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BACKGROUND PAPER

THE CHANGING STRUCTURE OF GVCS: ARE CENTRAL HUBS KEY FOR PRODUCTIVITY?

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THE CHANGING STRUCTURE OF GVCS: ARE CENTRAL HUBS KEY FOR PRODUCTIVITY?

Chiara Criscuolo and Jonathan Timmis

Abstract

This paper uses "centrality" metrics to reflect position with Global Value Chains (GVCs), identifying central hubs and peripheral countries and sectors. Applying these metrics to OECD ICIO data, reveals there have been large changes in the structure of GVCs; with large shifts in some manufacturing value chains away from traditional centres of production, but also the rising importance of some types of services almost universally. Using cross-country firm-level from ORBIS, the paper finds that changing structure of GVCs can play a role in the catch up of firms, but the effects are heterogeneous across firms and countries. Firstly, becoming more central as a customer is associated with faster productivity growth of smaller or non-frontier firms, or firms in smaller or post-2004 EU member countries. But these correlations weaken with firm size or proximity to the frontier, such that there is no correlation over all firms in the data. Secondly, the average productivity (centrality weighted) of buyers matters for the productivity firms in our data overall, however this is particularly true for economies that are large or for non-frontier or smaller firms. Flexible labour market policy appears to be important in translating the changing structure of GVCs into faster productivity growth of these non-frontier firms.

Introduction

1. The productivity effects of Global Value Chains (GVCs) may stem from position within them and not just participation. It is well-established that such GVC participation can increase productivity, for example through access to new varieties of inputs and knowledge spillovers (see review in Criscuolo et al., 2016). However, these spillover effects may depend not only on participation, but also on the structure of global production networks, the position within them and the characteristics of other participants in the value chain. Real world global production networks are complex networks of flows of knowledge, goods and services inputs, combined at various stages of production. Firms and industries positioned at the centre of complex production networks have access to a greater variety of foreign inputs, compared to those at the periphery. Since these inputs are the embodiment of all the skills and technologies used to produce them, these central hubs may also have access to a greater breadth of disembodied knowledge, with greater potential for knowledge spillovers. Potential knowledge spillovers may be further reinforced when firms are part of networks connecting highly productive frontier suppliers or customers, with access to more advanced knowledge. Therefore whether firms and industries sit at the fringes of global production or are tightly knotted at the centre of a complex network, connecting highly productive foreign firms, is likely to affect economic outcomes.

2. This paper presents new "centrality" metrics that go beyond GVC participation, reflecting central hubs and peripheral industries and countries within production networks, and examine their role in the diffusion of knowledge. We utilise well-established metrics from network literature to identify those sectors and countries that are highly central hubs and those that are peripheral. As explained later, this class of centrality measures reflect the influence of sectors and countries within production networks. Central sectors and countries reflect those that are highly connected (both directly and indirectly) and influential within global production networks, and conversely, peripheral sectors and countries exhibit weak linkages to other sectors and countries and so are less influential. Central hubs are likely to affect the diffusion path of new knowledge, with central sectors that are highly connected to these new sources of knowledge likely

to benefit more. Changes in the structure of the global production network, both in terms of centrality and which sectors are connected, may be correlated with the evolution of these trends.

3. The aim of the paper is twofold. First, it shows there have been profound changes in the structure of GVCs over the period 1995-2011. Whilst some activities remain clustered around the same central hubs as was the case at the start of the period, for others there have been dramatic restructuring of the geography of economic activity. Many of these patterns in the data concord with anecdotal evidence concerning the shifting patterns of production. For example, motor vehicle, and machinery and equipment manufacturing remain centred around key hubs in Germany and the USA. In contrast, computer and electronics manufacturing value chains have undergone a pivot away from traditional centres of manufacturing towards increasingly being centred around emerging economies in Asia, with the UK and Japan witnessing a particularly pronounced decline in importance. Several emerging economies and their industries have become more central to global production networks (with much smaller changes in domestic production networks). This is particularly true of most peripheral industries of Eastern European countries, with their growing importance coinciding with the timing of their EU accession.

4. Second, the paper finds that the changing structure of GVCs can play a role in the catch up of firms, but that the effects are heterogeneous across firms and countries. We match our centrality metrics to cross-country firm-level data, to examine the effects of the structure of the GVC network on the diffusion of productivity. Firstly, becoming more central as a customer (but not a supplier) is associated with faster productivity growth of smaller or non-frontier firms, or firms in post-2004 EU members or smaller countries. But we find either insignificant or even negative effects for larger or frontier firms or firms in larger countries. These heterogeneous effects means centrality does not seem to be associated with firm productivity growth across all firms and countries in our sample. Secondly, we find that being connected to more productive foreign sectors can also play a role in firm catch up. We supplement the standard centrality metrics by examining changes in the average productivity (centrality weighted) of buyers / suppliers. Supplying or buying from faster growing foreign sectors is correlated with faster productivity growth of smaller or non-frontier firms, with these effects weakening with firm size or proximity to the frontier. But these correlations are stronger for larger or higher-income Factory Europe economies, and less evident for smaller economies or post-2004 EU members. The productivity growth of non-frontier firms is more strongly evident in economies with flexible labour markets, and not present in those with more constraining labour market policy settings. These results suggest that policies supporting flexible markets play a role in allowing those smallest or least productive firms to yield the potential benefits from structural changes in GVCs.

5. We apply the "Bonacich-Katz" eigenvector centrality metric to the OECD ICIO 2015 edition data, which underly OECD-WTO TiVA metrics. We are not the first paper to apply centrality metrics to inter-country input-output data, and indeed there are a variety of potential centrality metrics to choose from. For example, Cerina et al. (2015) compute a range of backward centrality metrics using WIOD IO data, corroborating the findings for the US, that industries are highly asymmetrically connected and also that GVCs are regionally clustered. Other papers have applied centrality metrics to trade in value-added data, rather than IO data, Gourdon et al. (2016) show central buyers and suppliers of value-added, with centrality reflecting their number of direct linkages to other sectors. We follow the microeconomic foundations outlined in Appendix Box A1.1 and apply Bonacich-Katz centrality to IO data on intermediate flows following the common approach in the economics literature on domestic shock transmission. However, we differ by calculating metrics based on both forwards and backwards linkages; identifying separately the role of key suppliers and key customers. Typically the literature has not distinguished between foreign and domestic linkages, often because most studies used IO tables for a single country (often the US) (one exception being Imbs and Pauwels, 2017, in the context of cross-country shock diffusion). We also decompose sectors into those that are key hubs because of their (direct and indirect) links to foreign sectors and those that are central because of domestic linkages.

6. We use these centrality metrics to examine the effects of the structure of the GVC network on the diffusion of productivity, by matching to cross-country firm-level data. Although this data is the most comprehensive source of firm-level data available to us, the data comprise mainly medium and large firms for high-income economies. Therefore it is not possible to comment on the effect of productivity of the smallest firms or on how these effects may differ for emerging economies. We first examine the effect of the large shifts in the structure of GVCs documented earlier in the paper, as reflected by changes in the (foreign) centrality of each country-industry. We consider separately centrality from a forwards and backwards perspective, as a key supplier or customer respectively. Secondly, we examine the additional effect of being connected to increasingly productive foreign sectors (conditional on centrality). Thus, allowing us to distinguish the effect of becoming a central hub (regardless of who is connected), and the effect of connecting fast growing foreign sectors (regardless of centrality). We use the panel structure of the data to examine how these effects differ based on initial characteristics of firms, such as by firm size and ex-ante productivity.

7. Our work builds on a growing literature that demonstrates a minority of highly connected firms and sectors are highly influential in determining aggregate outcomes. Research has begun to shift towards addressing the importance of interconnections between firms and sectors in the transmission of micro shocks (e.g. Magerman et al., 2016). In an economy with symmetric interconnections, where each sector sources inputs equally from each other, a shock to any individual sector would average out, having a small effect in the aggregate. However, where the networks of input flows are asymmetric, sectoral shocks do not dissipate in the aggregate, and well-connected sectors play a key role in their transmission (Acemoglu et al., 2012). Several theoretical models have been advanced that describe the influence that a minority of highly interconnected firms and industries have on aggregate GDP or sales volatility (see Appendix Box A1.1). Specifically, these models all advance a particular metric of influence, the "Bonacich-Katz eigenvector centrality", which is the metric used in this paper (and is elaborated later). This measure of centrality reflects crucially not only direct interconnections, but indirect higher-order connections too. For instance, a shock to a particular firm, affects not only their suppliers (customers), but also the suppliers (customers) of their suppliers (customers) and so on. Similarly, a shock (natural disaster, political upturn etc.) to a particular country or sector-country pair is transmitted to other country-sectors in the network of supplier/customers in global value chains. Thus, central firms, industries and countries, with a high number of direct and indirect connections (what we call "hubs") play a disproportionate role in determining aggregate performance.

8. Highly central firms and industries – "key hubs" – by linking agents, can also play an important role in propagating shocks from one part, throughout the network. An emerging body of work has found that central firms and industries facilitate shock transmission domestically. US sectoral data shows the intermediate input linkages are indeed highly asymmetric, with a heavy-tail of highly central sectors (Acemoglu et al, 2012; Carvalho, 2014). It is therefore unsurprising that research using US Input-Output tables finds that a minority of these key sectors drive a large portion of aggregate outcomes. For instance, productivity growth in the 10 most central US sectors (out of 417 sectors in the US Input-Output tables, approximately at the NAICS 4 digit level) account for 80% of the variation in US aggregate output growth over the period 1959-2009 (Carvalho, 2014). Using novel firm-to-firm transaction data for Belgium, Magerman et al. (2016), find productivity shocks to the 100 most central Belgian firms (out of 80,000 firms in their sample) account for 91.3% of Belgian aggregate volatility. Using US firm-to-firm linkage data, the propagation of natural disasters from suppliers to their customers are particularly pronounced for relationship-specific inputs, and these shocks are magnified through the supply chain, with overall customer sales falling $2.40 for every $1 lost sales of their suppliers (Barrot and Sauvagnat, 2016).

9. Ownership and input networks also play a key role in the transmission of shocks internationally. The international transmission of inflation is strongly influenced by cross-country input-output linkages, with these linkages doubling the cross-country impact of common global shocks (Auer et al., 2016). Using

a similar approach to this paper but applied to WIOD data (rather than OECD TIVA data), Imbs and Pauwels (2017) find that the centrality is strongly correlated with the volatility of GDP, particularly for high-income economies. Micro-level linkages, both in terms of trade flows and ownership linkages similarly act as an international propagation mechanism for shocks, however due to data constraints the literature typically only considers direct, first-order linkages, rather than the full indirect network effects. For instance, the growth of French firms is robustly correlated with the economic performance of countries with which they have gross trade linkages, and especially if there are ownership linkages as well (in the case of affiliated of multinationals) (Di Giovanni et al., 2016). Cross-country firm-level data confirm co-movement between affiliates and their source-country, and also highlight the mechanism of intra-firm transmission, with 10% headquarter sales growth associated with a 2% sales growth of their foreign affiliates (Cravino and Levchenko, 2016). Boehm et al. (2015) show that the US affiliates of Japanese multinationals were most affected by the 2011 Japanese Tohoku earthquake. These micro-linkages have important macro effects, with the presence of foreign affiliates in France synchronising shocks between French regions and the affiliate's country of origin (Kleinert et al., 2015). Identifying central banks in the inter-bank lending network has been found to predict systemic risk of the banking system and helps in suggesting which banks require a bailout in order to avoid a financial crisis (see reviews by Jackson et al., 2016 and Glasserman and Young. 2016).

10. Centrality is also crucial to the diffusion of knowledge, the focus of this paper. Central players by definition have a high degree of connectivity (both directly and indirectly), more widespread and closer linkages to other agents, and therefore potentially broader access to knowledge that these other agents possess. Alatas et al. (2016) use the network social structure of Indonesian villages and find that central households have access to better information (on household wealth) and play a key role in diffusing this to other households. Villagers in India consistently identify the most central person in terms of both direct and indirect social linkages as the person best-placed to spread information, rather than the person with the highest direct linkages (Banerjee et al, 2016). Diffusion of participation in a weather insurance scheme reaches a greater proportion of farmers, when information on insurance is provided to those farmers that are more central, in terms of both direct and indirect social linkages within the village (Caie et al, 2015). Students randomly allocated into groups of other students with high centrality tend to out-perform those randomly allocated to groups with lower centrality and the Katz-Bonacich centrality metric, also used in this paper, is the most relevant centrality metric to determine this performance (Hahn et al., 2015). Central brokers appear to have access to superior stock market information, resulting in excess returns on their trades, with this information disseminating through network linkages to other brokers, who subsequently imitate the specific trades of central brokers (Di Maggio et al., 2016).

11. Emerging evidence suggests network linkages also affect the diffusion of new technologies. Social linkages between farmers predict the diffusion of fertiliser technology in Ghana, with farmers copying neighbours who were unexpectedly successful in prior periods (Conley and Udry, 2010). Similarly, farmers in Malawi are more likely to adopt a new "pit planting" agricultural technology when the information diffuses from several people in their social network (Beaman et al., 2015). US industries and firms are more likely to adopt new types of inputs when those inputs are already inputs to their current suppliers. But the diffusion extends backwards through the supply chain too, with firms also more likely to adopt new inputs currently used by the suppliers of their suppliers. However, as the authors acknowledge, further work is needed to uncover the precise mechanisms at play (Carvalho and Voitgländer, 2015).

12. We apply the "Bonacich-Katz" eigenvector centrality metric to the OECD ICIO 2015 edition data. We are not the first paper to apply centrality metrics to inter-country input-output data, and indeed there are a variety of potential centrality metrics to choose from. For example, Cerina et al. (2015) compute a range of backward centrality metrics using WIOD IO data, corroborating the findings for the US, that industries are highly asymmetrically connected and also that GVCs are regionally clustered. Other papers have applied centrality metrics to trade in value-added data, rather than IO data, Gourdon et al. (2016)

show central buyers and suppliers of value-added, with centrality reflecting their number of direct linkages to other sectors. We follow the microeconomic foundations outlined in the Appendix Box A1.1 and apply Bonacich-Katz centrality to IO data on intermediate flows following the common approach in the economics literature on domestic shock transmission. However, we differ by calculating metrics based on both forwards and backwards linkages; identifying separately the role of key suppliers and key customers. Typically the literature has not distinguished between foreign and domestic linkages, often because most studies used IO tables for a single country (often the US) (one exception being Imbs and Pauwels, 2017, in the context of cross-country shock diffusion). We also decompose sectors into those that are key hubs because of their (direct and indirect) links to foreign sectors and those that are central because of domestic linkages.13. Centrality metrics do not simply reflect GVC participation or size. Clearly one cannot be a key hub without participating in GVCs, and so it is unsurprising that we observe some positive correlation between centrality and participation metrics. However, the correlation we observe is weak both in the cross-section and in changes over time. We do find a stronger correlation of centrality with size of the sector, as measured by the value of intermediate imports or exports. This is consistent with the extensive international trade literature showing that the larger and more productive firms trade a broader range of goods and services with a broader range of partners (Bernard et al., 2011b; Bernard et al., 2016). Unsurprisingly, it is more difficult for small firms and industries to become a key hub given the high sunk costs of transacting with many international partners. We find that size-centrality relation is particularly evidence for key customers (and less so for key suppliers). However, conditioning on size we find there is meaningful variation in the centrality metric, which we illustrate with respect to a case study on Japan. The centrality of Japanese industries has fallen dramatically from a position in 1995 of being the key hub within Asian value chains, but surprisingly this is true for almost every industry and the bulk of this fall does not appear to be due to the decline in size of the Japanese economy over this period.

14. The structural changes in GVCs we observe, reflected by centrality, are determined both by policy and technological developments. Advances in communication technology have enabled the fragmentation of production, and permitted production to develop into the complex global network it is today, with firms at the centre coordinating production stages across many firms, countries and regions. However, the changing structure of GVCs is not entirely a technology story, since communication costs are only one aspect of the costs of trade. Indeed many trade barriers falling globally and within regions, both in terms of tariffs and non-tariff bariers behind the border. Indeed, earlier research has found the GVCs operate predominantly within regions (Baldwin, 2012), and this is likely to be influenced by EU expansion and increased regional policy integration more generally. Focusing on Factory Europe in particular, we find that those most peripheral industries in E. Europe have become increasingly central to GVCs, with this increasing influence coinciding with the timing of their EU accession.

15. We use these centrality metrics to examine the effects of the structure of the GVC network on the diffusion of productivity, by matching to cross-country firm-level data. We first examine the effect of the large shifts in the structure of GVCs documented earlier in the paper, as reflected by changes in the (foreign) centrality of each country-industry. We consider separately centrality from a forwards and backwards perspective, i.e. as a key supplier or customer respectively. Secondly, we examine the additional effect of being connected to increasingly productive foreign sectors (conditional on centrality). Thus, allowing us to distinguish the effect of becoming a central hub (regardless of who is connected), and the effect of connecting fast growing foreign sectors (regardless of centrality). We use the panel structure of the data to examine how these effects differ based on initial characteristics of firms, such as by firm size and ex-ante productivity. Finally, we examine how these conclusions are influenced different policy settings across countries.

16. The paper proceeds as follows. The next section explains network concepts as applied to GVCs and elaborates our methodology to identify key hubs and the periphery. Section 3 briefly illustrates the summary statistics of the resulting centrality metric. Section 4 presents graphical illustrations of key

changes in the structure of GVCs reflected by changes in centrality, both across industries, countries and regions over time. In section 5, we contrast the new centrality metrics with commonly used existing GVC and trade metrics, to show this metric reflects features not fully captured by these existing metrics. In section 6, we briefly describe the firm-level data, and section 7 introduces our empirical framework. Section 8 presents our empirical results and the final section provides a discussion of our main conclusions.

Measuring Central Hubs in GVCs

17. Recent research has begun to uncover that the network of linkages between firms, industries and economies matter for economic outcomes, as outlined in the previous section. In this section we first briefly illustrate how the network structure of global production and in particular, being a key hub or in the periphery, may affect the diffusion of shocks and knowledge throughout the network. The second part to this section explains the methodology to identify central hubs in OECD ICIO data using theoretically-grounded metrics of Bonacich-Katz eigenvector centrality.

Network Structure Illustration

18. This section illustrates how differences in the structure of production networks might affect diffusion of shocks or knowledge across sectors. We first introduce some illustrative production structures, sequential, simultaneous and hybrid networks (following Baldwin and Venables, 2013). We then highlight that these differing structures have different implications for the diffusion throughout the network. Finally, we briefly contrast the role of central hubs and peripheral nodes in diffusion.

19. Some parts of GVCs can approximate sequential production networks. Firms are part of complex production networks that embody diverse goods and services inputs from other domestic and foreign firms. The inputs are combined through a composite variety of production hierarchies (see for example, Baldwin and Venables, 2013). At one (theoretical) extreme, sequential production[1] structures processes in a predetermined order with each task feeding into the next, as reflected in Figure 1 below. This is akin to a vertical economy where each input flows from upstream processes or sectors (such as A), through intermediate sectors sequentially, to the downstream sector (labelled D). The processing of raw materials or production of chemicals is often cited as examples closely resembling sequential production[2].

20. Other parts of GVCs can approximate simultaneous production networks[3] centred around key hubs. The first type of simultaneous production reflects the intermediates produced by several processes that are joint inputs into one key hub. Figure 2a depicts such a scenario, where the intermediate inputs produced by B to E are simultaneously combined by the key hub A. Such production networks reflect assembly activities, where the inputs from several upstream processes are simultaneously assembled into a final good in the downstream sector. Conversely, simultaneous production may reflect the production of one key hub feeding into many other processes. In Figure 2b the intermediates produced by A feed as inputs into several downstream sectors B to E. These may reflect general purpose inputs such as real estate and construction, banking and finance, energy, information technology that are used in many other sectors (Carvalho, 2014).

21. GVCs as a whole are complex production networks that are a hybrid of sequential and simultaneous production processes. The sequential and simultaneous production networks outlined above

1 Sequential production has also been termed "snakes" by Baldwin and Venables (2013).

2 See for example, discussion of the production of magnets from rare-earths within Carvalho (2014), or sequential chemical production scheduling within Smith (2014)

3 Simultaneous production has also been termed "spiders" by Baldwin and Venables (2013).

are theoretical extremes of real-world production. In reality, most GVCs are a hybrid of the two, with some aspects of production following sequentially and other aspects simultaneously. Figure 3 depicts such a hypothetical hybrid structure where production follows sequentially from F to D, and there is a simultaneous production network linking A to D. The key hub A not only provides a bridge between the sectors directly linked (B to D), but also indirectly links many sectors to one another (B and C are indirectly linked to E and F). Intuitively, A therefore plays the role of a central hub within the network. Conversely, sector F is relatively peripheral, with few direct linkages and is only indirectly linked to others through many steps. These concepts of centrality and their measurement are formally elaborated in later sections.

Figure 1. Example of Sequential Production Network

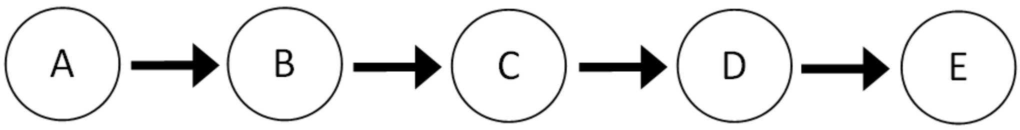


Figure 2a: Example of Simultaneous Production Network (Intermediate inflows)

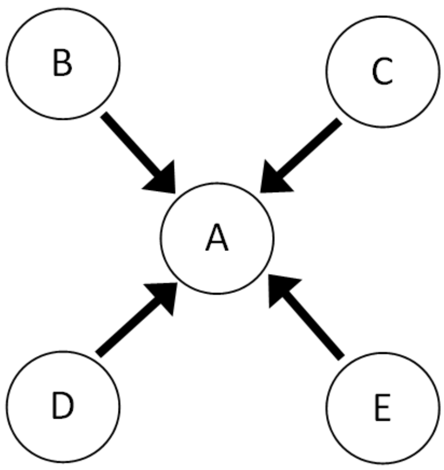


Figure 2b: Example of Simultaneous Production Network (Intermediate in and outflows)

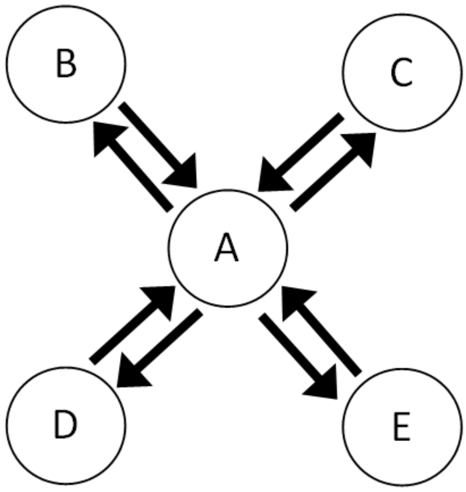
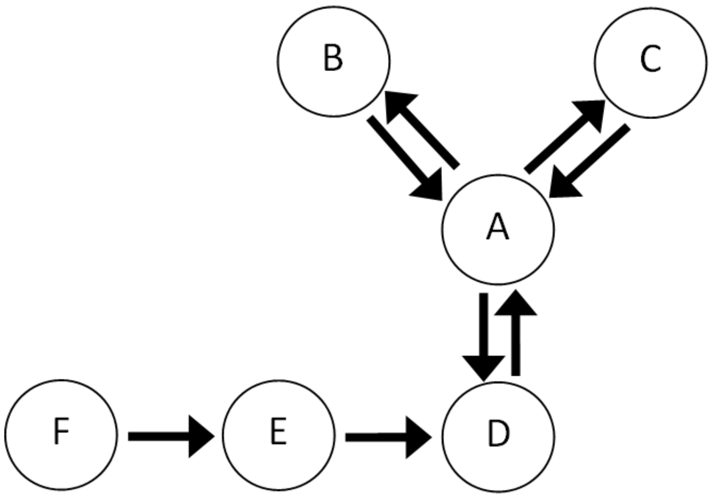


Figure 3: Example of Hybrid Production Network



22. The structure of production networks affects the propagation path of shocks. In the sequential model of Figure 1, a supply shock to any one of the upstream input suppliers (say a production disruption to firm A impacts its immediate downstream buyer (B). The shock may further propagate to other downstream buyers (such as C, D and E), propagating through indirectly linkages, even though they are not directly linked. Similarly, a demand shock to E will directly affect the inputs demanded from intermediates supplier D, which in turn will affect the inputs demanded from C and so on. Therefore the network of direct and indirect production linkages influences the propagation path of shocks. Note that this illustration is consistent with emerging research that finds, for the US at least, that demand shocks tend to propagate upstream, whereas supply shocks tend to propagate downstream (Acemoglu et al., 2015).

23. The structure of production networks may also affect the diffusion of embodied and disembodied knowledge. Inputs of goods and services embody all the factors and technologies used to produce them. Therefore the extent of direct and indirect input linkages may determine the set of knowledge (embodied in inputs) available to downstream firms / sectors. In the sequential model of Figure 1, E can benefit from the technology embodied in inputs from D. But also, since D embodies all the technology from all of its

upstream suppliers (A to C), E indirectly also has access to technology from all upstream sectors as well (A and C). In addition, global production networks are often coordinated by large multinationals that often actively transfer (disembodied) knowledge, management practices, and know-how to their suppliers. Therefore, production (and also ownership) linkages also determine the range of disembodied technologies firms and sectors are likely to have access to.

24. Central hubs are crucial conduits in shock transmission and knowledge diffusion throughout the network. In the example of Figure 2b, any shock to the key hub (A) is transmitted directly to all the spoke sectors (B to E). Whereas in the sequential network of Figure 1, without a central hub, a shock to any sector (such as A) is only directly transmitted to a single sector (B), with transmission to other sectors relying on indirect linkages. Furthermore, the key hub acts as a bridge to reduce the distance between sectors. In Figure 2b, each sector is at most only two links away from one another (through linkages via the key hub A), whereas under the sequential model A and E are four links apart. In general, the bridging role of key hubs is more important in networks that are sparsely connected, compared to those with already a high-degree of interconnectivity (as noted by Jackson et al., 2017). Clearly the impact of key hubs on the proximity of sectors is amplified for much larger real-world networks with many more nodes.

Methodology to Identify Central Hubs

25. This section explains our methodology to identify central hubs in production networks. We first introduce our Bonacich-Katz eigenvector centrality metric, discuss the key parameters and how we measure foreign versus domestic centrality. We then briefly discuss the OECD ICIO data, scaling the data such that we are concerned with input shares and conclude the section by summarising our approach and key contributions.

Bonacich-Katz Eigenvector Centrality

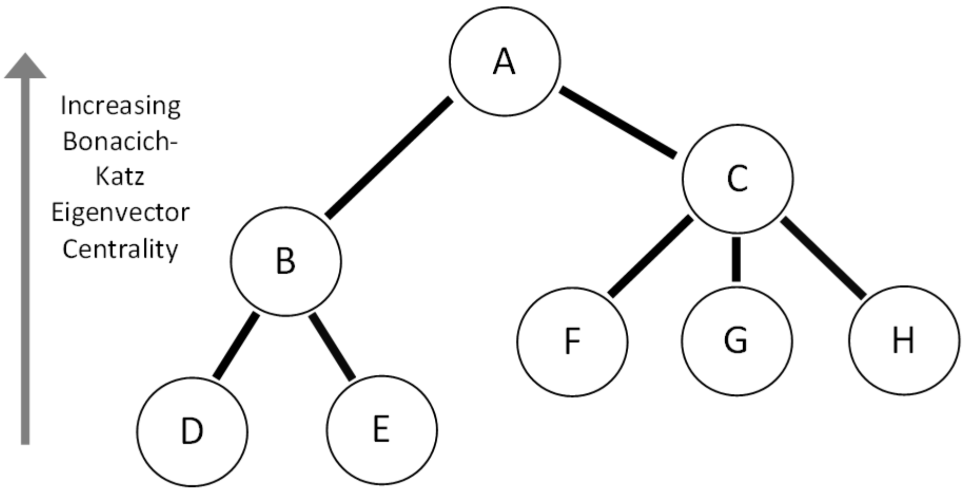
26. Our work leverages standard network measures of Bonacich-Katz eigenvector centrality, taking into account both direct and indirect linkages to identify key hubs. These metrics have recently been applied to identify key players in several literatures, as noted earlier, including the macroeconomic research on shock diffusion (e.g. Acemoglu et al., 2012; Carvalho, 2012; 2014), and more broadly to knowledge diffusion in social networks (Alatas et al., 2016; Banerjee et al., 2016). This measure takes into account both direct and indirect network linkages. Thus centrality is determined not only based on direct trade linkages, but also the linkages of your trade partners, and the trade partners of your trade partners and so on. This class of measure encompasses several variants applied in the sociology literature (such as eigenvector, Katz and Bonacich centrality) or in computer science, such as Google's PageRank search algorithm (Brin and Page, 1998).

27. Eigenvector-type centralities capture much richer features of production networks than those involving only direct linkages. Figure 4 shows an example of a production network, where for simplicity we assume each linkage is of equal weight. Here C has the highest strength of direct connections and B has the second highest. However, eigenvector centrality reflects the strength of both direct and indirect linkages. Although A only has two direct linkages (to B and C), both these sectors themselves have a high number of linkages. A is a key hub in the network and would have highest[4] eigenvector centrality. B and C would have an intermediate level of eigenvector centrality, reflecting their position as satellites to the key hub (A).

4 Note the precise magnitude of eigenvector centrality depends on the parameters used (as discussed later).

28. Bonacich-Katz eigenvector centrality for each sector in a particular country[5] is calculated as a baseline centrality, plus a weighted sum of centralities of their trade partners. Thus, Bonacich-Katz eigenvector centrality is a recursive relationship, where centrality is inherited from your partners. A given sector is central because it trades with central hubs and vice versa. But crucially not all customers/suppliers of a key hub benefit equally, the “inheritance” is weighted by how important they are to the key hub. The centrality is higher for sectors that are major customers/suppliers of a central hub than those that are minor customers/suppliers. Therefore both who you trade with (central hubs or peripheral sectors) and the strength of those trading relationships determines your centrality.

