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Abstract

Increasing fragmentation of production is posing new challenges to the measurement of productivity. Traditional approaches focus on firms, industries or countries as the unit of analysis. In this article we argue that studies of global value chains (GVCs) are needed. We introduce the GVC accounting approach as a complement to traditional KLEMS type productivity studies. We define cost shares and productivity growth and show how they can be empirically implemented using synthetic input-output tables. We discuss advantages of the new approach, provide caveats and outline new areas of research and statistics in order to better understand today's global production systems.

Increasing fragmentation of production processes is posing new challenges for the analysis and measurement of productivity. Traditional approaches focus on firms, industries or countries as the unit of analysis. In this article we argue that studies of global value chains (GVCs) are needed in situations where production is highly fragmented across firms and geographical borders.

Global value chains refer to the combined set of production stages that are needed to produce a final good. Due to improvements in information and telecommunication technologies, production processes increasingly fragment across borders in order to gain from access to cheap resources, both natural and human, as well as to acquire customer market access.

This process was boosted in the 2000s as major emerging economies like China and India opened up borders and became integrated into the world economy. As a result now a production process of a good typically consists of a set of different activities in various stages of production which can be carried out in many places around the world. For example, an iPad is designed in California, but assembled in Shenzen, China on the basis of more than a hundred components manufactured around the world, with logistics handled by a Hong Kong firm. This is referred to as global value chain (GVC) production.

The emergence of GVCs raises many new questions and its analysis requires novel methodologies and data. In this article we will review the conceptual and empirical issues that arise in analysing productivity in the context of international production fragmentation. We discuss how patterns of substitution and productivity growth can be measured in such chains and illus-

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trate this by empirical exercises using new data from the World Input-Output Database (WIOD). To this end, we will build upon the standard tool kit of production analysis, known as the KLEMS approach.

In their classical study of the US economy Jorgenson, Gollop and Fraumeni (1987) introduced this approach which is built around the concept of a gross output production function with two groups of factor inputs, capital (K) and labour (L), and three groups of intermediate inputs, energy (E), materials (M) and services (S). This approach offers useful insights into the changes in efficiency with which the inputs are being used in the production process of the industry (or firm) as measured by productivity growth. It also offers the conceptual framework to analyse econometrically the various substitution elasticities between inputs, as well as possible biases in productivity change. The KLEMS approach has become a standard tool in the applied economist's tool kit.

However, modelling and measuring patterns of substitution and productivity growth at the industry (or firm) level has become both more difficult and less meaningful. With increased outsourcing and offshoring, the share of industry value added in gross output is declining such that analysis based on industry value added have to rely on strong assumptions of separability. Conditions that are jointly necessary and sufficient for the existence of sectoral value added functions are typically rejected, and intermediate inputs should be treated symmetrically with factor inputs (Jorgenson, Gollop and Fraumeni, 1987; Diewert and Wales, 1995). As ratios of imported intermediate input to gross output continue to increase, the robustness of this approach becomes increasingly dependent on proper price measurement of intermediate inputs. However, tracking prices of intermediate inputs is challenging, in particular when they are imported and/or contain intangible characteristics (Houseman and Mandel, 2015).

In this article we outline how the existing KLEMS methodology can be modified to analyse GVC production and what type of data would be needed. We argue that in order to understand trends in productivity and technical change in global production, one needs to go beyond the traditional analysis of separate industries (or firms) and focus on a set of discrete activities in distinct locations, which altogether form a global value chain starting at the conception of the product and ending at its delivery. Unfortunately, our official statistical systems are not well equipped to identify the emergence and existence of these global production chains. We outline an approximation method to derive cost shares in GVCs, based on a linear system of cost equations rooted in the input-output approach introduced by Leontief (1936). Simply put, the production function G in the KLEMS approach is given by:

Gross output of industry = G (factor inputs in domestic industry, intermediate inputs)

Instead we will analyse a production function F where final output is produced based on factor inputs only, including both domestic as well as foreign factors.

Final output of product = F (factor inputs in all industries domestically and abroad)

Basically, in this approach the flow of intermediate inputs will be netted out such that the production function of a final good can be written in terms of factor inputs only. These factor inputs are located in the industry where the last stage of production takes place as well as in other industries (domestic and foreign) contributing in earlier stages of production. This opens up the possibility to study the various substitutions of factor inputs and the possible biased nature of productivity change.

