_N \mathbf{GVCPureBack}_s}{\mathbf{u}_N \mathbf{GVC}_s}. \quad (47)$$

In addition, it is equal to 0 at the aggregate level, given the relation in equation (45).

It should be clear now why \mathbf{GVC}^X is a much more general indicator with respect to $\mathbf{GVC}^Y = \mathbf{GVCPureBack}^X$ and $\mathbf{GVC}^{VA} = \mathbf{GVCPureForw}^X$. Not considering as part of the GVC participation the inputs exchanged in the intermediate stages of a production chain leads to largely understate the actual engagement in GVCs of countries and sectors. In fact, the total value of the inputs sold and bought during the intermediate stages of global supply chains represents more than half of the total output related to GVCs, as shown in Section 5.

Another drawback of relying only on \mathbf{GVC}^{VA} or \mathbf{GVC}^Y is the inaccurate mode of GVC participation that can be inferred from them *once they are expressed as a share of total value-added and total final goods and services production*, respectively, as in Wang et al. (2017). Suppose, for instance, that a sector produces only final goods (total value of 100), with imported inputs related to GVCs (75), adding a very small amount of value-added (25), which is in turn completely GVC-related. The share of value-added related to GVCs with respect to total value-added, i.e. \mathbf{GVCX}^{VA} in equation (26), will be equal to 100%, while the share of final goods production related to GVCs with respect to total final goods production, i.e. \mathbf{GVCX}^Y in equation (29), will be 75%. This might lead to the incorrect conclusion that the sector is mostly integrated in GVCs with forward linkages, even if it participates in GVCs especially in the completion of final products, at the end of a chain. Instead, the index of ‘forwardness’ based on GVC-related output, P_s^X , will correctly indicate a higher backward participation compared to forward, i.e. $-0.50 = (25 - 75)/(25 + 75)$. The reason is that

it traces, within the total GVC-output,²⁰ the amount of it that is related to pure backward or pure forward participation, and it does not depend on the scale of value-added or final goods production. In addition, since it is equal to zero at the global level, the actual position of a country or a sector with respect to the average (i.e. zero) is immediately evident.

5 Characterizing countries and sectors participation in GVCs through the new indicators

Using the EORA dataset, which covers the period 1990-2015, and the Asian Development Bank MRIOT database (ADB), which covers the period 2007-2019 we are able to construct a series of GVC participation from 1990 to 2019. These data can inform two types of questions. First, they allow to evaluate the extent to which countries/sectors participate in GVC, or in other words, what part of trade and output are involved in GVC. Secondly they allow to assess how countries and sectors participate in GVCs. The question in this second case is whether a given country-sector is mainly a supplier of inputs or a downstream user.

Taking the view of both the exporting and producing sectors enriches the characterization of GVC involvement and add a layer of complexity that has been overlooked in previous works. Figure 4 and 5 report the quintiles of the distribution of GVC trade (y-axis) and GVC output (x-axis) for manufacturing and services respectively. The bivariate distributions at the country-sector level are quite disperse, meaning that GVC Output and GVC trade does not fully overlap in terms of information content. However, the information content of GVC output seems to be richer than the one provided by GVC-trade (Table 1), as the coefficient of variation of the former is 3 to 4 times larger than the one of the latter. This holds across sectors at the global level, across countries, and across country-sector.

Figure 4: Bivariate density plot of GVC Output and GVC trade, manufacturing, EORA 2015.

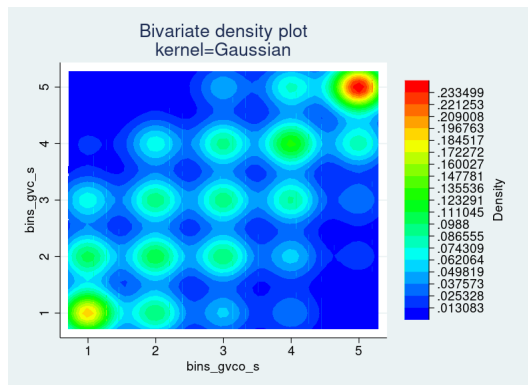
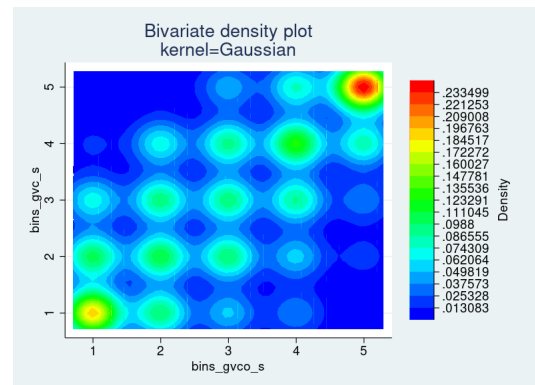


Figure 5: Bivariate density plot of GVC Output and GVC trade, services, EORA 2015.



5.1 What part of a country's trade and output are involved in GVCs?

GVC output is important. Looking only at GVC trade understates the actual extent of GVCs by around 10 trillion USD, as GVC trade amounts to about 5 trillions USD while GVC output amounts to about 15 trillions USD (Figures 6 and 7).

²⁰In this simplified example we considered a sector producing only final goods, thus GVC-related output and GVC-related final goods obviously coincide. However, its conclusions are valid also in more general cases.

Table 1: GVC Output and GVC trade coefficients of variation across ICIO sources in 2014.

		Inter-Country Input Output Table			
Coefficient of variation		ADB-MRIO	EORA	OECD-TIVA	WIOD
Sector	GVC-trade	0.24	0.23	0.34	0.26
	GVC-output	0.72	0.67	0.78	0.67
	<i>Ratio</i>	2.99	2.93	2.33	2.63
Country	GVC-trade	0.23	0.24	0.25	0.22
	GVC-output	0.84	0.70	0.95	0.91
	<i>Ratio</i>	3.61	2.87	3.74	4.07
Country-sector	GVC-trade	0.35	0.30	0.43	0.39
	GVC-output	1.38	1.09	1.45	1.52
	<i>Ratio</i>	3.89	3.58	3.40	3.92

Intermediate, or two-sided, participation is the most relevant component of GVC output, accounting for more than 60% of the total GVC participation. Considering only GVC output pure forward (GVC in value added) or pure backward (GVC in final goods) understates the actual extent of GVC participation. The two-sided or mixed participation is less relevant in GVC trade. This is explained by the fact that most exporting sectors and firms engage at the end or at the beginning of the chains. Instead, most producing sectors (GVC output) are characterized by two-sided exposure - import to export or sourcing to sell (see Figures 8-9).

