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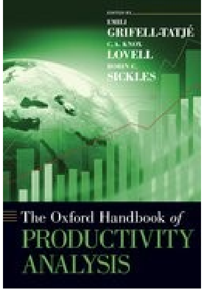

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CHAPTER

21 Productivity and Substitution Patterns in Global Value Chains

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Abstract

Fragmentation of production is posing new challenges to the analysis and measurement of productivity. Traditional approaches focus on firms, industries, or countries as the unit of analysis. This chapter argues that studies of global value chains (GVCs) are needed in situations where production is fragmented across firms and geographical borders. The chapter outlines how existing tools for measuring productivity, factor substitution, and (biased) technological change can be modified to analyze GVC production. A key concept is a production function where final output is generated based on factor inputs only, including both domestic as well as foreign factors. The chapter outlines what type of data would be needed and provides illustrative analyses of GVCs of manufacturing products based on the WIOD (world input-output database).

Keywords: productivity, production fragmentation, technological change, factor substitution, global value chains

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21.1. Introduction

THE increasing fragmentation of production processes is posing new challenges to the analysis and measurement of productivity. Traditional approaches focus on firms, industries, or countries as the unit of analysis. In this chapter we argue that studies of global value chains (GVCs) are needed in situations where production is highly fragmented across firms and geographical borders. Due to improvements in information and telecommunication technologies, production processes increasingly fragment across borders in order to gain access to cheap resources, both natural and human, as well as to acquire customer market entrance. This process was boosted in the first decade of the 2000s as major emerging economies like China and India opened up borders and became integrated into the world economy. As a result, today 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, United States, but is 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 chapter we will review the conceptual and empirical issues that arise in analyzing productivity in the context of international production fragmentation. We discuss how patterns of substitution and productivity growth can be measured in such chains and illustrate this by empirical exercises using new data from the World Input-Output Database (WIOD). To this end, we will build upon the standard ↳ toolkit p. 700 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 labor (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 analyze 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 toolkit (see, e.g., Jorgenson, Chapter 20 in this *Handbook*).

However, modeling 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 the industry value added in gross output is declining such that analyses 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 (Diewert and Wales 1995; Jorgenson, Gollop, and Fraumeni 1987). As ratios of intermediate input to gross output continue to increase, the robustness of the standard 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 chapter we outline how the existing KLEMS methodology can be modified to analyze 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 to focus on a set of discrete activities in distinct locations, which altogether form a GVC.. 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, 1949). Simply put, the production function *G* in the KLEMS approach is given by

> Gross output of industry = *G* (factor inputs in industry, intermediate inputs).

Instead, we will analyze 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 traced to the ultimate factor usage such that the production function of a final good can be written in terms of factor inputs only. These factor inputs p. 701 are located in the industry where the last stage ↳ of production takes place, as well as in other industries contributing in earlier stages of production. These can be other domestic industries, as wel as industries abroad. This opens up the possibility of studying the various substitutions of factor inputs and the possible biased nature of technical change.[1]

This GVC modeling approach will allow us to focus on three important issues. First is 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 also the full set of activities both in the pre- and post-production phases. This comprises for example research and development, software, design, branding, finance, logistics, after-sales services, and system integration activities. Recent case studies of electronic products such as the Nokia smartphone (Ali-Yrkkö, Rouvinen, Seppälä, and Ylä-Anttila, 2011; 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 so 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) and Wen et al. (2017) have shown that compensation for capital assets has been increasing, in particular in emerging economies.

Second, and related to the first issue, there is mounting evidence that suggests that advanced countries are increasingly specializing in skill- and capital-intensive activities within GVCs, 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 characterized 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 modeling of inter-industry linkages.

Third, there is renewed interest in a possible factor bias in technological change in order to explain the widespread polarization within the labor market that characterizes advanced nations today. According to the "routinization hypothesis" put forward by Autor, Levy, and Murnane (2003), information technology capital complements highly educated workers engaged in abstract tasks, substitutes for moderately educated workers performing routine tasks, and has little effect on less-skilled workers performing manual and services tasks. At the same time, routine tasks are also often offshored, so the effects of increasing imported intermediates and factor bias in productivity may be observationally equivalent when only using data on domestic factor use.

More generally, increasing international production fragmentation limits our understanding of the
p. 702 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.