This GVC modelling approach will allow us to focus on three important issues. First, the increasing importance of intangible capital. GVC production entails not only a flow of goods and materials, but also of information, technology and managerial knowledge. It not only includes physical production processes but the full set of activities both in the pre- and post-production phases. This includes research and development, software, design, branding, finance, logistics, after-sales services and system integration. Recent case studies of electronic products such as the Nokia smartphone (Ali-Yrkkö and Rouvinen, 2015) and the iPod and laptops (Dedrick *et al.*, 2010) suggest that it is especially in these activities that most value is added. With international production however it has become more difficult to trace the profits for these capital assets. Due to among other factors transfer pricing and shifting of accounting profits, analyses of a single firm or industry might be inadequate. For example, a multinational might record its profits in a production facility abroad such that an analysis on domestic data will not reveal the importance of its capital inputs. This can only be accounted for in an analysis of cost shares of all factors of production used in any stage of production. Using this approach, Timmer *et al.* (2014) has shown that compensation for capital assets has been increasing, in particular in emerging economies.

Second, and related to the first, there is mounting evidence that suggests that advanced countries are increasingly specializing in skill- and capital-intensive activities within global value chains, more popularly described as a process of turning into "headquarter economies". This indicates that together with fragmentation the nature of production processes is changing: a firm or industry can no longer be characterised by its outputs (the products it is selling), but only by what it does in terms of activities. Production fragmentation goes hand-in-hand with functional specialization across firms, regions and countries, and this needs to be studied in a coherent framework with explicit modelling of inter-industry linkages.

More generally, increasing international production fragmentation limits our understanding of the substitution and complementarity of various inputs in the production process, and the measurement of possible biases in technical change. Rather than studying this from the perspective of individual firms, industries or countries, one needs an approach in which the various stages of production are analyzed together.

General Approach and Terminology

A global value chain of a product is a description of all the factor inputs needed for its production, taking into account all phases of production, starting at conception and ending at its delivery. As such it can be viewed as a special case of vertically integrated production (Williamson, 1971), characterized by the fact that production stages are carried out in at least two countries. The coordination of the various stages can be done within a multi-national cooperation or it can be market mediated through arms-length transactions. Typically, it has a governance mode that lies within these two extremes (Antras and Yeaple, 2014). It is important to stress that our approach refers not only to the physical production process but to the full set of activities both in the pre- and post-production phases including research and development, software, design, branding, finance, logistics, after-sales services and system integration. Therefore Timmer *et al.* (2014) have proposed to use the term "global value chains" to distinguish this approach from studies of "global supply chains" or "international production chains" that typically refer only to the physical production stages.

To analyse vertical integrated production we rely on a standard methodology that allows for a decomposition of the value of a final product into the value added by all factors (labour and capital) in any country that is involved in its production process. This decomposition method is rooted in the analysis introduced by Leontief (1936) in which the modelling of input-output (IO) structures of industries is central. The IO structure of an industry indicates the amount and type of intermediate inputs needed in the production of one unit of output such that one can trace the gross output in all stages of production that is needed to produce one unit of final demand. To see this, take the example of car production in Germany. Demand for German cars will in the first instance raise the output of the German car industry. But production in this industry relies on car parts and components that are produced elsewhere, such as engines, braking systems, car bodies, paint, seat upholstery or window screens, but also energy inputs, and various business services such as logistics, transport, marketing and financial services. These intermediate goods and services need to be produced as well, thus raising output in the industries delivering these, say the German business services industry, the Czech braking systems industry and the Indian textile industry. In turn, this will raise output in industries delivering intermediates to these industries and so on. These indirect contributions from both manufacturing and non-manufacturing sectors will be explicitly accounted for through the modelling of input-output linkages across sectors. When we know the gross output flows associated with a particular level of final demand, we can derive the value added by multiplying these flows with the value-added to gross-output ratio for each industry. By construction the sum of value added across all industries involved in production will be equal to the value of the final demand. Following the same logic, one can also trace the number of workers that is directly and indirectly involved in GVC production, or the amount of capital (Timmer *et al.*, 2013, 2014).