Figure 6: GVC Output Participation, USD

Figure 7: GVC Trade Participation, USD

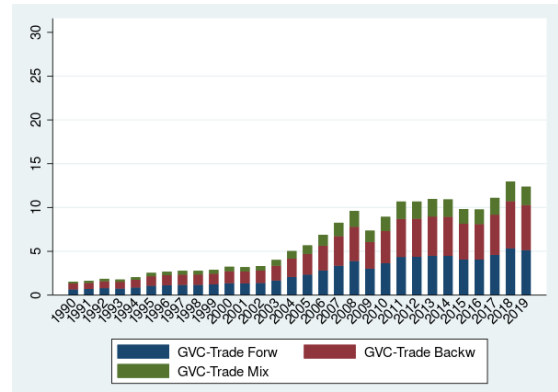
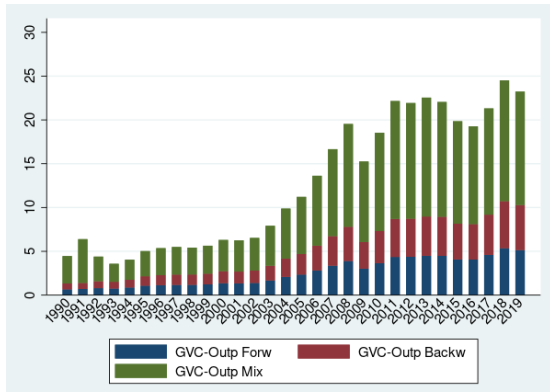
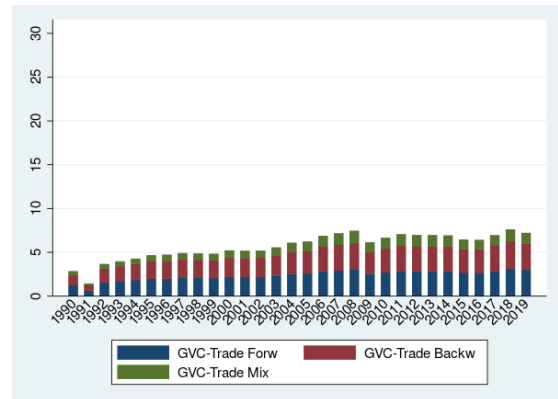
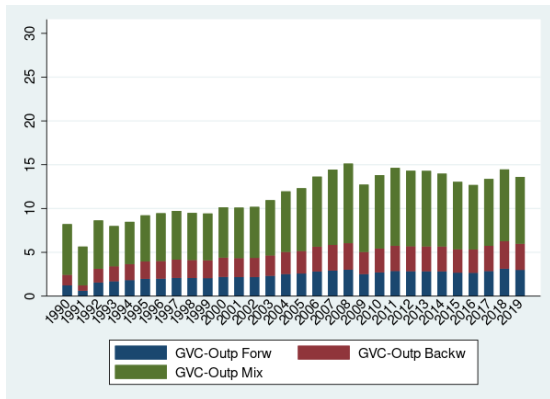


Figure 8: GVC Output Participation, as share of total output

Figure 9: GVC Trade Participation, as a share of total output



This evidence is valid not only at the global level, but also at the country-sector level, as shown in Figure 10 and Figure 11, which report the distribution of the different participation modes divided by the total GVC participation. For more than 60% of country-sector pairs the intermediate

mode of GVC output participation is the prevalent one, while one third of country-sector pairs has a two-sided participation accounting for more that two thirds of their total GVC participation.

Figure 10: Distribution of GVC output participation modes over total GVC output, WIOD 2014.

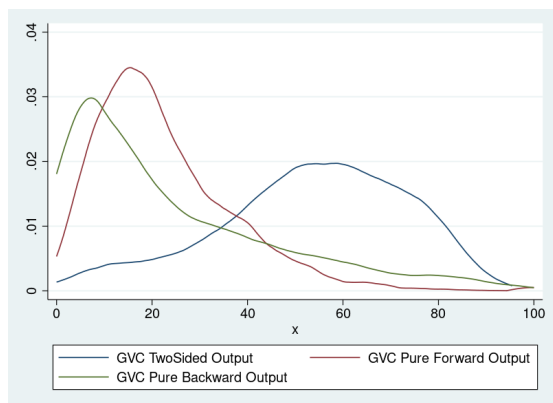
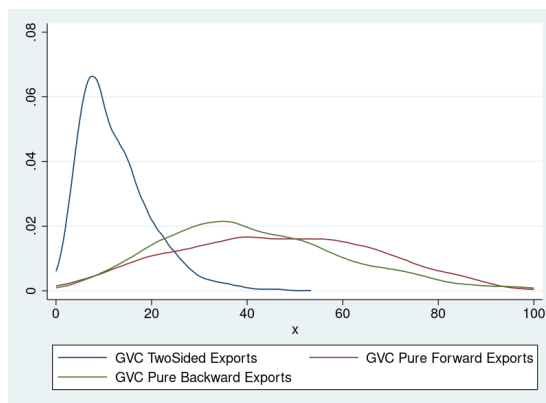


Figure 11: Distribution of GVC exports participation modes over total GVC exports, WIOD 2014.



From the point of view of sectors, services participation in GVC is negligible when we look at the share of GVC-trade over output. It is noticeably larger when participation is measured from the viewpoint of GVC output. The reason is that services sectors do not export directly but exploit domestic chains to export indirectly, and when one looks at export only their contribution ends up recorded as exports of a downstream using sector. Meanwhile about one quarter of all manufacturing output is connected to GVC trade (see Figure 12 and Figure 13).

Figure 12: GVC Output Participation in Manufacturing and Services, as share of total output. EORA and ADB MRIO.