The remainder of this chapter is organized as follows. In section 21.2, we outline the concept of GVCs using a linear system of cost equations rooted in the input–output approach introduced by Leontief (1936). Using this framework, we can derive the cost shares and total factor requirements of a sector's (final) output employing the so-called Leontief inverse. We model producer behavior through a translog production function, and construct corresponding index numbers of output and input growth. Productivity growth is measured by the rate of decline in the total (direct and indirect) labor and capital requirements in the production of a good, weighted by their cost shares. In section 21.3 an illustrative empirical example is given based on an analysis of the GVC production of German automobiles. In section 21.4 we apply our approach to a broad set of products and analyze trends in the factor cost shares in 240 GVCs of manufacturing goods. We show how the cost shares of capital and high-skilled labor are rapidly increasing, while the cost shares of medium- and in particular low-skilled labor are rapidly declining between 1995 and 2007. In section 21.5 we econometrically estimate the unknown parameters of the translog function to analyze the possible causes for the changes in factor shares in GVCs. A system of cost equations is estimated to measure substitution elasticities and possible factor biases in productivity change. Section 21.6 concludes, emphasizing the approximate nature of the GVC approach and stressing the need for new data collection efforts in order to better understand the causes and consequences of fragmenting production processes.

21.2. Framework to Analyze Global Value Chain Production

In this section we introduce a framework for measuring factor cost shares and productivity in global value chains (GVCs). We start outlining our general approach and clarify some of the terminology used. In subsection 21.2.2 we provide a more technical exposition of the framework.

21.2.1. 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. 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 multinational corporation, 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). Baldwin and Venables (2013) introduced the concepts of "snakes" and "spiders" as two archetypal configurations of production systems. The snake refers to a production chain organized as a sequence of production stages, whereas the spider refers to an assembly-type process on the basis of delivered components and parts. Of course, actual production systems are composed of a combination of various types. Our method measures the value added in each activity in the process, irrespective of its position in the network. It is important to stress that our approach refers not only to the physical production process, but also to the full set of activities both in the pre- and post-production phases, including research and development (R&D), software, design, branding, finance, logistics, after-sales services, and system integration. Therefore Timmer et al. (2014) propose using 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 analyze 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 (labor 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 modeling 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, so 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, as well as energy, 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 modeling 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 are directly and indirectly involved in GVC production, or the amount of capital.

p. 704 **21.2.2. Technical Exposition**

This section gives a mathematical exposition of our measurement framework, grounded in the older literature on input–output accounting with multiple regions, going back in particular to work by Miller (1966), and surveyed by Millar and Blair (2009). The usefulness of the input–output approach has recently been rediscovered by scholars of vertical specialiation in trade such as in Johnson and Noguera (2012), Koopman, Wang, and Wei (2014) and Los, Timmer, and de Vries (2016). 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-sector 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. We use the term "good", but this may refer to a physical product as well as a service. 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 good produced in a particular country-sector must equal the quantities of this goodused domestically and abroad. This condition can be written as

$$y_i(s) = \sum\nolimits_j f_{ij}(s) + \sum\nolimits_j \sum\nolimits_t m_{ij}(s,t) \tag{21.1}$$

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 (*SN* x 1), which is obtained by stacking output levels in each country-sector. Define **f** as the vector of dimension (*SN* x 1) 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 (*SN* x *SN*). 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 goods of each country-sector are produced using a combination of various intermediate products, both domestic and foreign.

p. 705 Using this we can rewrite the stacked *SN* market-clearing conditions from (21.1) in compact form as $\mathbf{y} = \mathbf{f} + \mathbf{A}\mathbf{y}$. Rearranging, we arrive at the fundamental input–output identity:

$$\mathbf{y} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{21.2}$$

where **I** is an (*SN* x *SN*) identity matrix with ones on the diagonal and zeros elsewhere. The matrix $(\mathbf{I} - \mathbf{A})^{-1}$ 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 *n*th element representing a euro of global consumption of goods from country-sector *n*, while all the remaining elements are zero. The production of $\mathbf{z}_n$ requires intermediate inputs given by $\mathbf{A}\mathbf{z}_n$. 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 $\Sigma_{k=0}^{\infty}\ \mathbf{A}^k\mathbf{z}_n$. This geometric series converges (under mild conditions) to $(\mathbf{I} - \mathbf{A})^{-1}z_n$.

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 labor per unit of gross output in sector *s* in country *i* and create the row-vector ***l*** containing these "direct" labor coefficients, and similarly for capital coefficients ***k***. Then the total (direct plus indirect) labor and capital requirements per unit of final output can be derived as

$$\Lambda = \hat{\imath}(I - A)^{-1} \quad \text{and} \quad \mathrm{K} = \hat{k}(I - A)^{-1} \tag{21.3}$$

in which a hat-symbol indicates a diagonal matrix with the elements of the vector on the diagonal. $\mathbf{\Lambda}$ is the matrix of dimension (*SN* x *SN*) with an element (*i, j*) indicating the amount of labor in country-sector *j* needed in the production of one unit of final output by country-sector *i*, referred to as the total labor coefficient, and similarly for the matrix of capital inputs $\mathbf{K}$.