Figure 4: Bonacich-Katz Eigenvector Centrality Illustration



29. We calculate both forwards and backwards Bonacich-Katz eigenvector centrality, reflecting key suppliers and key customers respectively. In the illustration of Figure 4, the direction of input flows was intentionally omitted; however sectors are both customers of upstream inputs and suppliers of inputs downstream. Correspondingly, there are forwards and backwards centrality metrics, with forwards metrics reflecting outflows and measuring key suppliers, and backwards metrics reflecting inflows and measuring key customers. These mirror the distinction made in GVC participation metrics between forward and backward GVC participation. To facilitate aggregate comparisons, we reflect total centrality as the average of forward and backward centrality. Further technical details of these calculations are noted in the Appendix Box A1.2.

30. Industries can be central because of their (direct and indirect) linkages to domestic sectors or linkages to foreign sectors: we focus on foreign linkages in this paper. We consider the two aspects of centrality separately (as described in the Appendix), and decompose centrality into that due to domestic versus foreign linkages. Our approach mirrors precisely the approach taken for GVC participation metrics, where the total value-added embedded in exports can be sourced either domestically or from other countries (with the latter the backward measure of participation in GVCs). Similarly, value-added can be used in foreign countries’ exports or used to meet domestic sales, where the former is the forward measure

5 Given the information available in the dataset used for the analysis, eigenvector centrality is calculated for each sector within a country. However, if information were available at the level of the firm and its trade network, eigenvector centrality could be measured at the firm level (for example see Magerman et al., 2016).

of participation in GVCs. This paper focuses on the foreign component of centrality. The domestic component of centrality is less likely to be relevant for international knowledge and shock transmission than foreign linkages, which are the topics of our planned next steps (see Section 6). Therefore, for the remainder of this paper we will focus on foreign centrality alone.

Data

31. We use the OECD ICIO data to capture the network structure of global production, this data underlies the OECD-WTO TiVA indicators. The 2015 edition employed here contains rich inter-country information, reflecting input flows of goods and services both across and within 62 economies (including the Rest of the World) for the period 1995-2011. These flows are disaggregated across 34 ISIC rev. 3 sectors, comprising manufacturing, services and industrial activities. Therefore the sectoral dimension to this data is relatively aggregated compared to US IO data for instance. However, there are two key advantages to this data. Firstly, it has a broad coverage of the main actors in global production networks, with a comprehensive coverage of European, North American and Asian economies in particular. Secondly, this reflects flows of services as well as goods, with the former not captured for instance in network analysis of customs data (e.g. De Benedictis et al, 2013). This distinction is likely to be important, as services are increasingly shown to be important for manufacturing sector performance (OECD, 2013).

32. The global production network we consider is therefore comprised of 2108 (= 62 * 34) country-sector units of observation, or "nodes" in the network. These nodes are reflected in the rows and columns of the OECD ICIO table depicted in Figure 5. Each input flow within and across these country-sectors represents the "links" (or "ties" or "edges") of the network. These input flows are reflected in the cells of the OECD ICIO table depicted in Figure 5. The breadth of country-sectors included means there are up to 4.4 million (= 2108 * 2108) potential input flows each year, confirming the richness of this data.

Figure 5: Structure of OECD ICIO data

			Use by Countries						
			Country 1			….	Country 62		
			Sector 1	….	Sector 34	….	Sector 1	….	Sector 34
Supply from Countries	Country 1	Sector 1							
		….							
		Sector 34							
	….	….							
	Country 62	Sector 1							
		….							
		Sector 34							

Source: Adapted from Timmer et al. (2015)

Scaling of the ICIO Network

33. We follow common practice in the literature and scale the network linkages, such that they reflect input shares (rather than absolute values). In addition, the practical purpose of the scaling is two-fold. Firstly this avoids technical convergence problems for calculating centrality when network linkages can be in very large units (e.g. billions of USD). Secondly, we scale to match the theoretical foundations of Acemoglu et al. (2012) and others (see Appendix Box A1.1). We follow conventional practice and choose a scaling such that the rows or columns of the network sum to unity[6]. The theoretical grounding of

6 As noted in the Appendix, the scaling depends upon whether forwards or backwards centrality is calculated, with shares such that the columns sum to unity for forwards centrality and such that the rows sum to unity for backwards centrality.

Acemoglu et al. (2012) and Carvalho (2012; 2014) implies the centrality should be calculated using a network of input shares (rather than absolute values), such that the shares sum to one. We follow this convention here. Therefore we are concerned with input shares rather than absolute values of input flows**.** Commonly, practitioners either scale explicitly, such that the rows or columns of the network flows sum to one (see for instance, Wasserman and Faust, 1994; Acemoglu et al., 2012; Carvalho, 2014). Or scale implicitly, for instance, by applying a PageRank[7] version of eigenvector centrality to the unscaled network (see for instance, Cerina et al., 2015). As we note in the Appendix, these two approaches are identical.

34. One implication of the measure, often not made clear in previous work, is that it implies a relative centrality. It follows that the mean Bonacich-Katz eigenvector centrality is constant over time, when the network of flows are expressed in terms of input shares and with parameters constant across industries, as is standard practice and our case here. In our case for instance, the mean country-industry centrality in each year is equal to unity in each year, because of our choice of parameters. One implication is that centrality is not an absolute measure, but rather a relative measure, relative to other country-industries in the network. One advantage of this is that the centrality metric has a consistent unit of measurement over time. However, it does require care to interpret changes in centrality over time, meaning increasing/decreasing influence relative to others in the network. For example, increasing centrality could in principle be because you are more influential in absolute terms or because peers in the network have become less influential.

Summary Approach and Contributions to the Literature

35. We identify key hubs within global production networks by applying centrality metrics to the network of input flows within the OECD ICIO data. The nodes in the network each year are country industries, with the ties between nodes being input flows between each pair of nodes. The bulk of the literature is focussed on a single country, often the US, we contribute to a smaller set of research focussing on cross-country applications[8]. We take advantage of the broad country coverage of the OECD ICIO data and apply these metrics to cross-country-industry data (62 economies, 34 industries in the 2015 edition).

36. We calculate Bonacich-Katz eigenvector centrality metrics on the scaled network of global input flows for each country-industry every year. We scale the network following the theoretical foundations we follow (Acemoglu et al., 2012; Carvalho, 2012; 2014), and conventional practice in the literature, so that the ties are input shares (which sum to unity). The centrality metrics identify key hubs based on not only the strength of their direct connections, but also higher order indirect linkages too.

37. We use the directionality of input flows to distinguish between forward and backward centrality, in the same way as GVC participation metrics do, to identify key suppliers (forward linkages) and key customers (backward linkages). Total centrality is measured as the average of forward and backward metrics. The existing literature has largely focused on one direction of centrality, Acemoglu et al. (2012), Carvalho (2011; 2014), Magerman et al. (2016) and Imbs and Pauwels (2017) all focus on forward linkages in their centrality metric, whereas Cerina et al. (2015) use only backward linkages. However, the input flow network is directed, with the OECD ICIO capturing both the inflows and outflows of inputs. Much like GVC participation metrics, which can be represented in terms of forwards and backwards participation, there can be important differences across the metrics. This is particularly true as countries

7 PageRank is a particularly common approach, which is designed to remove the effect of the size of economies and sectors, which would otherwise dominate centrality statistics. For instance, this is the algorithm underlying the ranking of webpages in Google's search engine.

8 This smaller set includes Imbs and Pauwels (2017) who study country-level volatility, Cerina et al. (2015) who provide a description of centrality for WIOD IO data and Santoni and Taglioni (2015) who find that becoming a more central buyers or suppliers is correlated with GVC participation.

specialise at different parts of the value chain, so may be more central as customers than as suppliers (or vice versa).

38. The parameters used in the Bonacich-Katz eigenvector centrality calculation follow from the approach suggested both theoretically and implemented for US data by Acemoglu et al. (2012) and Carvalho (2012, 2014). Applying this method to OECD ICIO data, results in us employing the same parameter values as those used by Carvalho (2014).

39. We isolate and focus on the foreign sources of centrality, due to direct and indirect connections to other countries. The existing literature, including cross-country applications, has almost entirely focussed on total domestic and foreign centrality, one exception being Imbs and Pauwels (2017). We follow the approach applied in GVC participation metrics to decompose domestic and foreign sources of value-added. This allows us to analyse foreign sources (both direct and indirect) of centrality.

Changing Structure of Global Production Networks: Central Hubs, Spokes and Periphery

40. This section draws upon our centrality metric to illustrate some of key changes in the structure of global production networks over time. We find there have been some profound changes in the organisation of production networks over the period 1995 to 2011, however the extent of these changes vary substantially across economies and industries. We first present overall changes at the country-level between 1995 and 2011. Next, we drill down on manufacturing and services sectors to highlight particular industries that have undergone substantial changes in the GVC structure. Third, we examine the country sources of centrality, examining the extent to which a country's centrality is driven by within and across-region network linkages. Finally, in the latter two sections we examine key changes centrality within the European and Asian regions respectively.

Country-Level Centrality

41. Here we provide an overview of (foreign) centrality across economies, aggregating industry centrality metrics to the country-level. We first present each country's aggregate centrality in 1995 and 2011, to contrast which economies overall have become much more central to global production and which have become more peripheral.

42. A minority of key hubs dominate regional value chains in 1995, and many remained key hubs in 2011, with Japan as the exception. Figure 6 shows the total centrality of economies in 1995. The size of nodes represents the average of forward and backward centrality from foreign sources; therefore key hubs are denoted with large nodes and peripheral economies with small nodes. One can observe that each regional value chain is mainly dominated by one key hub in 1995. Japan is the key hub for Factory Asia and USA for Factory North America. The distinction is somewhat less clear in Europe, where Germany is the central hub, but is accompanied by several other central economies such as France, Italy and the UK. By 2011, Germany and USA remain as dominant hubs within their respective regions as shown in Figure 7. However, there are substantial changes in GVCs over this period; with the declining importance of Japan and rise of China within Factory Asia a salient example. By 2011, the position of Japan as a key hub within Asian value chains has diminished substantially, with China and India exhibiting strong growth and other economies such as Korea maintaining their position (see Figure 8). In later sectoral analysis we show a similar pattern for many industries, with many manufacturing and service industries structured around the same key hubs throughout the period. However, for some industries there are profound changes, with clear changes across countries.

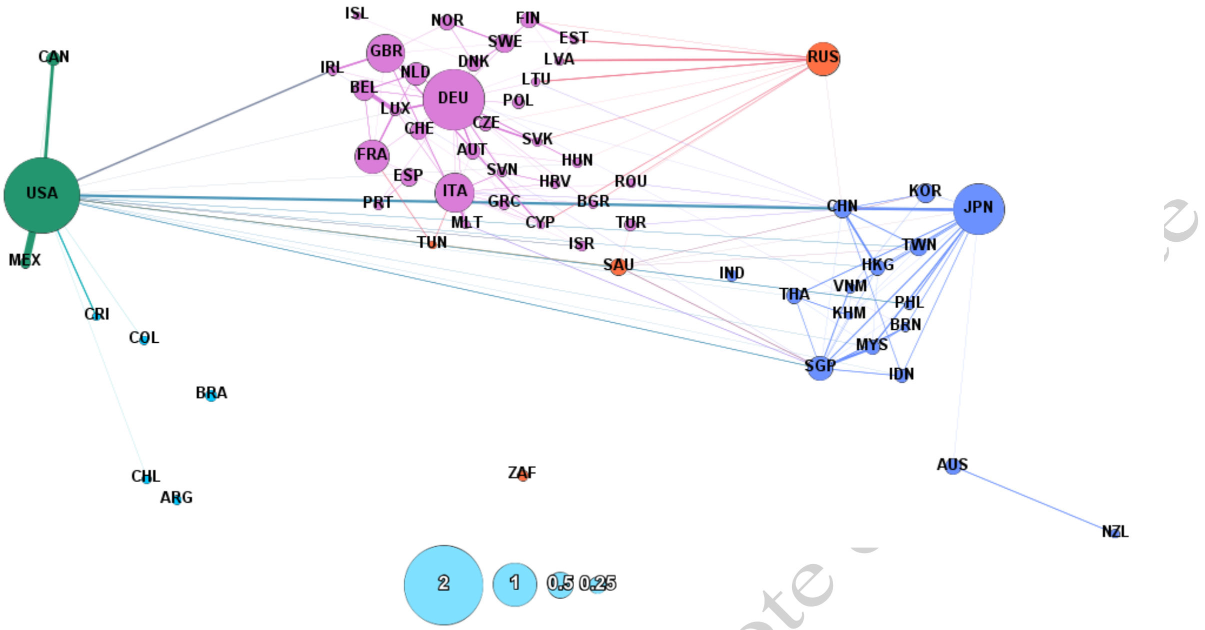
43. More generally, there is rising centrality beyond the key hubs in both European and Asian production networks. Many of the economies in Europe and Asia that were relatively more peripheral in

1995 (seen in Figure 6) become increasingly central by 2011 (see Figure 7). Indeed, as we show later, for some industries such as computer and electronic or automotive manufacturing there is a strong reallocation from developed economies to these emerging European and Asian economies. One of the major changes within Factory Europe has been increasing centrality of the periphery. We show later that those country-industries that were most peripheral at the start of the period exhibited particularly large growth, and this growth is particularly concentrated in the post-2004 EU accession countries, following their EU accession. In Factory Asia on the other hand, the changes in production networks have come mainly from the spokes: those that were moderately central to start with. We observe more limited aggregate trends observed in Factory North America and in Central & Southern America. However, the OECD ICIO coverage for the latter in particular, is rather more limited than for other regions.

44. An increasing importance of natural resources, particularly as reflected in key supplier metrics (forward centrality) is observed. Some of the economies showing the largest increases in centrality are those specialised in primary commodities. Comparing 2011 and 1995, one can see large increases in total centrality for Russia and Saudi Arabia in particular (see Figure 6 and Figure 7). When we look at key suppliers (as captured by forward centrality), one can see the importance of natural resources even more clearly (Figure 8), particularly when contrasted with the peripheral role of these economies as key customers (Figure 9). We show later that increasing centrality of mining sectors applies beyond Russia and Saudi Arabia, with several natural resource abundant economies, such as China, Australia, Indonesia, USA, Canada and Brazil also exhibiting a similar pattern of increasing centrality for these industries.

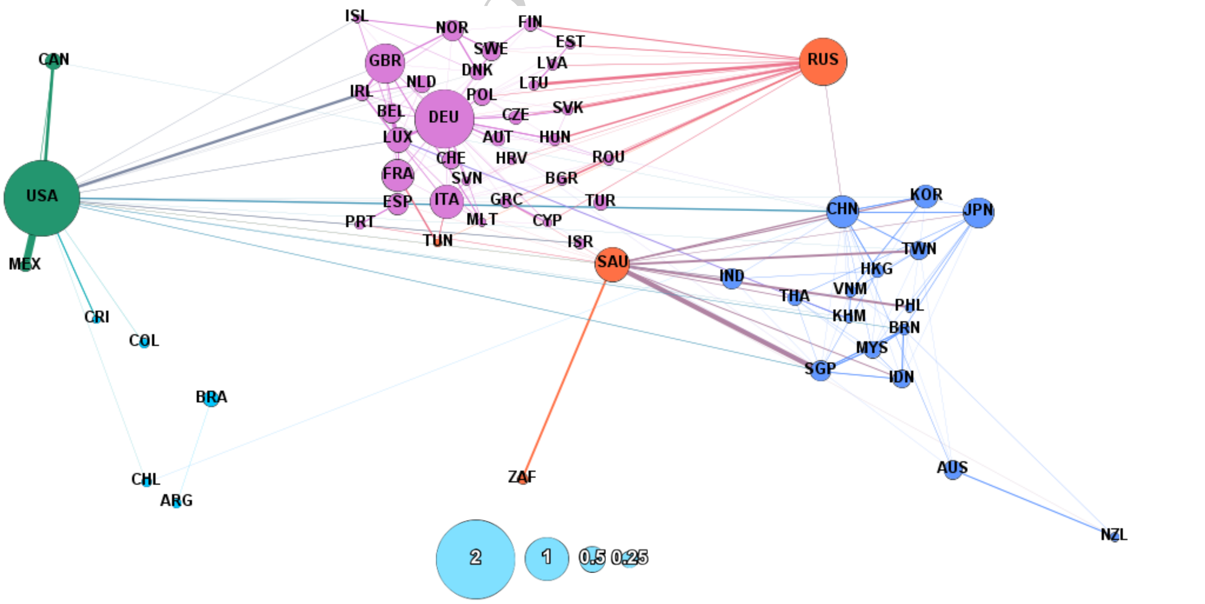
45. Service inputs are also becoming increasingly important to production networks, particularly in developing economies. A number of economies specialising in services are particularly central as key suppliers, for example, Luxembourg, Switzerland and the UK (see Figure 8). Later analyses will show that in high-income economies this seems to reflect a mixed pattern involving some reallocation from manufacturing towards services. However, the growth of services in production networks is not simply a restructuring story for high-income economies. For some services, however, such as IT services, these have become more important to production networks for almost every economy for which we have data. Furthermore, within low and middle-income economies services have also become increasingly important. As we shall see later, several emerging economies have witnessed pronounced growth in services centrality across a broad range of services (e.g. India and China). In addition, we show foreign service sector inputs have become particularly important for the manufacturing centrality of emerging economies.

Figure 6: Aggregate Central and Peripheral Economies – (Foreign Centrality) 1995



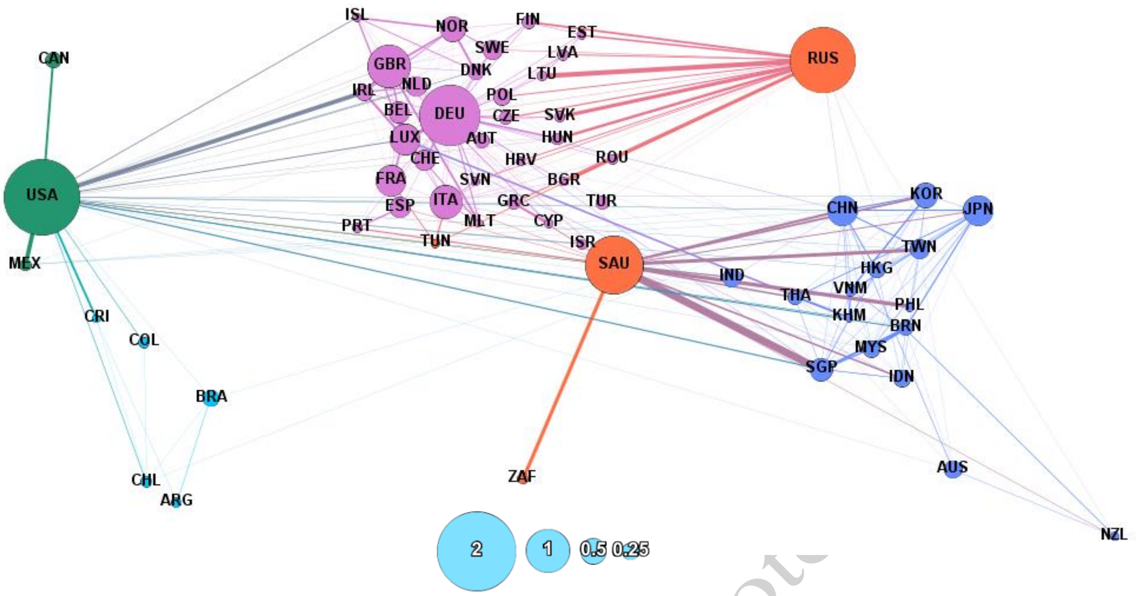
Notes: Economies are placed according to their location. Node size denotes total centrality (forward and backward) aggregated at an economy-level and includes all sectors within global production networks. Edges reflect direct input flows. For clarity only the largest input flows are reflected, those exceeding 2% of total inputs used in the importing or exporting economy.

Figure 7: Aggregate Central and Peripheral Economies - (Foreign Centrality) 2011



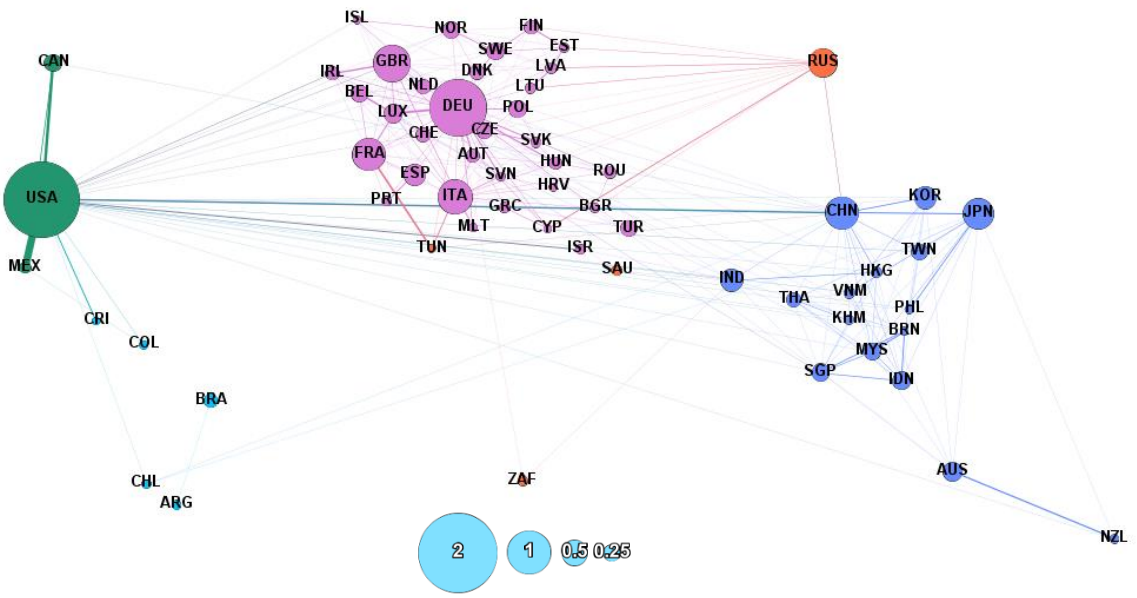
Notes: Economies are placed according to their location. Node size denotes total centrality (forward and backward) aggregated at an economy-level and includes all sectors within global production networks. Edges reflect direct input flows. For clarity only the largest input flows are reflected, those exceeding 2% of total inputs used in the importing or exporting economy.

Figure 8: Aggregate Key and Peripheral Suppliers – (Forward Foreign Centrality) 2011



Notes: Economies are placed according to their location. Node size denotes forward centrality aggregated at an economy-level and includes of all sectors within global production networks. Edges reflect direct input flows. For clarity only the largest input flows are reflected, those exceeding 2% of total inputs used in the importing or exporting economy.

Figure 9: Aggregate Key and Peripheral Customers – (Backward Foreign Centrality) 2011



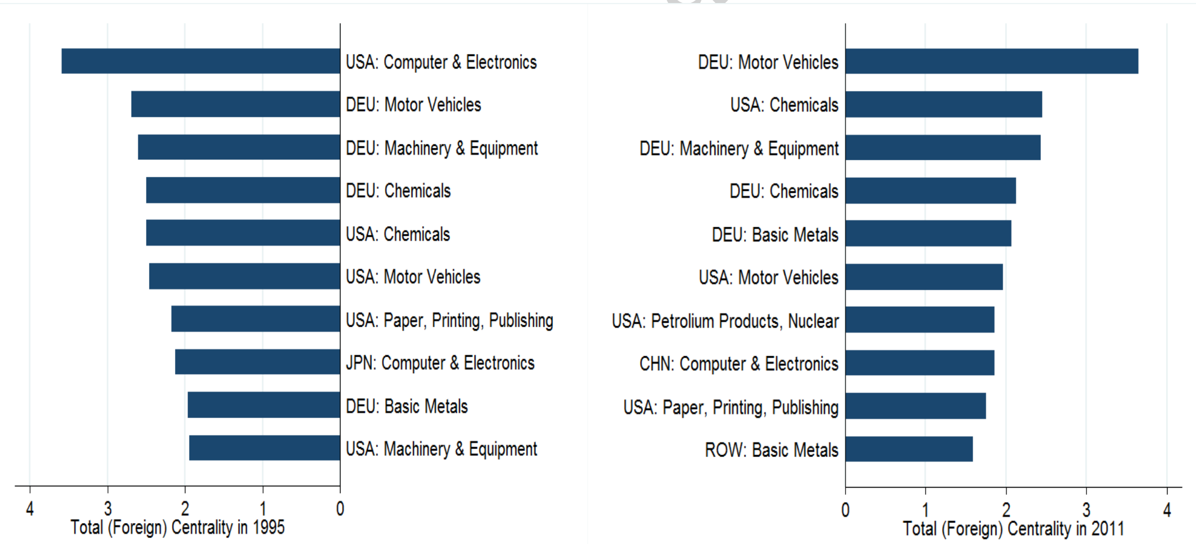
Notes: Economies are placed according to their location. Node size denotes backward centrality aggregated at an economy-level and includes of all sectors within global production networks. Edges reflect direct input flows. For clarity only the largest input flows are reflected, those exceeding 2% of total inputs used in the importing or exporting economy.

Industry-Level Centrality

46. Here we provide an overview of (foreign) centrality from an industry perspective. We first present the most central manufacturing hubs in 1995 and 2011, and highlight the computing and electronics manufacturing industry, which has undergone large changes over this period. Secondly, we show most central services hubs in 1995 and 2011, and continue the digital theme by examining centrality of IT services, followed by R&D and other business services. Finally, we examine central hubs for natural resource sectors, focusing on mining and quarrying in particular.

47. Many of the most central manufacturing central hubs in 1995, often in Germany and US, remain central by 2011. Ranking the 10 most central country- manufacturing industries reveals a strong overlap between 1995 and 2011 (see Figure 10). The German and US motor vehicles industry remain two of the most central manufacturing industries globally, in both 1995 and 2011. Indeed, centrality has grown strongly for German motor vehicles making it the most central manufacturing industry in 2011 (increasing from a centrality of 2.7 in 1995 to 3.7 in 2011). Similarly, German and US chemicals manufacturing and German machinery and equipment manufacturing remain in the 10 most central industries throughout the period. However, focusing on central hubs alone can mask substantial changes in the structure of GVCs over the period. For example, in 1995 computing and electronics was centred around hubs in USA and Japan, whereas by 2011, we see this has shifted, with China being the most central computing and electronics manufacturer (see Figure 10). We examine this industry in more detail in the following paragraphs.

Figure 10: Top 10 most central manufacturing hubs in 1995 and 2011



48. In computing and electronics manufacturing, several of the same central hubs remain in 1995 and 2011, but the most central hubs are generally less influential in 2011, with influence in GVCs more evenly distributed across countries in 2011. In 1995 much of computer and electronics manufacturing centred around traditional centres of developed economies Europe and North America. The USA and Japan, followed by Germany and the UK, were most central hubs for computing and electronics in 1995 (see Figure 11). In 2011, many of these economies remain central for computing and electronics, with USA and Germany remaining in the top 5 most central hubs. However, by 2011 the centrality of these hubs is consistently lower than in 1995, and since centrality is a relative measure, this suggests convergence in the centrality between these key hubs and other economies' industries.

49. Moreover, many emerging economies have become more central for computing and electronics manufacturing over time. By 2011, there are pronounced changes, with rising centrality of emerging economies and relatively declining centrality of many established hubs. Those existing hubs in developed economies have witnessed an almost universal and substantial decline in relative influence (see Figure 12). Conversely, many Asian and Eastern European economies have witnessed large increases in centrality, not only in China, but also large increases in the Czech Republic, Hungary, Korea, Chinese Taipei and Malaysia (see Figure 12). These changes have been large, and enough to lead to some emerging economies that were relatively peripheral in 1995 to become key hubs by 2011 (see Figure 11). For example, China (20th in 1995) has replaced USA as the most central country-industry. This is consistent with the trend over this period towards outsourcing production of computing and electronics to large contract manufacturers (The Economist, 2013) with a global network of plants and high-volume production activities in Asia, Mexico and E. Europe (Sturgeon and Lester; 2004). Notably, however, that Korea stands out as a high-income economy that bucks the general trend of shifting influence from high-income clusters to emerging economies. The increasing centrality of emerging economies, combined with relatively declining influence of key hubs, implies a more even distribution of influence in computing and electronics value chains across countries at the end of 2011, than in 1995.

