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ICT AND PRODUCTIVITY GROWTH WITHIN VALUE CHAINS

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Growth accounting has documented an important contribution of information and communication technology (ICT) capital deepening to sectoral labor productivity growth during the late 1990s, especially for the knowledge-intensive services that are used to an important extent as intermediate inputs to other sectors. Our approach traces labor productivity growth not within sectors but within value chains of final products. A main result is that more than half of the productivity gains related to ICT capital deepening for manufactured goods are contributed by upstream industries, mostly by knowledge-intensive services. For a number of countries, similar magnitudes of upstream contributions of ICT capital deepening are observed for ICT products and for services that are not knowledge-intensive. The major part of these contributions is domestic rather than foreign. Moreover, the high sectoral growth in total factor productivity (TFP) in the ICT sector contributes only moderately to effective TFP growth in non-ICT value chains.

JEL Codes: E22, F62, O47

Keywords: ICT, economic growth, productivity, value chains, growth accounting

1. INTRODUCTION

The diffusion of digital technologies has transformed the economy and increased productivity, which raises incomes and product quality and lowers product prices. During the first decades of the twenty-first century, technological transformation seems to be accelerating again while the productivity numbers are not. To better understand the potential of further digital transformation ahead, it is useful to turn back to the period of the Internet boom and to deepen our understanding of the productivity growth at that time. While the Solow paradox, according to which the productivity effects of information and communication technologies (ICT) were not visible in statistics, remains a popular saying, the research undertaken since Solow's observation in the late 1980s has gained solid evidence that many sectors and countries experienced visible, though not always dramatic, productivity growth related to the diffusion of ICT. At the sectoral level,

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ICT-related labor productivity growth occurs in two forms, first, in the form of more and better ICT capital used in all sectors of the economy and, second, in the form of more productive use of capital and labor in the ICT sector itself, thanks to new inventions ("Moore's Law") and other improvements.

1.1. *Results on the Role of ICT Capital from Sectoral Growth Accounting*

Many studies on the effects of ICT on labor productivity were conducted at the sectoral level. While the results of growth accounting and econometric studies differ to some degree, a rough consensus among these studies is established by Cardona *et al*. (2013). In a survey of a large number of papers, they find that ICT capital deepening, which is the increase in ICT capital per unit of labor input, has contributed visibly to labor productivity growth at the sectoral level. The median increase in labor productivity associated with a 1 percent increase in ICT capital per worker is about 0.05–0.06 percent. While both econometric estimation and growth accounting can be used for such studies, the method of growth accounting has been more popular at the sectoral level, whereas econometric estimation is used more frequently at the firm level.

In one of the early growth-accounting studies with a focus on ICT contributions, Jorgenson (2001) shows that investment in ICT and growth in total factor productivity (TFP) in the ICT-producing sector already made a visible but not very large contribution to US labor productivity growth between 1973 and 1995. During years of the "Internet revolution" after 1995, these contributions doubled. Jorgenson points to several measurement issues that are important for assessing them adequately, such as the availability of constant quality price indices for ICT investment and measures of capital services rather than just capital stock. Building on newly constructed harmonized measures of ICT investment, van Ark *et al*. (2002) undertake a similar study for EU countries for 1980s and 1990s. They find that ICT capital deepening in all sectors and TFP growth in the ICT sector are increasing since the mid-1990s in Europe, but continue to lag behind US values. Further studies take a closer look at the sectoral pattern of the contribution of ICT capital deepening to labor productivity growth. Comparing four EU economies to the US, Inklaar *et al*. (2005) find ICT-using services industries (financial services, business services, and wholesale trade) to be mainly responsible for accelerating aggregate ICT capital deepening in the 1990s. The effect is more important in the US than in the EU countries. Considering the development in the years after 2000 in the US, Oliner *et al*. (2008) show that ICT capital deepening continues to contribute to labor productivity growth but that its importance is decreasing relative to TFP growth in ICT-intensive industries. Productivity in the US and the EU continues to drift apart throughout the early 2000s, with the EU countries experiencing lower labor productivity growth in business services, financial services, and distribution services (transport and trade). ICT capital deepening and TFP growth are the main drivers of the divergence between the US and EU countries in labor productivity growth in market services. Exceptions to the pattern of divergence are observed in Finland and the UK (van Ark and Inklaar, 2006; Inklaar *et al*., 2008; van Ark *et al*., 2008). The hypothesis of spillovers of ICT use affecting TFP in ICT-intensive industries is tested, but evidence for it is weak from sector-level data

(Stiroh, 2002; Inklaar *et al*., 2008; Cardona *et al*., 2013). The publication of the EU KLEMS database was pivotal in gaining empirical evidence on ICT-related labor productivity growth for a larger number of developed countries (O'Mahony and Timmer, 2009).

1.2. *Analyzing Productivity Growth in Value Chains*

The ICT-using industries that were found to experience increasing ICT capital deepening along with increasing labor productivity growth after 1995, especially in the US and the UK, were industries that deliver a substantial share of their output as an intermediate input to other industries. Intermediate products do not directly benefit final users (which are consumers, government, and firms buying capital goods) but are in turn used to produce something else. We aim to quantify the contribution of ICT-related labor productivity growth along value chains of final products to see to which extent final products incorporate ICT-related productivity improvements contributed by upstream industries. As a result, it could turn out that the labor productivity increase related to ICT capital deepening is much stronger for certain final products than it was known to be based on purely sectoral analysis.

A global value chain is the chain of value-creating activities that take place in different sectors and countries to create a particular final product in a certain country, e.g., a car in Germany. The analysis of value chains has a long tradition going back to the input–output analysis pioneered by Leontief (1936, 1949). Early input–output analysis did not dispose of the data sources to permit the breakdown of foreign intermediate inputs by country and sector. While the first studies on global value chains had to rely on data sets assembled ad hoc from different sources, the publication of the WIOD database gave rise to opportunities to investigate a wide range of aspects of global value chains using a single harmonized data source (Timmer *et al*., 2015).

To study labor productivity growth, we must use a dynamic rather than a static form of input–output analysis. The dynamic method that extends sectoral growth accounting to value chains is intersectoral growth accounting. The seminal contribution by Hulten (1978) sets out this method in the context of neoclassical production theory. He introduces the notion of "effective" TFP of a value chain as opposed to conventional sectoral TFP, drawing on the analogy to nominal versus effective tax incidence. Early applications of measures of effective TFP growth include the contribution by Wolff (1985), who decomposes aggregate TFP growth into effects of changing final demand composition and changing input–output coefficients between industries using the US data. Wolff (1994) further elaborates on methodological aspects of this measurement framework such as total factor requirements along value chains. Aulin-Ahmavaara (1999) establishes the equality between effective TFP growth and the relative decrease in unit production cost in a closed economy.

Applications of intersectoral growth accounting continued to be much rarer than those of sectoral growth accounting and focused on domestic economies (ten Raa and Wolff, 2001; Correa, 2006), ignoring factor content of imported intermediates. The reason for the scarcity of applications is probably that data demands are

TABLE 1
Contribution to Growth of German Automotive Final Output

	1995–2007	
	Log Change	Share of Final Output Growth
Factors in Germany		
Labor	6.3	10.5
ICT capital	4.1	6.9
Non-ICT capital	8.5	14.1
Factors outside Germany		
Labor	7.1	11.8
ICT capital	2.6	4.2
Non-ICT capital	7.0	11.7
Total factor productivity	24.6	40.8
Final output growth	60.3	100.0

higher than for sectoral growth accounting. Using the WIOD database (Timmer *et al.*, 2015), Gu and Yan (2017), and Timmer and Ye (2018) extend the application of intersectoral growth accounting, or, in other words, growth accounting for value chains, to the global economy.

1.3. *An Illustrative Example*

To illustrate the decomposition of growth in value added of a global value chain, we take up the example of final output of the German automotive sector from Timmer (2017) in Table 1. While Timmer (2017) includes only the contribution of total capital growth in intersectoral growth accounting, we display the contribution of ICT capital growth separately.[1]

The table breaks down the contributions to final output growth in the German automotive industry during 1995–2007. Total growth over this period is 60.3 percent. The novel aspect compared to sectoral growth-accounting studies is the inclusion of both factors of production employed in the German automotive industry itself and factors of production employed in German and foreign upstream industries. The first three rows show the contributions by German factors of production to final output growth. The next three rows contain contributions to output growth by foreign factors of production, which can be employed in any foreign industry delivering intermediate inputs directly or indirectly to the German automotive industry. As in sectoral growth accounting, TFP growth represents a residual measure of output growth not statistically accounted for by input growth. However, the relevant outputs and inputs are defined in a different way in growth accounting for value chains. TFP growth in turn could be split down by upstream industries contributing to it.