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 labor and capital available in each country-sector. As such, this approach provides 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 GVC 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 labor 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-
p. 706 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 $\mathbf{p}(\mathbf{I} - \mathbf{A})$. As profit rates are measured residually such that wages and profits exhaust value added for each country-sector, the following accounting identity holds:

$$p(I - A) = w\hat{\imath} + r\hat{k} \tag{21.4}$$

Post-multiplying both sides of (21.4) with the inverse of (**I** – **A**) and substituting from (21.3), 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

$$\mathbf{p} = \mathbf{w}\Lambda + \mathbf{r}K \tag{21.5}$$

with $\mathbf{\Lambda}$ and $\mathbf{K}$ the matrices with total labor and capital coefficients. The identity in equation (21.5) forms the basis for deriving cost shares of labor 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 $\mathbf{\Lambda}$ and $\mathbf{K}$, 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 in the preceding can also be used to measure total factor productivity (TFP) growth in the production of a final good (following Wolff 1994). The consolidated data provide 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) labor 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 labor requirements for producing one unit of good *j* from $\mathbf{\Lambda}$ and similarly κ_j a column of $\mathbf{K}$. Under the standard assumptions of constant returns to scale and perfectly competitive input markets, we can define productivity growth π in the GVC of product *j* by the weighted rate of decline of its total labor and capital requirements:

$$\frac{\partial \pi_j}{\partial t} \equiv -\alpha_j^L \frac{\partial \ln \lambda_j}{\partial t} - \alpha_j^K \frac{\partial \ln \kappa_j}{\partial t} \quad (21.6)$$

where $\partial \ln \lambda_j / \partial t$ is a (column) vector containing the differentials of the logarithms of all elements in λ_j. The weights are given by α_j^L, a (row) vector of value shares with elements reflecting the costs of labor from all country-sectors used in the production of one unit of product *j*, and similarly for the capital value shares given in α_j^K. Summed over all contributing sectors and countries, the elements in α_j^L add up to the labor share in final output of *j*, and similarly for capital. As all factor inputs are accounted for, the labor 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 (see Jorgenson et al. 1987). The productivity measure in (21.6) essentially shows the rate of productivity growth in the composite sector producing good *j*
p. 707
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 analyzed. 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 (21.6). 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 in a single domestic stage of production, and when the prices of intermediate inputs are well measured; that is, any decline in the factor requirements in upstream sectors will be translated into a lower price for intermediates used by sectors downstream. Only in that case can the price of value added 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 (see 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 (e.g., Atalay et al. 2014),[4] but so far their measurement is elusive (see Corrado et al. 2012 for pioneering attempts). 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, so 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 same situation arises when production is fragmented across countries, adding to the measurement problem. The GVC approach, based on an integrated assessment, will thus provide a useful alternative to measure productivity growth in modern integrated
p. 708
production systems. ↳

21.3. An Illustrative Example: Global Value Chain Production of German Automobiles

In this section, we illustrate our GVC methodology by analyzing the production of German cars. Throughout this chapter 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 (see 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 21.2 and given in equation (21.5).

Table 21.1 indicates the geographical origin of the value added in production of German cars in 1995 and in 2008. It reveals striking developments. Between 1995 and 2008, the share of domestic value added decreased rapidly from 79% to 66% of the value of a German car. Conversely, foreign value increased from 21% to 34%. With the new availability of cheap and relatively skilled labor, firms from Germany relocated p. 709 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.

Table 21.1 Value Added Shares in Final Output of Automotives Finalized in Germany (%)

Generated in	1995	2008	Change
Germany	78.9	66.0	–12.8
Eastern Europe	1.3	4.3	3.0
Other European Union	11.9	14.3	2.4
NAFTA	2.5	3.1	0.6
East Asia	2.1	4.3	2.2
Other	3.3	8.0	4.7
Total	100.0	100.0	

Source: Authors' calculations based on WIOD (2013 release).

Notes: Decomposition of final output of the transport equipment manufacturing industry in Germany (ISIC rev. 3 industries 34 and 35) based on equation (21.5). Eastern Europe refers to countries that joined the EU as of January 1, 2004. East Asia refers to China, Japan, South Korea, and Taiwan. Numbers may not sum due to rounding.

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 (21.6). Data on workers are 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 following the SNA 2008 (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 21.2: final output volumes of German automotives increased by 59 log points over the period 1995–2007.[5] This was mainly due to increases in the use of capital, both domestically and abroad, together accounting for almost half 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 p. 710 more skilled workers. Growth in workers in Germany contributed to 19% of final output growth, and workers abroad contributed another 21%. 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 are presumed to reflect lower quality compared to German workers. While this might be true for higher-skilled workers, this can reasonably be doubted for less skilled workers. Integration of labor markets across countries is still incomplete such that wage differentials are not necessarily arbitraged away. Obviously, the potential cost saving was a main determinant for firms' decision to offshore. Econometric estimation of output elasticities (as done later on in this chapter) provides a way to arrive at estimates of marginal productivity. Capital input was growing fast, both within Germany and abroad. The cost share of domestic capital even rose, whereas labor shares declined, and it contributed 22% to final output growth for the period 1995–2007. Capital abroad grew even faster, but given its lower cost share contributed 18%. Productivity growth is derived as a residual, as in equation (21.6). It corresponds to an annual rate of 0.99% and is shown to contribute 20% of final output growth over this period.