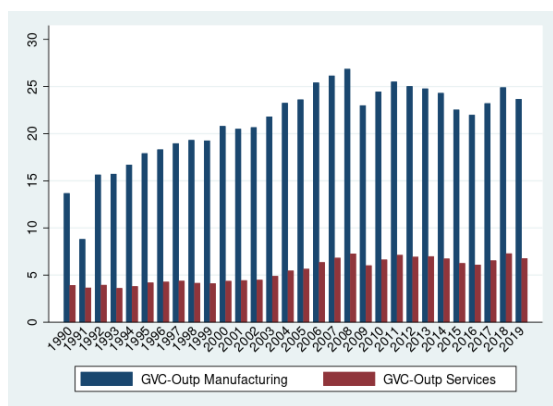
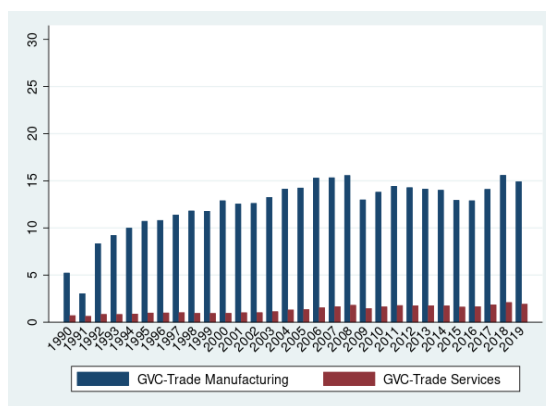


Figure 13: GVC Trade Participation Manufacturing and Services, as a share of total output. EORA and ADB MRIO.



At the country level GVC trade and output are clearly correlated, but the country rank is different. Each dot in Figure 14 and Figure 15 is a country among the 30 countries worldwide with the highest real GDP. We highlight those countries whose rank moves by at least 25 positions when we compare GVC output to GVC trade participation. For example, in the left hand panel Germany is ranked 22nd in terms of GVC output participation but 53rd in terms of GVC trade participation, out of a total of 189 countries reported in the EORA dataset.

Figure 14: GVC Output Participation vs Trade Participation in Manufacturing, EORA 2015.

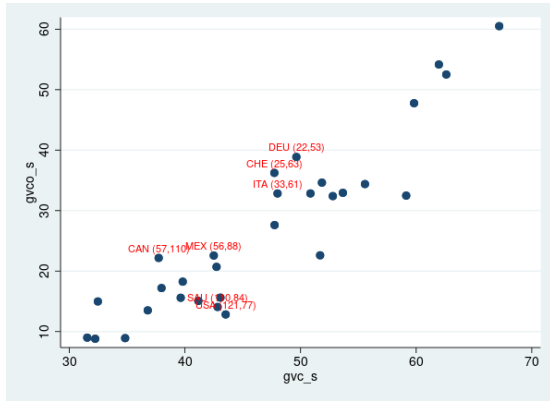
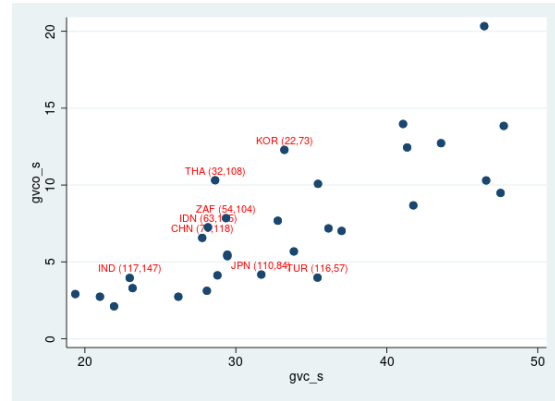


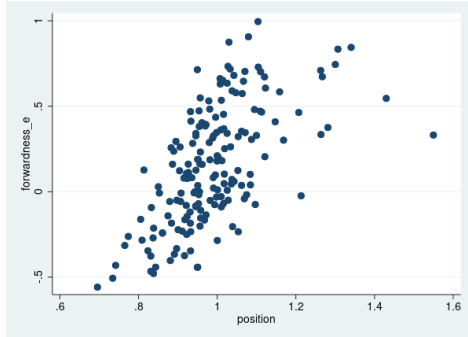
Figure 15: GVC Output Participation vs Trade Participation in Services, EORA 2015.



5.2 Supplier or user of intermediate inputs?

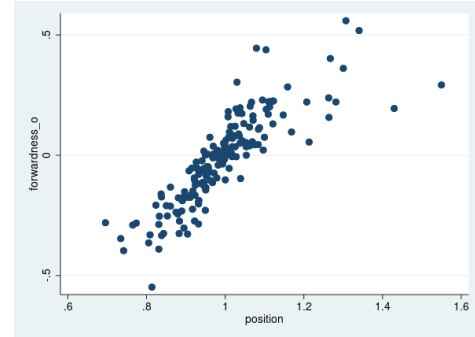
The indices of forwardness discussed in Section 3 and Section 4 are useful to assess the type of engagement of countries in GVCs. Indeed, they are also correlated with relative position, computed as the ratio of upstreamness and downstreamness (see Antràs and Chor, 2019 and Wang et al., 2017). Figure 16 and Figure 17 show that correlation is higher for forwardness in output, more in line with the standard measures of positioning.

Figure 16: Forwardness in exports vs position, EORA 2015.



Position is computed as the ratio of upstreamness and downstreamness.

Figure 17: Forwardness in output vs position, EORA 2015.



Position is computed as the ratio of upstreamness and downstreamness.

6 Proof of concept: using the new GVC participation indicators to assess exposure to direct and indirect demand and supply shocks

One of the main economic reasons why GVCs are important is the exposure of countries and sectors to external shocks. In particular, sourcing input from abroad (backward participation) may expose productions to upstream supply shocks, while being a supplier of inputs for further transformation (forward participation) may expose countries and sectors to indirect downstream demand shocks. By the same token, two-way participation may increase the sensitivity to both upstream and downstream

shocks.

We conduct an empirical exercise to prove that our measures of GVC participation are essential to assess country/sector exposure to shocks. First, we isolate demand and supply shocks exogenous to the specific country-sector pair; then, we regress output variations at country-sector level on these shocks and on an interaction of the shocks with the indicators of different types of GVC participation.

We identify demand innovations directly from global I-O tables by means of a shift-share instrument approach as proposed by Ferrari (2021). The idea is to construct a country-sector specific demand shock as a weighted average of destination-specific aggregate changes. The latter can be estimated using a fixed effect model (Ferrari 2021, Kramarz et al. 2016 and Alfaro et al. 2019).