Figure 11: Top 10 most central computing & electronics sectors in 1995 and 2011

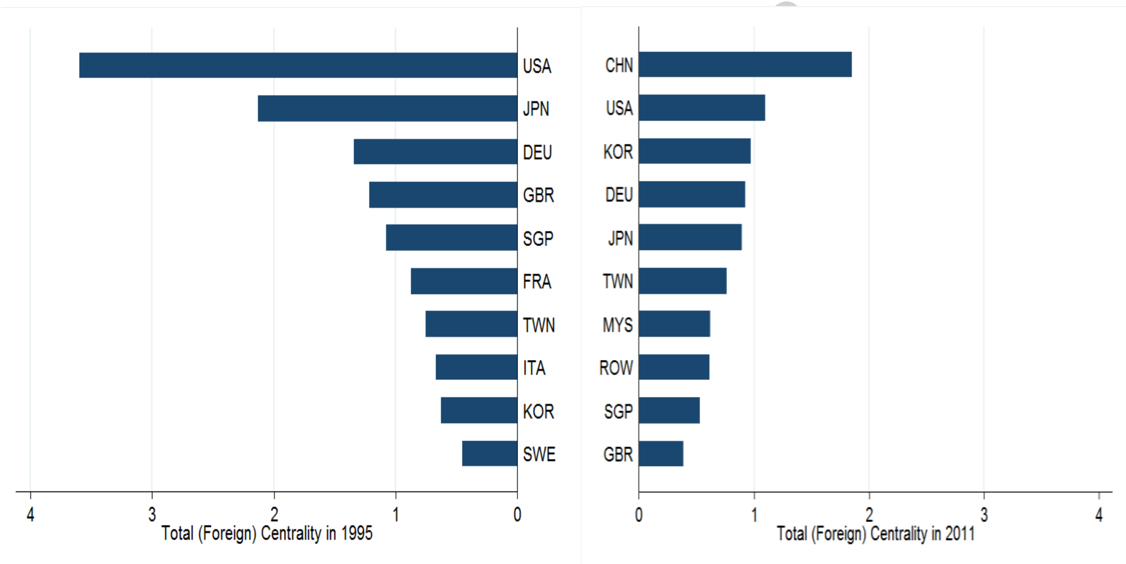
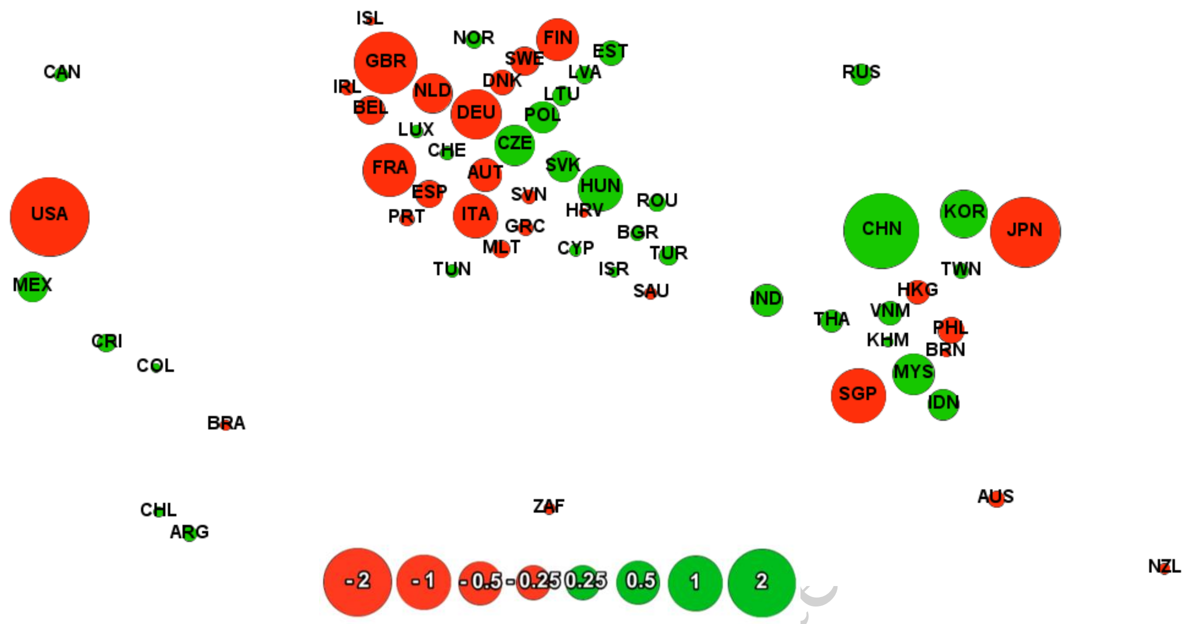


Figure 12: Relative change in centrality of computing & electronics sector across economies (1995-2011)



Notes: Economies are placed according to their location. Size of the nodes reflects the magnitude of the change (in levels) of total foreign centrality over the period 1995-2011. As reflected in the key, these changes are graphed using a log scale for readability. Green coloured nodes reflect increasing centrality and red denotes falling centrality.

50. Turning to services, many of the same central hubs for services industries persist both in 1995 and 2011. In 1995, we see many of the economies with large service sectors amongst the most central, namely Germany and the USA. In 1995, the most central service hubs include US financial and insurance services, German and US business services (including R&D), and, German, US and Italian wholesale and retail services (see Figure 13). All of these sectors listed remain in the top 10 most central service hubs in 2011. However, there is also the emergence of several new central services hubs, notably, such as transport and wholesale and retail services for the Rest of the World. Even amongst high-income countries the distribution of activity is not static, for instance, with business services in the UK emerging as a central hub by 2011.

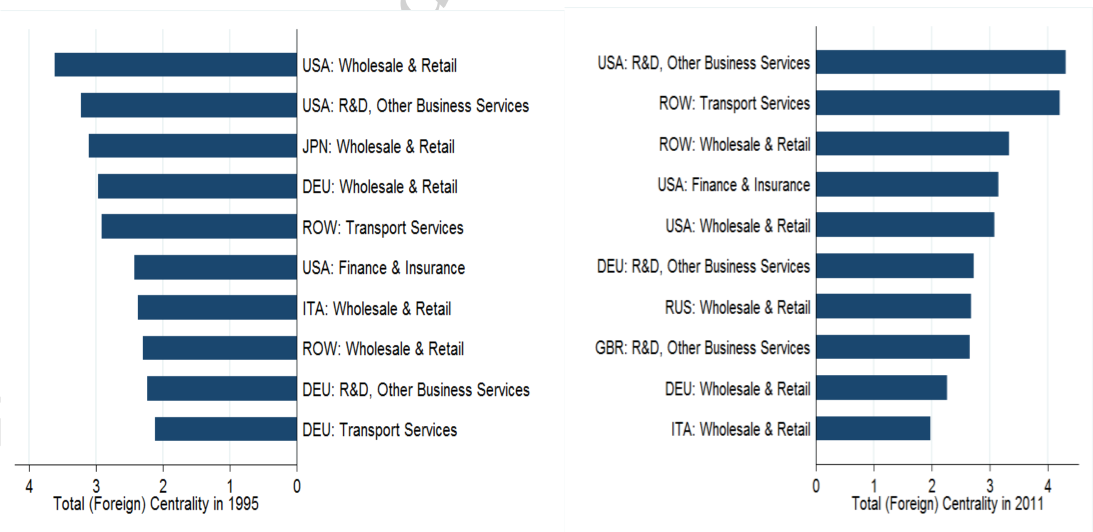
51. However, some service industries have witnessed large changes in their production structure, such as IT services. IT services have become almost universally more influential for production networks. IT services were not particularly influential for global production in 1995, with even the most central countries having a low centrality (see Figure 14). From this low starting point, the importance of IT services sectors to global production networks has increased almost universally between 1995 and 2011 (see Figure 15). Furthermore, these increases in the importance of IT services have been the largest in many of the same countries witnessing the most acute falls in computing and electronics manufacturing centrality; namely UK, Germany and the US. However, to put this in context, these changes to IT services are somewhat smaller in magnitude than the extent of the relocation of computing and electronics manufacturing, as can be seen Figure 15. The rising importance of IT services is not simply a story of the restructuring of high-income economies. The rising centrality of IT services extends to a broad range of economies, such as Ireland, Spain and Korea, as well as many emerging economies, especially India, China and Singapore.

52. Business services have also become relatively more influential in many high-income and emerging economies. Ranking the most central countries for business services in 1995 corresponds to

many of the large economies, such as USA, Germany, France, UK and Japan. Again many of these countries remain as central hubs by 2011. One exception is Japan, which is relatively less central compared to other country-industries in 2011. However, a more interesting picture emerges looking at relative changes over time. As the line between services and manufacturing becomes increasingly blurred over time and services become an increasing part of the value-added content of manufacturing production (OECD, 2013), one would expect to see increasing influence of services in global production networks over time. This is what we observe for business services here. For almost all countries, business services have become relatively more central for global production over time (see Appendix Figure A3). Some of the largest increases are in emerging economies, such as China, India and Singapore, and for China[9] these increases are large enough such that becomes the 5th most central country for business services in 2011, behind the USA, Germany, UK and France (see Appendix Figure A2). However, there are some exceptions to this trend, notably Japan and France, where the relative influence of their business services industry to global production has actually fallen a little.

53. Finally, we observe natural resources becoming relatively more important to global production, with countries with large primary commodity sectors witnessing large increases in centrality. Existing research has noted that natural resource rich countries tend to have lower foreign value added content in their exports, but that this can facilitate insertion of emerging economies with large resource endowments into GVCs (OECD, 2013; OECD, World Bank and WTO, 2014). We noted in earlier aggregate figures (Figure 8) that some natural resource abundant countries had become central suppliers to global production networks. Comparing the changes in centrality between 1995 and 2011, reveals that natural resources have become increasingly important for production networks over time. We find there has been substantial growth in centrality for countries specialising in primary activities (see Appendix Figure A4). This reflects countries with large oil and gas deposits, such as Canada, Norway, Russia, Saudi Arabia and USA, and, those with substantial mining of metals and coal, such as Australia, Brazil, China and Russia in particular. Whilst exports of resource-rich countries may contain a relatively large domestic content of value-added, our results suggest these exports are becoming increasingly influential in downstream production networks.

Figure 13: Top 10 most central services hubs in 1995 and 2011



9 China also increases their domestic centrality of business services, suggesting growing importance of direct and indirect linkages from business services to other domestic sectors. However, the changes in foreign centrality dominate the changes in domestic centrality, with domestic centrality increasing from around 0.6 to 1.8 over 1995-2011, compared to foreign centrality increasing from close to zero in 1995 to 1.4 in 2011.

Figure 14: Top 10 most central IT services sectors in 1995 and 2011

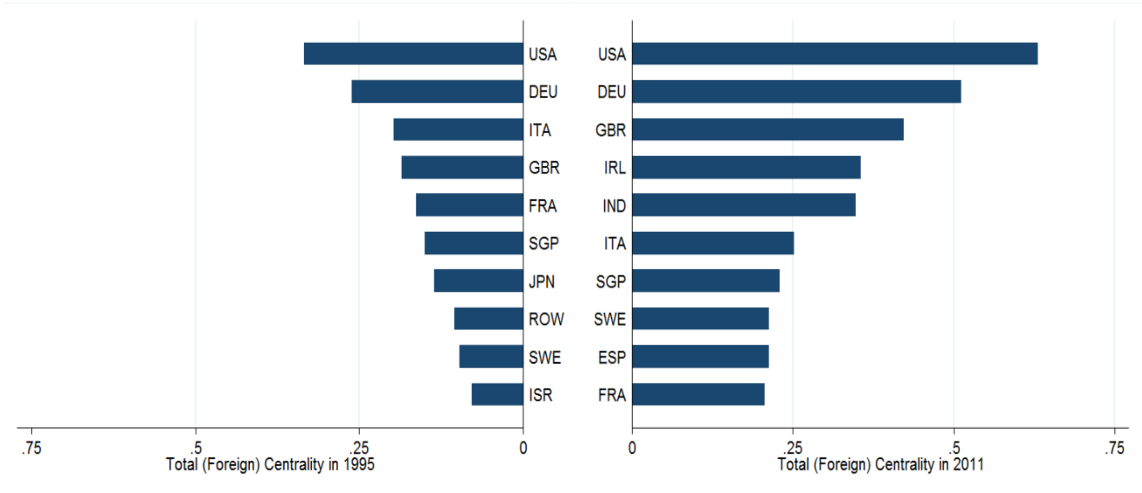
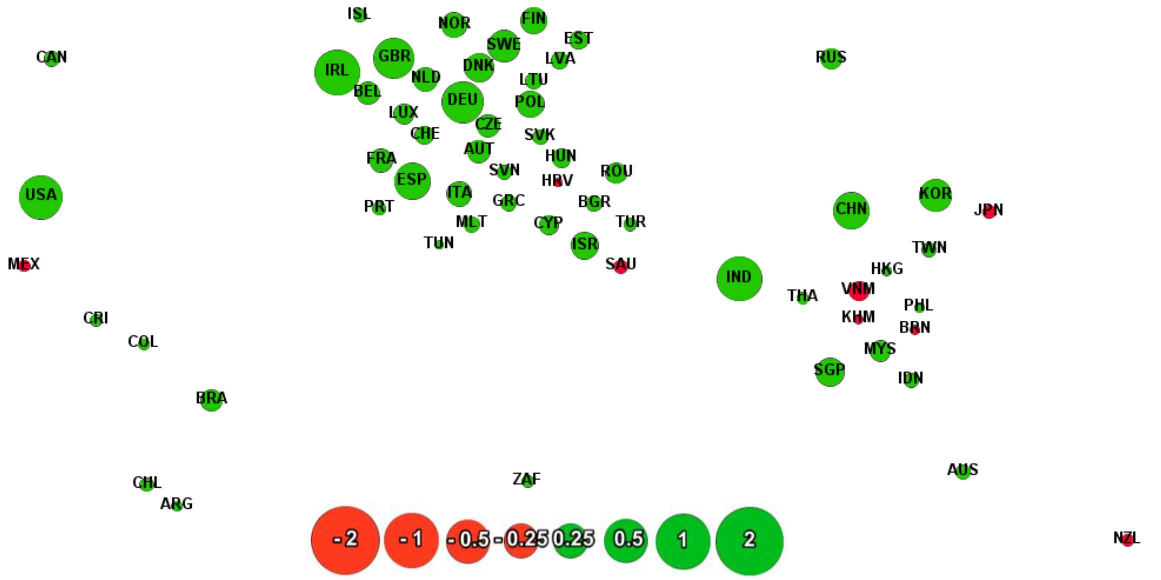


Figure 15: Relative change in centrality of IT services across economies (1995-2011)



Notes: Economies are placed according to their location. Size of the nodes reflects the magnitude of the change (in levels) of total foreign centrality over the period 1995-2011. As reflected in the key, these changes are graphed using a log scale for readability. Green coloured nodes reflect increasing centrality and red denotes falling centrality.

Within- and Cross-Region Linkages

54. In previous sections we examined changes for each country in the aggregate (across all sectors), and considering specific industries in particular. Here we provide an overview of (foreign) centrality from an intra and extra regional perspective. We decompose the centrality of countries into those sources of centrality from within the same or from different regions, examining in turn Europe, Asia and North and Latin America. An alternative approach would be to examine cross-sector linkages, for instance, examining the extent to which manufacturing centrality comes from linkages to services or other manufacturing sectors, which is illustrated in the Appendix.

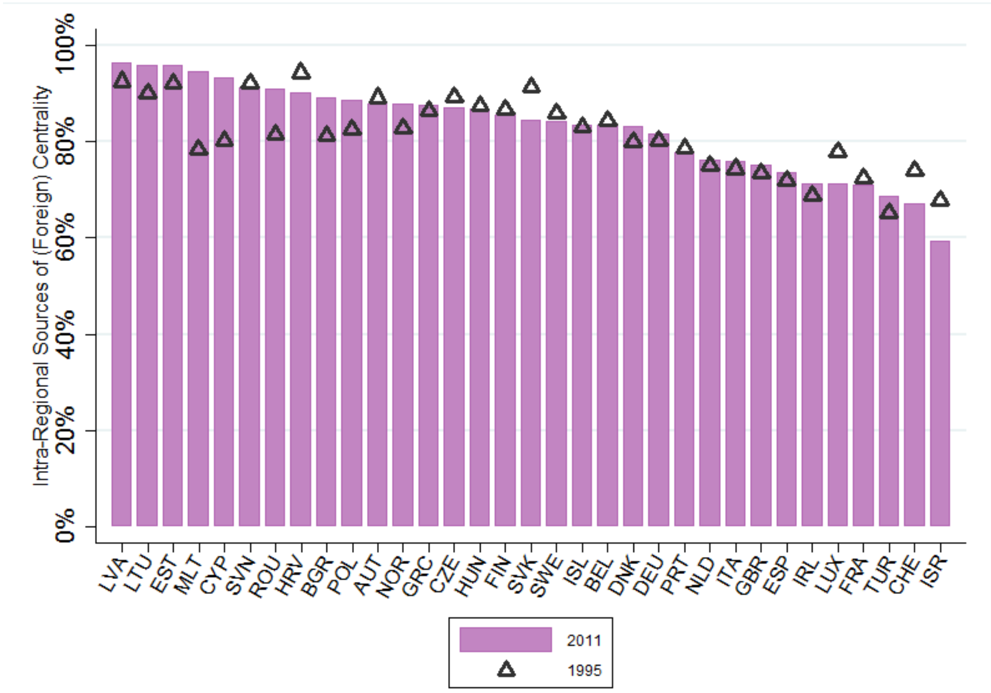
55. We observe very strong intra-regional linkages within Factory Europe. To measure the strength of intra-regional linkages we decompose foreign centrality into the component relating to foreign countries in the same region and other regions. Within Factory Europe almost all the centrality is relates to linkages with countries within the same region, with sources within the same region accounting for between 59% (Israel) and 96% (Latvia) of a country's centrality in 2011 (see Figure 16). Clearly there is some variation within the region, with larger (such as UK and France) and more geographically peripheral countries (such as Israel and Turkey) tending to be more integrated with countries outside of Europe. Smaller countries and those more geographically central tend to source more of their centrality within Europe. These patterns are as expected, given the importance of physical distance as a barrier to trade and also because smaller and less productive firms tend to trade more intensively with closer markets than with more remote markets (Holmes and Stevens, 2012, Bernard et al., 2011a; Bernard et al., 2016). Comparing values in 1995 and 2011, we also find evidence of increased regional integration of Eastern European economies, which is something we examine further in the subsequent section. However, the regional share of centrality for most other European economies has remained relatively constant over the period.

56. Similarly, there are strong intra-regional linkages within Factory Asia. A high proportion of the centrality of Asian economies derives from within the region, accounting for between 42% (India) and 95% (Brunei) in 2011 (see Figure 17). Although there is a little more heterogeneity than in Factory Europe, overall levels of regional integration remain high in Asia. Again we see similar patterns of the largest and more remote economies with lower intra-regional linkages, such as China and India, compared to those that are smaller of more geographically centrally located. These findings are also consistent with research suggesting a strong regional component to value chains (Baldwin and Lopez-Gonzalez, 2015). At an economy-level we find limited evidence of further regional integration (compared to extra-regional integration) over the period. Comparing the proportion of centrality derived from within Asia remains broadly contain for most Asian economies, and some Asian economies increase their influence outside Asia (e.g. Vietnam, Cambodia).

57. However, intra-regional linkages are much weaker in North American or Central and South American production networks. Less than 20% of the centrality of US, Canada and Mexico derives from other North American linkages, far lower than intra-regional European or Asian linkages (see Figure 18). Similarly, less than 40% of the centrality of Central and South American countries derives from linkages within the same region[10]. These limited levels of intra-regional integration for Latin America mirrors findings using regional sources of value-added in exports by Cadestin et al. (2016). Furthermore, these patterns seem to be broadly consistent over time, with low levels of intra-regional linkages in both 1995 and 2011 for many countries. Part of this is likely because of specialisation in raw materials in Latin America, which tend to have stronger linkages to other regions. However, we find that this pattern of weaker intra-regional sources of centrality holds more generally, for example within many manufacturing sectors too.

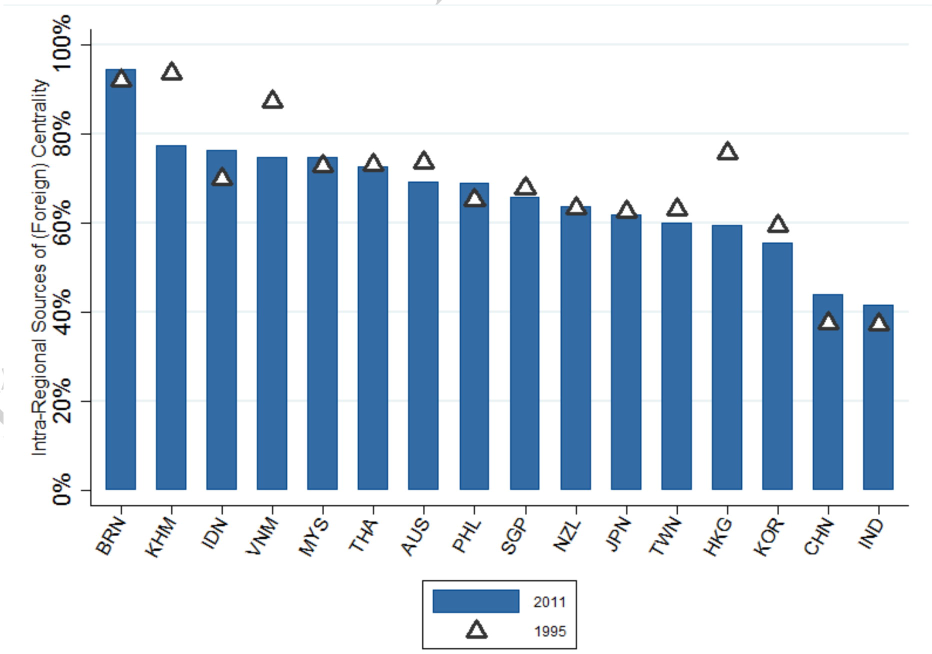
10 For Central and South America, the lower levels of intra-regional integration may in part reflect the more limited coverage of OECD-WTO ICIO/TiVA data within the region, which encompasses only five countries from this region. Consequently, a number of regional trade partners are included in "Rest of the World".

Figure 16: Very Strong Intra-Regional Linkages in Europe



Notes: Intra-regional sources of (foreign) centrality in 2011 denotes the share of total (foreign) centrality that relates to sources from the same region. Thus a value of 100% would denote all foreign centrality is derived from economies in the same region, and 0% would denote all foreign centrality is derived from countries in other regions.

Figure 17: Strong Intra-Regional Linkages in Asia



Notes: Intra-regional sources of (foreign) centrality in 2011 denotes the share of total (foreign) centrality that relates to sources from the same region. Thus a value of 100% would denote all foreign centrality is derived from economies in the same region, and 0% would denote all foreign centrality is derived from economies in other regions.

Figure 18: Weak Intra-Regional Linkages in North America and Central/South America

Notes: Intra-regional sources of (foreign) centrality in 2011 denotes the share of total (foreign) centrality that relates to sources from the same region. Thus a value of 100% would denote all foreign centrality is derived from countries in the same region, and 0% would denote all foreign centrality is derived from countries in other regions. For this analysis, Mexico has been included in N. America due to NAFTA linkages, following the approach of Baldwin and Lopez-Gonzalez (2015).

Centrality of European Country-Industries

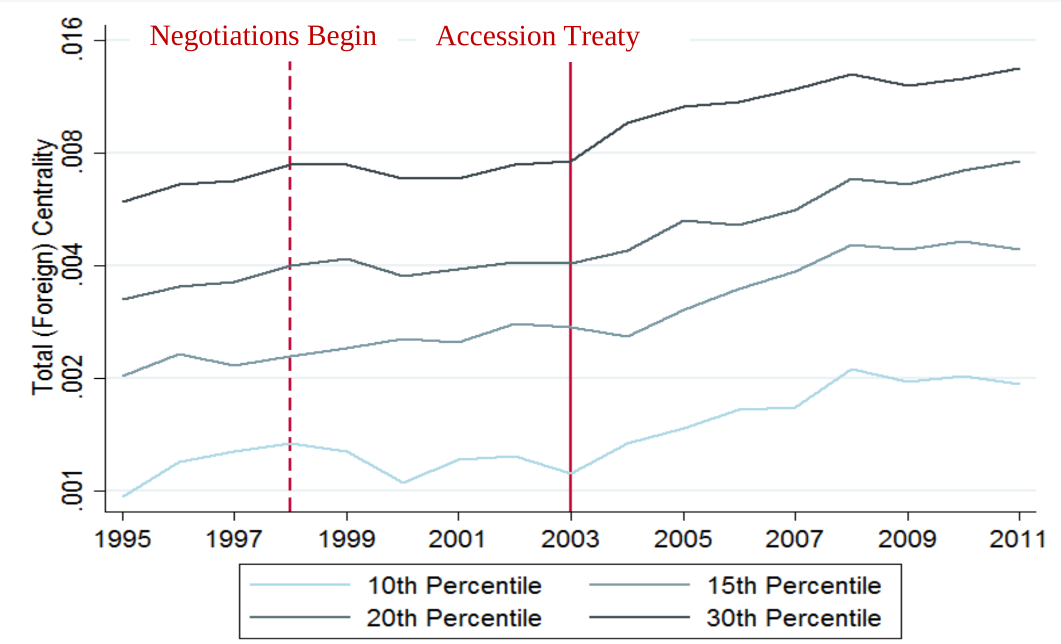
58. This section focuses on Europe, examining the centrality of European country industries in 1995 and 2011. We build on the analysis of previous sections, which found increases in the relative centrality of Eastern European countries for computing and electronics manufacturing, as well as an increasing reliance on intra-European sources of centrality for these countries. We first examine changes in the distribution of centrality in terms of changes at the periphery or those central hubs. We then drill down on the set of post-2004 EU countries to examine their centrality over time. Finally, we illustrate some examples of countries that have experienced broad changes in the centrality of their manufacturing and services industries.

59. The most peripheral European sectors have become more integrated within Factory Europe, which has been mainly driven by post-2004 EU accession countries and the increased centrality of the periphery coincides with the period of EU accession. Figure 19 shows that for the periphery (the least central 30 percent of industries), the trend growth of centrality increases post-2004, at least until the crisis in later years. The trends in production linkages broadly mirror those in ownership linkages, captured by data on FDI flows for these same peripheral country-industries (Figure 20). We find that those peripheral industries of post-2004 EU accession countries experienced large increases in FDI around the same time as EU accession and increasing centrality, which suggests there may be complementarities between ownership and input linkages. Indeed, other authors have found that the rise the entry of foreign firms into Eastern Europe has been an important factor affecting GVC upgrading (e.g. Harding and Javorcik; 2012, Bajgar and Javorcik, 2016).

60. Some countries that appear to have experienced comprehensive structural changes across broad sectors over 1995-2011. For instance, every services sector in our data for Luxembourg and Ireland has become more influential to global production over time (as noted in Figure 27). However, the changes for Luxembourg have been concentrated in financial services, whereas Ireland has benefited from broad growth in services centrality across the board. In contrast, the business services sector in the UK has shown pronounced increases in importance, but this is not a trait shared across all UK service sectors. However, if we consider the period before the financial crisis (1995-2007), we see a broad growth in centrality across all UK service sectors (see Appendix Figure A5). In particularly, before the crisis the UK financial services sector showed strong centrality growth, on a par with that of Luxembourg. Furthermore, the fall in centrality for UK wholesale and retail and transport services revealed over the whole period 1995-2011, did not emerge until after the crisis, with these sectors showing little obvious changes in centrality before 2007 (see Appendix Figure A6).

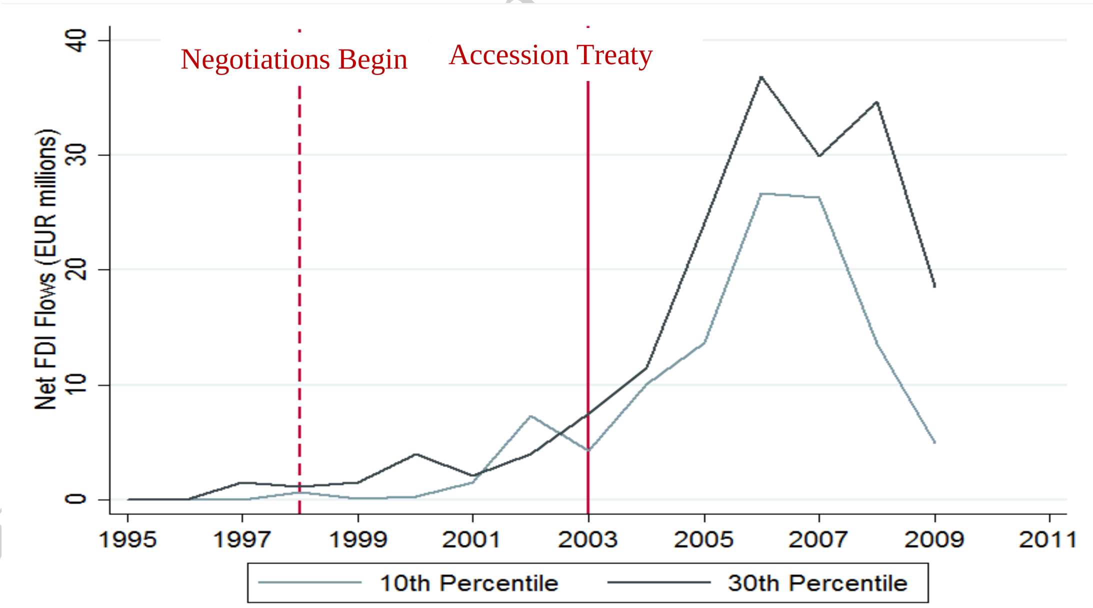
61. Manufacturing in the UK and to a lesser extent in Italy, which both started from an initial high-level of centrality, have both experienced broad declines in centrality (see Appendix Figure A7). In both the UK and Italy, petroleum products is the only manufacturing industry to substantially increase its importance, mirroring the increasing importance of natural resources to global production networks noted earlier. In general, almost every manufacturing industry in the UK and Italy has become less influential over the period (although to put these declines in context, still remaining above the European average in 2011).

Figure 19: Centraity Growth of the periphery of 2004 EU Accession Countries over the period of EU Accession



Notes: The percentiles reflect those country-industries that are most peripheral within the set of 2004 EU accession countries. 2004 EU Accession economies include: Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Slovakia and Slovenia. The percentiles are defined afresh for each year and so represent different country-industries over time. Total (foreign) centrality is measured at the country-industry level.

Figure 20: FDI Growth of the periphery of 2004 EU Accession Countries over the period of EU Accession



Notes: The percentiles reflect those country-industries that are most peripheral within the set of 2004 EU accession countries. FDI flow data sourced from EUROSTAT. To minimise noise in the FDI data, "30th percentile" reflects the mean FDI flows for those industries between 20th and 40th percentiles of foreign centrality (where centrality percentiles are defined as in Figure 25, "10th percentile" reflects the mean FDI flows for industries between 1st and 20th percentiles of foreign centrality. 2004 EU Accession economies include: Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Slovakia and Slovenia. The percentiles are defined afresh for each year and so represent different country-industries over time. Total (foreign) centrality is measured at the country-industry level.