[1]In our later analysis, we quantify contributions of capital deepening, which is the growth of capital used per unit of labor, rather than contributions of absolute capital growth. Here we display the contribution of absolute capital growth to link our approach to Timmer (2017). At the difference of Timmer (2017), we do not account for growth in human capital, which affects labor contributions and TFP growth.

Table 1 reveals that domestic and foreign ICT capital used in the German automotive value chain contributes about 11 percent of growth in final output in the period observed. The ICT contribution to final output growth is almost half as large as the contribution of non-ICT capital. Given the still relatively small share of ICT capital in total capital stock, this points to substantial productivity effects of ICT investment.

1.4. *Research Approach*

While sectoral growth accounting has already investigated the ICT contribution to output and labor productivity growth in detail, it has so far not been considered separately from the total capital contribution in value chains. There is a considerable amount of anecdotal and quantitative evidence on the economy-wide repercussions of digitalization (see, e.g., Oulton 2012; Cardona *et al.*, 2013), but a quantitative characterization of ICT-related gains in labor productivity that are passed on to downstream sectors is lacking. To analyze this issue, we extend the still-nascent literature on growth accounting for global value chains, which includes the study by Gu and Yan (2017), focusing on offshoring and international competitiveness based on effective TFP measures, and the studies by Timmer and Ye (2018) and Timmer (2017), focusing on increasing fragmentation and factor substitution.

To the best of our knowledge, the present paper is the first to analyze ICT-related labor productivity growth along value chains. The novel elements compared to Gu and Yan (2017) and Timmer and Ye (2018) are to consider ICT capital separately in a growth-accounting decomposition of final output and to split down the contribution additionally by sectors of origin. Gu and Yan (2017) consider only effective TFP (computed based on sectoral TFP) and not factor contributions. We mainly focus on labor productivity growth related to ICT capital deepening at all stages of production, but we extend the analysis to include effective TFP growth in value chains contributed by the ICT-producing sector as an upstream sector.

The quality of the available ICT investment data varies across countries. Despite growing international fragmentation of value chains, large shares of value creation still take place at the final stage of a value chain. For this reason, we focus on the empirical analysis on final products produced in countries for which we have relatively good ICT data.

We find that the aggregate contribution of ICT capital deepening to labor productivity growth in value chains is overall similar for non-ICT goods and non-ICT services, while being higher for knowledge-intensive services than for other services. Across all countries, more than half of the labor productivity gains related to ICT capital deepening for manufactured goods are contributed by upstream industries. The majority of this contribution is domestic rather than foreign. The most important upstream sector contributing to labor productivity growth in value chains is the sector of business, financial, and distribution services. Meanwhile, high sectoral TFP growth in the ICT-producing sector contributes only moderately to growth in effective TFP in downstream non-ICT value chains.

2. Growth-Accounting Method

Following Timmer (2017) and Timmer and Ye (2018), we consider an input–output framework with N countries and S sectors.[2] This gives $S \times N$ different value chains for the production of final products. Product markets are assumed to be clear, which means that the total quantity of the product produced in a particular sector and country equals the final use of this product i plus the intermediate input use of this product in all country-sectors:

$$y_i = \sum_j m_{ij} + f_i, \tag{1}$$

where y_i is the gross output of sector i, f_i the output from this country-sector for final use, and m_{ij} the output of country-sector i used as intermediate input by country-sector j. In the following, matrices are represented by capital letters in bold, vectors are represented by small letters in bold, and scalars are represented in italics. Let $\mathbf{y}$ be the stacked $SN \times 1$ vector of all gross outputs and $\mathbf{f}$ the stacked $SN \times 1$ vector of all final outputs from each country-sector. The global intermediate input coefficients matrix $\mathbf{A}$ has the dimension $SN \times SN$ and its elements are $a_{ij} = m_{ij}/y_j$. The elements represent the output from country-sector i used as intermediate input in country-sector j, expressed per unit of gross output of country-sector j.

The stacked market clearing conditions from (1) can be now written in matrix notation:

$$\mathbf{y} = \mathbf{A}\mathbf{y} + \mathbf{f}. \tag{2}$$

This means that total gross output produced in all country-sectors is the sum of all intermediate inputs needed for production and total final output.

Solving for gross output $\mathbf{y}$ yields the fundamental input–output identity:

$$\mathbf{y} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}, \tag{3}$$

where $\mathbf{I}$ is a $SN \times SN$ identity matrix and $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix. The element in row i and column j of this matrix represents the amount of output of country-sector i needed to produce one unit of final output of country-sector j.[3]

Total sectoral output $\mathbf{y}$ at prices $\mathbf{p}$ is equal to intermediate input plus sectoral value added by non-ICT capital $\mathbf{k}^N$, ICT capital $\widehat{\mathbf{k}}^{IT}$, and labor $\mathbf{l}$, which are paid at factor prices $\mathbf{r_N}$, $\mathbf{r_{IT}}$, and $\mathbf{w}$. We now show that final output is equal to the value added by capital and labor at all stages of production (see Aulin-Ahmavaara 1999 for a similar derivation from the cost side). In the following, $\mathbf{e}$ represents a summation vector of ones, and a hat indicates a diagonal matrix with the elements of the vector on the diagonal:

[2]In the theoretical part, we call the units of observation sectors, whereas in the empirical part we will observe data at the level of 30 industries and refer to aggregates of these industries as sectors.

[3]For the theoretical exposition, this equation is expressed in volumes, which are not directly available in the data for the Leontief inverse and the vector of final use. We compute the growth rates of their elements in practice by making use of the data expressed in current prices and in previous year's prices for each year.

(4) $$\mathbf{e}'\hat{\mathbf{p}}\hat{\mathbf{y}} = \mathbf{e}'\left[\hat{\mathbf{p}}\mathbf{A}\hat{\mathbf{y}} + \hat{\mathbf{r}}^N\hat{\mathbf{k}}^N + \hat{\mathbf{r}}^{IT}\hat{\mathbf{k}}^{IT} + \hat{\mathbf{w}}\hat{\mathbf{l}}\right]$$

(5) $$\mathbf{e}'\hat{\mathbf{p}} = \mathbf{e}'\left[\hat{\mathbf{p}}\mathbf{A} + \hat{\mathbf{r}}^N\hat{\mathbf{k}}^N\hat{\mathbf{y}}^{-1} + \hat{\mathbf{r}}^{IT}\hat{\mathbf{k}}^{IT}\hat{\mathbf{y}}^{-1} + \hat{\mathbf{w}}\hat{\mathbf{l}}\hat{\mathbf{y}}^{-1}\right]$$

(6) $$\mathbf{e}'\hat{\mathbf{p}}[\mathbf{I}-\mathbf{A}] = \mathbf{e}'\left[\hat{\mathbf{r}}^N\hat{\mathbf{k}}^N\hat{\mathbf{y}}^{-1} + \hat{\mathbf{r}}^{IT}\hat{\mathbf{k}}^{IT}\hat{\mathbf{y}}^{-1} + \hat{\mathbf{w}}\hat{\mathbf{l}}\hat{\mathbf{y}}^{-1}\right]$$

(7) $$\mathbf{e}'\hat{\mathbf{p}}\hat{\mathbf{f}} = \mathbf{e}'\left[\hat{\mathbf{r}}^{\mathbf{N}}\hat{\mathbf{k}}^{\mathbf{N}}\hat{\mathbf{y}}^{-\mathbf{1}} + \hat{\mathbf{r}}^{\mathbf{IT}}\hat{\mathbf{k}}^{\mathbf{IT}}\hat{\mathbf{y}}^{-\mathbf{1}} + \hat{\mathbf{w}}\hat{\mathbf{l}}\hat{\mathbf{y}}^{-1}\right][\mathbf{I}-\mathbf{A}]^{-1}\hat{\mathbf{f}}.$$

We can single out the volume of factor inputs used at all stages of production by defining the matrices $\mathbf{K^N}$, $\mathbf{K^{IT}}$, and Λ with dimension $SN \times SN$ as:

(8) $$\mathbf{K^N} = \hat{\mathbf{k}}^{\mathbf{N}}\hat{\mathbf{y}}^{-\mathbf{1}}(\mathbf{I}-\mathbf{A})^{-\mathbf{1}}\hat{\mathbf{f}}$$

(9) $$\mathbf{K^{IT}} = \hat{\mathbf{k}}^{\mathbf{IT}}\hat{\mathbf{y}}^{-\mathbf{1}}(\mathbf{I}-\mathbf{A})^{-\mathbf{1}}\hat{\mathbf{f}}$$

(10) $$\Lambda = \hat{\mathbf{l}}\hat{\mathbf{y}}^{-\mathbf{1}}(\mathbf{I}-\mathbf{A})^{-\mathbf{1}}\hat{\mathbf{f}},$$

and rewrite equation (7) as:

(11) $$\mathbf{e}'\hat{\mathbf{p}}\hat{\mathbf{f}} = \mathbf{e}'\left[\hat{\mathbf{r}}^N\mathbf{K}^N + \hat{\mathbf{r}}^{IT}\mathbf{K}^{IT} + \hat{\mathbf{w}}\Lambda\right].$$

Equation (11) decomposes final output into value added by all factor input directly and indirectly used in its production.