The fixed effects model used to estimate demand innovations can be specified as follows:

$$\Delta y_{ij,t}^r = \eta_{j,t} + \gamma_{i,t}^r + \nu_{ij,t}^r \quad i \neq j. \quad (48)$$

where y_{ij}^r is the (log of) final sales of goods and services of sector r shipped from i to j ; $\eta_{j,t}$ is the country-time demand innovation; $\gamma_{i,t}^r$ is the exporting country-sector-time fixed effect; $\nu_{ij,t}^r$ is the error term.²¹ The estimation is carried out excluding country i from the sample when computing the jt demand innovation that might affect it, to reduce concerns of endogeneity.

We can use the destination-specific demand innovations to build a producer-specific shock by measuring the potential exposure to final demand variations. In particular, for our purpose we should distinguish between two different types of shocks: i) 'the direct demand shock' that is related to the sales of final products of a given country-sector pair; ii) 'the indirect demand shock' which is related to the sales of intermediate products. The latter is the one that should be associated with the integration in GVC (in particular 'forward' or 'two sided' participation), whereas the former should be common also to traditional trade and purely domestic productions.

Using the shift-share approach the direct demand shock can be constructed as:

$$f_{i,t}^r = \sum_j^G \phi_{ij,t-1}^r \eta_{j,t}. \quad (49)$$

where $\phi_{ij,t}^r$ is the share of foreign market j in the final sales of country s in sector r :²²

$$\phi_{ij,t}^r = \frac{y_{ij}^r}{\sum_j^G y_{ij}^r}. \quad (50)$$

Similarly we can build an indirect demand shock as:

$$h_{i,t}^r = \sum_j^G \psi_{ij,t-1}^r \eta_{j,t} \quad (51)$$

where $\psi_{ij,t-1}^r$ measures the exposure of sales of intermediates in sector r that are exported by

²¹Results throughout the paper are robust to the inclusion of different sets of fixed effects in the estimation of demand innovations.

²²Note that $\phi_{ii,t}^r = 0$.

country s and consumed in country j , excluding those that are directly embedded in final goods sales:

$$\psi_{ij,t}^r = \frac{\sum_k^G \sum_s^N b_{ik}^{rs} y_{kj}^s - l_{ii}^{rs} y_{ij}^s}{\sum_j^G \sum_k^G \sum_s^N b_{ik}^{rs} y_{kj}^s - l_{ii}^{rs} y_{ij}^s}. \quad (52)$$

We can follow a similar approach also for upstream supply shocks. In this case we can focus on common-worldwide sectoral innovations:

$$\Delta va_{ij,t}^{sr} = \theta_t^s + \gamma_{j,t}^r + \epsilon_{ij,t}^r \quad s \neq r. \quad (53)$$

where $va_{ij,t}^{sr} = v_{i,t}^s z_{ij,t}^{sr}$ is the value-added content of the inputs sold by country-sector (i, s) to the country-sector (j, r) , considering only sales to different sectors to reduce endogeneity concerns, i.e. $va_{ij,t}^{sr} = 0$ for each $s = r$, and θ_t^s are the supply side innovations common to all sector s productions across different countries and $\gamma_{j,t}^r$ are country-sector-time fixed effects.

We can construct an upstream supply shock by resorting to the same shift-share approach presented above. A given sector-country pair (i, r) is exposed to a shock originated in the upstream phases of the production process that can be computed as follows:

$$u_{i,t}^r = \sum_s^N \omega_{i,t-1}^{sr} \theta_t^s. \quad (54)$$

where $\omega_{i,t-1}^{sr}$ is the weight of the sector of origin s in the inputs used for the production of industry r in country i . It can be computed as:

$$\omega_{i,t}^{sr} = \frac{\sum_{j \neq i}^G w_{jt}^{sr}}{\sum_j^G \sum_s^N w_{jt}^{sr}}. \quad (55)$$

where w_{jt}^{sr} is the js, ir element of the $GN \times GN$ matrix $\widehat{\mathbf{V}}\mathbf{B}\widehat{\mathbf{X}}$.

Lastly, we notice that when $j = i$ the unweighted demand innovation, η_{jt} might be considered as a purely direct domestic demand shock for country i . In the same fashion, when $s = r$ the unweighted supply innovation, θ_{st} , might act as supply shock for sector r .

Having constructed the exogenous shocks, we first check whether they are correlated with changes in output for producing country i -sector r pair.²³ Thus, we estimate the following regression model

$$\Delta x_{i,t}^r = \alpha + \beta_1 u_{i,t}^r + \beta_2 h_{i,t}^r + \beta_3 f_{i,t}^r + \epsilon_{i,t}^r. \quad (56)$$

where $\Delta x_{i,t}^r$ is the (log)change of gross output at the country i -sector r level in t . The indirect demand $h_{i,t}^r$ and supply shocks $u_{i,t}^r$ do affect the (log)change of gross output at the country-sector level in a given year t , as shown in Table 2. Together with the direct demand shock $f_{i,t}^r$, they explain around 35% of the total variation in output (column 2). This result holds even after controlling for domestic shocks, sectoral shocks and a full set of country-sector and year fixed effects, as reported in

²³In the rest of the section, all the data are winsorized at the 1% and 99% level of the corresponding sectoral distribution. Results are robust to alternative winsorizing thresholds and to no winsorization at all. They are available upon request.

column 5.²⁴

We can now test whether different type of GVC participation can affect country-sector exposure to external shocks, augmenting the regression model in equation 56 with interaction terms between the different shocks and the corresponding level of engagement in GVC-related output at the country-sector level

$$\begin{aligned}
\Delta x_{i,t}^r = & \alpha + \beta_1 u_{i,t}^r + \beta_2 h_{i,t}^r + \beta_3 f_{i,t}^r + \\
& + \beta_4 \mathbf{GVC}PureBack_{i,t-1}^r + \beta_5 \mathbf{GVC}PureForw_{i,t-1}^r + \beta_6 \mathbf{GVCTwoSide}_{i,t-1}^r + \\
& + \beta_7 u_{i,t}^r \times \mathbf{GVC}PureBack_{i,t-1}^r + \beta_8 h_{i,t}^r \times \mathbf{GVC}PureForw_{i,t-1}^r + \\
& + \beta_9 u_{i,t}^r \mathbf{GVCTwoSide}_{i,t-1}^r + \beta_{10} h_{i,t}^r \mathbf{GVCTwoSide}_{i,t-1}^r + \delta_t + \gamma_i^r + \epsilon_{i,t}^r. \quad (57)
\end{aligned}$$

Results reported in Table 3 show that estimated coefficients related to interaction terms (i.e. $\beta_7, \beta_8, \beta_9$ and β_{10} of equation (57)) are all positive and statistically significant. This confirms that higher forward (backward) participation in GVC is associated with a larger exposure to demand (supply) shocks originating downstream (upstream) the production chain (Table 3). In addition, the positive coefficient of the mixed mode of GVC-participation interacted with both indirect demand and supply shocks, indicates that country and sectors more engaged in the intermediate stages of GVCs are exposed to both shocks.