Technical exposition

This section gives a mathematical exposition of our measurement framework grounded in the older literature on input-output accounting with multiple regions surveyed in Millar and Blair (2009). We start with the fundamental input-output identity and use this to derive an expression for the factor cost shares in the production of final products. Output in each country-sector is produced using domestic production factors and intermediate inputs, which may be sourced domestically or from foreign suppliers. Output may be used to satisfy final demand (either at home or abroad) or used as intermediate input in production (either at home or abroad as well). To track the shipments of intermediate and final goods within and across countries, it is necessary to define source and destination country-sectors. For a particular product, we define i as the source country, j as the destination country, s as the source sector and t as the destination sector. Each country(N)-sector(S) produces one good such that there are SN products. We use the term country-sector to denote a sector in a country, such as the French chemicals sector or the German transport equipment sector. Although we will apply annual data in our empirical analysis, time subscripts are left out in the following discussion for ease of exposition.

Product markets clear, so the quantity of a product produced in a particular country-sector must equal the quantities of this product used domestically and abroad. This condition can be written as

$$y_i(s) = \Sigma_j f_{ij}(s) + \Sigma_j \Sigma_t m_{ij}(s, t) \qquad (1)$$

where $y_i\ (s)$ is the output in sector s of country i, $f_{ij}(s)$ the products shipped from this sector for final use in any country j, and $m_{ij}(s,t)$ the products shipped from this sector for intermediate use by sector t in country j. Note that the use of products can be at home (in case $i = j$) or abroad ($i \neq j$). Using matrix algebra, the market clearing conditions for each of the SN goods can be combined to form a compact global input-output system. Let y be the vector of production of dimension (SNx1), which is obtained by stacking output levels in each country-sector. Define **f** as the vector of dimension (SNx1) that is constructed by stacking world demand for final output from each country-sector $f_i(s)$. World final demand is the summation of demand from any country, such that $f_i(s) = \Sigma_j f_{ij}(s)$. We further define a global intermediate input coefficients matrix **A** of dimension (SNxSN). The elements $a_{ij}(s,t) = m_{ij}(s,t)/y_j(t)$ describe the output from sector s in country i used as intermediate input by sector t in country j, expressed as a ratio of output in the latter sector. Columns in the matrix **A** describe how the products of each country-sector are produced using a combination of various intermediate products, both domestic and foreign.

Using this we can rewrite the stacked SN market clearing conditions from (1) in compact form as **y=f+Ay**. Rearranging, we arrive at the fundamental input-output identity

$$\boldsymbol{y} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \tag{2}$$

where **I** is an (SNxSN) identity matrix with ones on the diagonal and zeros elsewhere. The matrix $(I-A)^{-1}$ is famously known as the Leontief inverse. The element in row m and column n of this matrix gives the total production of sector m needed for production of one unit of final output of product n. To see this, let $\mathbf{z}_n$ be a column vector with the nth element representing a euro of global consumption of goods from country-sector n, while all the remaining elements are zero. The production of zn requires intermediate inputs given by $\mathbf{Az}_n$. In turn, the production of these intermediates requires the use of other intermediates given by $\mathbf{A}^2\mathbf{z}_n$, and so on. As a result the increase in output in each sector is given by the sum of all direct and indirect effects $\sum_{\kappa=0}^{\infty} A^{\kappa} z_n$. This geometric series converges to

$$(I-A)^{-1} z_n \tag{3}$$

Using the Leontief inverse we can derive the total factor requirements of a unit of final output by netting out all intermediate input flows. Let us define $l_i(s)$ as the labour per unit of gross output in sector s in country i and create the row-vector $\boldsymbol{l}$ containing these 'direct' labour coefficients, and similar for capital coefficients **k**. Then the total (direct plus indirect) labour and capital requirements per unit of final output can be derived as

$$\Lambda = \hat{\boldsymbol{l}}(I - A)^{-1}$$

and

$$K = \hat{\kappa}(I - A)^{-1}$$

in which a hat-symbol indicates a diagonal matrix with the elements of the vector on the diagonal. Λ is the matrix of dimension (SNxSN) with an element (i,j) indicating the amount of labour in country-sector j needed in the production of one unit of final output by country-sector i, referred to as the total labour coefficient, and similar for the matrix of capital inputs **K**.