Table 21.2 Growth Accounting for Vertical Production of Automotives from Germany

	Cost shares (%)		**Quantities (1995 = 1)**		**Contribution to Final Output Growth**	
	1995	**2007**	**1995**	**2007**	**log pts**	**%**
Factors in Germany						
Low-skilled labor	7.3	4.5	1.00	1.05	0.3	0.5
Medium-skilled labor	34.5	24.7	1.00	1.18	4.8	8.2
High-skilled labor	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						
Low-skilled labor	4.0	3.8	1.00	1.99	2.7	4.5
Medium-skilled labor	6.1	8.6	1.00	2.05	5.3	8.9
High-skilled labor	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: Authors' calculations based on equations (21.5) and (21.6) using data from WIOD (2013 release). The shares and volumes for foreign factors are based 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.

Has productivity growth mainly took 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 entire 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.[6] Annual productivity growth thus derived is a high 2.62%. 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 productivity growth rate in last stage by the ratio of last-stage value added to final output.[7] Averaged over the period, this ratio was 0.28, so 0.73 (= 2.62 x 0.28) percentage points out of 0.99% GVC productivity growth was realized in the German car industry, and the remainder of 0.26 in other industries in the GVC. However, as mentioned, the validity of this decomposition analysis depends heavily on the quality of the intermediate input deflator.

21.4. Factor Income Shares in Manufacturing Global Value Chains

In this section we extend the analysis and provide factor cost share measures for a wide set of p. 711 manufacturing goods. We denote these goods by the term *manufactures*. ↳ Production systems of manufactures are highly prone to international fragmentation, as activities have a high degree of international contestability: they can be undertaken in any country with little variation in quality. It is important to note that GVCs of manufactures do not coincide with all activities in the manufacturing sector, or with all activities that are internationally contestable. Some activities in the manufacturing sector are geared toward the production of intermediates for final non-manufacturing products and are not part of manufactures GVCs. On the other hand, GVCs of manufactures also includes value added outside the manufacturing sector, such as business services, transport, communication, and finance, and in raw materials production. These indirect contributions will be explicitly accounted for through the modeling of input-output linkages across sectors.

To start, we first illustrate the pervasiveness of the production fragmentation process. This includes domestic as well as international outsourcing. The former predates the latter: since the 1970s a steady process of outsourcing has taken place in advanced economies. In order to benefit from economies of scale and specialization, manufacturing firms outsourced non-core activities such as cleaning, catering, accounting, and other administrative back-office activities to other firms, often in the services industries.[8] More recent is the trend of international production fragmentation of services as well as manufacturing activities (see, e.g.. Feenstra 1998 for an overview).

Figure 21.1 provides trends in fragmentation in the production of manufactures. Product GVCs are identified by the country-industry of completion, and we have data for 240 manufacturing product chains: 12 groups of final manufacturing goods completed in 20 advanced countries, including 14 advanced EU economies (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, and the United Kingdom) and six non-European economies (Australia, Canada, Japan, South Korea, Taiwan, and the United States). In Figure 21.1A, we provide a Kernel density plot of the share of last-stage production in GVC output. This share is defined as the value added to the product in the industry of completion as a ratio of the final output of the product.[9] Already in 1995 only around 36% (unweighted average) value was added in the last stage, and this has further declined to 34% in 2007. In Figure 21.1B, we document the international fragmentation trend (“offshoring”), adding the value-added contributions by domestic industries in earlier stages of production to the value added by the industry of completion. By definition, these shares of domestic value added in GVC output will be higher than the last-stage shares only, but the trend is even clearer: the (unweighted) average foreign share rose from 24.7% to 30.0%. For 84.5% of the product chains, the foreign value-added share has increased, indicating the pervasiveness of international fragmentation.[10]