This result holds also substituting GVC-output measures with GVC-trade (Table 4), with deflated output changes and real shocks (Table 5, column 1-2), using the long-run version of WIOD, from 1965 to 2000 (Table 5, column 3-4).

The empirical analysis of the paper brings new insights to a rapidly growing academic literature that investigates how shocks propagate along production networks. This literature concludes that many factors, including the nature of the shock (Carvalho and Tahbaz-Salehi, 2019), the position in GVCs (Ferrari, 2021), the level of substitutability of inputs (Barrot and Sauvagnat 2016; Baqaee and Farhi 2019), and many more concur to determine to which extent countries and sectors are exposed to shocks through their participation to national and global supply networks. This paper brings an important addition to this literature. It shows that there is a high degree of interdependence in GVC participation. As a result, disentangling the various factors identified in the above literature may be not an easy feat. All in all, the indicators developed in this paper represent a valuable tool to investigate further the various dimensions of exposure.

²⁴As shown in Figure 18 in the Appendix, the average correlation between upstream supply shocks and downstream demand shocks is around 0.2 across time. As expected, the correlation between direct demand shocks and downstream demand shocks is higher, on average around 0.5.

Table 2: WIOD GVC-Output

	(1)	(2)	(3)	(4)	(5)
	Δ Out	Δ Out	Δ Out	Δ Out	Δ Out
f	0.055*** (0.020)	0.079*** (0.020)	0.075*** (0.018)	0.072*** (0.018)	0.064*** (0.018)
h	0.754*** (0.021)	0.319*** (0.029)	0.147*** (0.027)	0.167*** (0.027)	0.251*** (0.044)
u		0.330*** (0.016)	0.146*** (0.015)	0.065*** (0.017)	0.304*** (0.050)
Domestic shock			0.326*** (0.008)	0.323*** (0.008)	0.282*** (0.008)
Sectoral shock				0.075*** (0.007)	0.095*** (0.008)
Country-sector FE	No	No	No	No	Yes
Year FE	No	No	No	No	Yes
R2	0.344	0.354	0.414	0.418	0.511
N	31,198	31,198	31,198	31,184	31,181

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: WIOD GVC-Output

	(1)	(2)	(3)	(4)
	Δ Out	Δ Out	Δ Out	Δ Out
f	0.055*** (0.018)	0.035** (0.017)	0.031* (0.017)	0.026 (0.018)
h	0.083* (0.044)	0.120*** (0.043)	0.095** (0.044)	0.146*** (0.047)
u	0.258*** (0.049)	0.210*** (0.048)	0.232*** (0.048)	0.212*** (0.048)
Domestic shock	0.338*** (0.007)	0.338*** (0.007)	0.281*** (0.008)	0.281*** (0.008)
Sectoral shock	0.108*** (0.007)	0.097*** (0.007)	0.095*** (0.007)	0.093*** (0.007)
L.GVC Pure Forw	0.082*** (0.029)	0.074** (0.035)	0.097*** (0.033)	0.433*** (0.091)
L.GVC Mix	0.018* (0.011)	0.033** (0.015)	0.066*** (0.016)	0.132*** (0.040)
L.GVC Pure Back	-0.034* (0.019)	0.024 (0.027)	0.050** (0.026)	0.094 (0.069)
h \times L.GVC Pure Forw	0.634** (0.275)	0.641** (0.277)	0.742*** (0.277)	0.694** (0.295)
h \times L.GVC Mix	0.610** (0.239)	0.640*** (0.238)	0.626*** (0.236)	0.485* (0.257)
u \times L.GVC Mix	0.275* (0.165)	0.270 (0.166)	0.281* (0.167)	0.440** (0.185)
u \times L.GVC Pure Back	0.317*** (0.107)	0.328*** (0.108)	0.349*** (0.109)	0.387*** (0.107)
Country-sector FE	No	No		Yes
Country FE	No	No	Yes	
Sector FE	No	Yes	Yes	
Year FE	Yes	Yes	Yes	Yes
R2	0.457	0.466	0.488	0.525
N	30,966	30,966	30,966	30,964

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

7 Conclusion

This paper states that measuring exposure to supply and demand shocks, be it domestic or imported, requires characterizing production linkages across and within countries and sectors. The paper shows that measuring GVC participation in country-sector (macro) settings allows to generate important insights about exposure to the full range of potential shocks that a countries and industries face: domestic and foreign, demand and supply, those originating from traditional trade and those originating from GVC linkages. However, traditional measures of GVC participation fall short in two respects. First, the paper shows that the traditional distinction of participation in backward versus forward leads to a false empirical regularity whereby countries are on average more GVC integrated backward than forward. Instead, separating pure backward and forward participation from intermediate activities, in which both sourcing and selling of inputs takes place, is empirically relevant. The resulting two-sided (or mixed) GVC participation is the largest segment of overall GVC output participation. When backward and forward participation are netted out of the intermediate steps, backward and forward participation balance out at the global level. Second, the paper also shows that GVC participation in services and some manufacturing sectors is severely underestimated when taking the viewpoint of the exporting sector. The services industry accounts for 15 percent of total GVC trade, but 30 percent of total GVC output. In dollar terms the shortfall in GVC participation amounts to 8.4 trillion USD and it is due to the fact that many service are not reported as inputs to traded activities in measures based on trade. Such bias is not limited to services. Some goods sectors and some countries are also affected by the same bias.