Due to the linearity of the system, these total factor requirements have the useful property that when multiplied with the actual levels of final demand **f**, they sum up to the overall quantity of labour and capital available in each country-sector. As such this approach provides for an exhaustive accounting decomposition of global final demand such that all production factors in the world are accounted for.

Using these total factor requirements matrices, we can define factor cost shares in a global value chain of a final product. At this point we first need to define prices of output and factor inputs. Let **p** be a (row) vector of output prices for products from each country-sector, **w** the (row) vector of hourly wage rates and **r** the (row) vector of profit rates. The profit rate is derived as a residual such that capital compensation (the profit rate times the quantity of capital) plus labour compensation (wage times hours worked) equals gross value added. We allow output and factor input prices to differ across sectors and countries. Value added in a country-sector is defined in the standard way as gross output value (at basic prices) minus the cost of intermediate inputs (at purchasers' prices)[2] or **p**(**I**-**A**). As profit rates are measured residually such that wages and profits exhaust value added for each country-sector, the following accounting identity holds:

$$\boldsymbol{p}(\mathrm{I}-\mathrm{A}) = \boldsymbol{w}\hat{\boldsymbol{l}} + \boldsymbol{r}\hat{\boldsymbol{k}} \tag{4}$$

Post-multiplying both sides of (4) with the inverse of (**I**-**A**) and substituting from (3) we arrive at an important result: the output price of a final product (from a given country-sector) can be rewritten as a linear combination of the prices of all factors that were directly and indirectly needed in its production, or

$$\boldsymbol{p} = \boldsymbol{w}\Lambda + \boldsymbol{r}\mathrm{K} \tag{5}$$

with Λ and **K** the matrices with total labour and capital coefficients. The identity in equation (5) forms the basis for deriving cost shares of labour and capital in the GVC of a particular product. Multiplying the left- and right-hand side by final output quantity, the share of wage and capital costs in total costs is generated for each final product. Through appropriate selection of elements in the matrices Λ and **K**, one may trace the country-sector origins of these factor costs. We will use this decomposition in the next section to investigate the shifting factor shares in GVCs of manufacturing products.

The cost shares and quantities derived above can also be used to measure total factor productivity (TFP) growth in the production of a final good (following Wolff, 1994). The consolidated data provides the opportunity to use the standard approach in growth accounting in measuring TFP assuming a final output production function with arguments based on total (direct and indirect) labour and capital used. Let F be a translog production function for a final product j: $f_j = F_j(\lambda_j, \kappa_j, T)$ where λ_j the column vector of total labour requirements for product j from Λ and similarly κ_j a column of **K**. T denotes technology. Under the standard assumptions of constant returns to scale and perfect input markets, we can define productivity growth π in the GVC of product j by the weighted rate of decline of its total labour and capital requirements

$$\frac{\delta\pi_j}{\delta t} \equiv -\alpha_{\boldsymbol{j}}^{\boldsymbol{L}}\frac{\delta \ln\lambda_j}{\delta t} - \alpha_{\boldsymbol{j}}^{\mathrm{K}}\frac{\delta \ln\kappa_j}{\delta t} \tag{6}$$

where $\delta ln\lambda_j/(\delta t)$ is a (column) vector containing the differentials of the logarithms of all elements in λ_j. The weights are given by $\alpha_{\boldsymbol{j}}^{\boldsymbol{L}}$, a (row) vector of value shares with elements reflecting the costs of labour from all country-sectors used in the production of one unit of product j, and similarly for the capital value shares given in $\alpha_{\boldsymbol{j}}^{\mathrm{K}}$. Summed over all contribut-

2 For ease of exposition we assume here that there is only one price for the output of each country-sector, and this price is paid by all intermediate and final users. This assumption is loosened up in the empirical application later.