Anecdotal evidence suggests that the factor content of the offshored activities might be different from the activities that remain onshore. For example, activities offshored to low-wage countries are typically low-skilled labor intensive. This will be reflected in changes in the factor cost shares in GVCs that are plotted in Figure 21.2. For each factor, we show on the horizontal axis the cost share in 1995 and on the vertical axis the share in 2008. Points above the 45-degree line indicate GVCs in which the factor has increased its share. It illustrates some clear major trends: cost shares of capital (and in particular, high-skilled labor) are increasing in many chains, while the cost shares of low-skilled labor are decreasing (see also Timmer et al. 2014). Capital captures around 36.7% of cost share in the value chain on average, increasing from 35.3% in 1995 to 38.7% in 2007 (unweighted average). Remember that capital income is derived as a residual and defined as gross value added minus labor income. It thus represents remuneration for capital in the broadest sense, including physical capital (such as machinery and buildings), land (including mineral resources), intangible capital (such as software and R&D, but also patents and trademarks), and financial capital. The share of high-skilled workers income increased as well and even more than the capital share, on average by 4.6% percentage points The value-added share of medium-skilled labor declined by 1.4, and low-skilled workers by a hefty 6.7 percentage points.

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Figure 21.1.

Cost share in final output (in percent), 1995 and 2007.

Cost share in final output (in percent), 1995 and 2007.

Figure 21.2.

Factor shares in 240 global value chains of manufactures.

Factor shares in 240 global value chains of manufactures.

21.5. Patterns of Substitution and Productivity Growth in Global Value Chains

What might explain the trends in factor income shares in global production of manufacturing goods? To this end we will employ an econometric framework to estimate parameters in the GVC production function to investigate the impact of substitution elasticities and possible biases in productivity on the distribution of the value of output.[11] Following Christensen, Jorgenson, and Lau (1973), it is assumed that the product cost-functions can be approximated by a translog function, which is twice differentiable, linearly homogenous, and concave in factor prices. For a particular product, it is given by (product subscripts are omitted throughout for ease of presentation)

$$\ln C\left(p_t, t\right) = \alpha + \sum_{i\in F} \beta_i \ln p_{it} + \tfrac{1}{2}\sum_{j\in F}\sum_{i\in F}\gamma_{ij}\ln p_{it}\ln p_{jt} + \beta_T t + \sum_{i\in F}\gamma_{iT} t \ln p_{it} + \tfrac{1}{2}\gamma_{TT} t^2 \tag{21.7}$$

where C represents variable cost per unit of output and is a function of prices p_i for factors i ($i \in F$, F refers to the set of factors) and time. The parameters γ_{ij} will provide information on the factor demand elasticities, while β_T represents the speed of Hicks-neutral technological change. The parameter γ_{iT} indicates a trend of productivity growth that complements factor i if positive, or substitutes when negative. γ_{TT} indicates the acceleration in productivity growth. If cost-minimization is assumed, Shephard's lemma can be used to derive the well-known factor cost-share (S) equation for a factor i:

$$S_{it} = \beta_i + \sum_{j\in F}\gamma_{ij}\ln p_{jt} + \gamma_{iT} t \tag{21.8}$$

As discussed in Jorgenson, Gollop, and Fraumeni (1987, Chapter 7), under necessary conditions for producer equilibrium the cost share of each input is equal to the elasticity of output with respect to that input. One can then define so-called share elasticities with respect to prices as the derivative of the value share with p. 715 respect to the (log) of factor ↳ prices. These elasticities can be employed to derive the implications of patterns of substitution for the relative distribution of the value of output among the factor inputs. This is captured by the second term on the right-hand side. Similarly, one can define the bias of productivity growth with respect to a particular factor quantity as the derivative of the value share with respect to time. If the bias is positive for a factor, the corresponding value share increases over time. If it is negative, the value share decreases with time. This is captured by the last term on the right-hand side.

To estimate this system, we further impose constant returns to scale to simplify and other standard restrictions on the parameters in order to have a valid cost-function system. Constant returns to scale requires that the cost function is linearly homogenous in factor prices, which implies $\Sigma_{i \in F} \beta_i = 1$, and $\Sigma_{j \in F} \gamma_{ij} = 0$ for any *i*. Without loss of generality, we also impose symmetry such that $\gamma_{ij} = \gamma_{ji}$. Finally, the summation of the cost shares of all factors by definition equals to one such that $\Sigma_{i \in F} \gamma_{iT} = 0$. Given the cross restrictions in the share equations, we can improve the efficiency of parameter estimates by estimating in a simultaneous equation system. Berndt (1991) shows that this restricted equation system can be estimated by first dropping one cost-share equation and transforming the other equations accordingly. The cost-share equation for capital is dropped, and this choice is arbitrary as it does not affect the estimates since we iterate using Zellner's method (using ISUR).[12]