Correcting for such measurement issues, the paper produces empirical evidence that two-sided participation exposes countries and sectors simultaneously to supply and demand shocks. This is unlike pure backward (forward) linkages, which create exposure only on the supply (demand) side only. Key econometric results of the paper are that deeper GVC integration, as measured by the indicators, simultaneously decreases the exposure to domestic shocks and to shocks related to traditional trade while increasing that to global shocks, and that the majority of countries engage in two-sided GVC participation, making them simultaneously exposed to both demand and supply shocks. Such findings have interesting policy and research implications that future research may want to investigate. First, the paper findings on the importance of two-sided exposure suggest that disruptions may not be easily managed by unilateral policy attempts at forcing a reorganization of buyers-seller relationships. Second, the findings of the paper point to the need to assess exposure to foreign (GVC-related) shocks not in isolation, but relative to exposure to domestic (non-GVC related) shocks, since GVC participation mediates both types of shocks. Finally, the paper offers tools to broaden the assessment of countries and sectors exposure to risks originating from shallower forms of international engagement (traditional trade) and from more geographically concentrated cross-border production (regional value chains).

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A Notation and basic I-O relations

This appendix simply recalls our notation, together with some basic accounting relationships.

We consider the general case of G countries producing N goods that are internationally traded both as intermediate inputs and as final goods. Thus, $\mathbf{X}_s = (x_1^s \ x_2^s \ \cdots \ x_N^s)'$ is the $N \times 1$ vector of the gross output of country s and \mathbf{Y}_s is the $N \times 1$ vector of final goods, which is equal to the final demand for goods produced in s in each country of destination r : $\sum_r^G \mathbf{Y}_{sr}$. To produce one unit of gross output of good i a country uses a certain amount a of intermediate good j produced at home or imported from other countries. Thus, each unit of gross output can be either consumed as a final good or used as an intermediate good at home or abroad:

$$\mathbf{X}_s = \sum_r^G (\mathbf{A}_{sr} \mathbf{X}_r + \mathbf{Y}_{sr})$$

where \mathbf{A}_{sr} is the $N \times N$ matrix of coefficients for intermediate inputs produced in s and processed further in r :

$$\mathbf{A}_{sr} = \begin{bmatrix} a_{sr,11} & a_{sr,12} & \cdots & a_{sr,1N} \\ a_{sr,21} & a_{sr,22} & \cdots & a_{sr,2N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{sr,N1} & a_{sr,N2} & \cdots & a_{sr,NN} \end{bmatrix}$$

Using the block matrix notation, the general setting of production and trade with G countries and N goods can be expressed as follows:

$$\begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \\ \mathbf{X}_G \end{bmatrix}_{(NG \times 1)} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \cdots & \mathbf{A}_{1G} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \cdots & \mathbf{A}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{G1} & \mathbf{A}_{G2} & \cdots & \mathbf{A}_{GG} \end{bmatrix}_{(NG \times NG)} \begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \\ \mathbf{X}_G \end{bmatrix}_{(NG \times 1)} + \begin{bmatrix} \mathbf{Y}_{11} & \mathbf{Y}_{12} & \cdots & \mathbf{Y}_{1G} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} & \cdots & \mathbf{Y}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Y}_{G1} & \mathbf{Y}_{G2} & \cdots & \mathbf{Y}_{GG} \end{bmatrix}_{(NG \times G)} \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{(G \times 1)} \quad (\text{A.1})$$

from which it is straightforward to derive the following relationship between gross output and final demand:

$$\begin{aligned} \begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \\ \mathbf{X}_G \end{bmatrix} &= \begin{bmatrix} \mathbf{I} - \mathbf{A}_{11} & -\mathbf{A}_{12} & \cdots & -\mathbf{A}_{1G} \\ -\mathbf{A}_{21} & \mathbf{I} - \mathbf{A}_{22} & \cdots & -\mathbf{A}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{A}_{G1} & -\mathbf{A}_{G2} & \cdots & \mathbf{I} - \mathbf{A}_{GG} \end{bmatrix}^{-1} \begin{bmatrix} \sum_r^G \mathbf{Y}_{1r} \\ \sum_r^G \mathbf{Y}_{2r} \\ \vdots \\ \sum_r^G \mathbf{Y}_{1G} \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{B}_{11} & \mathbf{B}_{12} & \cdots & \mathbf{B}_{1N} \\ \mathbf{B}_{21} & \mathbf{B}_{22} & \cdots & \mathbf{B}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{B}_{G1} & \mathbf{B}_{G2} & \cdots & \mathbf{B}_{GG} \end{bmatrix} \begin{bmatrix} \sum_r^G \mathbf{Y}_{1r} \\ \sum_r^G \mathbf{Y}_{2r} \\ \vdots \\ \sum_r^G \mathbf{Y}_{1G} \end{bmatrix} \end{aligned} \quad (\text{A.2})$$

where \mathbf{B}_{sr} denotes the $N \times N$ block of the Leontief inverse matrix in a global IO setting. It indicates how much of country s 's gross output of a certain good is required to produce one unit of country r 's final production.

The direct value-added share in each unit of gross output produced by country s is equal to

one minus the sum of the direct intermediate input share of all the domestic and foreign suppliers:

$$\mathbf{V}_s = \mathbf{u}_N \left(\mathbf{I} - \sum_r^G \mathbf{A}_{rs} \right) \quad (\text{A.3})$$

where \mathbf{u}_N is the $1 \times N$ unit row vector. Thus, the $G \times GN$ direct domestic value-added matrix for all countries can be defined as:

$$\mathbf{V} = \begin{bmatrix} \mathbf{V}_1 & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{V}_2 & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{V}_G \end{bmatrix}$$

while the overall $G \times GN$ value-added share matrix is obtained by multiplying the \mathbf{V} matrix by the Leontief inverse \mathbf{B} :

$$\mathbf{VB} = \begin{bmatrix} \mathbf{V}_1 \mathbf{B}_{11} & \mathbf{V}_1 \mathbf{B}_{12} & \cdots & \mathbf{V}_1 \mathbf{B}_{1G} \\ \mathbf{V}_2 \mathbf{B}_{21} & \mathbf{V}_2 \mathbf{B}_{22} & \cdots & \mathbf{V}_2 \mathbf{B}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{V}_G \mathbf{B}_{G1} & \mathbf{V}_G \mathbf{B}_{G2} & \cdots & \mathbf{V}_G \mathbf{B}_{GG} \end{bmatrix}$$