The matrices of factor income shares earned by factor inputs used to produce final output are correspondingly defined as:

(12) $$\boldsymbol{\Omega}^N = \hat{\mathbf{r}}^N\mathbf{K}^N\hat{\mathbf{f}}^{-\mathbf{1}}\hat{\mathbf{p}}^{-\mathbf{1}}$$

(13) $$\boldsymbol{\Omega}^{IT} = \hat{\mathbf{r}}^{IT}\mathbf{K}^{IT}\hat{\mathbf{f}}^{-\mathbf{1}}\hat{\mathbf{p}}^{-\mathbf{1}}$$

(14) $$\boldsymbol{\Omega}^L = \hat{\mathbf{w}}\Lambda\hat{\mathbf{f}}^{-\mathbf{1}}\hat{\mathbf{p}}^{-\mathbf{1}}.$$

Column vectors of the matrices $\boldsymbol{\Omega}$ containing factor income shares for single value chains j will be denoted by a lowercase $\boldsymbol{\omega}_j$.

The ICT factor shares in value chains are related to the shares of direct ICT factor income in sectoral value added, which are used in sector-level growth accounting, in the following way:

(15) $$\boldsymbol{\Omega}^{IT} = \hat{\boldsymbol{\pi}}^{IT}\hat{\mathbf{v}}\hat{\mathbf{p}}[\mathbf{I}-\mathbf{A}]^{-1}\hat{\mathbf{p}}^{-\mathbf{1}},$$

with the vector of sectoral shares as

$$\widehat{\boldsymbol{\pi}}^{IT} = \widehat{\mathbf{r}}^{\mathbf{IT}} \widehat{\mathbf{k}} \widehat{\mathbf{y}}^{-\mathbf{1}} \widehat{\mathbf{p}}^{-\mathbf{1}} \widehat{\mathbf{v}}^{-\mathbf{1}}. \tag{16}$$

The vector **v** contains the sectoral shares of nominal value added in nominal sectoral output:

$$\mathbf{v}' = \mathbf{e}' \widehat{\mathbf{p}} [\mathbf{I} - \mathbf{A}] \widehat{\mathbf{p}}^{-\mathbf{1}}. \tag{17}$$

The equations for non-ICT capital shares and labor shares follow in an analogous way.

Our aim is to identify the contribution of ICT capital deepening to growth in final output and labor productivity along global value chains. To do so, we use the approach of intersectoral growth accounting pioneered by Hulten (1978), Wolff (1985), Wolff (1994), and Aulin-Ahmavaara (1999) and applied in an international context more recently by Gu and Yan (2017), Timmer (2017), and Timmer and Ye (2018). The contribution of ICT capital deepening to growth in final output is determined based on a growth-accounting transformation of equation (11).

Following Hulten (1978) and Aulin-Ahmavaara (1999), we define effective TFP growth as the difference between final output growth and the contributions of input growth in a value chain, making use of the fact that in a competitive equilibrium, marginal products are equal to factor prices. Hulten (1978) shows the conditions under which the effective TFP measure is uniquely defined. One condition is that the production possibility frontier of the economy (in our case the worldwide economy) has to be bounded and continuously differentiable as well as homogenous of degree zero in output and in factor supply. Additionally, sectoral technology is assumed to be non-joint with exogenous factor supply, constant returns to scale and Hicks neutral technical change and and the economy has to be in a uniquely identified competitive market equilibrium. Under these conditions, the conventional TFP measure is defined as a measure of joint factor productivity at the sectoral level and the effective TFP measure introduced below is defined as a measure of joint factor productivity for global value chains. In an extension, Hulten relaxes the assumptions of Hicks neutrality and non-jointness.

Using the factor shares defined in equations (12)–(14) and denoting time as τ, the growth-accounting decomposition of growth in the final output of a particular product j displayed in equation (11) corresponds to:

$$\frac{\delta \ln f_j}{\delta \tau} = \frac{\delta \ln \theta_j}{\delta \tau} + \boldsymbol{\omega}_{j'}^{N} \frac{\delta \ln \mathbf{K}_j^{N}}{\delta \tau} + \boldsymbol{\omega}_{j'}^{IT} \frac{\delta \ln \mathbf{K}_j^{IT}}{\delta \tau} + \boldsymbol{\omega}_{j'}^{L} \frac{\delta \ln \Lambda_j}{\delta \tau}. \tag{18}$$

Effective TFP of the value chain j is denoted as $\theta_j(t)$. Its growth is the residual obtained when taking the total logarithmic differential of f_j and subtracting the components determined by changes in direct and indirect factor inputs. In an analogous way, conventional sectoral TFP (which we need not compute for our analysis) would be obtained taking the total differential of sectoral value added and subtracting the components determined by changes in direct sectoral factor input.[4]

[4]Note that it is not necessary to assume vertically integrated sectors of final products to define effective TFP, but that effective TFP of a value chain mathematically corresponds to that of a vertically integrated sector. We treat sectors producing the same products in different countries conceptually as different sectors.

Unlike the theoretical exposition by Hulten (1978), we allow for differences of factor prices across sectors. This is usually done in practice in both sectoral and intersectoral growth accounting (see, e.g. Timmer and Ye, 2018). The deviation in sectoral factor prices from uniform rates can be interpreted as evidence of non-competitive price setting or of heterogenous quality of inputs across sectors (Wolff, 1985).

Our main focus is on the contribution of ICT capital deepening, which is growth in ICT capital per unit of labor. We subtract labor growth from capital growth in the capital contributions in equation (18) to single out contributions of capital deepening:

$$\frac{\delta \ln f_j}{\delta\tau} = \frac{\delta \ln \theta_j}{\delta\tau} + \boldsymbol{\omega}_{j'}^{N}\left(\frac{\delta \ln \mathbf{K}_j^{N}}{\delta\tau} - \frac{\delta \ln \Lambda_j}{\delta\tau}\right) + \boldsymbol{\omega}_{j'}^{IT}\left(\frac{\delta \ln \mathbf{K}_j^{IT}}{\delta\tau} - \frac{\delta \ln \Lambda_j}{\delta\tau}\right) + \left(\boldsymbol{\omega}_{j'}^{N} + \boldsymbol{\omega}_{j'}^{IT} + \boldsymbol{\omega}_{j'}^{L}\right)\frac{\delta \ln \Lambda_j}{\delta\tau}. \tag{19}$$

We can split contributions of ICT capital deepening by sectors of origin by setting the factor shares of all other sectors equal to zero.

Equation (19) can be used for growth accounting at the level of value chains. A further step in equation (20) makes the growth-accounting equation more complex, but it is useful to display a decomposition of labor productivity growth instead of output growth. Labor productivity growth represents a measure that is more closely related to competitiveness and living standards than output growth.