We estimate the model with country-fixed as well as product-fixed effects using annual data (1995–2007) for 240 product GVCs. Both sets of dummies jointly show significance at a high level, and a Hausman test clearly rejects the pooled regression. Before one can start interpreting the results, it is necessary to check whether the estimated cost function is consistent with economic theory and cost-minimization behavior. Cost functions are well behaved if they are quasi-concave. This implies that the so-called Hessian matrix of second-order derivatives with respect to factor prices must be negative semi-definite. A test for this is rather complex, and Diewert and Wales (1987) provide a simpler alternative: namely, whether the Hessian matrix $(H - \mathrm{Diag}(s) + ss')$ is negative semi-definite, where *H* refers to the symmetric matrix containing all γ_{ij} of factors, and *s* is a column vector of cost shares of each factor. The eigenvalues of this matrix should be evaluated for each observation, and it is unlikely that negative semi-definity holds for all observations. Nevertheless, we have checked the quasi-concavity for each observation, and only 150 out of 3,116 observations have positive eigenvalue, which suggests that the Hessian matrix associated with the estimated translog cost function is negative semi-definite in most of the cases.[13] Production functions for GVCs thus generally appear to be consistent with economic theory and cost-minimization behavior.

Given the strong changes in relative prices, it is also interesting to investigate the elasticities of substitution and price elasticities of factor demand. The coefficients γ_{ij} in system (21.8) are the second-order derivatives with respect to factor prices. A positive γ_{ij} can be roughly interpreted as a net substitution between factor *i* and *j*, since it means that a price increase of factor *j* would increase the cost share paid to factor *i*, which p. 716 implies that the usage of *i* must have increased. Formally, the relationship ↳ between the γ parameters and substitution elasticities between factors *i* and *j* (σ_{ij}) can be given by the so-called Morishima elasticities of substitution. Compared to the more well-known Allen-Uzawa (partial) elasticities, the Morishima elasticities have superior characteristics, particularly in cases with more than two inputs, in particular, they can beasymmetric (see Blackorby and Russell 1989). The cross-price elasticity of demand of factor *i* with respect to price of *j* (ε_{ij}) is given by

$$\varepsilon_{ij} = \frac{\gamma_{ij}}{s_i} + s_j \ (\text{for} \ \ i \neq j) \quad \text{and} \quad \varepsilon_{ii} = \frac{\gamma_{ii}}{s_i} + s_i - 1. \tag{21.9}$$

Then the Morishima elasticities of substitution are given by

$$\sigma_{ij} = \varepsilon_{ji} - \varepsilon_{ii}. \tag{21.10}$$

As is clear from these definitions, elasticities depend on the actual cost shares and can vary across observations. We follow common practice and evaluate the elasticities on the basis of simple average cost shares across all observations. Results are given in Table 21.3 with price elasticities (at left) and elasticities of substitution between each factor (at right). The implied own-price elasticities are negative for all factors, as expected given the concavity of the cost functions, and are strongest for unskilled labor, while weakest for capital. For low-skilled labor, the self-price elasticity is as low as −0.66, which means that 1% decrease in the wage of a low-skilled worker corresponds to a 0.66% increase in the number of low-skilled hours worked in the value chain. This elasticity suggests that the rapid decline in the price of low-skilled work will only have a modest impact on its cost share. Indeed, the majority of the falling cost share is attributable to the low-skill saving nature of productivity growth, as shown in the following.

Table 21.3 Factor Demand Elasticities in Manufacturing Global Value Chains

	Implied Price Elasticity				Implied Elasticity of Substitution			
	w_L	w_M	w_H	r	L	M	H	K
L	−0.661	0.366	0.153	0.143	—	0.868	0.814	0.726
M	0.207	−0.443	0.127	0.109	0.808	—	0.668	0.531
H	0.153	0.225	−0.450	0.072	0.603	0.577	—	0.483
K	0.065	0.089	0.033	−0.187	0.329	0.296	0.259	—

Note: The elasticities are based on equations (21.9) and (21.10) in main text using parameters estimated in system of cost equations given in (21.8) based on annual data for 240 manufacturing GVCs, with ISUR including country and product group dummies. R^2 for each equation 0.9478 (*L*); 0.9243 (*M*); 0.8740 (*H*). *w* refers to wages of high-skilled labor (*H*), medium-skilled labor (*M*), low-skilled labor (*L*) and *r* to the price capital (*K*). Elasticities are evaluated at the simple average cost

 Also interesting are the elasticities of substitution between the various factor inputs given in the right-hand part of the table. All elasticities are below one, suggesting that the four factor inputs are complements in global production of manufacturing products. Most notable is the low substitution elasticities of capital with all labor types. Capital appears to be particularly complementary to high-skilled workers, but there is also a strong complementarity to medium-skilled and low-skilled labor.