ing sectors and countries, the elements in α_j^L add up to the labour share in final output of j, and similarly for capital. As all factor inputs are accounted for the labour and capital share add up to unity. Since productivity growth rates are measured over discrete time periods rather than instantaneously the average value shares over the sample period can be used to measure productivity, generating the so-called Tornqvist-Divisia productivity index (Jorgenson *et al.* 1987). The productivity measure in (6) essentially shows the rate of productivity growth in the composite sector producing good *j* if all the sectors that contributed directly or indirectly to sector *j*'s final output were fully integrated.[3]

At this point it is instructive to compare the GVC productivity measure to the more traditional measure used in growth accounting studies in the KLEMS tradition. The main point to notice is that in standard applications only one stage of production is analysed. It relates the output of a sector (firm) to the inputs used by this sector (firm) consisting of the factor inputs in the sector (firm) itself and intermediate inputs produced elsewhere. The direct factor requirements as well as the value shares are now expressed in value added of the sector, not final output of the product as in (6). The traditional productivity measure thus reflects only changes in direct factor requirements instead of the total requirements. This is a valid measure of the rate of productivity growth in the case when technical change only affects factor inputs, and when the prices of intermediate inputs are well measured, that is, any decline in the factor requirements in upstream sectors will be translated in a lower price for intermediates used by sectors downstream. Only in that case the price of value added can be properly measured through separate deflation of gross output and all intermediate inputs, also known as double deflation.

However, double deflation is becoming increasingly difficult as production fragmentation progresses. There is increasing doubt about the reliability of price indices for imported intermediates due to the practice of intra-firm transfer pricing and more generally inadequate statistical systems to monitor prices of imports (Houseman *et al* 2011). A particular instance of this is the measurement of intangible service flows such as the use of knowledge, disembodied technology brand names and software. Intangibles are becoming increasingly important in production, but so far their measurement is elusive.[4] For example, Foxconn in China is producing iPhones using intangible designs and technology from Apple. These services are typically not recorded in production and trade statistics, such that any study of the productivity of the Chinese or the US electronics industry is seriously hampered. The attribution of productivity growth to either industry will crucially depend on the measurement of intermediate inputs and their prices. In fact this reflects a more general issue of attribution of productivity growth across industries when intermediate input prices are not well measured. Triplett (1996) has forcefully shown that in the case of measuring productivity in the US production of computers, the use of alternative quality-adjusted prices leads to radically different assessments of the location of productivity, which may be in the computer industry itself, or in the semi-conductor industry that delivers the main inputs to the computer industry, or even further back in the chain, namely the manufacturing of semi-conductor machinery. The GVC approach based on an integrated assessment will thus provide a useful alternative to measure pro-

3 Analyses of productivity in vertically integrated chains harks back to the work by Pasinetti (1977). See also Wolff (1994). Gu and Yan (2017) provide a recent empirical application.

4 See Corrado *et al.* (2012) for pioneering attempts.

ductivity growth in modern integrated production systems.

An illustrative example: GVC production of German automobiles

We illustrate our GVC methodology by analysing the production of German cars. Throughout this article we will use data from the World Input-output database (WIOD). This database provides data for 40 countries as well as for the rest-of-the-world region such that all inputs can be accounted for (Timmer *et al.*, 2015). We decompose the value of output of all final products delivered by the German transport equipment industry (NACE rev. 1 industries 34 and 35) in short "German cars". This includes the value added in the last stage of production, which will take place in Germany by definition, but also the value added by all other activities in the chain which take place anywhere in the world. To decompose value added in production, we make use of Leontief's decomposition method outlined in section 2 and given in equation (5).

The geographical origin of the value added in production of German cars in 1995 and in 2008 reveals striking developments. Between 1995 and 2008, the share of domestic value added decreased rapidly from 79 to 66 per cent of the value of a German car. Conversely foreign value increased from 21 to 34 per cent. With the availability of cheap and relatively skilled labour, firms from Germany relocated parts of the production process to Eastern Europe. At the same time, the industry quickly globalized by sourcing more and more from outside Europe. Countries outside Europe actually accounted for more than half of the increase in foreign value added.