To obtain labor productivity growth on the left-hand side, labor input growth in value chain j needs to be subtracted on both sides of equation (19). Total labor growth in value chain j is obtained multiplying the vector of growth rates of labor quantities contributed in all sectors, $\delta \ln \Lambda_j / \delta\tau$, by the vector of their shares in the total quantity of labor contributed to value chain j, $(\mathbf{e}'\Lambda_j)^{-1}\Lambda'_j$. In conventional sectoral growth accounting, solving for labor productivity yields an equation that decomposes labor productivity growth into contributions of capital deepening and TFP growth only, because the term of the labor contribution cancels out. This is not the case in growth accounting at the level of value chains, because labor growth with quantity weights does not equal labor growth with value added weights.[5] In consequence, the last term of equation (20) represents a labor reallocation term, which reflects differences in value added per labor across sectors:

$$\begin{aligned}\frac{\delta \ln f_j}{\delta\tau} - (\mathbf{e}'\Lambda_j)^{-1}\Lambda'_j\frac{\delta \ln \Lambda_j}{\delta\tau} = {} & \\ \frac{\delta \ln \theta_j}{\delta\tau} + \boldsymbol{\omega}_{j'}^{N}\left(\frac{\delta \ln \mathbf{K}_j^{N}}{\delta\tau} - \frac{\delta \ln \Lambda_j}{\delta\tau}\right) & + \boldsymbol{\omega}_{j'}^{IT}\left(\frac{\delta \ln \mathbf{K}_j^{IT}}{\delta\tau} - \frac{\delta \ln \Lambda_j}{\delta\tau}\right) \\ & + \left(\boldsymbol{\omega}_{j'}^{N} + \boldsymbol{\omega}_{j'}^{IT} + \boldsymbol{\omega}_{j'}^{L} - (\mathbf{e}'\Lambda_j)^{-1}\Lambda_j\right)\frac{\delta \ln \Lambda_j}{\delta\tau}.\end{aligned} \tag{20}$$

[5]For any upstream sector i, the value added weight is represented by the sum of its factor shares in total final output of j, i.e., by $\boldsymbol{\omega}_{ij}^{N} + \boldsymbol{\omega}_{ij}^{IT} + \boldsymbol{\omega}_{ij}^{L}$. The labor quantity share and the value added share of sector i in the production of final output of j differ if sector i contributes more value added per unit of labor to the production of f_j than an average contributing sector. This difference is driven by wages in sector i and also by capital input and capital cost.

The elements of $\boldsymbol{\omega}_{ij}^{N}$, $\boldsymbol{\omega}_{ij}^{IT}$ and $\boldsymbol{\omega}_{ij}^{L}$ add up to one when summed over all sectors i and all three vectors. However, this is useful for rearranging an equation only if the vectors are multiplied by a scalar (as the scalar f_j in equation (21)), not if they are multiplied by another vector as it is the case in equation (20).

This term is not straightforward to interpret. It arises as a by-product of our framework because we solve the growth-accounting equation for labor productivity growth rather than just for output growth.

In addition to ICT capital deepening, we are analyzing the contribution of TFP growth passed on downstream from the ICT sector to other sectors. This is of interest as TFP growth in the ICT sector itself is known to be very large as a result of technological progress. Note that this approach implies to focus only on ICT products used as intermediate inputs, not on those used as capital goods, which are conceptually treated as final goods. The decomposition of TFP growth by sector of origin can be obtained solving equation (18) for θ_j and rewriting the elements on the right-hand side explicitly as a sum over all contributing sectors:

$$(21)\quad \frac{\delta \ln \theta_j}{\delta \tau} = \sum_{i=1}^{SN} \left((\omega_{ij}^{N} + \omega_{ij}^{IT} + \omega_{ij}^{L}) \frac{\delta \ln f_j}{\delta \tau} - \omega_{ij}^{N} \frac{\delta \ln K_{ij}^{N}}{\delta \tau} - \omega_{ij}^{IT} \frac{\delta \ln K_{ij}^{IT}}{\delta \tau} - \omega_{ij}^{L} \frac{\delta \ln \Lambda_{ij}}{\delta \tau} \right).$$

The share of value added contributed by country-sector i (which is the final sector for $i = j$ and an upstream sector otherwise) to final product j is equal to $\omega_{ij}^{N} + \omega_{ij}^{IT} + \omega_{ij}^{L}$. The difference between growth in value added provided by country-sector i and contributions of input growth in country-sector i is the TFP growth contributed to value chain j by country-sector i. The part of TFP growth of value chain j originating in ICT production can now be isolated by summing up only over the country-sectors i that produce ICT. Implicit to equation (21) is the result shown by Hulten (1978) and Aulin-Ahmavaara (1999) that effective TFP growth in a value chain is a weighted average of the conventional sectoral TFP growth rates of all contributing sectors.

3. Data

The main data sources are the World-Input-Output Database (WIOD) and the EU KLEMS database. We use the 2013 release of the WIOD input–output tables and the 2012 release of the WIOD socioeconomic account data. The data set consists of 35 ISIC rev. 3 industries for 40 countries and a hypothetical country called Rest of the World (RoW). From EU KLEMS, we use the November 2009 release of the basic files and the capital input files. The data set consists of 32 industries for 30 countries. Capital input data are available only for a subset of countries.

The input–output tables contain data on intermediate inputs from every country-industry in the database delivered to any other country-industry as well as final use per country and type of use. We compute the nominal Leontief inverse from the input–output table in current US dollars. The input–output tables are also available in previous year's prices and adjusted for changes in exchange rates. We use these tables to compute the real Leontief inverse. From the WIOD socioeconomic accounts, we use gross output, gross output deflators, real capital stock, hours worked, and capital and labor income.

To investigate the effects of ICT in growth accounting, we need data on real ICT capital stock. ICT capital stock comprises computer hardware, communications equipment, and software. The lack of a separate real ICT capital stock and ICT capital income for many countries in the data represents a challenge. For 13 countries, both variables are available from the EU KLEMS 2009 release and can be easily merged (O'Mahony and Timmer, 2009). For additional four countries, at least ICT capital compensation is available.[6]

For all other countries, we use information on ICT capital services and ICT capital income at the national level from the Conference Board Total Economy Database[7] to extrapolate the variables at the industry level using information from another country. Because most countries in EU KLEMS are much more ICT-intensive than the countries with missing data, we use sectoral shares of ICT capital stock and income in total capital stock and income of Italy as a country with relatively low ICT intensity as a proxy. This is an admittedly crude procedure, but from prior evidence we know that the sectoral ranking of ICT capital intensities measured by various intensity indicators is likely to be similar across countries (see Chen *et al*., 2016 for a comparison between the EU and the US).

Because we are not studying the detailed sectoral structure of foreign ICT-related contributions to labor productivity growth, approximating the ICT investment of some foreign upstream sectors by an extrapolation based on available data of aggregate ICT capital services and sectoral total capital stock does probably not introduce an extremely large error. International differences in ICT investment that affect all sectors of a country equally are well reflected in our data as we are using country-level ICT data from the Conference Board Total Economy Database, which leverages the data of national spending on ICT goods published by the World Information Technology and Services Alliance (WITSA). Still a bias might be created to the extent that the value chains we consider might contain a disproportionate amount of imported intermediates produced in sectors for which the share of ICT capital in total capital at the sectoral level deviates from its imputed ratio.

Another limitation is that we follow Timmer and Ye (2018) in using capital stock instead of capital services. Capital services is a concept that considers different productivity of assets, which may also change over time. Because of the need to aggregate capital input over the entire value chain and the limited availability of capital services data, capital stock data are used as a measure of capital input. This may somewhat underestimate the measured ICT contributions to the extent to which compositional changes between the three ICT assets, hardware, software, and telecommunications equipment, have positive effects. Sector-level research for advanced economies finds these effects to be mostly positive but rarely exceeding 20 percent of the total contribution. A further measurement error might be introduced by the highly variable data quality of national ICT investment deflators, although some harmonization is already performed in the construction of databases (see also Niebel and Saam 2016).

[6]For Australia, Austria, Czech Republic, Denmark, Finland, Germany, Italy, the Netherlands, Slovenia, Spain, Sweden, the UK, and the US, real ICT capital stock is available from EU KLEMS. Only ICT capital compensation is available for Belgium, France, Hungary, and Ireland.

[7]https://www.conference-board.org/data/economydatabase.

After merging the two data sets, our data set covers 40 countries and the RoW, and 30 sectors within these countries (see Appendix) for the years 1995–2007 in the NACE 1.1 industry classification.