Centrality of Asian Country-Industries

62. Here we build on the previous sections, which found increases in the relative centrality of several Asian countries. We first graph the distribution of centrality in 1995 and 2011, to examine whether changes are primarily in terms of the periphery or central hubs. We then illustrate some examples of countries that have experienced broad changes in the centrality of their manufacturing and services industries.

63. Within Factory Asia the country-sectors of moderate centrality have become increasingly central. Some countries emerge become increasingly central across a range of industries over this period. Earlier industry-level analysis showed that many Asian economies had become increasingly central for IT services and R&D and other business services, particularly China, India and Singapore. Services industries more generally in India and Singapore have consistently become much more central over the period (see Appendix Figure A8). India witnessed large increases in centrality not only of IT and business services sectors, which no doubt partly reflects service offshoring, but also transport services and wholesale and retail services. In addition, the manufacturing sectors of Malaysia and India have become much more central to global production, showing large increases albeit from a low starting point in 1995 (see Appendix Figure A9). The centrality growth is across a range of heterogeneous industries, part of this growth is in manufacturing of primary products, such as petroleum and chemicals for India and food for Malaysia, but others are in more complex manufacturing such as motor vehicles.

64. But the dominant change in Asia is the rise of China and the declining position of Japan as a key hub. As noted in the earlier overview section, Japan started the period as the dominant key hub in factory Asia. However, by 2011, China's influence in global production had risen, and Japan's relatively declined so that they display similar levels of aggregate centrality. Looking at specific industries within these economies, Appendix Figure A10 and Figure A11 show surprisingly that these aggregate patterns hold systematically for almost every one of the 34 industries in our data. The centrality of every Chinese manufacturing and service industry has increased substantially over the period, with some Chinese industries amongst the most influential in the world by 2011 (such as computing and electronics manufacturing noted earlier). However, motor vehicle manufacturing also shows a similarly strong trend of increasing centrality in China and declining centrality of Japan, this is to be contrasted against earlier observations of motor vehicles manufacturing in Germany and USA persisting as key hubs. Indeed the declining influence of almost every Japanese manufacturing and services industry is clearly reflected in the aggregate patterns seen earlier. However, the declining influence of many Japanese industries should be somewhat tempered by the observation that because of their starting point in 1995, some Japanese industries still remain amongst the most central in Factory Asia.

65. In particular, Chinese processing & export sectors have fast become central to global value chains, much more so than Mexican processing sectors. Almost every Chinese processing sector has become much more central to global production over 1995-2011 (see Appendix Figure A12). However, this is particularly pronounced in the case of the Chinese computing and electronics processing sector, which experienced a rapid rise to become a key hub for this industry (as noted in earlier sections). This contrasts markedly with Mexican processing sectors, which exhibit a much slower increase in centrality. These trends persist whether one considers growth rates or annualised growth rates (not reported here); Chinese processing sectors have become much more influential for global production. This is not simply a catch-up story, since Chinese processing sectors started from a higher level of centrality in 1995 than Mexican processing sectors (the only exception being motor vehicles). Chinese manufacturing processing industries started from an average foreign centrality of 0.09 in 1995, compared to the average for Mexican manufacturing processing industries 0.02. However, both Mexico and China's processing sectors started from far less influential compared to the global average, with the mean country-industry centrality equal to unity.

66. At the same time, this is not entirely a processing story, since Chinese export sectors have witnessed a similar increasing importance to global production networks. For most industries, aside from computing and electronics and electrical machinery, Chinese export sectors have become more influential for global production over time than their processing sectors (see Appendix Figure A13). Given this, one concern may be that we are simply picking up relative changes in the size of Mexican and Chinese economies, and the rapid growth of the Chinese economy in particular. If this was the case, one would expect to see a particularly pronounced increase in the domestic centrality of these Chinese sectors. However, in fact one observes the opposite, swift growth in foreign centrality is coupled with relatively slow growth in Chinese domestic centrality (see Appendix Figure A13). We examine the correlation between size and centrality further in the next section.

How does centrality compare with existing GVC metrics?

67. This section contrasts the Bonacich-Katz eigenvector centrality metric against those metrics commonly used in the trade and wider GVC literature. We compare first in levels, using both the forwards and backwards centrality metric, and then in changes over 1995-2011. We illustrate the new information provided by the centrality measure using a case study of Japan, which as noted earlier, exhibited one of the most pronounced declines in centrality over the period.

68. In levels, we find that both forwards and backwards centrality are strongly correlated with size in 2011. Appendix Table A3 presents correlations in 2011, at the country-industry level, between forwards centrality and various standard metrics used in the trade literature. We find that forwards centrality is strongly correlated with size, measured by the value of exported inputs, and somewhat correlated with forwards GVC participation. However, there is little correlation with revealed comparative advantage (RCA) in either gross or value-added terms (following Koopman et al., 2014) or the Fally (2011) measure of GVC upstreamness. Similar results hold for backwards centrality in levels in 2011, which is strongly correlated with size, measured by the value of imported inputs, but is not strongly correlated with the other metrics (see Appendix Table A4).

69. In changes over the period 1995-2011, we find backwards centrality is strongly correlated with size, but forwards centrality is only weakly correlated. Changes in forwards centrality is only weakly correlated with size changes over 1995 to 2011 (correlation = 0.36) and not strongly correlated with changes in other metrics (see Appendix Table A5). In addition, size growth is far more strongly correlated with metrics of revealed comparative advantage on either a gross or value-added basis than it is with changes in forwards centrality. However, changes in backwards centrality remains strongly correlated with size growth (correlation = 0.83), but is not strong correlated with changes in other metrics. Therefore size seems to be relatively important to determining centrality as a buyer (i.e. backwards centrality), but less important for determining centrality as a supplier.

70. The correlation with size is expected since larger firms and sectors are able to incur the costs of incurring more diverse and stronger linkages across the production network, accordingly we include industry size controls in later regressions. The trade literature commonly finds that only those largest, most productive firms are able to incur the sunk costs of trading with a wide variety of international trade partners (Bernard et al., 2011a; Bernard et al., 2016). Similarly, the literature on micro shock diffusion finds that a minority of firms are important for aggregate outcomes, both if they are large, but also if they are highly connected (e.g. Magerman et al., 2016). Clearly, both size and connectedness are endogenous outcomes of firm decision processes. Given their joint determination, it is not simple to separate these two factors. However, preliminary evidence attempting to decompose these two channels, suggest that network interconnectedness may be at least as important as size (Magerman et al., 2016). We perform a simple decomposition in the following analysis, to determine the extent to which centrality rather than size are driving the observed descriptive statistics.

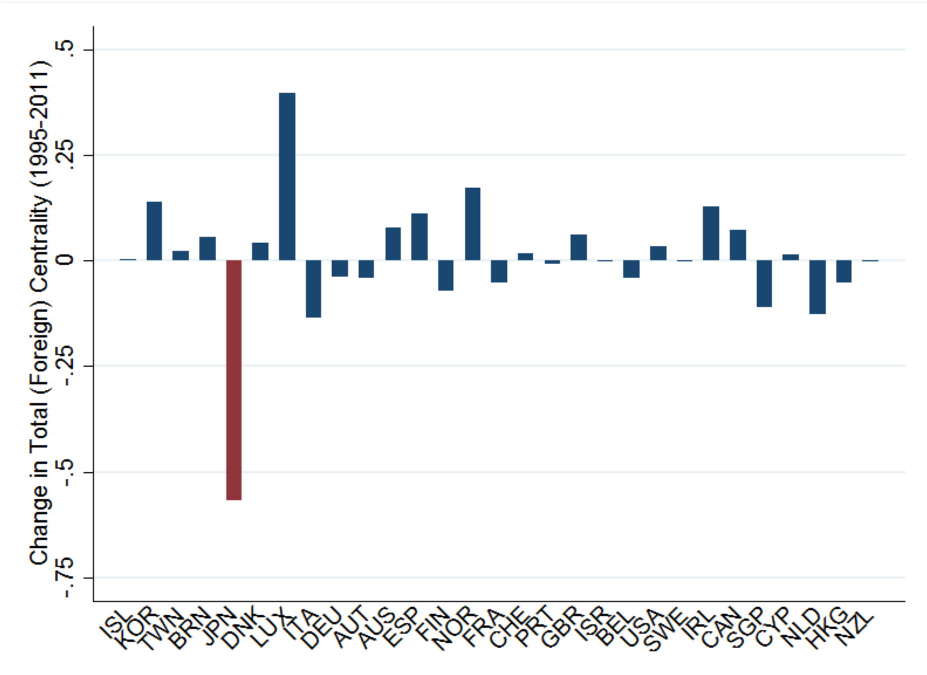
71. To illustrate the new features captured by our centrality metric, we focus on the case study of Japan. Earlier we saw patterns of a relative decline in centrality for almost every Japanese manufacturing and services industry. Unsurprisingly at the country-level Japan's total foreign centrality has fallen substantially (see Figure 21), with a fall in levels of 0.6. This is of a large magnitude. Even taking into account Japan's high initial level of centrality, this corresponds to nearly a 50% fall in foreign centrality over the 16 year period. The case of Japan contrasts sharply with other high-income economies such as Korea, Luxembourg and Ireland, which have shown broad increases in their centrality.

72. But in terms of GVC participation, Japanese participation has increased amongst the fastest of all high-income economies in our data. Japanese total GVC participation (both forward and backward) increased by 18% of gross exports over the period 1995-2011 (Figure 22). This reflects one of the largest increases in GVC participation amongst high-incomes economies, with only Iceland, Korea, Chinese Taipei and Brunei experiencing larger increases. Furthermore, the increased participation has resulted from both forward and backward GVC participation, with each metric increasing by around 9% of gross exports (Figure 38). Japan therefore presents an ideal test case to examine the extent to which the observed centrality changes are simply captured by either the growth in size of its economy or GVC participation. Both Korea and Luxembourg also sharply increase their GVC participation between 1995 and 2011, with Korea's participation increasing 23% and Luxembourg's 16%, similar in magnitude to Japan's increased participation (Figure 22). However, unlike Japan, both of these countries have shown increases in centrality over the period (Figure 21).

73. However, the decline in Japanese centrality does not seem to be mainly driven by the slow growth of the Japanese economy over the same period. Over the 1990s and 2000s, Japan has experienced relatively slow growth in its economy, relative to many developed economies. In Appendix Figure A14 we present centrality changes having stripped out the effect of size from the centrality metrics[11]. Clearly some portion of the decline in Japanese centrality is due to the slow growth in traded inputs, however, the bulk is not explained by size. Japan's decline in centrality remains a clear outlier even when removing the size effect. A similar pattern is observed across other OECD members, for example Luxembourg experienced a large increase in centrality due to its services sectors (as noted earlier). Although the size effect accounts for around half of Luxembourg's increasing centrality, after removing the size effect, it remains one of the largest increases in centrality within the OECD member economies. Thus although size seems to explain some of the centrality changes we observe, it explains only a relatively small fraction of the changes we observe.

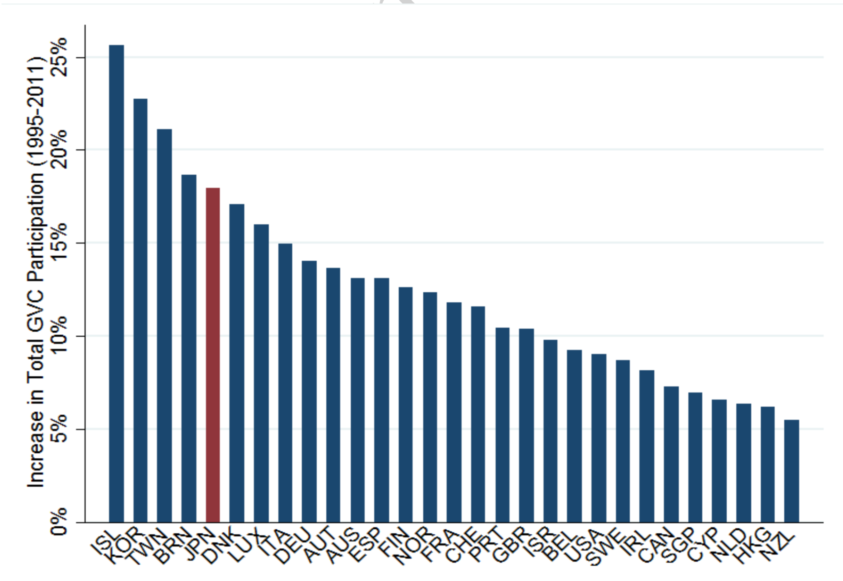
[11] We estimate the link between size changes and changes in centrality, and decompose the proportion of centrality changes into that explained by size and the residual unexplained by size. We define changes in size consistent with the correlation tables above, as the change in the value of traded inputs.

Figure 21: Japan's aggregate centrality has declined the most amongst High Income Economies



Notes: Total centrality (forward and backward) is aggregated at a economy-level and includes all sectors within global production networks. Changes here reflect the long-difference in centrality levels between 1995 and 2011.

Figure 22: Japan had one of the largest increases in GVC participation amongst High Income Economies



Notes: Total GVC Participation is the sum of Backward and Forward GVC Participation Metrics, measured as a proportion of Gross Exports. The Increase in Total GVC Participation reflects the change in levels between 1995 and 2011. High-income economies are classified following the grouping of the World Bank World Development Indicators in 1995, at start of the period.

GVC Centrality and Productivity

74. The first part of this paper has provided a detailed overview of centrality and how this has changed over time for different countries and sectors within global value chains. In the second part we analyse how centrality and its changes have affected the productivity of firms in different parts of GVC networks. We first briefly summarise the firm-level data, before outlining the empirical framework and then presenting the results and robustness analyses.

Firm-Level Data Description

75. This paper uses firm-level data from ORBIS, a harmonised cross-country dataset provided to the OECD by Bureau Van Dijk. To fully exploit our cross-country and cross-industry centrality measure, we use a broad coverage of countries and industries, retaining all countries with more than 250 observations in the matched data. This results in data that mainly reflects OECD economies, with data for 24 OECD economies and 5 non-OECD economies[12]. The industry detail is at the 2-digit in NACE rev. 2 and comprise the non-farm non-financial business sector excluding mining, petroleum manufacturing and real estate activities (i.e. codes 10-82, excluding 19, 64-66 and 68). ORBIS has relatively poor coverage of small firms, therefore we restrict the sample to firms with more than 20 employees (on average over the sample period).

76. We undertake a number of cleaning steps, closely following the suggestions by Kalemli-Ozcan, et al. (2015) and previous OECD analysis (Gal, 2013; Andrews et al., 2016). As discussed in Gal and Hijzen (2016) and Andrews et al. (2016), these data are cleaned and benchmarked using a number of common procedures such as keeping accounts that refer to entire calendar year, using harmonized consolidation level of accounts, dropping observations with missing information on key variables as well as outliers identified as implausible changes or ratios[13]. Nevertheless, a number of issues that commonly affect productivity measurement should be kept in mind, including: i) differences in the quality and utilisation of inputs cannot be accounted for as the capital stock is measured in book values; ii) firm-level prices cannot be observed, so firm-level differences in measured productivity may also reflect differences in market power[14]; and iii) measuring outputs and inputs in internationally comparable price levels remains an important challenge[15].

77. We match firm-level ORBIS data to our centrality metrics calculated using OECD ICIO data (discussed earlier), using a firm's country, NACE rev. 2 industry code and year. We employ a concordance between 2 digit NACE rev. 2 and 34 TiVA (ISIC rev3) industries to account for differing industry definitions between ORBIS and OECD ICIO data. The OECD ICIO data is available for years 1995-2011, which ultimately determines the number of years of our analysis. As noted in our empirical framework, we use one year lagged values of centrality, meaning that our period of analysis is 1996-2012.

12 OECD economies are Australia, Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Latvia, Luxembourg, Netherlands, Portugal, Spain, Sweden, Slovenia, Turkey, the United Kingdom and the United States. Non-OECD economies are Bulgaria, China, Indonesia, India and Romania.

13 We follow Andrews et al. (2016) and where firms record both consolidated and unconsolidated accounts, we keep consolidated data, dropping duplicate unconsolidated data.

14 As noted in the empirical framework, we examine robustness of our analysis to mark-up adjusted MFP following the approach of De Loecker and Warzynski (2012).

15 Monetary variables are deflated using 2-digit industry deflators from OECD STAN and national accounts and prices are expressed in industry purchasing power parities (PPPs), using the country-industry level purchasing power parity database of Inklaar and Timmer (2014).

The firms included in the final sample are predominantly of medium to large in size and are older firms, with a mean employment of 336 employees and a mean age of 22 years (see Table 1). Just over half these firms are in the services sector.

Table1: Summary Statistics of Firm-Level Data

	Mean	Std. Dev	N
MFP (logs)	10.9	0.98	2,013,223
Employment	335.63	4,632.04	2,013,223
Sales (PPP$ millions)	95.60	1372.80	2,013,223
Age	21.78	18.03	1,991,556
Services	0.57	0.49	2,013,223

Note: Age is not included as a control variable in our regressions as it is collinear with our fixed effects, but is included in this table for information purposes.

Centrality and Productivity: Empirical framework

78. In this section we outline our approach for examining how centrality affects the diffusion of productivity across firms, sectors and economies. We focus on how productivity changes in foreign sectors diffuse through key hubs to influence the productivity of domestic firms. We consider two aspects of this diffusion, as noted in Box 1.1. The first reflects the effect of becoming a central hub (regardless of which sectors are connected), and the second, the effect of connecting fast growing foreign sectors (regardless of centrality). We measure the former using the centrality metric explained earlier, and the latter using the average productivity (centrality weighted) of buyers / suppliers (as noted in Box 1.1).

79. We first examine whether becoming more central within GVCs translates into firm productivity growth. Specifically, we consider whether firms in industries that become more central over time, increase productivity faster than those in industries that become more peripheral. As noted in the introduction, central hubs play a key role in linking agents throughout the network. Central hubs by definition have a high degree of connectivity (both directly and indirectly), more widespread and closer linkages to other buyers and suppliers, and therefore potentially broader access to knowledge that these other agents possess. An emerging literature shows that central hubs play a key role in the transmission of shocks, both domestically and across borders. One may expect that central hubs may also facilitate the transmission of knowledge. As noted earlier centrality is a measure of influence within a network. This first metric therefore reflects whether becoming more or less influential within GVC networks matters for firm productivity.

80. Secondly, we examine whether who an industry connects matters for firm productivity growth. We measure whether firms have faster productivity growth in industries connected to faster growing foreign buyers or suppliers. The diffusion path of new knowledge is unlikely to be determined solely by influence within GVC neworks, but rather those sectors that are highly connected to new sources of knowledge are likely to benefit more. For instance, a key hub connecting highly productive, technologically advanced foreign buyers and suppliers is likely to have greater access to knowledge than a key hub connecting less productive ones. The diffusion of foreign knowledge may therefore depend upon the composition of buyer / supplier connections. We reflect this with the (centrality weighted) average productivity of foreign buyers / suppliers. The latter therefore reflects whether the productivity of a sector's more influential buyers or sellers matters for firm productivity.

Box 1.1 Technical Details of Diffusion Empirical Framework

We consider two aspects in our analysis of productivity diffusion. The first reflects the effect of becoming a central hub (regardless of which sectors are connected), and the second, the effect of connecting fast growing foreign sectors (regardless of centrality).

The first aspect is captured by the centrality measure elaborated in the first part of this paper. The second aspect is reflected by the average productivity (centrality weighted) of foreign buyers / suppliers and is discussed further below.

For each country-industry we can decompose all the various country and industry sources of backwards and forwards centrality and reflect the sources of influence of a country-sector on the GVC network. For example, in terms of country-industry i's backward (foreign) centrality, we can write as:

$$c_i^{back} = \sum_{j \in fgn} c\_source_{ij}^{back}$$

where c_source_{ij} are the foreign sources of backwards centrality, which are technically defined as (foreign) elements ij of the inverse matrix given by $\eta(\mathbf{I} - \lambda \mathbf{W}^{\mathbf{T}})^{-1}$.

We measure the average productivity of foreign suppliers or customers using sources of centrality as weights. Since centrality is a measure of influence within the GVC network, this reflects the productivity of a sectors' more influential foreign buyers and suppliers. Intuitively, productivity is assumed to diffuse more strongly to sectors that are more influential on one another, and less strongly to sectors that are more peripheral.

$$\overline{PROD}_i^{back} = \sum_{j \in fgn} \left({c\_source_{ij}^{back}} \Big/ {c_i^{back}} \right) \cdot Prod_j$$

Where $\overline{PROD}_i^{back}$ is the (centrality weighted) average productivity of foreign suppliers of country-sector i and $Prod_j$ is the productivity of each foreign country-sector supplier j, and the term in parentheses is the backward linkage centrality weights (that sum to one). To remove noise, we measure each foreign sector's productivity as the 3 year moving average of log labour productivity (value-added per worker in international PPP dollars).

Similarly we can write the (centrality weighted) average productivity of foreign customers:

$$\overline{PROD}_i^{fwd} = \sum_{j \in fgn} \left({c\_source_{ij}^{fwd}} \Big/ {c_i^{fwd}} \right) \cdot Prod_j$$

Where $\overline{PROD}_i^{fwd}$ is the (centrality weighted) average productivity of foreign buyers of country-sector i and $Prod_j$ is the productivity of each foreign country-sector buyer j, and the term in parentheses is the forward linkage centrality weights (that sum to one).

81. The empirical framework estimates the within-firm productivity effect of sector centrality and the effect of being connected to more productive (foreign) sectors. Firstly, it measures whether firms have faster productivity growth within sectors that become more central, compared to those that become more peripheral. Secondly, it also reflects whether growth in the productivity of foreign sectors translates into productivity growth of firms in sectors that are connected to them.

$$MFP_{ist} = \beta_1 c_{st-1} + \beta_2 \overline{PROD}_{st-1} + \beta_3 Industry\ Controls_{st-1} + \beta_4 Firm\ Controls_{st-1} + \delta_i + \delta_t + \varepsilon_{ist} \qquad [1.0]$$

where MFP_{ist} refers to the Multi Factor Productivity of firm i, in sector s and time t. c_{st-1} is the centrality of sector s, which is lagged one period, and refers to either total, forwards or backwards centrality in the results below. $\overline{PROD}_{st-1}$ is the average productivity (centrality weighted) of foreign buyers / suppliers, lagged one period, and refers to either total, forwards or backwards linkages. Industry controls include domestic sources of centrality, total (forwards and backwards) GVC participation, Fally's (2011) GVC upstreamness measure, Industry exports of intermediate goods and services, Industry imports of intermediate goods and services, Industry gross output (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage. Lagged firm employment is included as a control for firm size; firm age is not included since it is reflected in the fixed effects. The model also includes both firm and year fixed effects – while robust standard errors are clustered at the country-industry level, where industry reflects the 34 TiVA industries underyling the centrality measure.

82. The inclusion of both firm and time fixed effects means we are comparing within firm changes in productivity, due to industry-level changes in centrality or changes in productivity of their suppliers/customers. The firm fixed effects control for any time-invariant firm (and thus also industry or country) characteristics and year fixed effects control for any time-variant factors common across firms. We therefore reflected within-firm changes based on changes in centrality across country-industries. As noted earlier, centrality is a relative measure, such that it is relative to all other countries and industries in the network. Including further fixed effects, such as industry-year or country-year dummies, would depart from this. For example, including industry-year dummies would mean we are measuring changes across countries but within the same industry and year (e.g. computing and electronics manufacturing in 2000). We follow the approach of Imbs and Pauwels (2017) and do not include further fixed effects, but instead introduce a broad range of industry controls reflecting factors that may explain any link between centrality and firm productivity.

83. In the baseline specification MFP is estimated using the IV method proposed by Wooldridge (2009), and to allow for technological differences across industries, the production function is estimated separately for each 2-digit industry, controlling for year fixed effects. Estimation uses a real value added based production function estimation with the number of employees and real capital as inputs (deflated using 2 digit country-specific deflators). However, there is a large literature examining how imports can affect competition in domestic markets and hence firm mark-ups. Therefore one concern might be that centrality may affect firm mark-ups (through competition) differently to physical or quantity-based MFP (through knowledge diffusion). In robustness analysis we control for unobservable firm markups using the method of De Loecker and Warzynski (2012) to report mark-up adjusted firm MFP.

84. Another potential concern is that the network of input linkages underlying our measures may not be exogenously determined. Firstly, since more productive firms tend to trade more intensively and with more countries and trade partners (e.g. Bernard et al, 2011b; 2014), productivity increases themselves may lead to increased centrality within the GVC network, rather than the other way round. Secondly, domestic productivity may affect the composition of trade partners. Increases in productivity may result in more intensive connections to more productive foreign sectors. For example, evidence suggests firms do not

select their trade partners at random, but are more likely to trade with more productive foreign firms (since only the most productive firms import or export). Similarly, more productive economies tend to produce higher quality goods, which often require higher quality foreign inputs and these are often supplied by more productive foreign firms (Bas and Strauss-Kahn, 2015; Atkin et al. 2017). Finally, if firms can benefit from knowledge spillovers from productive foreign sectors, one may expect firms to actively choose to trade with such sectors. Thus, any productivity effect on firms may not be because of diffusion of knowledge through the network, but the endogenous formation of network linkages to yield such effects.

85. We address the potential endogeneity concern in several ways. The use of firm-level data and industry-level centrality measures reduces the scale of the problem, as it is unlikely that many firms are able to influence the centrality of their entire industry within the GVC network. Centrality of the industry is therefore likely to be exogenous from a firm perspective, especially when considering small and medium sized firms. However, a minority of highly productive firms often account for the bulk of input flows across borders and a minority of multinationals are often found to drive GVCs (De Backer et al., 2017). To mitigate this concern, we examine our results separately for different firm types, isolating whether the productivity effects are driven by a minority of these frontier firms that may be able to influence industry centrality or those smaller and medium-sized firms, far from the frontier, that are not likely to be able to influence industry metrics.

86. Finally, we use instrumental variables to predict the exogenous effects our variables of interest. In terms of our first variable, centrality, we use lagged values as a predictor. Since our specification already uses centrality lagged one period, we use centrality lagged three periods as an instrumental variable. Thus we are measuring the effect of centrality, due to historic changes, rather than any contemporaneous technology shocks that may lead to both increases in productivity and reorganisation of value chains. In terms of the productivity of buyers / suppliers, we use the initial structure of an industry's foreign buyer and supplier networks but current values of their foreign productivity. Thus we are measuring the effect of contemporaneous changes in foreign productivity, taking the network of buyers and suppliers as fixed over the period.

Empirical Results

87. In this section we present our empirical results on how productivity changes in foreign sectors diffuse through key hubs to influence the productivity of domestic firms. We consider two aspects as noted earlier, the first reflects the effect of becoming a central hub (regardless of which sectors are connected), and the second, the effect of connecting fast growing foreign sectors (regardless of centrality). We first present our baseline results, for all firms in the sample. Secondly, we examine various aspects of heterogeneity: by firm size / productivity, by country and by sector. Thirdly, we consider the robustness of the results and finally examine the role of policy in affecting productivity diffusion.

Baseline Results

88. Table 2 presents the baseline estimates of equation 1.0, examining the effects of changes in (foreign) centrality and productivity of foreign suppliers / buyers on domestic firm productivity. In terms of centrality, firms within sectors that become increasingly central do not tend to show faster productivity growth than firms in sectors that become more peripheral. This holds across both total centrality (column 1), as well as decomposing into centrality as a key supplier (forwards linkages – column 3) or as a key customer (backwards linkages – column 5), or even including a broad range of industry controls (columns 2, 4 and 6). Thus becoming a key hub or becoming more peripheral does not seem to impact firm productivity on average.

89. However, the average productivity (centrality weighted) of buyers / sellers does seem to be associated with firm productivity overall (see Table 2, columns 1 and 2). Decomposing total connections into those forwards and backwards, shows that what matters are forward linkages, i.e. forwards linkages as a supplier to more productive foreign buyers (columns 3 and 4). This is consistent with the notion that productive foreign buyers share knowledge with their suppliers, backwards through the value chain. A large literature on the productivity effects of FDI finds similar mechanisms, with evidence of spillovers from multinationals to their affiliate suppliers, with less evidence of forwards spillovers to their customers (Godart and Görg, 2013; Havránek and Iršova, 2011). In contrast, we find no effect of backwards linkages, i.e. being a customer of more productive foreign suppliers (columns 5 and 6). Thus using inputs from more productive foreign sectors does not seem to translate into domestic productivity gains. This latter result, might appear counterintuitive and in contrast with evidence on input liberalisation, suggesting that importing high quality inputs can lead to productivity gains of domestic firms (e.g. Amiti and Konings, 2007). However, this evidence is mainly based on data for emerging economies, whereas our sample of firms are being mainly from high-income countries, that may have pre-existing sources of high technology inputs. These results are again robust to including a range of industry controls in columns 2, 4 and 6.

Table 2: Baseline Results

MFP Wooldridge	(1)	(2)	(3)	(4)	(5)	(6)
	Total		Forward		Backward	
Centrality	-0.022	0.065	-0.021	0.024	0.050	-0.020
	(0.066)	(0.090)	(0.052)	(0.044)	(0.154)	(0.161)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	0.548***	0.493***	0.749***	0.757***	0.005	0.066
	(0.184)	(0.133)	(0.254)	(0.236)	(0.056)	(0.087)
Observations	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	N	Y	N	Y	N	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage.

Heterogeneity – Which Firms?