Another determinant of the factor share change is the possible factor-saving or factor-augmenting nature of technological change, which is captured by interactions with a linear time trend, γ_{iT}, in the specification. There is no a priori reason to assume that the effects are linear, and hence we follow Baltagi and Griffin (1988), who proposed a more general index approach in which the time trend *t* is replaced by year dummies using the first year as base. For a factor *i*, $\gamma_{it}t$ is replaced by $\Sigma_{t=2}^{12}\lambda_{it}D_t$ where D_t are year dummies. The parameter restrictions $\Sigma_{i\in F}\gamma_{iT}=0$ are subsequently replaced by $\Sigma_{i\in F}\lambda_{it}=0$ for all *t*. The results for the year dummies can be found in Table 21.4, accumulating from the beginning year. A strong bias is found for each factor. On average, productivity growth in GVCs of manufactures was saving on low- and medium-skilled labor, while using on high-skilled labor and capital. For low- and high-skilled labor, the accumulated factor biases are highly significantly different from 0 throughout the period. Accumulated factor bias is significant for capital in all years except the first two. For medium-skilled labor only, the bias in technical change is initially insignificant, but significant after 2004.

Using the estimates of the substitution elasticities and factor biases, we can use equation (21.8) to decompose the change in factor income shares shown in the previous section. The results are given in Table 21.5 and show that the model provides generally a good prediction for the average change in cost share of each factor. The effect of the factor bias in productivity growth strongly dominates the effects of factor price changes. Factor prices of low-skilled labor have declined on average 1% annually relative to capital, and about 2% relative to high-skilled labor, but this can explain only a little of the great decline in the low-skill cost share, which instead is driven by biased technological change. The substitution effects are strongest in the case of capital. Capital prices declined relative to medium- and high-skilled worker wages, which should lead to a decline in its cost share of 1.48. But strong capital using productivity growth pushed up its share by 4.43, more than counteracting the price effects (see Reijnders et al, 2016, for more).

21.6. 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 modeling framework (as in Jorgenson et al. 1987) needs ↳

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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, the accurate measurement of prices of intermediates becomes paramount to the measurement of productivity. These are increasingly hard to measure due to the practice of transfer pricing within multinational enterprises, the difficulty of pricing the flow of intangibles, as well as an inadequate statistical system to track the prices of intermediates when quality is improving.[14]

Table 21.4. Estimates of factor bias in productivity growth in manufactures GVCs

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
γ_{LT}	−0.0073	−0.0160	−0.0240	−0.0301	−0.0362	−0.0400	−0.0476	−0.0379	−0.0553	−0.0593	−0.0626	−0.0650
	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0019	0.0019	0.0019	0.0019
γ_{MT}	*−0.0004*	*0.0023*	*0.0002*	*−0.0023*	*−0.0022*	−0.0049	-0.0072	−0.0122	*−0.0047*	−0.0110	−0.0180	−0.0208
	0.0019	*0.0019*	*0.0019*	*0.0019*	*0.0019*	0.0019	0.0020	0.0019	*0.0020*	0.0020	0.0021	0.0021
γ_{HT}	0.0042	0.0083	0.0129	0.0150	0.0196	0.0235	0.0255	0.0262	0.0342	0.0363	0.0376	0.0369
	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0016	0.0015	0.0016	0.0016	0.0016	0.0017
γ_{KT}	*0.0034*	*0.0053*	0.0109	0.0174	0.0189	0.0215	0.0293	0.0239	0.0258	0.0340	0.0430	0.0489
	0.0026	*0.0026*	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0027

Note: Accumulation of estimates on year-dummies in system of cost share equations, see Table 21.3. Subscripts refer to high-skilled labor (*H*), medium-skilled labor (*M*), low-skilled labor (*L*) and Capital (*K*). Parameters involving *K* are implicitly derived using the parameter restrictions discussed in the main text. Standard errors are given below. Values that are not significant at 1% level are in italics.

Table 21.5 Explaining the changes in average cost shares in manufacturing GVCs

	Actual Change in Cost Share	Predicted Cost Share Changes	Due to Change in Relative Prices of			Sum of Price Effects	Tech Bias
			Low-Skilled Labor	Medium-Skilled Labor	High-Skilled Labor		
LS	−6.67	−6.50	−0.38	0.17	−0.04	−0.24	−6.26
MS	−1.37	−1.31	−0.15	1.17	−0.20	0.82	−2.13
HS	4.64	4.86	0.03	−0.18	1.05	0.89	3.96
K	3.39	2.95	0.49	−1.16	-0.81	−1.48	4.43

Note: Change in cost over 1995–2007, averaged over 240 manufacturing GVCs. Predictions based on cost equations model; see Tables 21.3 and 21.4 for elasticities and factor bias in productivity. Relative wages are the wage rate relative to capital return.