The countries for which we present results at the level of value chains producing final output are Australia, Austria, Czech Republic, Denmark, Finland, Germany, Italy, the Netherlands, Spain, Sweden, the UK, and the US.[8] We group the 30 industries into four broad sectors using the share of nominal final output of industries in total final output of the broad sector as weights (Hulten, 1978). The broad sectors are ICT products, non-ICT goods, business, financial, and distribution services, and other services.[9]

4. Results

4.1. *Factor and TFP Contributions to Growth Along Value Chains*

The results of the growth-accounting analysis at the level of final products are presented in Tables 2 and 3 for two separate periods, 1995–2000 and 2000–2007. This split of periods is in line with much of the earlier sector-level research that points to a decline in ICT capital deepening from the year 2000 on (van Ark and Inklaar, 2006; Oliner *et al*., 2008; Niebel and Saam, 2016).

Because the aggregation of labor is more questionable in the case of value chains than in the case of sectors, making the interpretation of labor productivity growth more complex, we display final output growth and labor input growth in separate columns of Tables 2 and 3. The difference between them represents growth in labor productivity in value chains. Columns (3)–(6) display the elements of the growth-accounting decomposition on the right-hand side of equation (20).

Final output growth is higher for ICT products than for other products, in many cases by a factor of two or three. Some countries experience higher growth of final output in non-ICT services, whereas others experience higher growth in non-ICT goods. Labor productivity growth is higher for goods than for services. In countries with high total labor productivity growth, this growth tends to be higher in business, financial, and distribution services than in other services. In many cases, labor input is declining in non-ICT goods production. This is reflecting in part the well-known process of structural change, which exists both at the level of sectors and at the level of value chains (Herrendorf *et al*., 2014).

Our main interest lies in the results on the contribution of ICT capital deepening to growth in final output and labor productivity, which are presented in column (4). In the period of 1995–2000, the highest contributions are observed in the UK and the US, where the contributions in the production of non-ICT goods and business, financial, and distribution services attain values above 1.0 percentage points. The contributions in other countries' non-ICT value chains generally

[8]The reason why we are not presenting results for more of the 40 countries is that domestic upstream linkages turn out to be important, and the patterns of ICT contributions identified for these countries are imputed because of the lack of ICT data.

[9]The classification can be found in Table 6 of the Appendix. The industries mining and quarrying (C), wood and products of wood and cork (20), and other non-metallic mineral products (26) are dropped from the analysis. Table 7 of Appendix lists the country abbrevations used.

TABLE 2
Decomposition of Final Output Growth in Value Chains 1995–2000, Percentage Points

	(1)	(2)	(3)	(4)	(5)	(6)
				Contributions of Capital Deepening		Contribution of Labor Reallocation
	Growth of Final Output	Growth of Labor Input	Growth of TFP	ICT	Non-ICT	
Australia						
ICT goods & services	8.7	4.5	1.4	1.3	0.5	1.0
Non-ICT goods	2.8	−0.9	1.7	0.7	0.6	0.7
Busin. & distr. services	6.0	2.0	2.1	1.0	0.3	0.7
Other services	2.3	−0.4	1.2	0.7	0.0	0.8
Total	3.4	0.2	1.5	0.8	0.2	0.8
Austria						
ICT goods & services	6.6	4.1	2.2	0.6	0.3	−0.6
Non-ICT goods	3.6	0.1	2.9	0.4	0.2	0.1
Busin. & distr. services	3.8	0.4	1.5	0.8	0.1	1.1
Other services	1.4	−0.1	0.0	0.3	0.0	1.3
Total	2.6	0.2	1.0	0.4	0.1	0.9
Czech Republic						
ICT goods & services	17.1	−19.3	1.1	2.6	2.1	30.7
Non-ICT goods	6.9	−6.6	1.6	0.7	1.7	9.5
Busin. & distr. services	1.2	−19.0	0.0	1.1	1.2	17.9
Other services	−0.2	−15.1	−1.9	0.6	0.8	15.4
Total	3.1	−13.4	−0.4	0.8	1.2	14.8
Denmark						
ICT goods & services	9.5	−23.3	1.6	1.6	0.4	29.2
Non-ICT goods	1.0	−18.7	1.2	0.8	0.7	17.1
Busin. & distr. services	5.1	−11.6	0.9	1.3	0.0	14.6
Other services	2.1	−13.8	0.1	0.7	0.0	15.1
Total	2.7	−14.8	0.5	0.9	0.2	15.9

(Continues)

TABLE 2 (CONTINUED)

	(1)	(2)	(3)	(4)	(5)	(6)
				Contributions of Capital Deepening		Contribution of Labor Reallocation
	Growth of Final Output	Growth of Labor Input	Growth of TFP	ICT	Non-ICT	
Finland						
ICT goods & services	17.1	7.2	8.0	1.0	1.0	−0.1
Non-ICT goods	2.4	−2.6	2.7	0.5	0.3	1.5
Busin. & distr. services	3.4	−0.9	2.4	1.1	−0.6	1.4
Other services	3.8	1.4	1.1	0.5	0.2	0.7
Total	4.5	0.7	2.1	0.6	0.2	0.9
Germany						
ICT goods & services	6.2	1.1	4.2	0.5	0.4	0.0
Non-ICT goods	2.8	0.2	1.9	0.5	0.5	−0.3
Busin. & distr. services	2.1	−0.3	0.3	0.8	0.5	0.9
Other services	1.1	−1.4	0.8	0.3	0.2	1.2
Total	2.0	−0.7	1.1	0.4	0.4	0.7
Italy						
ICT goods & services	4.7	2.1	1.6	0.5	0.3	0.2
Non-ICT goods	2.5	−0.5	1.0	0.4	0.6	0.9
Busin. & distr. services	1.8	0.5	0.3	0.6	0.1	0.3
Other services	1.5	0.8	0.1	0.3	0.1	0.2
Total	1.9	0.4	0.5	0.4	0.3	0.4
The Netherlands						
ICT goods & services	11.4	4.1	4.1	1.0	0.8	1.4
Non-ICT goods	3.3	−1.1	1.8	0.6	0.7	1.3
Busin. & distr. services	6.8	3.6	1.7	1.0	0.3	0.2
Other services	2.8	0.9	0.4	0.6	0.4	0.5
Total	4.1	1.1	1.2	0.7	0.4	0.7
Spain						
ICT goods & services	9.0	6.5	0.7	1.2	0.8	−0.2
Non-ICT goods	5.2	2.3	1.3	0.4	0.5	0.7

(Continues)

TABLE 2 (CONTINUED)

	(1)	(2)	(3)	(4)	(5)	(6)
				Contributions of Capital Deepening		Contribution of Labor Reallocation
	Growth of Final Output	Growth of Labor Input	Growth of TFP	ICT	Non-ICT	
Busin. & distr. services	8.1	7.6	−0.5	0.7	0.2	0.1
Other services	3.0	2.8	−0.4	0.3	−0.6	0.9
Total	4.5	3.5	0.0	0.4	−0.1	0.7
Sweden						
ICT goods & services	14.8	10.5	7.7	0.9	1.0	−5.4
Non-ICT goods	4.7	0.9	1.6	0.7	1.3	0.3
Busin. & distr. services	4.1	1.2	0.7	0.9	0.9	0.3
Other services	1.1	0.2	0.4	0.3	1.1	−0.9
Total	3.3	1.2	1.2	0.6	1.1	−0.7
UK						
ICT goods & services	10.6	2.6	5.0	1.8	0.9	0.3
Non-ICT goods	1.6	−2.2	0.7	1.2	1.0	0.9
Busin. & distr. services	7.3	3.1	0.1	2.4	1.2	0.5
Other services	2.4	0.4	−0.1	1.0	0.6	0.4
Total	3.7	0.6	0.4	1.4	0.8	0.5
US						
ICT goods & services	12.1	5.1	4.3	2.1	0.7	−0.2
Non-ICT goods	3.5	−0.1	1.1	1.2	0.6	0.7
Busin. & distr. services	7.2	3.0	1.7	1.8	0.6	0.0
Other services	3.0	2.2	−0.3	0.8	0.6	−0.3
Total	4.5	2.2	0.6	1.2	0.6	−0.1

TABLE 3
Decomposition of Final Output Growth in Value Chains 2000–2007, Percentage Points