90. The previous section examined productivity effects for the "average" firm, however, it is not necessarily true that these effects will be homogenous across firms[16]. Further, if the positive effects are present for only a subset of firms, they may not be revealed in the previous section. On the one hand, frontier firms are more likely to be directly engaged in GVCs through trade and FDI linkages, so will have the greatest direct exposure to foreign technologies. In addition, these larger firms are more likely to be able to overcome the sunk costs of the complementary organisational investments needed to benefit from exposure to new technologies (see for example Brynjolfsson and Hitt, 2000). On the other hand, those firms further from the frontier are most likely to have the largest catch-up potential productivity gains from knowledge spillovers from foreign sectors.

91. This section examines whether heterogeneous effects by type of firm according to their productivity and size[17]. Firm type is determined by initial firm characteristics, taken at the start of the period, since these characteristics may be influenced by changes in the trade network over time. Firm size is measured with both employment and sales, with MFP reflecting initial productivity. One caveat to reaffirm with the firm size measure is that these data contains mainly medium and large firms, therefore we are not able to talk about small or micro firms. As a simple measure of heterogeneity, initial firm characteristics are interacted with the two variables of interest: centrality measure and productivity of centrality sources. The non-interacted term captures effect for smaller or non-frontier firms, whereas the interaction captures additional effect of centrality for larger firms or more productive firms.

92. In terms of the first measure, centrality, the baseline specification of the previous section suggested there was no evidence of centrality affecting the productivity of firms on average. Table 3 shows that this average result masks substantial heterogeneity across firm types for backwards centrality (becoming a key customer), with the fastest productivity growth for those furthest from the frontier

16 Monetary variables are deflated using 2-digit industry deflators from OECD STAN and national accounts and prices are expressed in industry purchasing power parities (PPPs), using the country-industry level purchasing power parity database of Inklaar and Timmer (2014).

17 Young firms are not well represented in our firm-level ORBIS data, limiting the ability to disentangle heterogeneous effects by age dimensions.

(columns 1 and 3). However this is significantly weaker for more productive firms. Assuming this effect weakens in a linear fashion, suggests that this effect becomes negative for the 20 per cent most productive, frontier firms in the sample. Note this relationship seems to be present only for backwards centrality, but not forwards centrality (as a key supplier, see column 2).

93. However, the heterogeneous effects are not quite as clear cut using size as compared to initial firm productivity above; with stronger evidence using sales, rather than employment as a size measure. Using firm sales as a measure of size suggests the productivity growth of smaller firms is positively correlated with their sector becoming more backwards central (as a key customer), and this effect diminishes for larger firms (columns 4 and 6). Assuming this effect weakens linearly, suggests this effect is negative for the 15 per cent largest firms in the sample. There is more limited evidence of heterogeneous effect of forwards centrality (see column 5) and there do not seem to be heterogeneous effects using employment as an alternative measure of size (columns 7 to 9).

94. In terms of the second measure, average productivity (centrality weighted) of buyers / sellers, the earlier baseline specification showed strong evidence that being connected to more productive foreign buyers (via forward linkages) is associated with domestic firm productivity growth. However, the average result again hides heterogeneous effects across firms of different types, with evidence that these positive effects are concentrated within those least productive firms, with the effects weakening for those closer to the frontier (see columns 1 and 3). There is also some evidence that productivity of non-frontier firms also grows faster when connected to faster growing foreign suppliers (via backwards linkages - column 2), however, the effects on non-frontier firms are stronger.

95. Looking at firms of different size, suggests that being connected particularly to more productive foreign buyers, but also foreign suppliers, matters for the productivity growth of smaller firms. Using firm sales as a measure of size, suggests smaller firms have faster productivity growth when connected to faster growing foreign buyers (via forward linkages) or foreign suppliers (via backward linkages), with those effects weakening for larger firms (columns 4 to 6). Again we find these effects are stronger for forwards linkages than for backwards linkages. This is broadly mirrored using employment as a measure of size, where similar, but weaker effects are found (columns 7 to 9).

96. An alternative way to measure heterogeneity is to examine the effects across different categories of firms, e.g. the largest 25%, smallest 25% of firms etc. The prior analysis assumed that the heterogeneous effect changed linearly with firm size or initial productivity, here we allow for differential effects across different categories of firm types. We segment the sample into quartiles based on initial firm characteristics, showing for example, the bottom quartile (25% least productive firms), 25-50th percentiles, 50th-75th percentiles and the top quartile (those above the 75% most productive firms). We similarly decompose our two measures of firm size into quartiles of the relevant distribution. These dummy variables are interacted with our variable of interest: the productivity of buyers / sellers. Unfortunately, the effect of the former variable, centrality, is too imprecisely estimated to identify separate effects for each quartile, which probably reflects the relatively limited coverage of ORBIS data of smaller firms, far from the frontier. One caveat to highlight is that since we only retain firms with more than 20 employees (on average over the sample period), our analysis distinguishes between medium and larger firms, rather than those very smallest.

97. The heterogeneous effects for firms of different productivity categories (frontier vs non-frontier) are shown in Figure 23. We report the estimated productivity effect for frontier and non-frontier firms, assuming the mean productivity growth of foreign buyers and sellers (using total linkages – both buyers and sellers). For frontier firms, the top quartile of most productive firms in our sample, their estimated productivity growth appears to be no different when connected to faster growing buyers and sellers. When looking beyond the frontier, we find a positive coefficient only for those furthest away from the frontier in

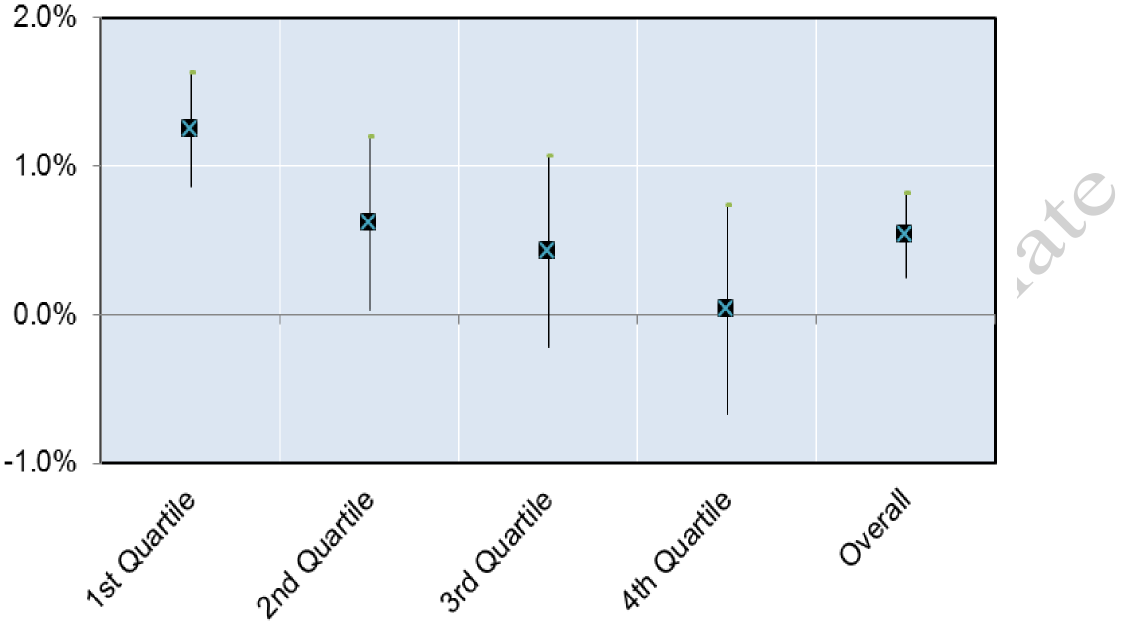
our sample, with an estimated firm productivity growth of just over 1% per annum. The figure also shows that the effect weakens with proximity to the frontier in a broadly linear fashion, supporting our approach in Table 3. Firm size shows similar results (see Figure 24). Again, we fail to find any positive effect for the largest firms, but for those smaller firms in our sample, the mean productivity growth of buyers and sellers relates to an estimated firm productivity growth of just under 1% per annum.

Table 3: Heterogeneous effects by firm type: Frontier vs Non-frontier and Large vs Small

MFP Wooldridge	Frontier vs Non-Frontier			Large vs Small Size (Sales)			Large vs Small Size (Employment)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Total	Forward	Backward	Total	Forward	Backward	Total	Forward	Backward
Centrality	1.406**	0.561	1.763***	0.893**	0.421*	1.043**	0.183	0.086	0.159
	(0.644)	(0.380)	(0.644)	(0.419)	(0.216)	(0.499)	(0.121)	(0.070)	(0.124)
Centrality * Initial Firm MFP	-0.121**	-0.048	-0.156***						
	(0.056)	(0.033)	(0.053)						
Centrality * Initial Firm Size				-0.050**	-0.024**	-0.059**	-0.027*	-0.012	-0.023
				(0.022)	(0.012)	(0.026)	(0.015)	(0.011)	(0.015)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	5.914***	6.209***	4.672***	3.024***	2.947***	2.277***	0.695***	1.063***	0.050
	(0.691)	(0.633)	(0.647)	(0.414)	(0.402)	(0.363)	(0.180)	(0.334)	(0.228)
Average Productivity (Centrality Weighted) of Buyers / Suppliers * Initial Firm MFP	-0.495***	-0.497***	-0.426***						
	(0.059)	(0.056)	(0.056)						
Average Productivity (Centrality Weighted) of Buyers / Suppliers * Initial Firm Size				-0.155***	-0.135***	-0.140***	-0.049***	-0.076**	-0.017
				(0.022)	(0.022)	(0.022)	(0.019)	(0.031)	(0.022)
Observations	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223
YEAR FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y	Y	Y	Y

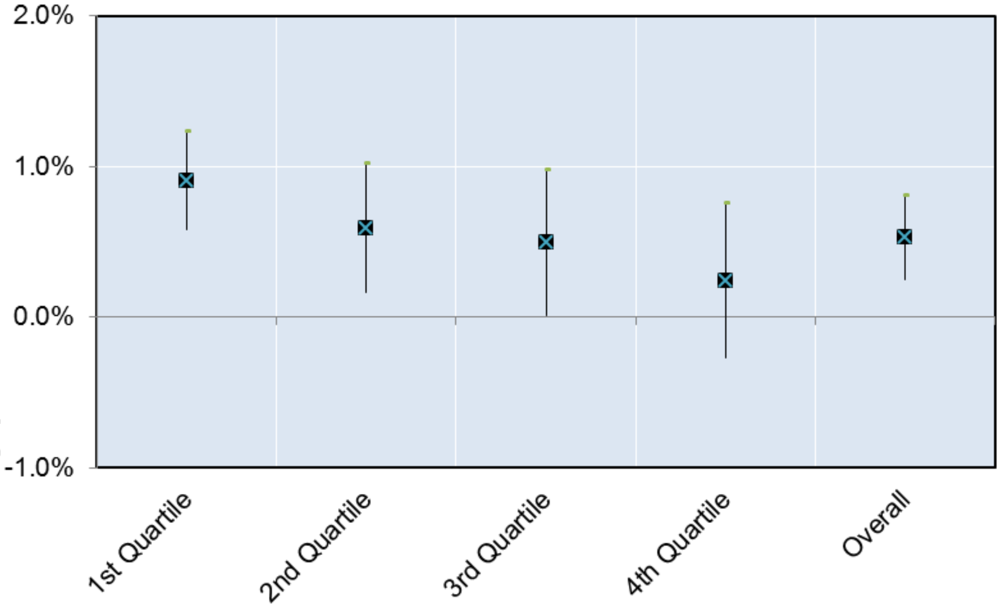
Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Initial firm size reflects employment in the first period. Firm size control reflects lagged employment and industry controls include GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage.

Figure 23: Annual Growth in MFP for Frontier and Non-Frontier Firms for mean growth in Productivity of Buyers / Suppliers



Notes: Mean estimated (annual) effects are reflected as points, with 95% confidence interval bars. Shown for firms of different quartiles of initial MFP, with 1st quartile representing the less productive initially to those most productive in the 4th quartile. Based on estimates from regressions including industry controls.

Figure 24: Annual Growth in MFP for Larger and Smaller Firms for mean growth in Productivity of Buyers / Suppliers



Notes: Mean estimated (annual) effects are reflected as points, with 95% confidence interval bars. Shown for firms of different quartiles of initial employment, with 1st quartile representing those smaller initially (sales less than 3million PPP$) to the largest in the 4th quartile (above 25million PPP$). Based on estimates from regressions including industry controls.

Heterogeneity – Which Countries?

98. This section examines potential heterogeneous effects by country, focusing on changes within Factory Europe and differences by country size (measured by population)[18]. In terms of changes within Europe, we consider the group of post-2004 EU accession countries and other European countries separately[19]. Earlier descriptive results showed that the European value chains have undergone large structural changes. The most peripheral European sectors have become more integrated within Factory Europe, which has been mainly driven by post-2004 EU accession countries. Earlier results revealed that although centrality does not seem to impact firm productivity on average, it can play a role in the catch up of non-frontier firms. However, many post-2004 EU economies had initial productivity levels (at the start of our period) below the European average. Therefore, the increasing integration of these economies into GVCs may affect firm performance differently to those European economies that were already relatively central and with relatively high productivity at the start of the period.

99. In terms of centrality, we find evidence of heterogeneity across countries in our sample; centrality appears to matter for the "average" firm in post-2004 EU accession countries but not for the rest of Factory Europe. Firms in post-2004 EU accession countries show faster productivity growth in sectors that become increasingly central to global value chains (see column 1, Table 4). Increasing centrality seems to be important in terms of becoming a key buyer (through backward linkages as a user of foreign inputs), rather than as a key supplier (columns 2 and 3). Many E. European countries have become offshore destinations of multinationals, with some industries such as automotive salient examples of this (as discussed earlier). Offshored production, particularly in assembly-type activities, is strongly driven by the ability to utilise a wide range of imported intermediates (see discussion in De Backer and Miroudot, 2013). Therefore, it is perhaps not surprising that becoming increasing central in terms of backward linkages that appears to relate to firm productivity growth. However, one caveat to note is that our firm-level data coverage of post-2004 EU economies is relatively limited and so the conclusions reached here may be stronger or weaker in more comprehensive data. In contrast, centrality does not appear to influence firm productivity in other European countries, consistent with the baseline (columns 4 to 6).

100. In terms of the (centrality weighted) average productivity of buyers / sellers we also find evidence of heterogeneity; the composition of buyers / suppliers appears to matter for the "average" firm in the rest of Factory Europe but less so for post-2004 EU members. In post-2004 EU members the productivity of buyers or suppliers or both does not seem to influence firm productivity (columns 1 to 3). In contrast, for the rest of Factory Europe, the results mirror the baseline. Firms on average have faster productivity growth in industries connected to faster growing buyers (through forwards linkages, column 5), but not faster growing suppliers (column 6). It therefore appears as though the composition of buyer and supplier networks matters more for the rest of Factory Europe, but less so for post-2004 EU members.

101. Considering frontier and non-frontier firms, we see broadly consistent evidence for both post-2004 EU members and other European countries, with strongest productivity growth of non-frontier firms (see Appendix Table A7). One distinction is that non-frontier firms in post-2004 EU members exhibit faster productivity growth when the industry becomes more central as a supplier or buyer or both. Whereas for other European countries this link holds only for centrality as a buyer. This mirrors the broad

[18] One alternative avenue is to group by income, for example splitting OECD and non-OECD countries or based on World Bank income classifications of countries. However, as noted earlier, the sample is overwhelmingly comprised of high-income OECD economies, representing more than 90% of firms in the analysis, limiting the reliability of any conclusions drawn from such a restricted sample.

[19] Unfortunately, it is not possible to perform a similar exercise considering Factory Asia separately, because of limited ORBIS coverage of Asian economies.

conclusion above, the integration of peripheral industries in post-2004 EU members seems to be related to firm productivity, much more so than other European countries. Finally, non-frontier firms have higher productivity growth when increasingly connected to both more productivity suppliers and buyers, and this holds across both sets of countries.

102. Our second measure of country heterogeneity examines differences by country size. We define smaller countries as those below the median population (fewer than 15.5million people) and larger countries with those above the median. It is not clear a priori whether productivity effects should be stronger in smaller or larger economies. On the one hand, smaller economies are often more integrated with foreign economies due to the limited scale of their domestic markets. The greater exposure to foreign sectors, combined with potentially shorter domestic supply chains, may increase the propensity for productivity to diffuse domestically. On the other hand, smaller markets are often more exposed to foreign shocks, which may be amplified by becoming a key hub, and so constrain any productivity effects of centrality. In addition, being a key hub is correlated with size (as shown earlier), suggesting that any effects of centrality may be reinforced by size of countries.

103. We find evidence of heterogeneity across country size: centrality is linked with overall productivity of firms in smaller countries but being connected to more productive suppliers or customers matters much less, whereas, for the larger countries we find the reverse (see Table 5). Firstly, becoming a key hub is associated with increases in the overall productivity of firms in smaller countries (column 1), and the increase in productivity is evident through both forwards and backwards centrality (columns 2 and 3). In contrast, for larger countries we find no effect of changing centrality, mirroring the baseline (column 4). Secondly, the productivity of buyers and suppliers is related to the productivity of firms in larger countries, but with less evidence for smaller countries. As in the baseline, for larger countries this is reflected mainly through forwards linkages (column 5).

104. Contrasting frontier and non-frontier firms, we see broadly consistent evidence for larger and smaller countries, which both mirror the results of earlier sections (see Appendix Table A8). Becoming more central as a key customer (backwards centrality) is associated with productivity growth of non-frontier firms in both large and small countries, but weakens with proximity to the frontier (columns 9 and 12). However, non-frontier firms have higher productivity growth when increasingly connected to both more productivity suppliers and buyers, and this holds across both larger and smaller countries.

Table 4: Heterogeneous effects by industry: Post-2004 EU Accession vs Other Factory Europe

MFP Wooldridge	(1)	(2)	(3)	(4)	(5)	(6)
	Post-2004 EU Accession			Other Factory Europe		
	Total	Forward	Backward	Total	Forward	Backward
Centrality	5.722***	2.621	4.295***	0.004	0.033	-0.083*
	(2.089)	(1.875)	(1.274)	(0.055)	(0.032)	(0.046)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	0.177	0.378	-0.358	0.398***	0.366***	0.133
	(0.331)	(0.459)	(0.267)	(0.122)	(0.119)	(0.086)
Observations	150,808	150,808	150,808	1,765,433	1,765,433	1,765,433
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage. The post-2004 EU accession countries in our sample are Bulgaria, Estonia, Hungary, Latvia, Romania and Slovenia. Other Factory Europe comprise Austria, Belgium, Germany, Denmark, Finland, France, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Sweden, Spain, Turkey and the United Kingdom.

Table 5: Heterogeneous effects by industry: Smaller vs Larger Countries

MFP Wooldridge	(1)	(2)	(3)	(4)	(5)	(6)
	Smaller Countries			Larger Countries		
	Total	Forward	Backward	Total	Forward	Backward
Centrality	0.551***	0.298**	0.334**	0.057	0.013	0.082
	(0.186)	(0.125)	(0.153)	(0.113)	(0.054)	(0.103)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	0.191	0.273*	-0.051	0.485***	0.879***	-0.083
	(0.159)	(0.156)	(0.110)	(0.163)	(0.333)	(0.226)
Observations	326,041	326,041	326,041	1,687,182	1,687,182	1,687,182
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage. Smaller countries are though below the median country's population at the start of the period (15.5million), and include Austria, Belgium, Bulgaria, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Luxembourg, Latvia, the Netherlands, Portugal, Slovenia and Sweden. Larger countries are Australia, China, France, Germany, India, Indonesia, Italy, Japan, Korea, Romania, Spain, Turkey, UK and the USA.

Heterogeneity – Which Sectors?

105. Earlier analyses found evidence of profound changes in the structure of GVCs, with notable contrasts across manufacturing and services sectors. In particular, some manufacturing value chains had shifted from traditional centres of production to E. Europe and Asia, whereas many services have become more important for value chains (almost) universally. This section examines whether earlier productivity results show similar distinctions across these sectors, by considering firms in manufacturing and services sectors separately.

106. Looking at performance of all firms in either services or manufacturing industries we find little evidence of differential effects between the two sectors. Table 6 repeats the baseline specification separately for services sector and manufacturing firms, with the results reported in columns 1 to 3 and 4 to 6 respectively. Firstly, as in the baseline we find no evidence of an overall role of centrality, as a key supplier or customer, for the productivity of manufacturing or services firms. Secondly, considering the productivity of foreign buyers and suppliers, the results also mirror the baseline. Firms have faster productivity growth when supplying faster growing foreign buyers (via forwards linkages) in either the services or manufacturing sector, but we find no correlation with backwards linkages.

107. Contrasting frontier and non-frontier firms, we also see limited evidence of heterogeneity across manufacturing and services sector (see Appendix – Table A9). Firstly, the results of the previous section suggested that becoming a key customer (backwards centrality) correlated with the productivity growth of non-frontier firms, but there was little association with becoming a key supplier. We find this is true of non-frontier service sector firms, and again the effect weakens with proximity to the frontier (column 2 and 3). However, there is no evidence of any effect of centrality on non-frontier or frontier manufacturing firms (column 5 to 6). Secondly, the previous section suggested that non-frontier firms have faster productivity growth when connected to faster growing foreign buyers or suppliers. We find consistent results here for non-frontier firms from both forwards and backwards linkages in both manufacturing and services, with again the correlation weakening with proximity to the frontier.

Table 6: Heterogeneous effects by industry: Services vs Manufacturing

MFP Wooldridge	(1)	(2)	(3)	(4)	(5)	(6)
		Services			Manufacturing	
	Total	Forward	Backward	Total	Forward	Backward
Centrality	0.198	0.094	0.100	-0.038	-0.030	0.025
	(0.132)	(0.062)	(0.111)	(0.176)	(0.133)	(0.129)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	0.528**	0.933**	-0.124	0.268	0.453***	0.017
	(0.211)	(0.470)	(0.256)	(0.173)	(0.168)	(0.176)
Observations	1,155,105	1,155,105	1,155,105	858,321	858,321	858,321
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage.

Robustness –Endogeneity, causality and Instrumental Variable Estimation

108. One concern noted earlier might be that centrality and the choice of buyers and suppliers may not be exogenous and thus the relationship described above only reflects correlations rather than causal effects. However, the earlier results limit some of these concerns. In particular, any productivity effects appear to be predominantly concentrated among smaller and non-frontier firms, with these effects declining with size and proximity to the frontier, and becoming insignificant for the largest, frontier firms. These smallest, non-frontier firms are those least likely to be able to influence position within the GVC network and are very unlikely to participate in GVCs directly through trade or FDI. However, it may be there are other industry factors that may lead to both increases in productivity and changes in centrality. We use instrumental variable estimation to address these concerns.

109. We find our baseline results are broadly unchanged using instrumental variables for centrality and the productivity of foreign buyers and suppliers. As noted earlier, our first instrument predicts changes in centrality with lagged changes. Our second instrument predicts changes in the productivity of foreign buyers and suppliers, using changes in foreign productivity but holding the network of buyers and suppliers fixed. We find that both instrumental variables strongly predict our variables of interest (as reflected in F-statistics and first stage results in the Appendix Table A10). However, our baseline results are largely unchanged although somewhat more imprecisely estimated, as is typically the case with instrumental variable estimation. We fail to find an effect of centrality on firm productivity overall, but productivity growth in foreign buyers (through forward linkages) is associated with productivity growth of domestic firms (see Table 7).

Table 7 Robustness: Instrumental Variable Estimation

MFP Wooldridge	(1)	(2)	(3)	(4)	(5)	(6)
	Total		Forward		Backward	
Second Stage:						
Centrality	-0.003	0.039	0.017	0.032	-0.042	-0.020
	(0.135)	(0.109)	(0.075)	(0.053)	(0.113)	(0.125)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	0.185	0.342	0.387*	0.441**	-0.172	0.067
	(0.276)	(0.242)	(0.211)	(0.205)	(0.298)	(0.244)
Kleinbergen-Paap F-statistic	145.790	59.282	195.71	131.256	87.274	63.076
Observations	1,877,565	1,877,565	1,877,565	1,877,565	1,877,565	1,877,565
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	N	Y	N	Y	N	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage. First stage regression results are reported in the Appendix.

Robustness – Comparison vs GVC Participation

110. One concern may be that our centrality results are simply reflecting what can be identified using measures of GVC participation or the sources of value added in exports. There is clearly a connection between centrality and GVC participation; an industry cannot be central if it doesn't participate in GVCs. However, as noted earlier the correlation between these two measures is weak. Rather it seems participation and position within the GVC network reflects complementary aspects of GVC integration.

111. In this section we repeat the baseline regression, but add the productivity of sources of value-added as an additional explanatory variable, as well as reporting the correlation with GVC participation (which was already included as a control variable in the baseline specification, but the estimated coefficient was not reported)[20]. We find the baseline results are unchanged as a result of the inclusion of these additional GVC participation variables (see Table 8). Firm productivity growth is not faster in industries that become more central or more peripheral. However, productivity growth is faster in industries connected through forward supplier linkages to increasingly productive foreign buyers (columns 3 and 4). We also find that firms have faster productivity growth in industries that are increasing GVC participation as a supplier (forwards linkages, columns 3 and 4). However, the foreign sources of value added (columns 5 and 6) or foreign destination of domestic value added (columns 3 and 4) do not seem linked with firm productivity.

Table 8: Robustness: Comparison vs GVC Participation

MFP Wooldridge	(1)	(2)	(3)	(4)	(5)	(6)
	Total		Forward		Backward	
Centrality	-0.080	0.075	-0.057	0.052	0.122	0.104
	(0.107)	(0.095)	(0.055)	(0.036)	(0.129)	(0.090)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	0.351**	0.385**	0.603***	0.766***	0.029	0.069
	(0.172)	(0.170)	(0.208)	(0.211)	(0.073)	(0.147)
GVC Participation	3.792	1.217	11.822**	14.443***	-5.781	-7.206
	(4.498)	(4.884)	(4.851)	(4.300)	(7.745)	(6.471)
(Value Added Weighted) Average Productivity of Buyers / Suppliers	0.430	0.294	0.264	-0.032	-0.157	-0.132
	(0.466)	(0.439)	(0.265)	(0.212)	(0.244)	(0.200)
Observations	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223	2,013,223
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	N	Y	N	Y	N	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage. First stage regression results are reported in the Appendix.

Robustness – Mark-up Adjusted MFP

112. Another concern might be that our results are picking up the effect of GVC networks on competition and prices/mark-ups, rather than quantity-based MFP. A large literature examines how imports can affect competition in domestic markets and hence firm mark-ups. The previous analysis estimated revenue based MFP, due to the absence of data on firm prices, which is a common problem in the literature. Therefore, revenue-based MFP reflects changes in quantify-based MFP as well as changes in mark-ups. It may be that increasing centrality may both lead to knowledge diffusion that increases quantity-based MFP, but is offset by increased foreign competition, and hence lower mark-ups. In this section we repeat the baseline estimation controlling for unobservable firm markups using the method of De Loecker and Warzynski (2012) to report mark-up adjusted firm MFP.

20 The average productivity of sources of value added is calculated identically to the productivity of buyers and suppliers, but instead of using sources of foreign centrality as weights, instead uses sources of foreign value-added.

113. The baseline results are broadly unchanged when consider mark-up adjusted firm MFP. We find weak evidence of faster firm productivity growth in sectors that become increasingly central, when using mark-up adjusted measures of firm productivity (see Table 9). Sectors that become more central as a customer (backwards linkages) exhibit faster firm productivity growth, but this is not robust to including a broad range of industry controls (columns 5 and 6). Conversely we see no evidence of forward centrality relating to overall firm productivity (columns 3 and 4). The results for the productivity of buyers and suppliers are unchanged from the baseline measure of MFP. In particular, firms have faster productivity growth in industries that supply more productive foreign customers (forwards linkages, columns 3 and 4).

Table 9: Robustness: Mark-up Corrected MFP

Mark-up Corrected MFP	(1)	(2)	(3)	(4)	(5)	(6)
	Total		Forward		Backward	
Centrality	0.112**	0.062	0.052	0.007	0.130**	0.102
	(0.056)	(0.081)	(0.040)	(0.043)	(0.059)	(0.088)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	0.500***	0.493**	0.659***	0.634***	0.106	0.101
	(0.176)	(0.193)	(0.225)	(0.235)	(0.098)	(0.086)
Observations	1,884,635	1,884,635	1,884,635	1,884,635	1,884,635	1,884,635
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	N	Y	N	Y	N	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage.

What is the Role of Policy?

114. In this section we examine the role of policy in shaping how changes in the structure of GVCs translate into firm productivity growth. We focus on two policies in particular, employment protection legislation and product market regulations[21]. The previous results suggested that centrality and being connected to more productive buyers may play a role in the catch-up of non-frontier or smaller firms. However, evidence suggests that to fully leverage new sources of knowledge or technology, firms require to upscale and make complementary investments in skills, management organisation, processes etc. (see for example Brynjolfsson and Hitt, 2000). Firms are less likely to make such investments if they are sunk, and cannot be recovered in the event they are unsuccessful. Therefore, policies that limit the flexible operation of labour markets are likely to constrain the extent to which smaller firms can yield these potential productivity gains. In addition, limited product market competition is likely to constrain the incentive of firms to expand and move into new product markets, as well as trapping resources in a minority of incumbents.

115. We repeat the baseline specification (considering firms of all types), but include interactions with our two policy variables as additional variables: employment protection legislation and product market

21 More detailed policy measures of product market regulation (barriers to investment and barriers to entrepreneurship) have been estimated, but show similar results to the overall measure included in the main body, so have not been reported.

regulations[22]. These policy variables reflect the stringency of regulations and hence limitations to competition labour and product markets. Thus the interaction captures the additional effect of more constraining regulations.

116. We find that labour market policy in particular influences the relationship between the productivity growth of buyers or suppliers and firm productivity, with a far stronger relationship in economies with more flexible labour markets. In terms of centrality, we find that as in the baseline specification there is no relationship between centrality changes and firm productivity growth on average and this is unchanged by the inclusion of policy variables (see Table 10). However, we find that productivity growth of buyers or suppliers or both is correlated with faster firm productivity growth, and this is stronger in economies with more flexible labour markets (columns 1 to 3). In contrast, we find that product market competition appears unrelated to how the productivity of buyers or suppliers translates to firm productivity growth (columns 4 to 6).