With additional information on the quantity of factors used in each country we can provide a growth accounting decomposition of the growth rate of final output of German automotives using equation (6). Data on workers is measured by the number of hours, classified on the basis of educational attainment levels as defined in the International Standard Classification of Education (ISCED): low-skilled (ISCED categories 1 and 2), medium-skilled (ISCED 3 and 4) and high-skilled (ISCED 5 and 6). Capital stock volumes are measured on the basis of capital stocks of reproducible assets as covered in national account statistics (thus including physical assets, software and R&D, but excluding other intangibles), measured at 1995 constant price. Capital income is derived as gross value added minus labor income.

The results are shown in Table 1: final output volumes of German automotives increased by 59 log points (81 per cent points) over the period from 1995 to 2007.[5] This was mainly due to increases in the use of capital both domestically and abroad, together accounting for 41 per cent of the increase in final output. The number of workers employed in production increased as well, both within Germany and abroad, with higher growth rates for more skilled workers. Growth in workers in Germany contributed to 19 per cent of final output growth, and workers abroad contributed another 21 per cent. Note that although the number of high-skilled workers located abroad increased much faster than the number of German high-skilled workers, their contribution to final output growth is much less. This follows from the assumption of perfect competition in factor markets in the KLEMS approach such that the lower wages of foreign workers is presumed to reflect lower quality compared to German workers.[6] Capital input was growing rapidly, both within Ger-

5 The data in WIOD is in current US$. The volume growth rate is based on constant prices in euros using the official exchange rate and the gross output deflator of German transport equipment manufacturing as deflators.

Table 1: Growth Accounting for Verticle Production of Automotives from Germany

	Cost shares (%)		Quantities (1995 = 1)		Contribution to final output growth	
	1995	2007	1995	2007	log pts	%
Factors in Germany	*78.9*	*67.7*				
Low-skilled labour	7.3	4.5	1.00	1.05	0.3	0.5
Medium-skilled labour	34.5	24.7	1.00	1.18	4.8	8.2
High-skilled labour	16.4	15.8	1.00	1.44	5.8	9.8
Capital	20.7	22.7	1.00	1.84	13.3	22.4
Factors outside Germany	*21.2*	*32.2*				
Low-skilled labour	4.0	3.8	1.00	1.99	2.7	4.5
Medium-skilled labour	6.1	8.6	1.00	2.05	5.3	8.9
High-skilled labour	2.8	5.3	1.00	3.02	4.5	7.5
Capital	8.3	14.5	1.00	2.57	10.8	18.2
Total factor productivity			1.00	1.13	11.8	20.0
Final output	100.0	100.0	1.00	1.81	59.2	100.0

Note and source: Own calculation based on equations (5) and (6) using data from WIOD, November 2013 release. The shares and volumes for foreign factors are based on summations across 39 countries and the rest-of-the-world region. Capital growth is proxied by growth in capital stocks. Input quantities are set to 1 in 1995. Growth rates are in logs. Numbers may not add due to rounding.

many and abroad. The cost share of domestic capital even rose, whereas labour shares declined and domestic capital contributed 22 per cent to final output growth for the period 1995-2007. Capital abroad grew even faster but given its lower cost share contributed 18 per cent. Total factor productivity growth is derived as a residual as in equation (6). It corresponds to an annual rate of 0.99 per cent and is shown to contribute 20 per cent of final output growth over this period.

Has total factor productivity growth mainly taken place within Germany, or did it affect all production factors in the chain? To answer this question we may compare productivity growth in the last stage with productivity growth in the whole GVC. Productivity in the last stage can be computed by subtracting growth in factor inputs from growth in real value added in the German car industry. Factor inputs are weighted by their cost shares and real value added should be derived using the double deflation method based on final output and intermediate input prices.[7] Annual productivity growth thus derived from the German transport equipment industry data in the EU KLEMS database is a strong 2.62 per cent. Under the assumption that intermediate input prices have been well measured and the GVC production is separable in the last stage factor inputs, one can derive the part of productivity growth due to the last stage by multiplying the productivity growth rate in last stage by the

6 While this might be true for higher-skilled worker, this can reasonably be doubted for less skilled workers. Integration of labour markets across countries is still incomplete such that wage differentials are not necessarily arbitraged away. Econometric estimation of output elasticities (as done in Timmer and Ye, forthcoming) provides an alternative way to arrive at estimates of marginal productivity.