An approach using global value chains as the unit of observation offers an alternative approach toward a framework to study the important but elusive characteristics of modern production systems. In this chapter we introduced the GVC accounting approach as a complement to the 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 emphasized, 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 the case of joint production and multiple-product output, it has to rely on strong (linear) proportionality assumptions in allocating the use of inputs. And although the accounting model is relatively straightforward, it is clear that the validity of the findings relies heavily on the quality of the database used. Data can, and needs, to be improved in many dimensions. For example, the WIOD is a prototype database developed mainly to provide a proof-of-concept, and it is up to the statistical community to bring international input-output tables into the realm of official statistics. Recently, the UNECE published its *Guide to Measuring Global Production* (UNECE, 2015), and the development work done by the OECD in its Trade-in-Vale-Added project is a step in the right direction.Ways forward would involve bringing information from establishment surveys into extended supply and use tables. In the longer term this would entail common business registers across countries and new data collections on value-chains beyond counterparty transactions.

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 production 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' interactions at the transaction level (see Bernard et al. 2015 for an example) and provide an interesting avenue for further research.

p. 721 A particular appealing avenue for new analysis of GVCs is the socalled “task-based approach” simultaneously arising in the literature on international trade and in labor economics. The task approach centers 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 labor and capital, both at home and abroad. Acemoglu and Autor (2011) outline a general framework that revolves around differences in the comparative advantages of factors in carrying out tasks: some workers are relatively better at performing certain tasks. Substitution of skills across tasks is possible, such that there is an endogenous mapping from workers to tasks depending solely on labor supplies and the comparative advantages of the various labor skill types. Capital may compete with labor 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 (de Vries et al., 2018). It highlights that income distributions are determined by the interplay of technological change and global trading of labour and capital services. Combining the task approach with the empirical tools developed in the venerable KLEMS tradition is a fruitful avenue for future research.

Notes

1. It is important to note that production fragmentation does not invalidate analysis of the welfare contribution of productivity change in sectors using the standard KLEMS growth accounting framework. The contribution of productivity growth in a sector to aggregate welfare in the country is well-defined in a setting with intermediate inputs (see, e.g., Hulten 1978), provided intermediate input prices are well measured.

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.

3. Analyses of productivity in vertically integrated chains harks back to the work by Pasinetti (1977); see also Wolff (1994) and ten Raa and Wolff (2001). Gu and Yan (2017) provide a recent empirical application.

4. In a study of US multinational firms, they find that vertical ownership is not primarily used to facilitate transfers of goods along the production chain, as is often presumed: roughly one-half of upstream plants report no shipments to their firms' downstream units. Instead, an acquired plant begins to resemble the acquiring firm along multiple other dimensions, such as production technologies and sales destination. This is consistent with the hypothesis that vertical integration promotes efficient intra-firm transfers of intangible inputs rather than of goods.

5. The data in WIOD are 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.

6. Note that conceptually, the figures should refer to inputs related to the production of final output of the industry, and not p. 722 to overall output and all factor inputs used in the industry, ↳ as part of output may be used as intermediate input elsewhere. Empirically, however, the latter approach will be equivalent to the former, as there are no separate data on production of final and intermediate products in the industry. Production technologies are assumed to be the same.

7. Again, in the data at hand, this ratio is equivalent to the value-added–gross-output ratio of the industry.

8. Ten Raa and Wolff (2001) analyzed the impact of services outsourcing on manufacturing productivity. Services input used by manufacturing industries is reduced into their constituent elements of material inputs, using an input–output technique akin to the one described in the preceding. They find that outsourcing of sluggish services can account up to one-fifth of the US manufacturing productivity recovery in the 1980s.

9. Note that this share is sensitive to the level of industry detail in the data. With higher industry detail, the shares will be lower by definition, and in the limit reflect plant (or firm) shares.

10. Los et al. (2015) investigated the regional origin of foreign value added, focusing on three regional trading blocs: Europe, NAFTA, and East Asia. They found that value added originating from outside the region to which the country-of-completion belongs is growing faster than the value added from within the region. This is suggesting a transition from production systems that were mainly regional to more extensive networks that are truly global. They also find that this tendency was only briefly interrupted by the financial crisis in 2008.

11. This section relies on results described in full in Reijnders, Timmer, and Ye (2016).

12. The simultaneous equation system can be estimated via Zellner's seemingly unrelated regression (SUR), either in one-step or using iterated SUR (ISUR). The one-step SUR combines multiple equations into one stack form, and the stack form is estimated via ordinary least square (OLS), while the iterated method is equivalent to maximum likelihood (ML) estimates. We use the latter, and although it might not always converge, it did in all our applications. Also, it appeared to be empirically close to the one-step SUR.

13. Typically, an even simpler method is used in the literature by investigating the eigenvalues evaluated at the simple average of the cost shares. Doing this, we find that all eigenvalues are non-positive (–0.1875, –0.1164, –0.0807, 0), which satisfies the requirement.

14. See Houseman and Mandel (2015) for an overview of the problems in the measurement of globalized production.

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