117. Earlier analysis suggested that non-frontier firms were most strongly influenced by changes in centrality or productivity of buyers / suppliers, with little evidence for frontier firms. As a final step we consider how policy influences this relationship, focusing on labour market flexibility given results of the prior paragraph. As before, we segment the sample into quartiles based on the initial firm productivity, the 25% least productive firms, 25-50th percentiles, 50th-75th percentiles and above the 75% most productive firms, interacting these quartile dummy variables with our variable of interest: the productivity of buyers / sellers. The role of policy is reflected by including additional interaction variables, which multiply our policy measures with these quartile dummy variables interacted with the productivity of buyers and sellers. Clearly this is a lot of interactions and is working the data quite hard, implying parameters will be estimated more noisily than in previous sections, with larger confidence intervals.

118. Labour market policy appears to particularly impact non-frontier firms, their productivity growth is strongly correlated with productivity growth of buyers/suppliers particularly in flexible labour markets, with no such correlation in those most rigid markets. The heterogeneous effects for firms of different productivity categories (frontier vs non-frontier) for two different labour market policy regimes are shown in Figure 25. We report the estimated productivity effect for frontier and non-frontier firms, assuming the mean productivity growth of foreign buyers and sellers (using total linkages – both buyers and sellers). Panel A reflects a more flexible labour market policy, taking the most flexible employment protection legislation in our sample (the US), and Panel B reflects a less flexible labour market, using the least flexible employment protection legislation in our sample (Portugal at the start of the period, 1998). We find in flexible labour markets, productivity growth of buyers/suppliers is correlated with nearly 2% faster productivity growth per annum of firms furthest from the frontier (quartile 1, panel A). Note this is stronger than the 1% average estimate across all policy regimes noted in earlier sections. There is a weaker, but positive correlation for firms in the second quartile too. However, for firms closer to the frontier we fail to find any relationship. In contrast, in less flexible labour markets we find no relationship between buyer/supplier productivity growth and firm productivity growth for frontier or non-frontier firms.

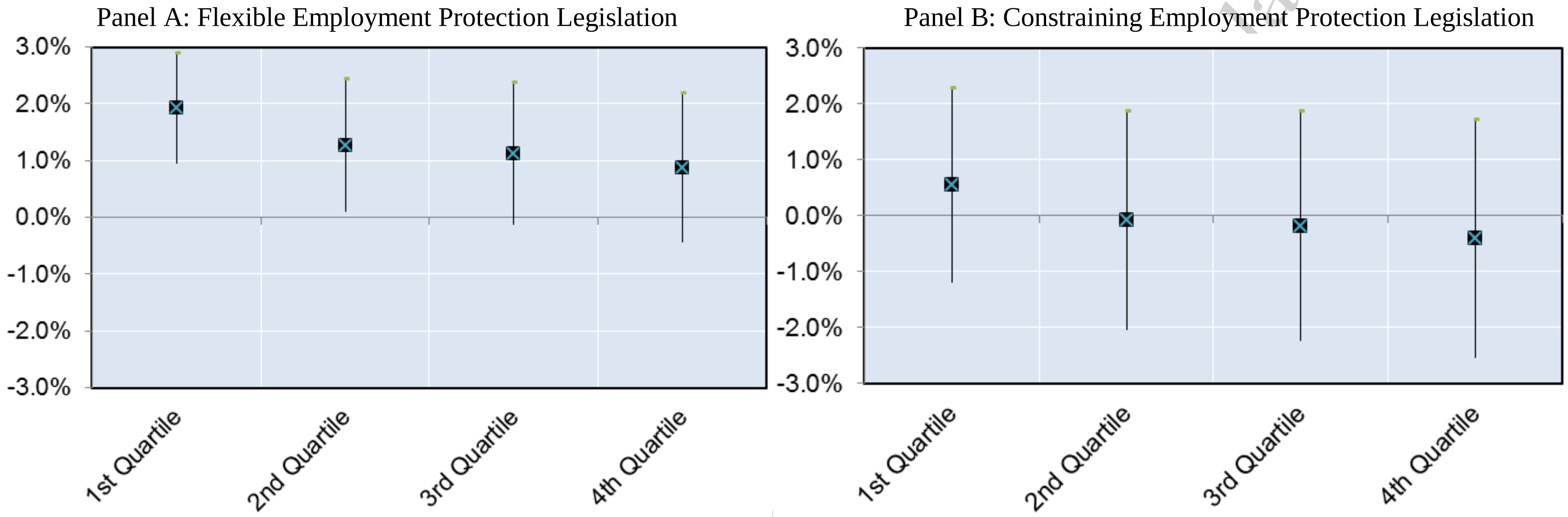
22 The economy-wide PMR indicator has been used in Table 10, however similar results are obtained if the 2013 Regimpact indicator or the components of the economy-wide PMR indicator.

Table 10: What is the Role of Policy?

MFP Wooldridge	(1)	(2)	(3)	(4)	(5)	(6)
Policy Barrier:	Employment Protection Legislation			Product Market Regulations		
	Total	Forward	Backward	Total	Forward	Backward
Centrality	0.204	0.095	0.321*	-0.019	0.050	0.032
	(0.148)	(0.099)	(0.173)	(0.096)	(0.154)	(0.071)
Centrality * Policy Barrier	-0.073	-0.034	-0.116*	0.017	0.011	0.012
	(0.055)	(0.040)	(0.061)	(0.022)	(0.019)	(0.020)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	1.624***	1.375***	1.420***	0.555***	0.273	0.393**
	(0.296)	(0.282)	(0.289)	(0.203)	(0.205)	(0.176)
Average Productivity (Centrality Weighted) of Buyers / Suppliers * Policy Barrier	-0.434***	-0.387***	-0.451***	-0.076	-0.005	-0.114
	(0.096)	(0.102)	(0.100)	(0.107)	(0.109)	(0.099)
Observations	1,749,475	1,749,475	1,749,475	1,748,087	1,748,087	1,748,087
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include the (non-interacted) Policy Variable, GVC participation, Domestic sources of centrality, Fally's (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa's Gross Revealed Comparative Advantage, and Koopman et al.'s (2012) Value-Added Revealed Comparative Advantage.

Figure 35: Annual Growth in MFP for Frontier and Non-Frontier Firms for mean growth in Productivity of Buyers / Suppliers –Labour Market Policy



Notes: Mean estimated (annual) effects are reflected as points, with 95% confidence interval bars. Shown for firms of different quartiles of initial MFP, with 1st quartile representing the less productive initially to those most productive in the 4th quartile. Based on estimates from regressions including industry controls, where employment protection legislation has been interacted with initial MFP quartile dummy variables interactions with Average Productivity (Centrality Weighted) of Buyers / Suppliers (from Figure 23). The effects are illustrated using the most flexible and least flexible labour market regimes in our sample: Flexible Employment Protection Legislation represents US 1998 values, constraining represents Portugal's 1998 values (the first year our policy variable is available).

Conclusions

119. We present new "centrality" metrics that go beyond GVC participation, reflecting central hubs and peripheral industries and countries within production networks. We utilise well-established metrics from network literature to identify those sectors and countries that are highly central hubs and those that are peripheral, i.e. reflecting the influence of sectors within production networks. Central sectors reflect those that are highly connected (both directly and indirectly) and influential within global production networks, and conversely, peripheral sectors exhibit weak linkages to other sectors and countries and so are less influential.

120. We illustrate that there have been profound changes in the structure of GVCs over the period 1995-2011. Whilst some activities remain clustered around the same key hubs as at the start of the period, for others there have been dramatic relocation of economic activity. We find that digital sectors in particular have undergone profound changes, with computer and electronics manufacturing value chains having undergone a pivot away from traditional centres of manufacturing towards increasingly being centred around emerging economies in Asia. In contrast, IT services have become more important for production networks in almost every country.

121. Policy can play a role in determining centrality and hence position within GVCs. Advances in communication technology have enabled the fragmentation of production, and permitted production to develop into the complex global network it is today. However, the changing structure of GVCs has not entirely been a technology story. We find that many emerging economies have increased their overall importance within global production networks. This is particularly true of most peripheral industries of Eastern European countries, with their growing importance coinciding with the timing of their EU accession.

122. We find that the changing structure of GVCs can play a role in the catch up of firms. We match centrality metrics to cross-country firm-level data from ORBIS to examine how changes in centrality affect the diffusion of productivity. Becoming more central as a customer (but not a supplier) is associated with faster productivity growth of smaller or non-frontier firms and also of firms in post-2004 EU members or smaller countries. But we find either insignificant or even negative effects for larger or frontier firms or firms in larger countries or the rest of Factory Europe (excluding post-2004 EU members). Consequently becoming more influential in GVCs appears to be important for the catch-up of those non-frontier firms and economies, whereas for those firms or economies that are already large or near the frontier, becoming more influential does not appear to impact productivity.

123. We find that the composition of buyers matters for firms in our data overall and this is particularly the case for the catch up of non-frontier or smaller firms. We supplement the standard centrality metrics by examining changes in the (centrality weighted) average productivity of foreign buyers / suppliers. Supplying or buying from faster growing foreign sectors is correlated with faster productivity growth of smaller or non-frontier firms, with these effects weakening with firm size or proximity to the frontier. But these correlations are only present in terms of the productivity of buyers for all firms, and also only in larger economies or the rest of Factory Europe (excluding post-2004 EU members). This may in part be due to poorer ORBIS coverage of firms in smaller economies and post-2004 EU members.

124. The impact of centrality and the composition of buyers and suppliers on the catch-up of firms is dependent upon the policy environment. Firstly, the positive correlation with productivity of non-frontier firms is more strongly present in economies with flexible labour markets, and weakens with the stringency of employment regulation. We find no evidence of productivity growth of non-frontier firms for those economies in our sample with the least flexible labour markets. Further, our results suggest that traditional policy measures to encourage integration into and influence within GVCs (such as trade facilitation, export

guarantees etc.) might be particularly important for the productivity of non-frontier or smaller firms, and also firms in smaller or non-frontier economies. Although our work examines international input linkages, it is also suggestive that policies that strengthen the domestic linkages between domestic suppliers and foreign firms may also be important in the diffusion of productivity gains, such as, local content requirements. However, our results also suggest the composition of buyer and supplier networks appear to also matter for spillovers to non-frontier firms and also for firms overall in larger or higher-income economies. These results suggest that more sophisticated policy to facilitate GVC integration may be needed, which particularly encourages the formation of linkages and diffusion of spillovers from highly productive, frontier foreign firms and economies.

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APPENDIX

1. Measuring Cental Hubs in GVCs – Additional Technical Details

a) Theoretical Models of Centrality – A Brief Overview

Box A1.1 Theoretical Models of Production Networks and Centrality

Several papers have recently proposed theoretical models where the influence of individual firms and sectors on aggregate outcomes is determined by their Bonacich-Katz eigenvector centrality (which is defined later) (see for instance Acemoglu et al., 2012; Carvalho, 2012; 2014; Magerman et al., 2016 and Imbs and Pauwels, 2017). These papers introduce a multi-sector model where the key assumption is that each good is either consumed or used by other sectors in production. Formally, they assume the production technology is Cobb-Douglas with constant returns to scale. The output of sector i is a combination of labour employed l_i, a sector-specific productivity shock z_i and intermediate inputs from all sectors (including itself) x_{ji}:

$$x_i = z_i^{\alpha} l_i^{\alpha} \prod_j x_{ji}^{(1-\alpha)w_{ji}}$$

$1 - \alpha \in (0\,,1)$ is the share of intermediates in production. w_{ji} is the share of input j in the total intermediates used in i, therefore these input shares sum to one, i.e. $\sum_j w_{ji} = 1$. As discussed later, this therefore provides a theoretical justification for scaling the raw OECD ICIO input flows, such that they reflect input shares rather than values.

Under these assumptions, aggregate GDP is the summation of industry-level productivity shocks ε_i, where the influence of each industry i on the aggregate is determined by their Bonacich-Katz eigenvector centrality within the network of input flows c_i. Productivity shocks in these models transmit from upstream industries through the production network to downstream industries. The industries' centrality reflects the strength of their direct and indirect backward linkages to upstream sectors and hence determines this propagation path of upstream productivity shocks. In addition, another implication is that productivity shocks to sectors that are more central, with greater direct and indirect linkages to others, influence aggregate GDP more, than those sectors with fewer direct and indirect linkages.

$$log\ GDP = \sum_i c_i \cdot \varepsilon_i$$

Conversely, demand shocks in these models (see for instance Magerman et al., 2016) propagate in the other direction, backwards from downstream to upstream sectors. Revenue of a firm / industry is determined by the sales of intermediates to downstream firms / sectors, plus sales to final consumers. These industries' centrality reflects the strength of their direct and indirect forwards linkages to downstream sectors and hence the diffusion path of downstream demand shocks.

Acemoglu et al. (2015) show that demand shocks propagating upstream and productivity shocks downstream is a feature of the Cobb-Douglas production technology, but that empirically for the US, demand and productivity shocks mainly operate in these predicted directions.

b) Technical Details of Centrality Calculations:

Box A1.2 **Technical Details of Centrality Calculations**

Backwards centrality is calculated as the baseline centrality (η) plus the weighted average of upstream (backwards) centralities, where the weights (w_{ji}) are the upstream input linkages (see 1.1). Similarly, forwards centrality is calculated as the baseline centrality (η) plus the weighted average of downstream (forwards) centralities, where the weights (w_{ij}) are the downstream input linkages (see 1.2). We outline in the appendix how these calculations are solved via matrix algebra.

$$c^{back}{}_i = \eta + \sum_j w_{ji} \cdot \lambda \cdot c_j^{back} \qquad [1.1]$$

$$c^{fwd}{}_i = \eta + \sum_j w_{ij} \cdot \lambda \cdot c_j^{fwd} \qquad [1.2]$$

We calculate total centrality as the average of forward and backward centrality. Using the average preserves the scale of the units, allowing direct comparison of total centrality with the forward and backward components. Instead of using the average, one could similarly define this as the sum of the two centralities, which in practice would differ only from our approach by a constant scaling factor.

$$c^{total}{}_i = {}^1\!/_2 \cdot \left(c^{fwd}{}_i + c^{back}{}_i\right) \qquad [1.3]$$

The parameter λ is key to determining the importance of higher-order linkages. The parameter λ determines the rate of decay of higher order network linkages. One can see from equation 1.1 that the centrality of i's direct suppliers (c_j^{back}) have a weight of λ. However, the centrality of i's suppliers of their suppliers has a weight of λ^2. One can see this in equation 1.4[23], where we the centrality of i's suppliers of their suppliers (c_k^{back}) has a weight λ^2. Thus, first-order linkages are weighted by λ, second-order linkages are weighted by λ^2, and this could be continued to even higher-order terms. A higher value of λ means that centrality is determined more by indirect linkages, conversely a lower value of λ implies centrality is determined less by indirect linkages.

$$c^{back}{}_i = \eta + \sum_j w_{ji} \cdot \left(\lambda \cdot \eta + \sum_k w_{kj} \cdot \lambda^2 \cdot c_k^{back}\right) \qquad [1.4]$$

We borrow from theoretical advances in the economics literature to specify the λ parameter. The theoretically-grounded models of Acemoglu et al. (2012) and Carvalho (2014) show the parameter λ reflects the average share of intermediate inputs in production. Carvalho (2014) uses a value of λ of 0.5, which reflects the average share of intermediates using their US data for 2002. Using ICIO/TiVA data the average share of intermediates in production is very stable across years, ranging from 0.52 in 1995 to 0.54 in 2011. We round this parameter value, λ, to 0.5.

The parameter η is a scaling factor, so is less crucial to determine centrality. One can see from equations 1.3 and 1.4 that the centrality of each sector is subject to a minimum level η. Under the theoretical extreme, where λ is equal to zero, all nodes would have this minimum level of centrality. Under the matrix calculation method we employ here (see Appendix), the choice of scaling is not particularly important[24]. The models of Acemoglu et al. (2012) and Carvalho (2014) show this should be (1-λ)/n, where n is the number of nodes in the network. However, Acemoglu et al. (2012) and Carvalho (2014) applied this to US data, where the number of nodes is only around 400 (with variations depending upon the precise year of data). Using OECD ICIO data there are 2108 country-sectors each year. Dividing by the number of observations in our cross-country-sector data would lead to a very low level of centrality per country-sector. For readability, we instead use 1-λ, i.e. 0.5, to avoid such small units.

23 To calculate 1.4, we use the recursive nature of 1.1. We start with expression 1.1, and substitute in for c_j^{back}, using expression 1.1.

24 This is not always case more generally, and thus this parameter attracts more attention in other literatures, for example, under a recursive calculation method which is more sensitive to the starting conditions in the calculation, or if an industry-specific value of η was used (for instance, as in Imbs and Pauwels, 2017)

c) Aggregation of Centrality Metrics

125. Centrality is calculated at the lowest level of aggregation in order to reflect the intricacies and complexities of the network structure. The OECD-WTO ICIO/TiVA data is a rich source of information which includes separate input-output tables for China and Mexico's processing and other sectors. This level of granularity is key as the importance of intermediate input flows is likely to differ substantially for processing and non-processing sectors. To allow for this, we calculate centrality at the most granular level available, taking advantage of these additional input-output tables, mirroring the approach for calculation of OECD GVC participation metrics. Therefore, for China and Mexico, we have separate centrality metrics for each processing and non-processing sector available in the data.

126. However, given the size of the network (with 4 million potential links per year) aggregation is needed to illustrate overall trends. Although aggregation is not needed for the performance analyses in the second part of this paper, some aggregation is needed for the illustration of aggregate trends in this paper. Furthermore, we also aggregate China and Mexico centrality metrics to a country-industry level to allow comparison with other country-industries, aggregating their processing and non-processing sectors. There is little theoretical guidance on how to aggregate centrality statistics with applications both in economics and beyond typically using data at the finest level of disaggregation. We aggregate each industry's centrality weighted by production share. For example, to calculate a country's aggregate manufacturing centrality we use the weighted average of manufacturing industry centrality, with weights equal to that industry's share in each country's total manufacturing production.

d) Equivalence of network scaling (ex-ante) vs PageRank centrality scaling (ex-post):

127. Here we briefly show that scaling the network, such that it reflects input shares (that sum to unity) and calculating Bonacich-Katz eigenvector centrality is equivalent to calculating PageRank centrality on the unscaled network of input flows (in values).

128. Suppose, the raw input flows z_{ij} are scaled to become w_{ij}, such that each of the columns of the matrix of scaled input flows **W** sum to one, i.e., $\sum_i w_{ij} = 1 \; \forall \; i$. The convention to achieve this in the literature is to divide each input flow z_{ij} by the total input ouflows $\sum_i z_{ij}$means as given below. Clearly summing each row of w_{ij} equals one by construction.

$$w_{ij} = {}^{z_{ij}}\Big/_{\sum_i \mathrm{z}_{ij}} \qquad [1.5]$$

129. Let us denote the sum of total outflows $\mathrm{s^{back}}_j = \sum_i \mathrm{z}_{ij}$, so we can write 1.5 as:

$$w_{ij} = {}^{z_{ij}}\Big/_{\mathrm{s^{back}}_j} \qquad [1.6]$$

130. The formula for calculating (forward) Bonacich-Katz eigenvector centrality using the scaled network **W** is repeated in 1.2 (from Appendix Box 1.2) below.

$$c^{fwd}{}_i = \sum_j w_{ij} \cdot \lambda \cdot c_j^{fwd} + \eta \qquad [1.2]$$

131. Using the definition of w_{ij}, we can write the (forward) Bonacich-Katz eigenvector centrality as:

$$c^{fwd}{}_i = \sum\nolimits_j {z_{ij}}\Big/{\mathrm{s^{back}}_j} \cdot \lambda \cdot c_j^{fwd} + \eta \qquad [1.7]$$

132. Similarly, one could scale the network such that the rows of the matrix of scaled input flows equal one. Following a similar logic to above, one can see that calculating (backward) Bonacich-Katz eigenvector centrality using this scaled network results in:

$$c^{back}{}_i = \sum\nolimits_j {z_{ji}}\Big/{\mathrm{s^{fwd}}_j} \cdot \lambda \cdot c_j^{back} + \eta \qquad [1.8]$$

133. One common variant of eigenvector centrality, commonly applied to networks beyond economics is PageRank[25]. These follow a similar formula to Bonacich-Katz eigenvector centrality noted earlier, except the raw intermediate input flows are scaled within the metric itself. Formally, the formulae for PageRank are given by 1.9 and 2.0 below. Forward PageRank centrality p_i^{fwd} is the weighted average of downstream centralities p_j^{fwd}, where now the weights are scaled by the total inflows of each downstream sector (denoted by $\mathrm{s^{back}}_j$). Similarly, backwards PageRank centrality p_i^{back} is the weighted average of upstream centralities p_j^{back}, where the weights are scaled by the total outflows of each upstream sector (denoted by $\mathrm{s^{fwd}}_j$).

$$p_i^{fwd} = \sum\nolimits_j {z_{ij}}\Big/{\mathrm{s^{back}}_j} \cdot \lambda \cdot p_j^{fwd} + \eta \qquad [1.9]$$

$$p_i^{back} = \sum\nolimits_j {z_{ji}}\Big/{\mathrm{s^{fwd}}_j} \cdot \lambda \cdot p_j^{back} + \eta \qquad [2.0]$$

134. As can be seen from 1.9 to 2.0, PageRank scales the underlying network flows (reflected by z_{ij} and z_{ji}). As noted above, the scaling of the forward linkages z_{ij} is by the total inputs used in the downstream sector. Therefore the rows of this scaled network sum to unity. Conversely, the scaling of backward linkages z_{ji} is by the total inputs produced by the upstream sector. Therefore the columns of this scaled network sum to unity. Comparing the ex-post scaling embedded within PageRank to calculating Bonacich-Katz eigenvector centrality on the ex-ante scaled network, one can see these are equivalent.

e) Calculating centrality in matrix form

135. In practice, the simplest way to compute these centralities is by expressing them in matrix form. If we stack the equations 1.1 and 1.2 (from Appendix Box 1.2) for each of the n country-sectors, we can express them in vector and matrix notation as given by 2.1 and 2.2 respectively. Where $\boldsymbol{c^{back}}$ and $\boldsymbol{c^{fwd}}$ are nx1 vectors of backwards and forwards eigenvector centralities of each of the n country-sectors respectively. $\mathbf{W}$ is a nxn matrix reflecting input linkages w_{ij} beween i and j, for all the combinations of pairs of country-sectors. **1** is a nx1 vector of ones, and λ and η are the parameters noted above.

$$\boldsymbol{c^{back}} = \lambda \mathbf{W}^{\mathbf{T}} \cdot \boldsymbol{c^{back}} + \eta \mathbf{1} \qquad [2.1]$$

25 PageRank centralities were first published by one of the founders of Google – Larry Page. These centralities underly the ranking of webpages in Google search results.

$$\boldsymbol{c}^{fwd} = \lambda\mathbf{W}\cdot\boldsymbol{c}^{fwd} + \eta\mathbf{1} \qquad [2.2]$$

136. These centralities may then be are solved by matrix inversion. Taking 2.1 and 2.2, by rearranging terms and talking the matrix inverse, one can solve for the vector of centralities, arriving at 2.3 and 2.4 respectively. Equivalently, these via matrix centralities could be solved recursively, which is an approach often other literatures when the full matrix of all network linkages is unknown (e.g. computer science applications to the Internet). As elaborated later, expressing in matrix form also has the added advantage that it permits easy decomposition of the resulting centrality into foreign and domestic components.

$$\boldsymbol{c}^{back} = \eta\left(\mathbf{I} - \lambda\mathbf{W}^{\mathbf{T}}\right)^{-1}\mathbf{1} \qquad [2.3]$$

$$\boldsymbol{c}^{fwd} = \eta(\mathbf{I} - \lambda\mathbf{W})^{-1}\mathbf{1} \qquad [2.4]$$

f) Decomposing Sources of centrality (e.g. Foreign vs Domestic, Intra vs Extra Regional)

137. We partition the inverse matrix to calculate foreign and domestic sources of centrality which follows the approach for standard decomposition of GVC participation metrics. For example, we can decompose the total forward centrality into the foreign and domestic component by partitioning the inverse matrix $(\mathbf{I} - \lambda\mathbf{W})^{-1}$. Thus $(\mathbf{I} - \lambda\mathbf{W})^{-1}_{fgn}$ contains the elements of the inverse matrix pertaining to foreign countries, with zeroes for domestic sectors, and $(\mathbf{I} - \lambda\mathbf{W})^{-1}_{dom}$ contains the domestic elements of the inverse matrix, with zeroes for foreign sectors. The resulting centrality from domestic sectors is given by $\boldsymbol{c}^{fwd}_{\boldsymbol{dom}}$ and foreign sectors by $\boldsymbol{c}^{fwd}_{\boldsymbol{fgn}}$ in 2.5 and 2.6 respectively. Clearly, summing the two partitioned matrices results in the original matrix, thus the sum of foreign and domestic and foreign centralities equals the overall forward centrality (reflected in 2.7).

$$\boldsymbol{c}^{fwd}_{\boldsymbol{dom}} = \eta(\mathbf{I} - \lambda\mathbf{W})^{-1}_{dom}\mathbf{1} \qquad [2.5]$$

$$\boldsymbol{c}^{fwd}_{\boldsymbol{fgn}} = \eta(\mathbf{I} - \lambda\mathbf{W})^{-1}_{fgn}\mathbf{1} \qquad [2.6]$$

$$\boldsymbol{c}^{fwd} = \boldsymbol{c}^{fwd}_{\boldsymbol{fgn}} + \boldsymbol{c}^{fwd}_{\boldsymbol{dom}} \qquad [2.7]$$

138. Similar partitions of the inverse matrix allow further disaggregation. Firstly, we use an equivalent approach to that described above, to partition the foreign sources of centrality into those from within the same region and other regions.). For example, we can decompose the foreign forward centrality given by 2.6 into the components from the same and other regions by partitioning the inverse matrix $(\mathbf{I} - \lambda\mathbf{W})^{-1}_{fgn}$. Thus$(\mathbf{I} - \lambda\mathbf{W})^{-1}_{fgn,\boldsymbol{intra-rgn}}$ contains the elements of the inverse matrix pertaining to foreign countries in the same region, with zeroes for elements relating to foreign countries in other regions (and of course domestic sectors). $(\mathbf{I} - \lambda\mathbf{W})^{-1}_{fgn,extra-rgn}$ the elements of relating to foreign countries in the other regions, with zeroes elsewhere (as noted by 2.8 to 3.0). Secondly, instead of using country partitions, one can similarly partition the inverse matrix along sectoral dimensions. This allows decomposition of each

sector's centrality into contributions of their own and other broad sectors; for instance, reflecting the influence of manufacturing sectors from service sectors or vice versa.

$$\boldsymbol{c}^{fwd}_{fgn,intra-rgn} = \eta(\mathbf{I} - \lambda\mathbf{W})^{-1}_{fgn,intra-rgn}\mathbf{1} \qquad [2.8]$$

$$\boldsymbol{c}^{fwd}_{fgn,extra-rgn} = \eta(\mathbf{I} - \lambda\mathbf{W})^{-1}_{fgn,extra-rgn}\mathbf{1} \qquad [2.9]$$

$$\boldsymbol{c}^{fwd}_{fgn} = \boldsymbol{c}^{fwd}_{fgn,intra-rgn} + \boldsymbol{c}^{fwd}_{fgn,extra-rgn} \qquad [3.0]$$

g) Summary Statistics of Centrality Metrics

139. This section presents summary statistics of our centrality metric to facilitate interpretation of the changes in the structure of GVCs shown in subsequent sections. These statistics also assess the extent to which the foreign components of centrality, the focus of this paper, are the key source of variation across economies and industries.

140. Centrality is a relative measure, reflecting influence relative to all other country-industries in the network. Notice that the mean overall (domestic and foreign centrality) is equal to unity in each year (Table 1). This follows directly from the specification of the parameters λ and η (that are constant across country-industries). One implication of this is that centrality is a relative measure, rather than an absolute measure. In particular, an increase in centrality does not mean that a country-industry is absolutely more central, in terms of stronger direct and indirect connections, but rather relatively more central compared to other country-industries in the network.

141. Domestic centrality exceeds foreign centrality in levels. Table A1 shows the summary statistics for foreign centrality (the focus of this paper), domestic centrality and overall (domestic and foreign) centrality for each country-industry in 2011. In levels the majority of centrality is accounted for domestically, for the mean industry 18% of their centrality results from foreign linkages and 82% from domestic linkages. This remains true even for the most central industries, at the top of the distribution. The top 5% most central industries have a foreign centrality of 0.78, slightly below the mean domestic centrality of 0.82. This suggests that many industries typically remain highly influential for their domestic economies.

142. However, there is much wider cross-sectional variation in foreign centrality than domestic centrality. The foreign centrality distribution is highly skewed, with the majority of country-industries having a very low foreign centrality, but also there are a minority of highly-influential central hubs[26]. The bottom 5% (least) central industries have almost zero foreign centrality, whereas the top 5% most central industries have a foreign centrality of more than 3 times the mean (see Table A1). This variation is much larger than domestic centrality, where the top 5% figure being less than twice the mean value. Alternatively one can show this same picture by graphing the distribution of foreign and domestic centrality across country-industries (Figure A1). One can see that relative to the mean, again there is a much wider spread of foreign centrality than for domestic centrality. Intuitively, country-industries are

26 The skewness of the foreign centrality distribution confirms the findings of related work, such as Cerina et al. (2015) considering first-order measures of centrality in WIOD data, and Carvalho (2014) applying the same Bonacich-Katz eigenvector centralities to US IO data.

much more heterogeneous in terms of foreign centrality, and more homogeneous in terms of domestic centrality.