Since the value-added shares of different countries in final goods have to sum to one, the following property holds:

$$\sum_t^G \mathbf{V}_t \mathbf{B}_{tr} = \mathbf{u}_N \quad (\text{A.4})$$

Defining the $GN \times G$ final demand matrix as:

$$\mathbf{Y} = \begin{bmatrix} \mathbf{Y}_{11} & \mathbf{Y}_{12} & \cdots & \mathbf{Y}_{1G} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} & \cdots & \mathbf{Y}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Y}_{G1} & \mathbf{Y}_{G2} & \cdots & \mathbf{Y}_{GG} \end{bmatrix}$$

we can derive the $G \times G$ value-added matrix by pairs of source-absorption countries:

$$\begin{aligned} \overline{\mathbf{VA}} &\equiv \mathbf{VB}\mathbf{Y} = \\ &= \begin{bmatrix} \mathbf{V}_1 \sum_r^G \mathbf{B}_{1r} \mathbf{Y}_{r1} & \mathbf{V}_1 \sum_r^G \mathbf{B}_{1r} \mathbf{Y}_{r2} & \cdots & \mathbf{V}_1 \sum_r^G \mathbf{B}_{1r} \mathbf{Y}_{rG} \\ \mathbf{V}_2 \sum_r^G \mathbf{B}_{2r} \mathbf{Y}_{r2} & \mathbf{V}_2 \sum_r^G \mathbf{B}_{2r} \mathbf{Y}_{r2} & \cdots & \mathbf{V}_2 \sum_r^G \mathbf{B}_{2r} \mathbf{Y}_{rG} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{V}_G \sum_r^G \mathbf{B}_{Gr} \mathbf{Y}_{rG} & \mathbf{V}_G \sum_r^G \mathbf{B}_{Gr} \mathbf{Y}_{rG} & \cdots & \mathbf{V}_G \sum_r^G \mathbf{B}_{Gr} \mathbf{Y}_{rG} \end{bmatrix} \quad (\text{A.5}) \end{aligned}$$

B GVC Database on the World Integrated Trade Solutions

The broad set of measures discussed in the paper is available on the World Integrated Trade Solutions (WITS) platform: the dataset is available [here](#) and the data visualizations [here](#).

Data sources

Inter-Country Input-Output data has been provisioned from multiple data sources. These are

- EORA26 (1990-2015) 199.82 version (**eora**). Lenzen, M., Moran, D., Kanemoto, K., Geschke, A. 2013. ‘Building Eora: A Global Multi-regional Input-Output Database at High Country and Sector Resolution.’ *Economic Systems Research*, 25:1, 20-49. Please remember that the Eora MRIO is free for academic (university or grant-funded) work at degree-granting institutions. All other uses require a data license before the results are shared.
- WIOD 2016 VERSION (2000-2014) (**wiodn**) and WIOD 2013 VERSION (1995-2011) (**wiodo**). Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer and G.J. de Vries, 2015. ‘An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production.’ *Review of International Economics*. 23: 575-605.
- OECD TiVA 2018 VERSION (2005-2015) (**tivan**) and OECD TiVA 2016 VERSION (1995-2011) (**tivao**). OECD, Trade in Value Added database, 2018, oe.cd/tiva
- ADB MRIO 2021 version (2000;2007-2020) (**adb**). Asian Development Bank MRIOT Database, mrio.adbx.online

The **GVC Trade dataset** contains measures related to international trade. The unit of observation is the exporting country-importing country-exporting sector-year. The **GVC Output dataset** contains measures related to gross output. The unit of observation is country-producing sector-year. All data are in millions of US dollars.

Variables description

GVC Trade dataset

GVC-related trade measures the value of goods and services exported by a sector or a country that crosses more than one border. The difference between gross trade and GVC-related trade is defined as **Traditional trade**, i.e. the value of goods and services that crosses just one border. The **Traditional trade** can also be divided into **Traditional trade in intermediate goods** and **Traditional trade in final goods**. **GVC-related trade** presents two desirable features:

- once expressed as a share of gross trade, it is bounded between 0 and 1;
- it is additive at any level of aggregation/disaggregation of trade flows; thus, data can be summed at any level – total country exports/world exports/world sector exports/country groups and so on – in order to obtain the proper GVC participation measures at the desired level of aggregation

GVC-related trade is always traced in the exporting sector. The overall **GVC-related trade** encompasses three different types of GVC linkages.

- **Pure forward GVC related-trade:** value-added in goods and services entirely generated within the domestic chains – without any border crossing – exported by the sector and re-exported further by the partner. The exporting sector is engaged in GVC activities at the origin of the chain.
- **Two-sided GVC related-trade:** imported inputs bought by the exporting sector directly from abroad or indirectly through domestic chains, exported and further re-exported by the partner. The exporting sector is located in a central position of the chain.
- **Pure backward GVC related-trade:** imported inputs bought by the sector directly from abroad or indirectly through domestic chains, exported by the sector to the final market, as intermediates or final goods. The exporting sector is engaged in GVC activities close to the end of the chain.

A natural measure of the **Type of participation in GVC-related trade (forwardness)** at any level of aggregation can be straightforwardly obtained as the difference between pure forward and pure backward participation as a share of the overall GVC related-trade. This measure is bounded between -1 and 1 and it is equal to zero at the global level.

GVC Output dataset

GVC-related output is the output of a country or sector that directly or indirectly crosses more than one border. It provides a more general assessment of the amount of productions of each sector that is related to GVCs, since it takes into account the entire supply chain the sector participates to, regardless of its direct involvement in export activities.

The **GVC-related output** shares the same properties of GVC related-trade:

- once expressed as the share of output, it is bounded between 0 and 1;
- it is additive at any level of aggregation/disaggregation.

Within the total output of a country or sector, the amount that never crosses a single border, neither directly or indirectly, is labeled **Purely domestic output**. Instead, the output that directly or indirectly crosses just one border is labeled **Output related to traditional trade**, i.e. value-added produced by the sector and sold abroad to the final market, directly by the producing sector or indirectly through domestic chains. The overall **GVC-related output** encompasses three different types of GVC linkages.

- **Pure forward GVC related-output:** value-added produced by the sector and sold directly abroad by the sector or indirectly through domestic chains; then, re-exported by the partner country. In other terms, the GVC-output is traced in the sector where the value-added originates, the very first link of a chain. **Pure forward GVC related-output** might also be labeled as **GVC related-value-added**.
- **Two-sided GVC related-output:** domestic inputs bought by the sector within domestic chains and sold directly abroad by the sector or indirectly through domestic chains, and re-exported by the partner; imported inputs bought directly from abroad by the sector or indirectly through domestic chains, and sold directly abroad as inputs or indirectly through domestic chains.