	(1)	(2)	(3)	(4)	(5)	(6)
				Contributions of Capital Deepening		Contribution of Labor Reallocation
	Growth of Final Output	Growth of Labor Input	Growth of TFP	ICT	Non-ICT	
Australia						
ICT goods & services	6.2	3.5	0.9	1.3	0.5	0.0
Non-ICT goods	0.9	−0.9	−0.3	1.0	1.0	0.2
Busin. & distr. services	4.4	2.7	0.0	1.4	0.1	0.1
Other services	4.3	2.9	0.1	0.8	0.1	0.5
Total	3.9	2.3	0.0	1.0	0.2	0.3
Austria						
ICT goods & services	3.0	−1.4	3.0	0.2	0.0	1.2
Non-ICT goods	3.7	−0.7	2.7	0.3	0.1	1.2
Busin. & distr. services	3.1	−0.2	1.1	0.6	0.3	1.4
Other services	1.1	−1.6	0.5	0.2	0.0	1.9
Total	2.2	−1.1	1.2	0.3	0.1	1.6
Czech Republic						
ICT goods & services	14.5	9.3	4.5	0.4	0.8	−0.6
Non-ICT goods	5.5	1.0	3.5	0.3	1.3	−0.5
Busin. & distr. services	4.6	−8.4	4.4	0.4	0.9	7.3
Other services	3.0	−6.6	1.1	0.3	0.7	7.4
Total	5.0	−3.3	2.7	0.3	0.9	4.3
Denmark						
ICT goods & services	3.9	−0.8	3.0	1.0	0.6	0.2
Non-ICT goods	0.1	−4.5	1.3	0.6	0.6	2.1
Busin. & distr. services	3.9	0.6	1.5	1.1	−0.2	0.9
Other services	1.6	1.0	−0.5	0.6	−0.2	0.8
Total	1.9	−0.2	0.4	0.7	0.0	1.0

(Continues)

TABLE 3 (CONTINUED)

	(1)	(2)	(3)	(4)	(5)	(6)
				Contributions of Capital Deepening		Contribution of Labor Reallocation
	Growth of Final Output	Growth of Labor Input	Growth of TFP	ICT	Non-ICT	
Finland						
ICT goods & services	6.2	−3.0	5.7	0.8	0.6	2.1
Non-ICT goods	2.3	−3.3	2.8	0.4	0.5	1.8
Busin. & distr. services	4.1	0.2	1.0	1.0	0.0	1.8
Other services	2.1	−0.1	0.1	0.4	0.4	1.3
Total	2.8	−0.9	1.2	0.5	0.4	1.5
Germany						
ICT goods & services	4.8	1.0	3.2	0.5	0.3	−0.3
Non-ICT goods	1.3	−1.1	1.8	0.4	0.4	−0.2
Busin. & distr. services	0.8	−1.5	0.6	0.6	0.4	0.7
Other services	0.2	−1.7	0.4	0.2	0.4	0.9
Total	0.9	−1.4	1.0	0.3	0.4	0.5
Italy						
ICT goods & services	2.6	0.5	0.7	0.3	0.7	0.5
Non-ICT goods	0.2	−1.7	0.1	0.2	0.4	1.1
Busin. & distr. services	1.4	0.6	−0.2	0.3	0.3	0.4
Other services	1.5	−0.2	0.0	0.2	0.0	1.5
Total	1.2	−0.4	0.0	0.2	0.2	1.2
The Netherlands						
ICT goods & services	2.3	−4.5	2.7	0.7	0.4	3.1
Non-ICT goods	1.0	−6.7	2.3	0.4	0.5	4.4
Busin. & distr. services	2.8	−2.9	1.9	0.6	0.0	3.2
Other services	1.4	−1.6	0.3	0.4	0.3	2.0
Total	1.7	−3.2	1.2	0.5	0.3	2.9
Spain						
ICT goods & services	4.7	2.1	1.2	0.5	0.6	0.3
Non-ICT goods	1.2	−2.1	0.8	0.3	0.7	1.4

(Continues)

TABLE 3 (CONTINUED)

	(1)	(2)	(3)	(4)	(5)	(6)
				Contributions of Capital Deepening		Contribution of Labor Reallocation
	Growth of Final Output	Growth of Labor Input	Growth of TFP	ICT	Non-ICT	
Busin. & distr. services	5.2	2.6	0.8	0.5	0.4	0.9
Other services	3.9	2.7	−0.3	0.3	0.1	1.1
Total	3.6	1.7	0.2	0.3	0.3	1.1
Sweden						
ICT goods & services	3.8	−6.0	7.0	0.4	0.6	1.8
Non-ICT goods	3.0	−2.4	2.8	0.5	0.9	1.4
Busin. & distr. services	3.4	−1.7	1.6	0.8	0.7	2.1
Other services	1.8	−1.3	0.0	0.3	0.3	2.5
Total	2.5	−1.9	1.3	0.4	0.5	2.1
UK						
ICT goods & services	−2.6	−5.7	2.5	0.7	0.6	−0.7
Non-ICT goods	−0.5	−4.3	2.6	0.6	0.8	−0.3
Busin. & distr. services	5.0	1.6	1.0	1.2	0.9	0.3
Other services	3.1	1.5	0.1	0.5	0.6	0.4
Total	2.8	0.4	0.8	0.7	0.7	0.2
US						
ICT goods & services	3.5	−2.7	4.5	1.0	0.6	0.2
Non-ICT goods	1.0	−3.4	2.8	0.8	0.5	0.4
Busin. & distr. services	3.4	−0.1	1.9	1.1	0.3	0.2
Other services	2.2	0.8	0.0	0.5	0.5	0.4
Total	2.4	−0.1	1.0	0.7	0.4	0.3

range between 0.4 and 0.8 percentage points. They attain values of 1.0 and more in the business, financial, and distribution services of Australia, Czech Republic, Denmark, Finland, and the Netherlands.

In the period of 2000–2007, the aggregate contribution of ICT capital deepening is declining to 0.7 percentage points in the UK and the US, while being more stable in other countries. ICT production has a higher contribution of ICT capital deepening than other final sectors. Meanwhile, differences in labor productivity growth across final sectors are mainly driven by TFP, not by ICT capital deepening. While the contribution of non-ICT capital deepening is generally higher in goods production than in services production, the contribution of ICT capital-deepening lies in a similar range for non-ICT goods and services. Within the final service sector, it is higher for business, financial, and distribution services than for other services. Previous sector-level studies have already found ICT contributions that are higher in the US and in the UK than in other countries. This result carries over to the value chain level.

Table 5 in the Appendix represents the sectoral shares in final output for the different countries to indicate to which extent cross-country differences in growth of aggregate final output are driven by differences in sectoral composition.

The reallocation term in column (6) of Tables 2 and 3 reflects both changing labor productivity in contributing industries and shifts in labor input between these industries. While this term is not of particular importance in our analysis, it may warrant closer consideration in future research. If labor growth in sectors with high value added dominates, this effect is positive. In interpreting the effect, one has to be aware that the labor aggregate for the value chain represents all labor input contributed by country-industries worldwide. The skill and training levels of workers may be much more heterogenous than within a single country-industry.[10] In our sample, most countries have a reallocation term in the range of 0.4–1.2 percentage points. The values are not straightforward to interpret, because they reflect a number of distinct influences: unmeasured changes in the quality composition of labor, capital-deepening in upstream sectors as well as changes in non-competitive factor prices. At least part of the effect can be explained by skill upgrading along value chains, which has been documented in previous research.

The Czech Republic and Denmark experienced a significant change in the input structure from 1995 to 2000, especially in 1998. The decline in the domestic intermediate input at the industry level gives rise to a sizable drop of labor input in the value chains of those two countries. Correspondingly, the positive and large reallocation terms suggest that labor in the value chains shifts from industries with lower productivity to industries with higher productivity. The drastic drop in input in value chains is not reflected in national employment rates. To which extent the

[10]Accounting for the three different skill levels available in WIOD would be an interesting extension of our work. To identify a measure of ICT capital deepening at the level of value chains, we would have to determine the weights to aggregate across skill categories. Wage data could be used, but would introduce a new measurement bias to the extent that wage differences reflect market frictions rather than quality differences. Capital deepening is defined as growing ICT capital use per labor input. Because there is on average both skill upgrading and upgrading in ICT capital stocks, biases of not using measures of capital services and labor services may cancel out to some extent in our measures of capital deepening.

change in input coefficients reflects structural change or measurement error is hard to determine.

An additional issue in interpreting the numbers arises from the fact that contributions by some country-industries to value chains increase from very low levels, thus exhibiting very large growth rates, for which the logarithmic approximation becomes worse.[11] As TFP growth is a residual measure, the caution in interpreting measures of labor reallocation and labor contribution to growth also has to be applied to TFP growth. Small differences in the order of 0.1–0.2 percentage points should not be regarded as substantial.