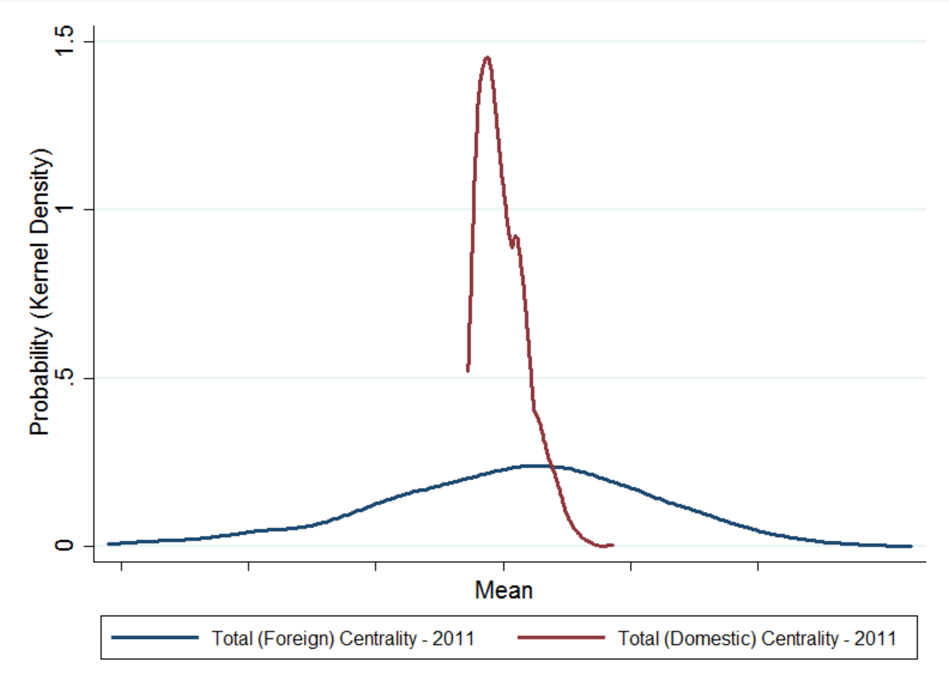
143. Foreign centrality also accounts for relatively more variation over time than domestic centrality. Table A2 shows the changes in foreign, domestic and overall centrality for the period 1995-2011. On average country-industries reveal increasing foreign centrality and declining domestic centrality. However, for the average country-industry these relative changes are rather small, with a mean increasing of foreign centrality by 0.02 and decreasing of domestic centrality by a similar magnitude. However, these small relative changes at the mean, mask large changes at the top and bottom of the distribution. The top 5% of country-industries increased their foreign centrality by at least 0.23, and the bottom 5% fell by at least 0.15. As we highlight later, the top 5% include computing and electronics manufacturing in China and motor vehicles manufacturing in Brazil, Eastern Europe, but also Germany. In addition, some of the largest increases in centrality are for business services in UK, USA and China, and financial services for Luxembourg and USA. We also witness substantial increases for petroleum and mining sectors for natural resource abundant countries (e.g. Australia, Brazil, Canada, China, Indonesia, Norway, Russia and USA). These changes are quite large, particularly when compared to the mean level of foreign centrality of 0.18 in 2011 (as noted above). Relative changes in domestic centrality are of a similar absolute magnitude, with the top 5% increasing by 0.22 and the bottom 5% falling by 0.27. However, these relative changes in domestic centrality are much smaller compared to the mean level of domestic centrality (0.82). Thus foreign centrality seems to account for more variation over time.

Table A1 - Distribution of Foreign and Domestic Centrality in 2011

	5^{th} Percentile	25^{th} Percentile	Mean	75^{th} Percentile	95^{th} Percentile
Foreign Centrality	0.00	0.02	0.18	0.17	0.78
Domestic Centrality	0.53	0.61	0.82	0.95	1.41
Overall (Domestic and Foreign) Centrality	0.54	0.66	1.00	1.11	2.05

Notes: Centrality is measured at the country-industry level, and reflects total centrality (the average of forward and backward values). Recall from section 2, overall centrality has a lower bound of 0.5, given by the minimum centrality parameter $\eta = 0.5$. Since some country-industries have no trade linkages the lower bound for foreign centrality is zero, and hence the lower bound for domestic centrality is 0.5.

Figure A1: Wider Variation in Foreign Centrality than Domestic Centrality



Notes: Kernel density function of cross-section values of total (foreign) and total (domestic) centrality in 2011, which are plotted on a log scale for readability. The values have been de-meaned, such that both foreign and domestic centrality has the same mean on the above graph. Note the truncation of domestic centrality due to the lower bound determined by the minimum centrality parameter $\eta = 0.5$ (see discussion in section 2.b).

Table A2 - Changes in the Distribution of Foreign and Domestic Centrality 1995-2011

	5^{th} Percentile	25^{th} Percentile	Mean	75^{th} Percentile	95^{th} Percentile
Foreign Centrality	-0.15	-0.01	0.02	0.03	0.23
Domestic Centrality	-0.27	-0.08	-0.02	0.03	0.22
Overall (Domestic and Foreign) Centrality	-0.35	-0.10	0.00	0.07	0.37

Notes: Centrality is measured at the country-industry level, and reflects total centrality (the average of forward and backward values). Changes here reflect the long-difference in relative centrality levels between 1995 and 2011, thus the units presented are comparable with those in Table 1.

2. Changing Structure of Global Production Networks

a) Additional Figures and Tables

Figure A2: Top 10 most central business services sectors in 1995 and 2011

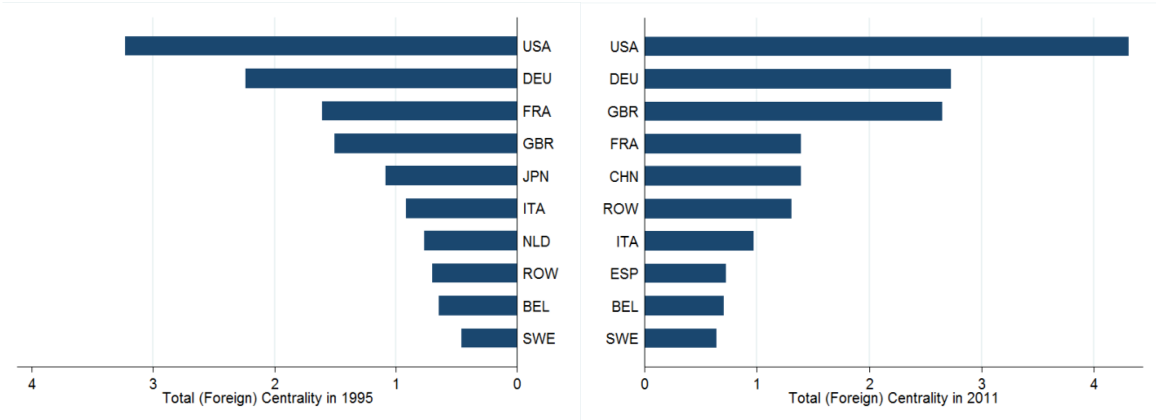
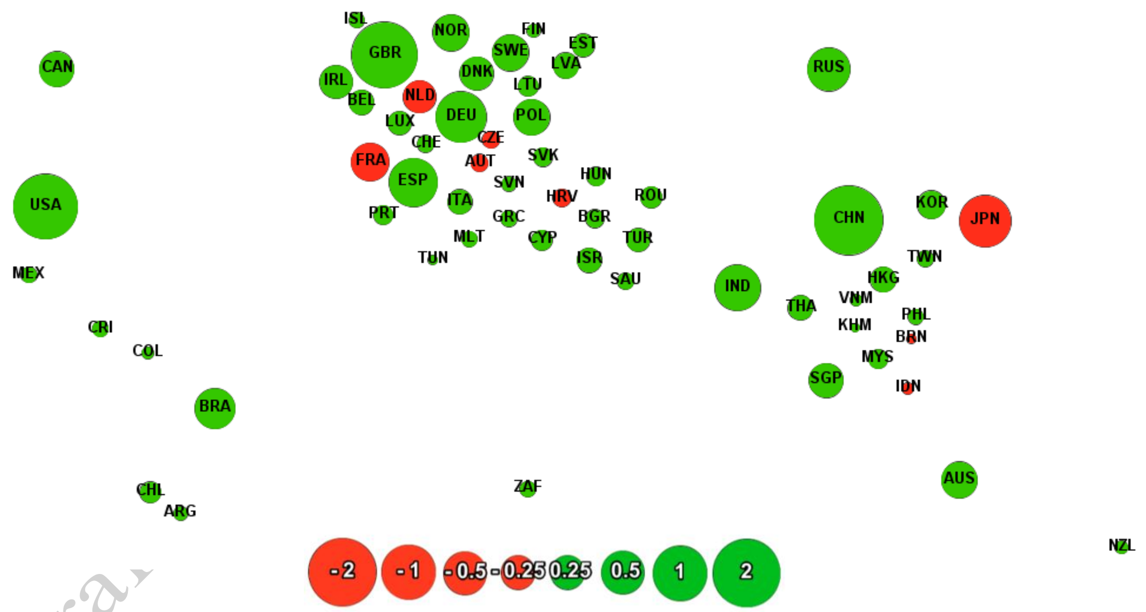
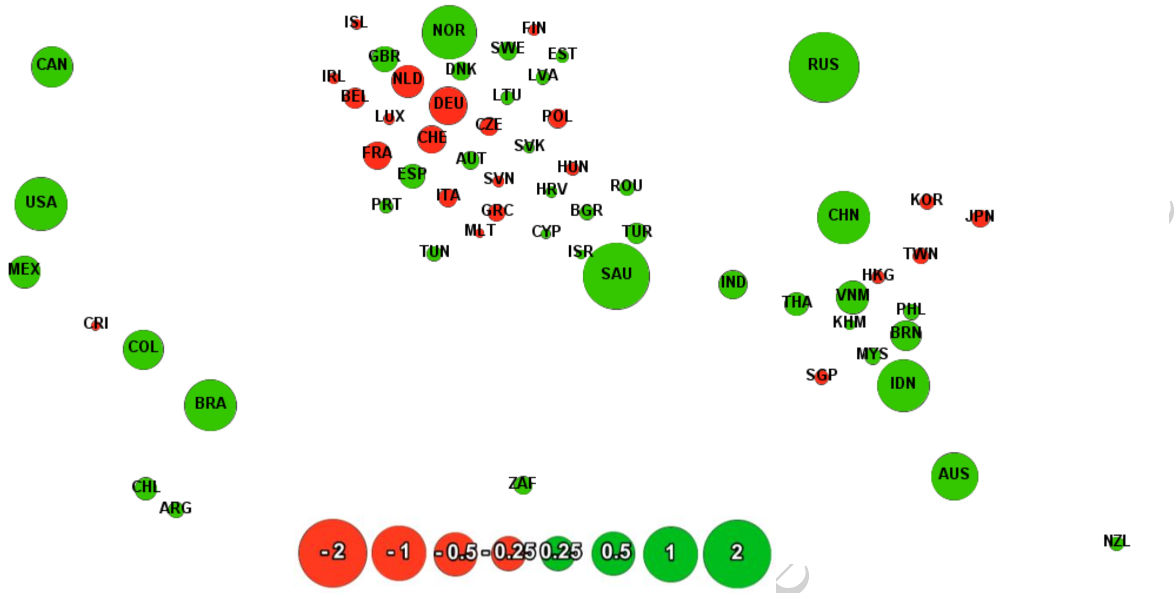


Figure A3: Relative change in centrality of R&D and other business services across economies (1995-2011)



Notes: Economies are placed according to their location. Size of the nodes reflects the magnitude of the change (in levels) of total foreign centrality over the period 1995-2011. As reflected in the key, these changes are graphed using a log scale for readability. Green coloured nodes reflect increasing centrality and red denotes falling centrality.

Figure A4: Relative change in centrality of mining & quarrying across economies (1995-2011)



Notes: Economies are placed according to their location. Size of the nodes reflects the magnitude of the change (in levels) of total foreign centrality over the period 1995-2011. As reflected in the key, these changes are graphed using a log scale for readability. Green coloured nodes reflect increasing centrality and red denotes falling centrality.

Figure A5: Broad increases in services centrality particularly for Ireland and Luxembourg

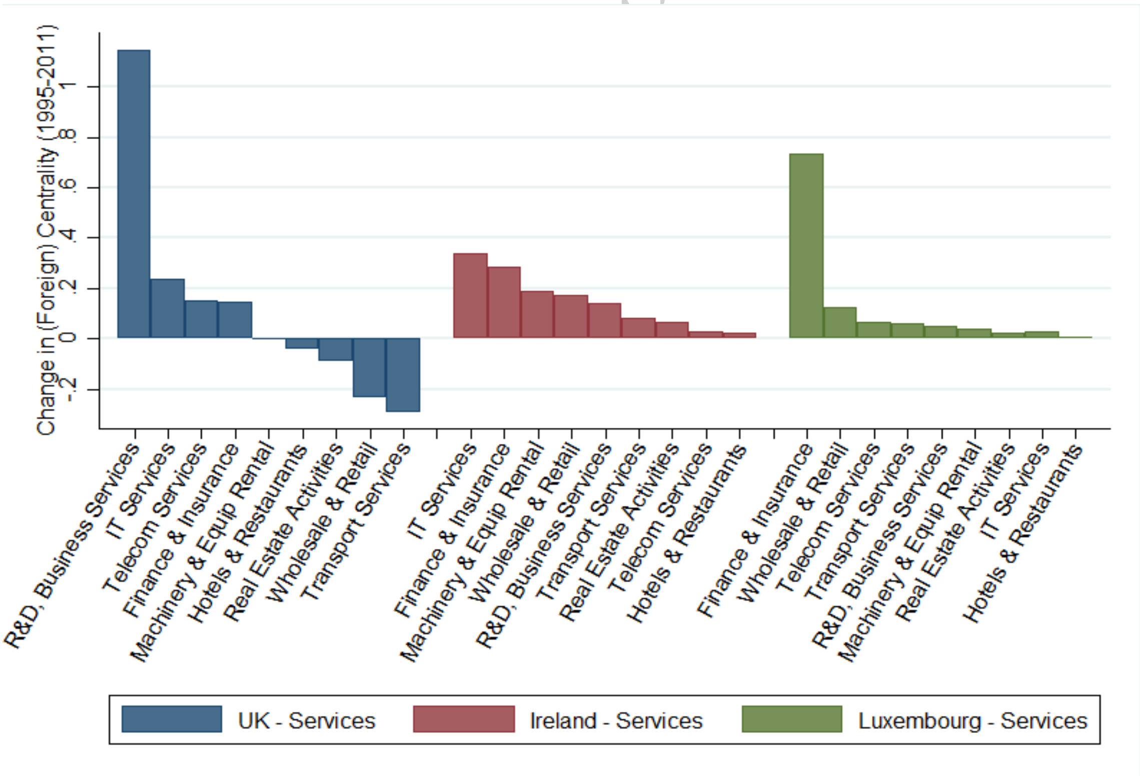


Figure A6: Strong financial services centrality growth in the UK before the Financial Crisis (pre-2007)

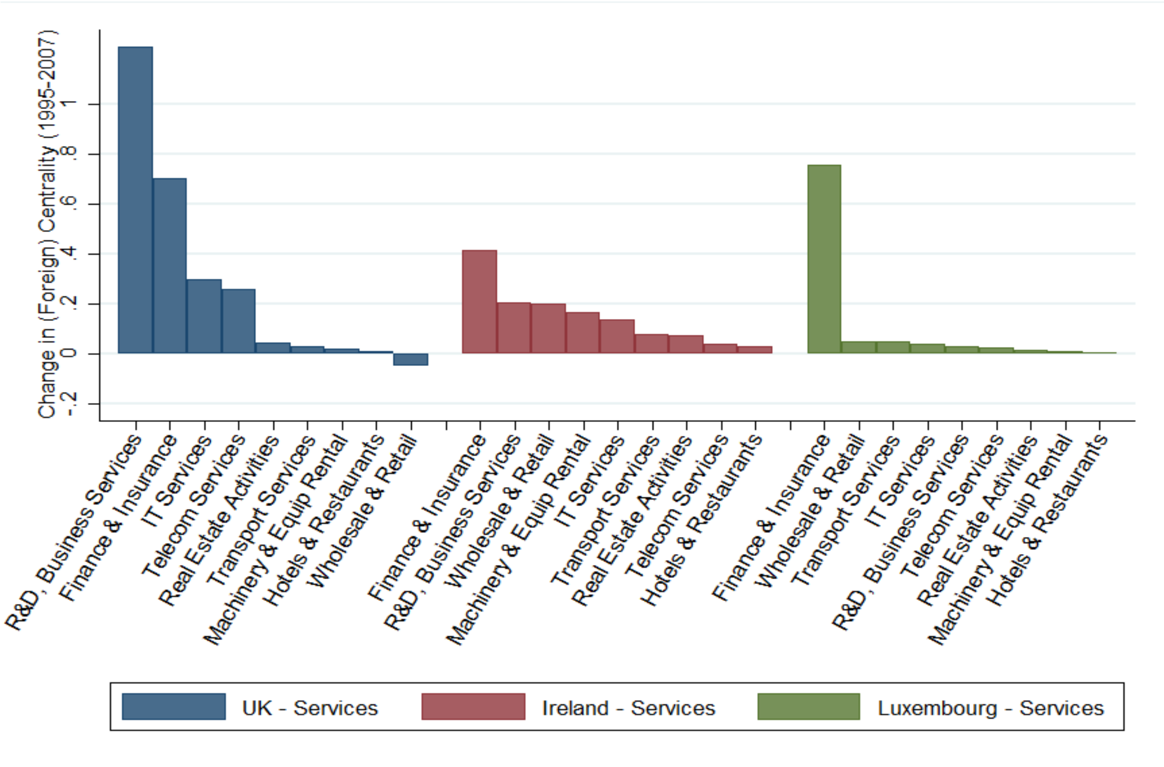


Figure A7: Broad declines in manufacturing centrality for UK and Italy

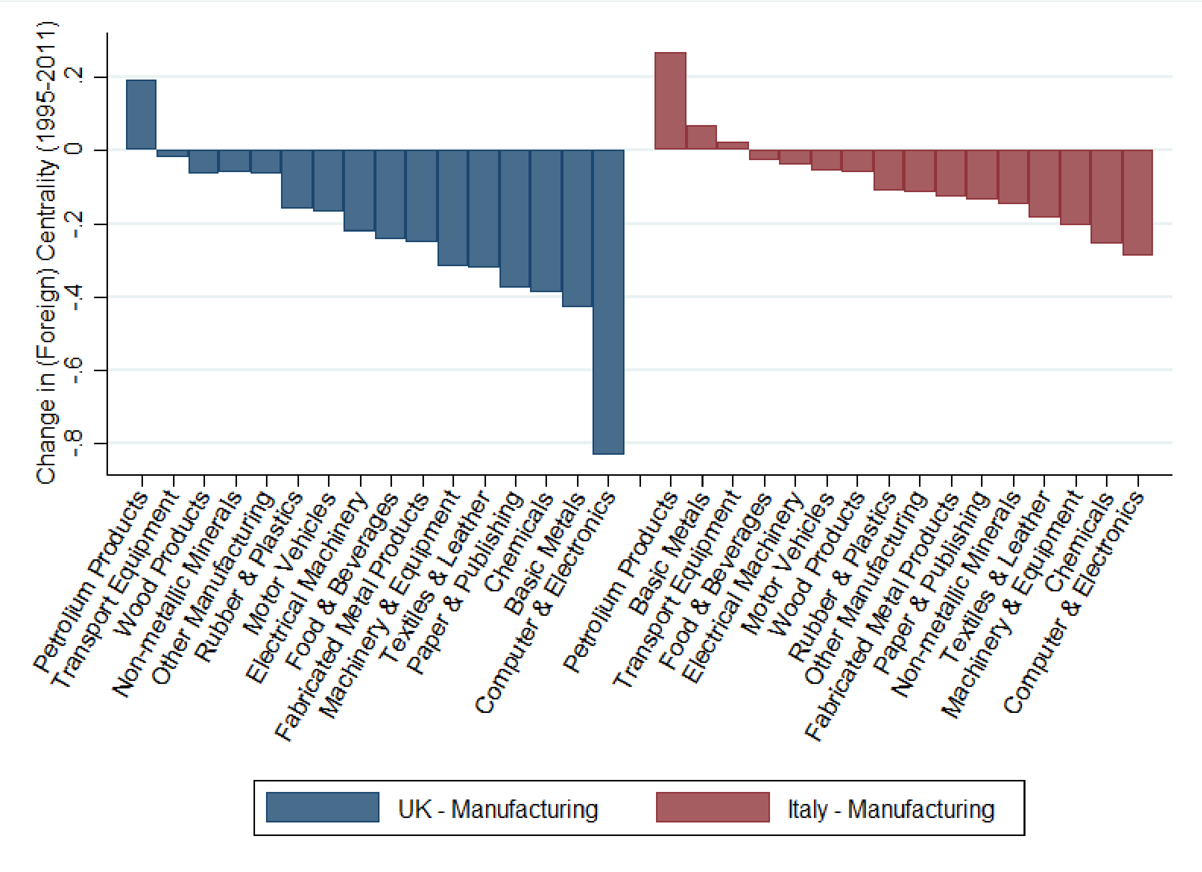


Figure A8: Who has become increasingly central for services in Factory Asia?

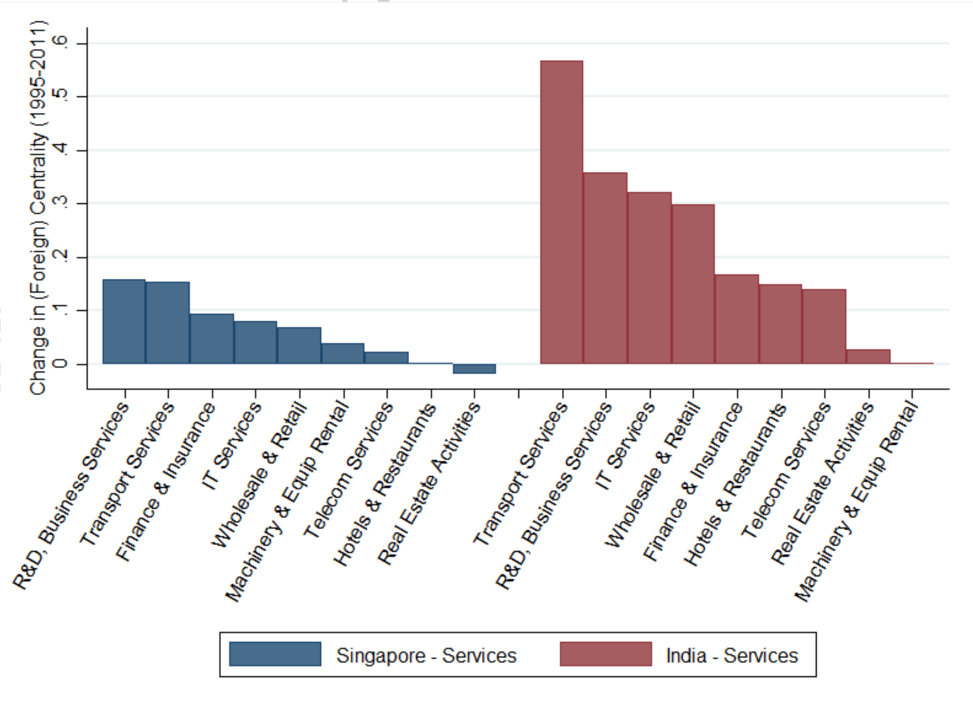


Figure A9: Who has become increasingly central for manufacturing in Factory Asia?