7 Note that conceptually, the figures should refer to inputs related to the production of final output of the industry, and not to overall output and all factor inputs used in the industry, as part of output may be used as intermediate input elsewhere. There is no separate data on production of final and intermediate products and we assume production technologies to be similar.

ratio of last stage value added to final output. Averaged over the period, this ratio was 0.28 such that 0.73 (=2.62 x 0.28) percentage points out of 0.99 per cent GVC productivity growth was realised in the German car industry, and the remainder of 0.26 in other industries in the GVC. However, as mentioned, the validity of this analysis into the industry location of productivity growth in the GVC depends heavily on the quality of the intermediate input deflator.

Concluding Remarks

Production systems have evolved from a one-stage process taking place in a single location to a multi-stage process involving multiple locations in various countries. This is posing new challenges to analyses of factor incomes, substitution and productivity growth. The canonical KLEMS modelling framework (as in Jorgenson *et al*, 1987) needs to be amended as it provides few insights into the effects of changing production linkages across industries and countries. Its central concept is a single firm or industry in one-stage production. Moreover, its empirical validity depends crucially on the tracking of prices and quantities of intermediate goods and services flowing across plants and borders. With low value-added to gross output ratios, accurate measurement of prices of intermediates becomes paramount to measure productivity. These are increasingly hard to measure due to the practice of transfer pricing within multinational enterprises, the difficulty to price the flow of intangibles as well as an inadequate statistical system to track prices of intermediates when quality is improving (Houseman and Mandel, 2015)

An approach using final products as the unit of observation offers a first step towards a framework to study the important but elusive characteristics of modern production systems. In this article we introduced the GVC accounting approach as a complement to traditional KLEMS type of analyses. Apart from being conceptually appealing, the GVC accounting approach bypasses some of the empirical problems that confront traditional analyses. We have defined cost shares, factor substitution and productivity growth in GVC production, providing a structural foundation in Leontief's input-output model. We showed that these measures can be empirically implemented using synthetic input-output tables and that the results offer new insights into the nature of today's global production systems.

It should be emphasised however, that the outlined GVC approach serves only as a first attempt. Arguably, the input-output model derives its popularity from the clear intuition of its measures in the case of "snake" production systems where industries produce only one output and deliver to only one industry. But in case of joint production and multiple product output, it has to rely on strong (linear) proportionality assumptions in allocating the use of inputs. More generally, the Leontief approach traces the value added without explicitly modelling the interaction of prices and quantities of intermediates that are central in a full-fledged general equilibrium models. While CGE models are richer in the modelling of behavioural relationships, there is the additional need for putting restrictions on the various key parameters of production and demand functions. The Leontief model is an attractive and tractable alternative but further research into more general alternatives would be worthwhile.

Firm-level studies are needed for a better understanding of substitution and productivity in international production systems. Unfortunately, there is very little direct detailed information on plant-to-plant transactions in multiple stages of production. Given firms' secrecy or even ignorance about their own position in global value chains, this situation will not easily improve without major new data collection efforts. Recent new data sources based on value added tax data provide fresh evidence on firms' interaction at the transaction level (see Dhyne and Duprez, (2017) for an example) and provide an interesting avenue for further research.

A particular appealing approach is the task-approach simultaneously arising in the literature on international trade and in labour economics. The task approach centres around a mapping from factor inputs to tasks and then from tasks to output so as to provide a structure on the possible substitution between labour and capital, both at home and abroad. Acemoglu and Autor (2011) outline a general framework that revolves around differences in comparative advantages of factors in carrying out tasks: all workers can carry out all tasks, but some are relatively better at carrying out certain tasks. Substitution of skills across tasks is possible, such that there is an endogenous mapping from workers to tasks depending solely on labour supplies and the comparative advantages of the various labour skill types. Capital may compete with labour in the supply of certain tasks such as routine activities. International specialization arises naturally as skilled workers in advanced countries have a comparative advantage in headquarter activities, while less skilled workers in emerging economies have a comparative advantage in carrying out low-tech activities like assembly, testing and packaging. In our view, the future in our understanding of international production systems lies in the combination of the new emerging task-approach to production with the sophisticated empirical tools developed in the KLEMS tradition.

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