4.2. *Disaggregation of the ICT Contribution in Value Chains by Origin*

So far we have not considered how the contributions of ICT capital deepening to labor productivity growth are spread along the value chains. The question is how much do more computers or software per worker used in the final industry of production contribute, how much those used in different domestic upstream industries and how much those used in foreign upstream industries? This issue is illuminated in Figures 1–5, which decompose column (4) of Tables 2 and 3 by sectoral origin.

We use a breakdown of four sectors, which implies that upstream linkages of an industry to other sectors are visible, whereas upstream linkages within the same sector cannot be distinguished from the final stage of the value chain. Figures 1–4 represent the results for the four different final sectors across all countries included, and Figure 5 represents the results for the total economy.

Foreign ICT capital deepening is contributing relatively less to labor productivity growth in value chains. The highest contribution amounting to 0.25 percentage points is observed in Finnish ICT production between 1995 and 2000 (Figure 1). Most values outside ICT production lie below 0.1 percentage points. While remaining low overall, the foreign contribution is higher for non-ICT goods than for non-ICT services. This reflects a higher degree of fragmentation and offshoring in the production of goods. Somewhat higher foreign contributions are observed in countries with a relatively low number of inhabitants, such as the Czech Republic, the Netherlands, or Sweden (Figures 2–4).

Domestic upstream contributions are generally more important. For the production of non-ICT goods, more than half of the ICT capital deepening contributed takes place in domestic or foreign upstream industries outside the final industries in all countries observed. In some countries, such as Germany, the share of upstream ICT contributions exceeds even three quarters (see Figure 2). In several countries, upstream contributions of ICT capital deepening are also dominating in the production of ICT (in Germany, Italy, and Sweden during 1995–2000 and in the majority of countries during 2000–2007, see Figure 1) and in the production

[11]Sensitivity analysis, which is not reported in this paper, suggests that overall the approximation still performs reasonably well for our purposes. One reason is that in many cases of high growth rates, logarithmic approximations underestimate growth, but at the same time the average output elasticity used for computing contributions to growth in a particular period gives too much weight to high growth rates at the beginning of the period. In theory, growth rates changing in continuous time would have to be multiplied with a continuously changing and initially very low output elasticity, unless marginal returns are initially high and then strongly declining. Based on empirical factor prices, such declining returns will usually not be obtained.

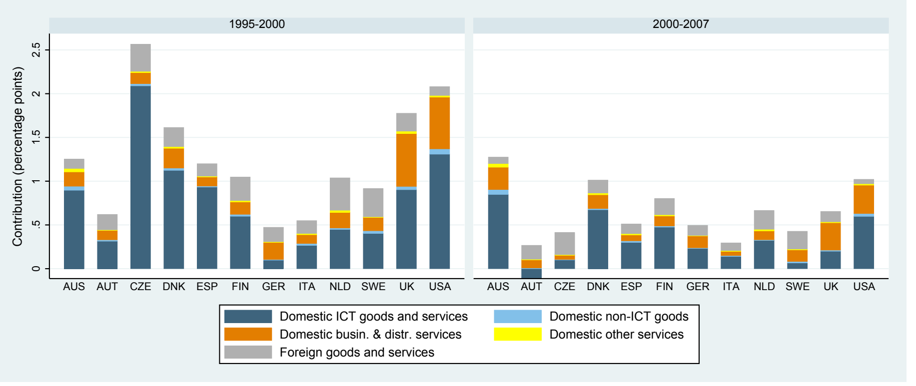

Figure 1. ICT Capital Deepening in Value Chains for ICT Goods and Services by Contributing Sector [Colour figure can be viewed at wileyonlinelibrary.com]

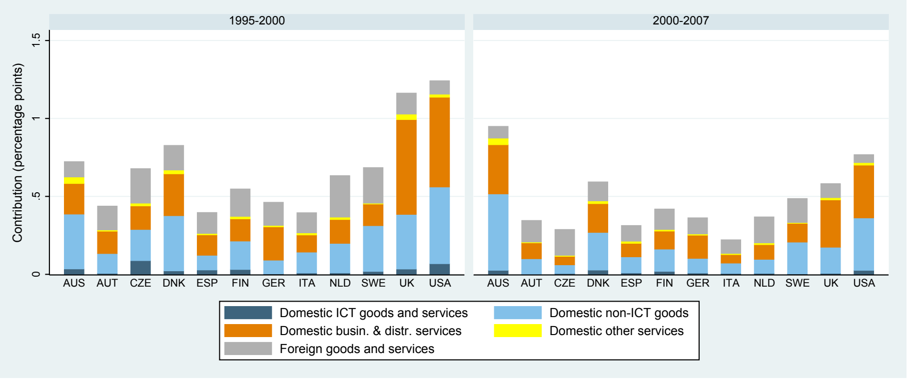

Figure 2. ICT Capital Deepening in Value Chains for Non-ICT Goods by Contributing Sector [Colour figure can be viewed at wileyonlinelibrary.com]

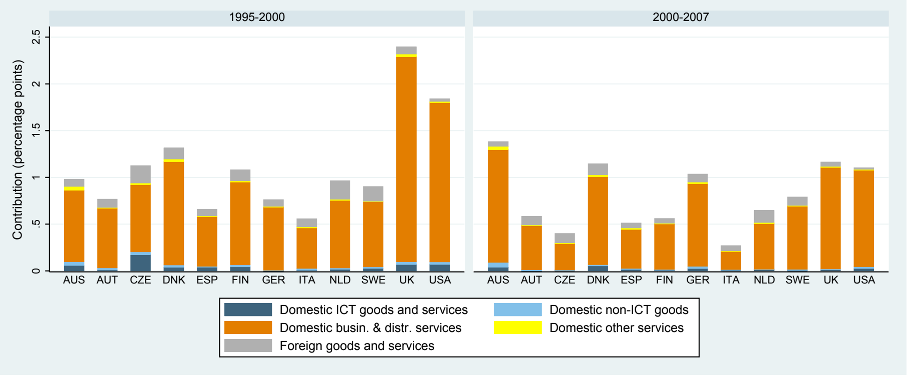

Figure 3. ICT Capital Deepening in Value Chains for Busin. and Distr. Services by Contributing Sector [Colour figure can be viewed at wileyonlinelibrary.com]

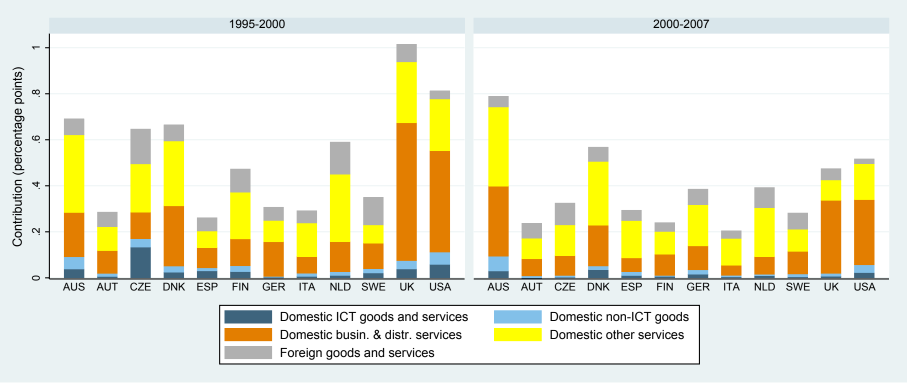

Figure 4. ICT Capital Deepening in Value Chains for Other Services by Contributing Sector [Colour figure can be viewed at wileyonlinelibrary.com]

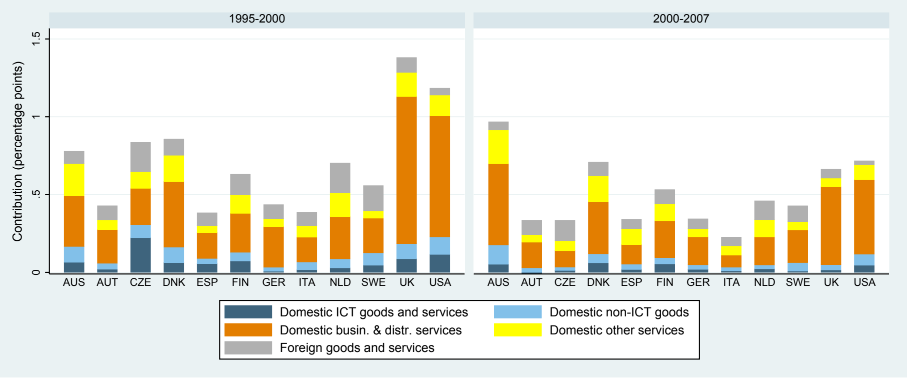

Figure 5. ICT Capital Deepening in Value Chains for Total Final Output by Contributing Sector [Colour figure can be viewed at wileyonlinelibrary.com]

of other services (for the majority of countries except notably the UK and the US during both periods, see Figure 4). Only for business, financial, and distribution services, far more than half of capital deepening is consistently contributed within the final sector (Figure 3).