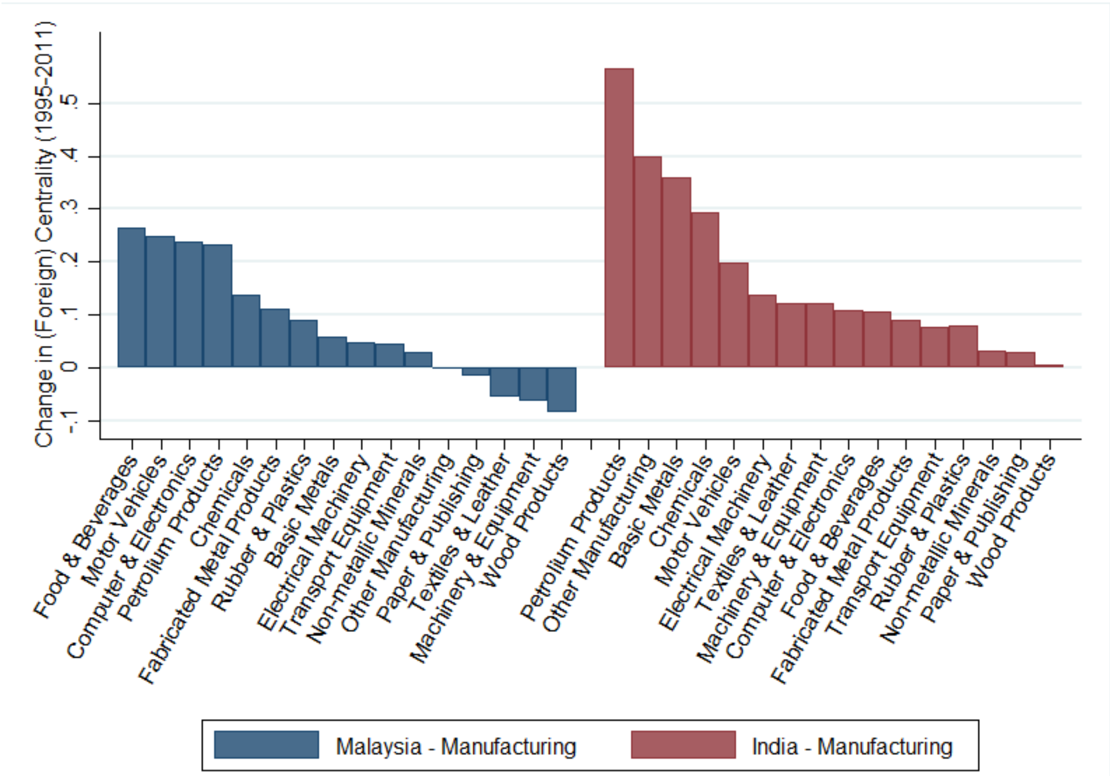


Figure A10: Changing centrality for China vs Japan – Services sector

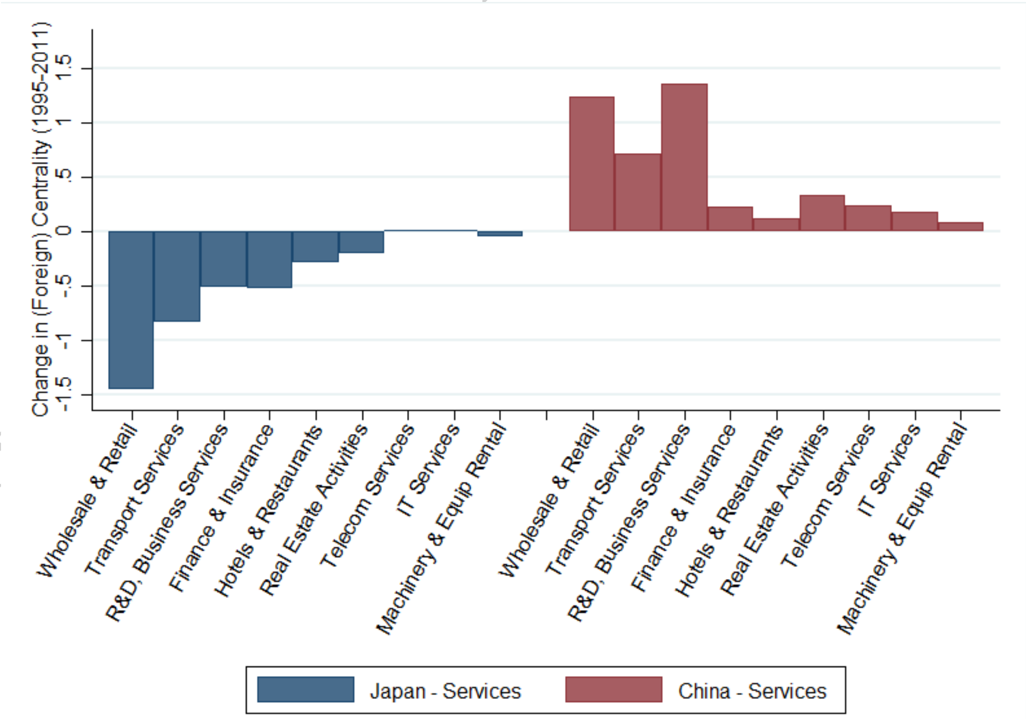


Figure A11: Changing centrality for China vs Japan – Manufacturing sector

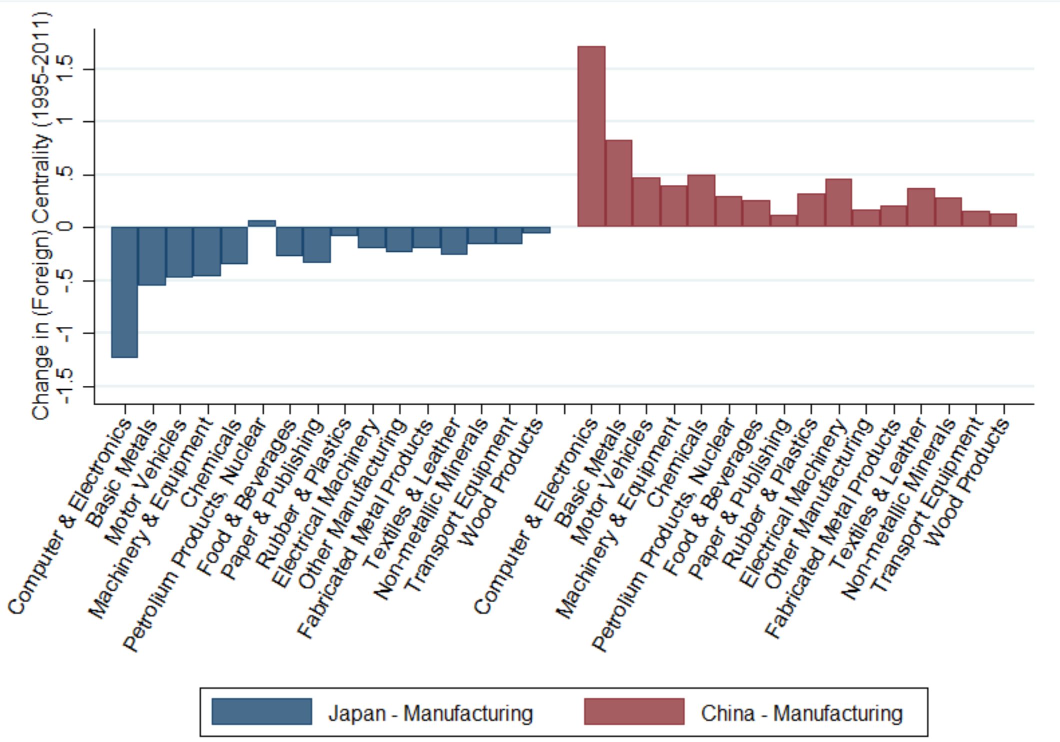
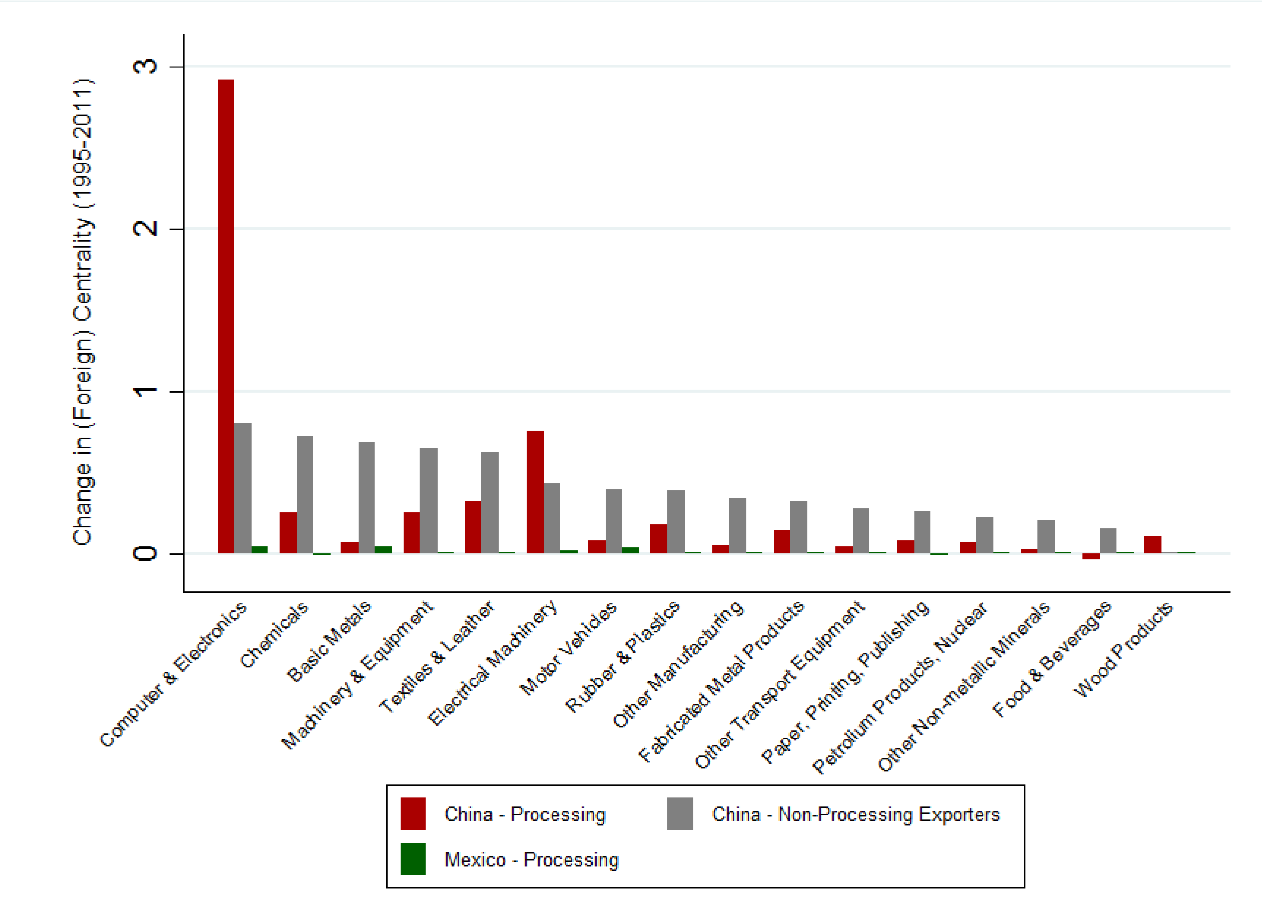
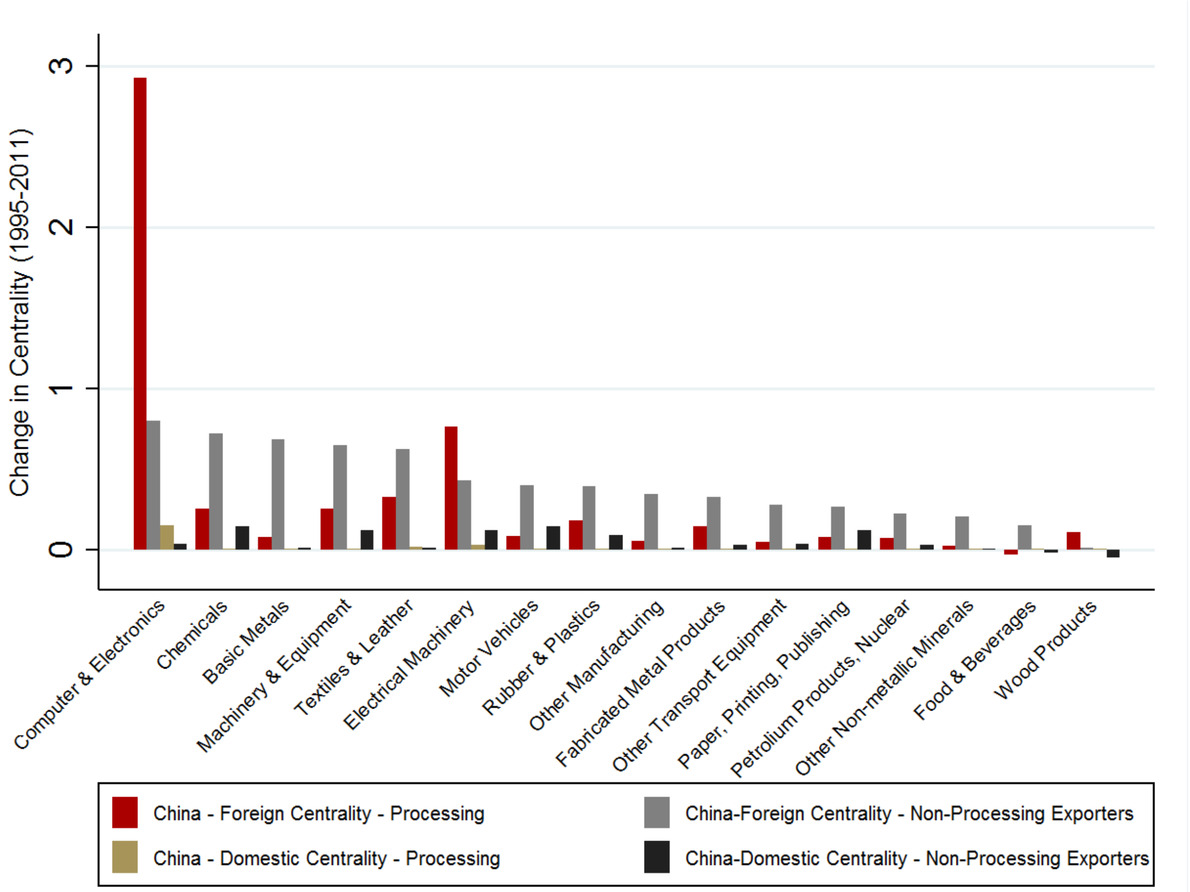


Figure A12: Swift Growth of Centrality of Chinese Processing & Non-Processing Sectors vs Mexico



Notes: Total (foreign) centrality is measured at the country-industry using specific OECD-WTO ICIO tables for China and Mexico's processing sectors, and China's (non-processing) export sector. Changes here reflect the long-difference in centrality levels between 1995 and 2011.

Figure A13: Sluggish Growth of Centrality of Chinese Domestic Centrality of Processing & Non-Processing Sectors



Notes: Total foreign centrality and total domestic centrality is measured at the country-industry using specific OECD-WTO ICIO tables for China's processing sector and China's (non-processing) export sector. Changes here reflect the long-difference in centrality levels between 1995 and 2011.

Table A3 In levels, forwards centrality is only strongly correlated with size (exported inputs)

Correlation of Levels (2011)	Forwards Centrality	Exported Input Share (of Total Inputs)	Exported Inputs (Value)	Forward GVC Participation	Value-Added RCA	Gross-Trade RCA	Upstream -ness
Forwards Centrality	1.00						
Exported Input Share (of Total Inputs)	0.06	1.00					
Exported Inputs (Value)	0.92	0.15	1.00				
Forward GVC Participation	0.47	0.17	0.55	1.00			
Value-Added RCA	0.01	-0.04	0.03	0.06	1.00		
Gross-Trade RCA	0.14	0.16	0.18	0.30	-0.02	1.00	
Upstreamness	0.14	0.15	0.12	0.19	0.00	0.00	1.00

Table A4 In levels, backwards centrality is only strongly correlated with size (imported inputs)

Correlation of Levels (2011)	Backwards Centrality	Imported Input Share (of Total Inputs)	Imported Inputs (Value)	Backward GVC Participation	Value-Added RCA	Gross-Trade RCA	Upstream -ness
Backwards Centrality	1.00						
Imported Input Share (of Total Inputs)	-0.12	1.00					
Imported Inputs (Value)	0.79	0.01	1.00				
Backward GVC Participation	0.14	0.27	0.24	1.00			
Value-Added RCA	-0.06	-0.31	-0.11	-0.21	1.00		
Gross-Trade RCA	0.07	-0.04	0.08	0.48	-0.02	1.00	
Upstreamness	-0.06	0.09	0.02	0.11	0.00	0.00	1.00

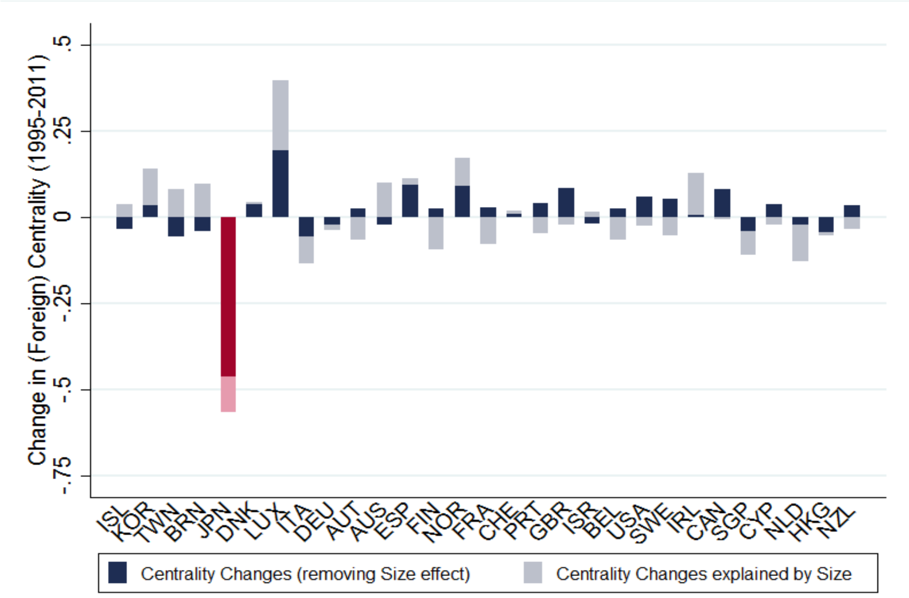
Table A5: In growth rates, forwards centrality not strongly correlated with size (exported inputs)

Correlation of Growth Rates (1995-2011)	Forwards Centrality	Exported Input Share (of Total Inputs)	Exported Inputs (USD Value)	Forward GVC Participation	Value-Added RCA	Gross-Trade RCA	Upstream-ness
Forwards Centrality	1.00						
Exported Input Share (of Total Inputs)	-0.08	1.00					
Exported Inputs (Value)	0.36	0.85	1.00				
Forward GVC Participation	0.06	0.01	0.05	1.00			
Value-Added RCA	0.28	0.73	0.84	0.02	1.00		
Gross-Trade RCA	0.29	0.73	0.84	0.02	1.00	1.00	
Upstreamness	0.23	-0.14	0.03	0.06	0.03	0.03	1.00

Table A6: In growth rates, backwards centrality remains correlated with size (imported inputs)

Correlation of Growth Rates (1995-2011)	Backwards Centrality	Imported Input Share (of Total Inputs)	Imported Inputs (Value)	Backward GVC Participation	Value-Added RCA	Gross-Trade RCA	Upstream-ness
Backwards Centrality	1.00						
Imported Input Share (of Total Inputs)	0.18	1.00					
Imported Inputs (Value)	0.83	0.45	1.00				
Backward GVC Participation	0.18	0.02	0.16	1.00			
Value-Added RCA	-0.04	-0.01	-0.04	0.01	1.00		
Gross-Trade RCA	0.16	0.04	0.16	0.09	0.66	1.00	
Upstreamness	0.07	-0.08	0.05	0.07	0.02	0.03	1.00

Figure A14: Japan's aggregate centrality has declined the most amongst High Income Economies after removing the effect of size changes



Notes: Total centrality (forward and backward) is aggregated at an economy-level and includes all sectors within global production networks. Changes here reflect the long-difference in centrality levels between 1995 and 2011. The effect of size is removed by regressing changes in forward (backward) centrality on changes in exported (imported) inputs, with the forward and backward metrics averaged to give the total centrality (removing size effect).

b) Cross-Sector Linkages

144. In the main body of this paper we focussed on industries' cross-country linkages, decomposing intra and extra-regional linkages. In this section we briefly outline another decomposition, by examining linkages across manufacturing and services sectors. A growing literature finds that domestic services are important for domestic manufacturing performance (e.g. Arnold et al., 2011; 2016) and that services reflect an increasing share of manufacturing value-added (OECD, 2013). Here we build on this literature by examining examine the changing structure of not only domestic, but also international linkages across sectors, i.e. from services to manufacturing industries and vice versa. We first show these influences for emerging economies, to examine to what extent the growing importance of manufacturing is due to domestic and foreign services linkages. We then contrast this with the picture for high-income economies.

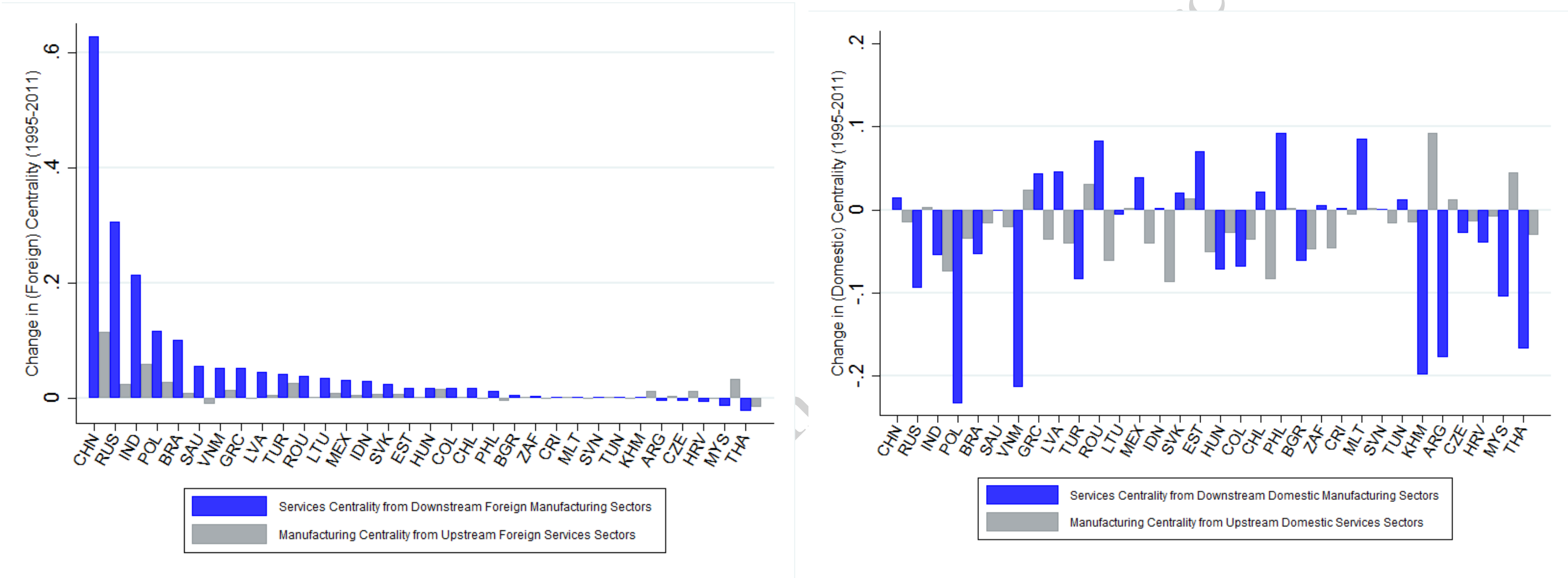
145. We find that service sectors in emerging economies are increasingly central to foreign manufacturing customers. We decompose the forwards centrality of services industries into centrality as a supplier to foreign manufacturing industries and domestic manufacturing industries. We find that for almost all emerging economies, services industries have increased the strength of their linkages to foreign manufacturing sectors (panel A of Figure A15). For some countries, such as China, Russia, India and Poland these increases have been pronounced. This may reflect an increasing tradability of services and is consistent with the swift growth in services trade observed for emerging economies (Loungani et al., 2017). Existing research shows that domestic services matter for domestic manufacturing productivity, our results imply that international services might matter for manufacturing too.

146. Manufacturing sectors in emerging economies are also increasingly connected to foreign services suppliers. The position of manufacturing sectors within global production networks is determined not only by their direct and indirect linkages to other manufacturing industries, but also services sectors. To measure inter-sector linkages we decompose total (forwards and backwards) centrality of manufacturing industries into the component relating to foreign services industries and domestic service industries. We find that for almost all emerging economies, manufacturing industries have increased the strength of their linkages to foreign services sectors (panel A of Figure A15). As in the preceding paragraph, this suggests that international cross-sector linkages are becoming more influential for emerging economies over time.

147. Conversely, there does not appear to be a clear pattern for emerging economy domestic linkages. One possible explanation for the increasing international inter-sectoral linkages in emerging economies could be increasing size of these sectors. If this were the case, one would expect to also observe an increase in the importance of domestic inter-sectoral linkages, between domestic manufacturing and domestic services industries, as well as increasing importance of international linkages noted above. Panel B of Figure A15 shows a very mixed pattern. Whilst some economies have shown increasing inter-sectoral linkages, for example Malta, on the whole they have declined in importance. Furthermore, there is no obvious relationship between the changes in domestic inter-sectoral linkages in panel B and the international inter-sectoral linkages in panel A. It does not seem to be the case that those countries with the largest increases in international linkages also have the largest increase in domestic linkages. We investigate the correlation between size and centrality further in the main body of the paper.

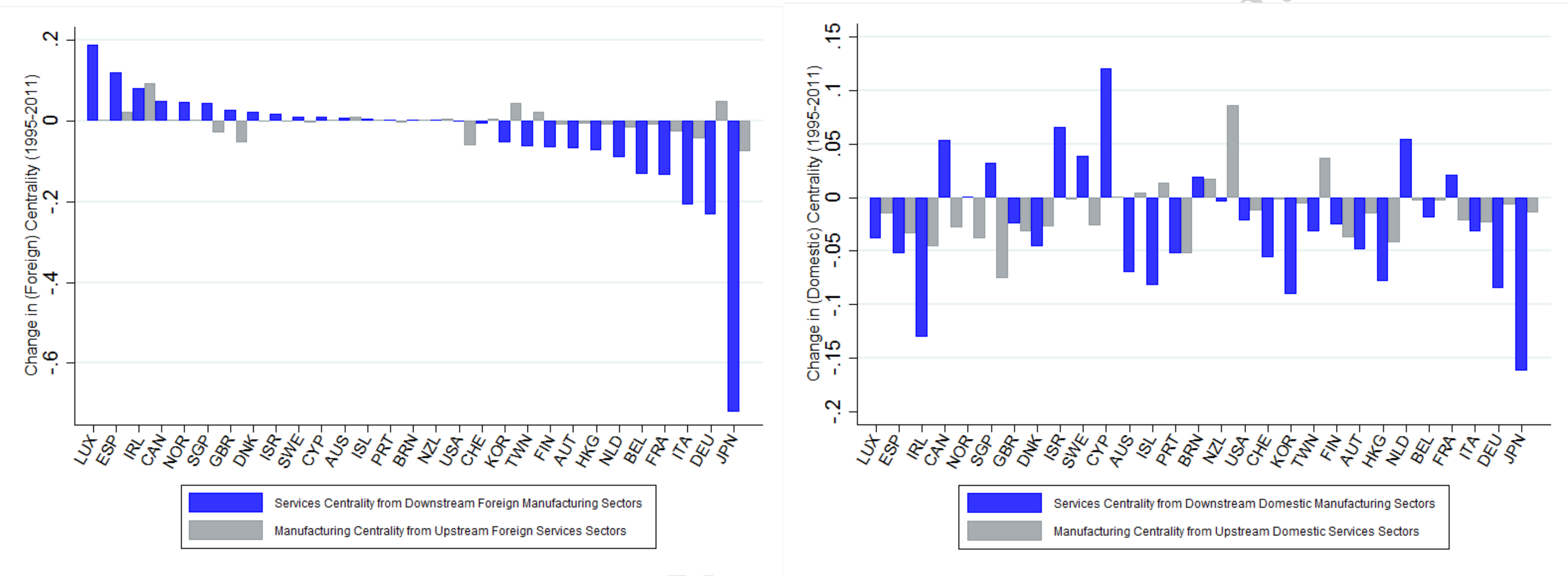
148. We also do not observe a consistent pattern for the inter-sectoral linkages of high-income economies, neither in terms of international nor domestic linkages. Figure A16 repeats the earlier analysis, for high-income economies. On the one hand some economies have increased the centrality of their service sectors for foreign manufacturing industries and these largely correspond to countries that have increased their foreign services centrality more generally, such as Luxembourg. On the other hand, there are a number of countries for which their services sectors are less important for foreign manufacturers, particularly Japan, which we examine in more detail in the main body of the paper.

Figure A15: Increasing Relative Importance of International Cross-Sector Linkages in Emerging Economies



Notes: Services centrality from manufacturing sectors reflects the centrality for manufacturing industries 15 to 37 derived from business sector services industries 50 to 74 and vice versa. Emerging economies are defined as low and middle income economies classified following the grouping of the World Bank World Development Indicators in 1995, at start of the period. Change in centrality is reflected as an annualised rate over 1995-2011.

Figure A16: No Consistent Picture Emerges for High Income Economies



Notes: Services centrality from manufacturing sectors reflects the centrality for manufacturing industries 15 to 37 derived from business sector services industries 50 to 74 and vice versa. Emerging economies are defined as low and middle income economies classified following the grouping of the World Bank World Development Indicators in 1995, at start of the period. Change in centrality is reflected as an annualised rate over 1995-2011

3. Empirical Results: Additional Figures and Tables

Table A7: Heterogeneous effects by country & firm type: Large & Small Countries – Frontier vs Non-frontier

MFP Wooldridge	Smaller Countries – Frontier vs Non-Frontier (7) Total	(8) Forward	(9) Backward	Larger Countries - Frontier vs Non-Frontier (10) Total	(11) Forward	(12) Backward
Centrality	3.596**	1.462	3.988***	1.311**	0.517	1.662***
	(1.583)	(1.228)	(1.183)	(0.641)	(0.421)	(0.608)
Centrality * Initial Firm MFP	-0.279**	-0.104	-0.346***	-0.113**	-0.045	-0.145***
	(0.136)	(0.108)	(0.103)	(0.054)	(0.036)	(0.048)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	6.440***	6.272***	5.608***	5.652***	6.285***	4.282***
	(0.627)	(0.675)	(0.613)	(0.849)	(0.845)	(0.784)
Average Productivity (Centrality Weighted) of Buyers / Suppliers * Initial Firm MFP	-0.583***	-0.562***	-0.518***	-0.465***	-0.485***	-0.396***
	(0.057)	(0.060)	(0.054)	(0.071)	(0.070)	(0.067)
Observations	326,041	326,041	326,041	1,687,182	1,687,182	1,687,182
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y

Table A8: Heterogeneous effects by country & firm type: Post-2004 EU Members & Other Factory Europe – Frontier vs Non-frontier

MFP Wooldridge	Post-2004 EU Members Countries – Frontier vs Non-Frontier (7) Total	(8) Forward	(9) Backward	Other Factory Europe - Frontier vs Non-Frontier (10) Total	(11) Forward	(12) Backward
Centrality	21.158***	32.078***	12.624***	0.433	0.196	0.774**
	(0.948)	(4.154)	(1.425)	(0.372)	(0.262)	(0.346)
Centrality * Initial Firm MFP	-1.475***	-2.698***	-0.846***	-0.041	-0.015	-0.080***
	(0.214)	(0.327)	(0.147)	(0.035)	(0.023)	(0.031)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	4.863***	3.522***	4.731***	4.684***	5.032***	3.835***
	(1.099)	(1.168)	(0.743)	(0.717)	(0.729)	(0.629)
Average Productivity (Centrality Weighted) of Buyers / Suppliers * Initial Firm MFP	-0.449***	-0.284***	-0.495***	-0.387***	-0.421***	-0.332***
	(0.089)	(0.102)	(0.067)	(0.060)	(0.061)	(0.055)
Observations	150,808	150,808	150,808	1,765,433	1,765,433	1,765,433
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y

Table A9: Heterogeneous effects by sector & firm type: Manufacturing & Services – Frontier vs Non-frontier

MFP Wooldridge	Services – Frontier vs Non-Frontier			Manufacturing - Frontier vs Non-Frontier		
	(1)	(2)	(3)	(4)	(5)	(6)
	Total	Forward	Backward	Total	Forward	Backward
Centrality	1.500**	0.694*	1.936**	1.479	0.556	1.429
	(0.732)	(0.408)	(0.820)	(1.106)	(1.181)	(0.890)
Centrality * Initial Firm MFP	-0.112*	-0.049	-0.167**	-0.150	-0.100	-0.133*
	(0.061)	(0.035)	(0.066)	(0.095)	(0.089)	(0.073)
Average Productivity (Centrality Weighted) of Buyers / Suppliers	6.563***	7.077***	4.744***	5.574***	5.910***	4.586***
	(0.910)	(0.872)	(0.793)	(1.065)	(0.901)	(1.077)
Average Productivity (Centrality Weighted) of Buyers / Suppliers * Initial Firm MFP	-0.545***	-0.555***	-0.438***	-0.489***	-0.502***	-0.421***
	(0.073)	(0.060)	(0.069)	(0.090)	(0.081)	(0.092)
Observations	1,154,882	1,154,882	1,154,882	858,321	858,321	858,321
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	Y	Y	Y	Y	Y	Y

Table A10: First Stage of Indstrumental Variable Estimation – Frontier vs Non-frontier

	(1)	(2)	(3)	(4)	(5)	(6)
	Total		Forward		Backward	
First Stage - Centrality:						
Lagged Centrality	0.631***	0.467***	0.670***	0.554***	0.569***	0.452***
	(0.043)	(0.042)	(0.040)	(0.034)	(0.037)	(0.044)
Productivity of existing Buyers/Suppliers	0.194**	0.021	0.055	-0.078	0.148	0.004
	(0.080)	(0.076)	(0.093)	(0.092)	(0.111)	(0.091)
First Stage – Average Productivity (Centrality Weighted) of Buyers / Suppliers:						
Productivity of existing Buyers/Suppliers	0.980***	0.994***	1.020***	0.996***	0.840***	0.903***
	(0.047)	(0.045)	(0.053)	(0.050)	(0.050)	(0.049)
Lagged Centrality	0.000	0.001	0.013	0.011	0.007	0.014
	(0.014)	(0.013)	(0.009)	(0.012)	(0.017)	(0.016)
Observations	1,877,565	1,877,565	1,877,565	1,877,565	1,877,565	1,877,565
YEAR FE	Y	Y	Y	Y	Y	Y
FIRM FE	Y	Y	Y	Y	Y	Y
FIRM SIZE CONTROLS	Y	Y	Y	Y	Y	Y
INDUSTRY CONTROLS	N	Y	N	Y	N	Y

Robust standard errors clustered at country-(34 TiVA) industry level, *** p<0.01, ** p<0.05, * p<0.1
Firm size control reflects lagged employment. Industry controls include GVC participation, Domestic sources of centrality, Fally’s (2011) GVC Upstreamness measure, Exports of intermediates, Imports of intermediates, Industry production (as a measure of industry size), Balassa’s Gross Revealed Comparative Advantage, and Koopman et al.’s (2012) Value-Added Revealed Comparative Advantage.

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