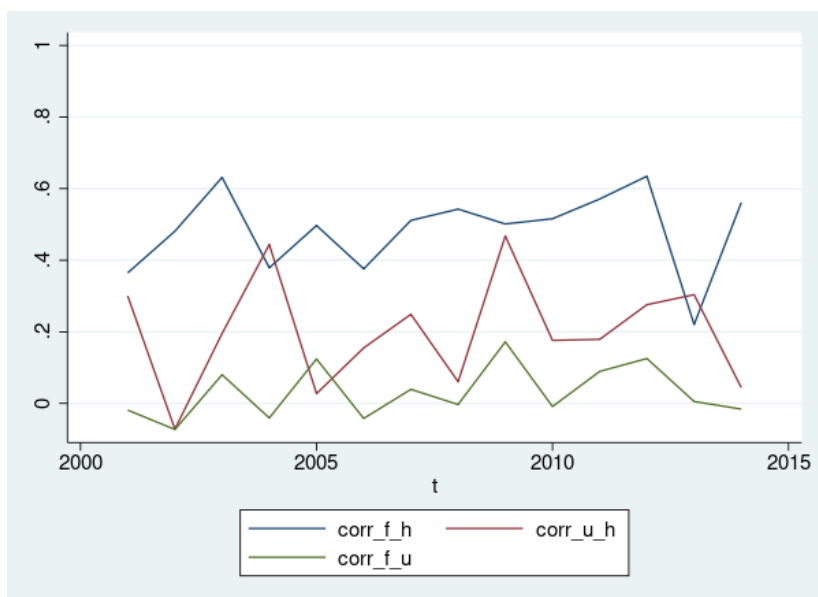
In other terms, the GVC-output here is traced in the sector that simultaneously buys and sells intermediate inputs, in a central position of the chain.

- **Pure backward GVC related-output**: imported inputs bought by the sector directly from abroad or indirectly through domestic chains, and embedded in final goods and services production sold to domestic consumers – if inputs crossed more than 1 border before – or to foreign consumers – if inputs crossed only 1 border. In other terms, GVC-output is traced in the sector that completes the final goods or services, the very last link of a chain. **Pure backward GVC related-output** might also be labeled as **GVC related-final goods and services**.

A natural measure of the **Type of participation in GVC-related output (forwardness)** at any level of aggregation can be straightforwardly obtained as the difference between pure forward and pure backward participation as a share of the overall **GVC related-output**. This measure is bounded between -1 and 1 and it is equal to zero at the global level. Finally, readers interested in computing their own measures of global value chain trade by origin and destination using also user-provided input output tables are referred to the [icio](#) module in Stata by Belotti et al. (2021). Please note that in [icio](#) backward participation is equal to pure backward + two-sided participation while forward participation corresponds to the pure forward participation described in this paper.

C Additional evidence

Figure 18: Correlation across shocks



Source: own elaboration based on WIOD.

Table 4: WIOD GVC-Trade

	(1)	(2)	(3)	(4)
	Δ Out	Δ Out	Δ Out	Δ Out
f	0.052*** (0.018)	0.034* (0.018)	0.029* (0.017)	0.024 (0.018)
h	0.071 (0.046)	0.110** (0.044)	0.075* (0.045)	0.123*** (0.048)
u	0.220*** (0.050)	0.170*** (0.049)	0.195*** (0.050)	0.162*** (0.049)
Domestic shock	0.336*** (0.007)	0.334*** (0.007)	0.278*** (0.008)	0.276*** (0.008)
Sectoral shock	0.106*** (0.007)	0.095*** (0.007)	0.093*** (0.007)	0.093*** (0.007)
L.GVC Forw Trade	0.000 (0.013)	-0.026* (0.015)	-0.018 (0.014)	-0.108*** (0.030)
L.GVC Mix Trade	0.118*** (0.031)	0.138*** (0.042)	0.137*** (0.042)	0.486*** (0.094)
L.GVC Back Trade	-0.027* (0.015)	-0.006 (0.020)	0.030 (0.020)	-0.030 (0.051)
h \times L.GVC Forw Trade	0.178* (0.103)	0.180* (0.101)	0.219** (0.102)	0.201** (0.102)
h \times L.GVC Mix Trade	1.457*** (0.473)	1.489*** (0.467)	1.562*** (0.462)	1.135** (0.488)
u \times L.GVC Mix Trade	0.551 (0.372)	0.589 (0.367)	0.512 (0.365)	1.075*** (0.394)
u \times L.GVC Back Trade	0.265*** (0.089)	0.254*** (0.088)	0.258*** (0.089)	0.272*** (0.088)
Country-sector FE	No	No		Yes
Country FE	No	No	Yes	
Sector FE	No	Yes	Yes	
Year FE	Yes	Yes	Yes	Yes
R2	0.457	0.466	0.487	0.524
N	30,966	30,966	30,966	30,964

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Other datasets

	(1)	(2)	(3)	(4)
	Wiod P const	Wiod P const	Wiod Long Run	Wiod Long Run
f	0.059*** (0.018)	0.029* (0.018)	0.025*** (0.009)	0.021** (0.009)
h	0.074* (0.043)	-0.040 (0.046)	0.058*** (0.013)	0.035** (0.014)
u	0.167*** (0.049)	0.051 (0.047)	-0.009 (0.018)	-0.020 (0.019)
Domestic shock	0.084*** (0.007)	0.084*** (0.007)	0.180*** (0.009)	0.180*** (0.009)
Sectoral shock	0.064*** (0.007)	0.065*** (0.007)	0.006** (0.003)	0.009*** (0.003)
L.GVC Pure Forw		0.485*** (0.085)		0.680*** (0.207)
L.GVC Mix		0.007 (0.038)		0.051 (0.061)
L.GVC Pure Back		-0.011 (0.065)		0.290*** (0.072)
h × L.GVC Pure Forw		0.397 (0.525)		0.810** (0.399)
h × L.GVC Mix		0.739** (0.299)		0.175** (0.080)
u × L.GVC Mix		0.351* (0.203)		0.187* (0.099)
u × L.GVC Pure Back		1.442*** (0.201)		0.325** (0.129)
Country-sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
R2	0.235	0.251	0.429	0.433
N	31,181	30,964	19,736	19,640

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$