Business, financial, and distribution services are in turn the most important domestic upstream sector contributing to labor productivity growth through ICT capital deepening. The other sectors transfer only small ICT-related contributions downstream, which in most cases lie below an annual 0.05 percentage points. In the US, the downstream contributions of ICT capital deepening in business, financial, and distribution services to other final sectors lie around between 0.3 and 0.6 percentage points per year in the period 1995–2000. In the period 2000–2007, the contributions are lower, but still exceed 0.2 percentage points. The UK also displays ICT contributions by business, financial, and distribution services to each of the three other final sectors of around 0.5 percentage points. Australia is the country that has generally the third highest contributions by these services.

TABLE 4
TFP Growth Contributed by ICT Sector to Different Final Products, Percentage Points

	(1)	(2)
	1995–2000	2000–2007
Australia		
ICT goods & services	0.76	0.58
Non-ICT goods	0.03	0.02
Busin. & distr. services	0.09	0.01
Other services	0.08	0.02
Total	0.09	0.03
Austria		
ICT goods & services	3.42	2.20
Non-ICT goods	0.11	0.06
Busin. & distr. services	0.07	0.08
Other services	0.07	0.02
Total	0.22	0.14
Czech Republic		
ICT goods & services	0.34	2.48
Non-ICT goods	−0.14	0.27
Busin. & distr. services	−0.07	0.20
Other services	−0.19	0.07
Total	−0.13	0.36
Denmark		
ICT goods & services	2.28	1.99
Non-ICT goods	−0.01	0.00
Busin. & distr. services	0.03	0.00
Other services	−0.03	−0.04
Total	0.06	0.05
Finland		
ICT goods & services	6.32	3.54
Non-ICT goods	0.12	0.11
Busin. & distr. services	0.05	0.14
Other services	0.01	0.02
Total	0.51	0.33
Germany		
ICT goods & services	4.47	2.38
Non-ICT goods	0.08	0.11
Busin. & distr. services	0.07	0.06
Other services	0.09	0.07
Total	0.29	0.20
Italy		
ICT goods & services	1.87	0.76
Non-ICT goods	−0.01	−0.03
Busin. & distr. services	−0.02	−0.05
Other services	0.01	−0.02
Total	0.07	0.00
The Netherlands		
ICT goods & services	3.34	1.51
Non-ICT goods	0.08	0.10
Busin. & distr. services	0.02	0.13
Other services	0.03	0.06
Total	0.17	0.14
Spain		
ICT goods & services	1.32	1.18
Non-ICT goods	−0.01	0.00
Busin. & distr. services	−0.08	0.02
Other services	−0.04	0.00
Total	0.00	0.04

(Continues)

TABLE 4 (CONTINUED)

	(1)	(2)
	1995–2000	2000–2007
Sweden		
ICT goods & services	5.11	3.28
Non-ICT goods	0.05	0.13
Busin. & distr. services	0.07	0.06
Other services	−0.05	0.06
Total	0.32	0.27
UK		
ICT goods & services	3.79	1.37
Non-ICT goods	0.01	0.15
Busin. & distr. services	0.01	0.13
Other services	−0.03	0.05
Total	0.18	0.13
US		
ICT goods & services	2.65	2.64
Non-ICT goods	0.12	0.21
Busin. & distr. services	0.07	0.11
Other services	−0.01	0.04
Total	0.14	0.18

4.3. *Contribution of TFP Growth in the ICT Sector to Value Chains*

In addition to ICT capital deepening along the value chain, ICT products contribute the total value of final products if used as intermediate products. Growth accounting at the level of value chains incorporates contributions of all factor inputs in upstream sectors and consequently also residual TFP growth generated at these stages. For this reason, it is possible to identify the contribution of TFP growth originating in the ICT-producing sector to final output growth in non-ICT value chains (see equation (21)). The results are presented in Table 4. Negative contributions may be related to declining intermediate input by the ICT sector.

The ICT sector itself has very high rates of sectoral TFP growth, and it can be expected that part of it is passed on downstream. Yet, these downstream effects turn out to be low. While some countries exhibit average annual effective TFP growth rates for ICT products as high as 4 percent, the TFP contributions to other value chains all lie below 0.3 percentage points, in most cases even below 0.1 percentage points. They are therefore lower than the contributions from ICT capital deepening in value chains, which attain values of around 0.5 percentage points (see previous sections). Because total effective rates of TFP growth in non-ICT goods and services production are between slightly negative and 3 percentage points, the TFP contribution from the ICT sector is also mostly moderate in relative terms, except in final sectors with overall low effective TFP growth.

5. Conclusion

This paper investigates ICT-related increases in labor productivity along value chains of products finally produced in different sectors and countries. Orders of magnitude and country differences in the contribution of ICT capital deepening to labor productivity growth in value chains are in line with those found in previous sector-level studies. The ICT contribution is similar for value chains of non-ICT goods and non-ICT services. Within services, it is higher for the more knowledge-intensive business, financial, and distribution services than for other services. Overall, ICT capital deepening contributes more to labor productivity growth in value chains than TFP growth in the production of upstream ICT inputs.

Looking more in depth at the origin of the contributions, we find that foreign ICT capital deepening contributes relatively little to labor productivity growth along value chains. While the phenomena of digitalization and globalization may be related in various ways, we find little evidence of ICT-related labor productivity growth being imported via intermediate inputs. It still may be the case that ICT investments enable new offshoring relations, but that the ICT investments in the exporting countries themselves contribute little to productivity growth along value chains. Our imputation of missing values for ICT capital may underestimate some foreign contributions, but we do not expect this effect to be very large. Another bias might arise from the fact that input–output data only identify values for average firms per industries. In case producers for final use within an industry differ in their import intensity and their ICT use from producers for intermediate use, this may distort the contribution of ICT capital deepening in value chains and its split between a domestic and a foreign component (for a related discussion, see Johnson 2018).

Domestic upstream contributions of ICT capital deepening to productivity growth play a more important role. For non-ICT goods production, far more than half of the ICT contribution originates in upstream sectors. For some countries, this is also true for ICT products and the category of other services. Policies aiming at digitalization of a sector with the goal of improving the competitiveness of the products should consider that the final stage of production may have a limited potential for this. Because most of the contributions along the value chains are domestic, fostering digitalization of national value chains could have a far greater effect.

The most important upstream sector contributing to ICT-related productivity growth in value chains is the sector of business, financial services, and distribution services. It is also the sector that in turn receives the lowest ICT contributions by other sectors.

Growth accounting along value chains therefore suggests that the diffusion of ICT increased particularly the productivity of the service contributions to value chains and did so through services that use information and knowledge intensively. As far as we can see at a relatively high level of aggregation, this contribution does not concentrate on particular sets of final products but is spread throughout the economy. Especially in the final sector of non-ICT manufactured goods, we find countries where the contribution of ICT capital deepening to labor productivity growth at the final stage is much lower than the contribution provided by upstream services.

After the financial crisis of 2008, the strong measured contribution of business and financial services has to be interpreted with caution. It is possible that part of the effect does not correctly measure the productivity contribution of this sector. More generally, it should be kept in mind that growth accounting reflects statistical associations rather than causal relationships.

To the best of our knowledge, this is the first paper to analyze ICT-related gains in labor productivity in a growth-accounting framework of value chains. It has set out the methodology and generated results at level of aggregated sectors of final goods. Further work could integrate capital as a produced input. When we currently split the contribution of ICT capital deepening into a domestic and a foreign contribution, we consider in which country the ICT capital was used to produce value added, but not in which country the capital itself was produced. This could be done following the approach by Aulin-Ahmavaara (1999). Further possible applications of growth accounting along value chains are not limited to ICT-related productivity contributions. The contribution of labor growth to output growth could be investigated decomposing labor by skill levels.

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