

**Testing Significance of Contributions in Growth Accounting,  
with Application to Testing ICT Impact on Labor Productivity of  
Developed Countries**

**Valentin Zelenyuk\***

*School of Economics and Centre for Efficiency and Productivity Analysis,  
The University of Queensland, Australia*

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**Abstract**

In this work we develop a framework for statistical testing of significance of contributions to changes in economic growth rates (and productivity changes) in the Solow's growth accounting framework, which is the main contribution of the paper. We then also illustrate the developed methodology for testing significance of the impact of information and communication technologies capital on the labor productivity distribution of developed countries in 1980–1995.

*Key words:* growth and productivity; developed countries; ICT impact

*JEL classification:* O31; O47; O52; P27

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**1. Introduction**

The goal of this work is two-fold. The theoretical and primary goal is to develop a framework for statistical testing of significance of contributions to changes in economic growth rates or productivity changes in the Solow growth accounting framework. The other goal is an empirical task—to illustrate the developed methodology in the context of testing the impact of information and communication technologies (ICT) capital on changes in the labor productivity distribution of developed countries over the period 1980–1995.

The methodological task of this paper is to adopt the Solow growth accounting methodology for statistical testing of significance of the contribution from each source of the decomposition of a country's labor productivity growth. We do modernization similar to the way Kumar and Russell (2002) worked within the data envelopment analysis framework for measuring productivity changes and its sources.

We first use the growth accounting (GA) methodology (Solow, 1957) to decompose the growth in labor productivity into three sources: (i) change in ICT-

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\*Correspondence to: School of Economics and Centre for Efficiency and Productivity Analysis, The University of Queensland, Colin Clark Building (39), St Lucia, Brisbane, Qld 4072, Australia. E-mail: v.zelenyuk@uq.edu.au.

capital per worker, (ii) change in non-ICT-capital per worker, and (iii) change in total factor productivity (TFP). Given estimates of these sources, we then construct the “virtual” or “fitted” samples of labor productivity for these developed countries under various assumptions that isolate the impact of one or more of these sources on the distribution of labor productivity. We then use the kernel density estimates for these samples to visualize and informally compare the impact of each of the sources alone, as well as jointly with another source. Finally, we use the Li (1996) test of equality of distributions and the Silverman (1981) test for multi-modality to formally investigate significance of contributions of each source separately or jointly with another source.

Interestingly, using the kernel density estimates of the distribution of labor productivity for the developed countries, we observe a dramatic change over these 15 years and, remarkably, the change from a uni-modal into a multi-modal distribution. This finding is intriguing but consistent with theoretical justification for a multi-peak convergence hypothesis offered by Quah (1996) and the theoretical model of Basu and Weil (1999). It is also consistent with the empirical evidence observed in Kumar and Russell (2002), who argued that the driving engine of growth in the world, from 1965 until 1990, was capital accumulation. This argument was also recently supported by Los and Timmer (2005). We find that the dramatic change has been caused more likely by the change in TFP—i.e., the mysterious Solow-residual—rather than by the ICT or non-ICT capital deepening. It is this factor that caused the largest change, comparable to overall capital (ICT and non-ICT together) change, in particular, causing a shift from a uni-modal distribution of labor productivity in 1980 towards a multi-modal distribution in 1995.

## 2. Methodology

For the sake of completeness, let us first briefly describe the growth accounting technique (Solow, 1957) that we use to decompose the growth in GDP (total income) into several sources. Let  $q_t^k$  and  $x_t^k = (x_{t,1}^k, \dots, x_{t,N}^k)' \in \mathfrak{R}_+^N$  denote the total output (GDP) and vector of endowed resources, respectively, that each country  $k$  ( $k = 1, \dots, n$ ) is endowed with in period  $t$ . For simplicity, assume that the production possibilities of a country  $k$  in any period  $t$  is characterized by the aggregate production function with Hicks-neutral-type technological change:

$$q_t^k \equiv \psi_t^k(x_t^k) = a_t^k \psi^k(x_t^k), \quad k = 1, \dots, n, \quad (1)$$

where  $\psi^k$  is the independent of time part of country  $k$ 's aggregate production function, which is augmented by  $a_t^k$ —a function of time representing TFP.

The growth accounting method is based on noting that, given appropriate differentiability of (1) with respect to time, the growth rate of the GDP, denoted  $g(q_t^k)$ , is given by:

$$\begin{aligned}
g(q_t^k) &\equiv \frac{dq_t^k / dt}{q_t^k} = \frac{d \ln q_t^k}{dt} = \sum_{i=1}^N e_{i,t} \frac{\partial \ln x_{i,t}^k}{\partial t} + \frac{\partial \ln a_t^k}{\partial t}, \\
&= \sum_{i=1}^N e_{i,t} g(x_{i,t}^k) + g(a_t^k),
\end{aligned} \tag{2}$$

for  $k=1, \dots, n$  and where  $e_{i,t}^k \equiv (\partial \psi_t^k(x_t^k) / \partial x_{i,t}^k) / (x_{i,t}^k / q_t^k)$  is the *partial scale elasticity with respect to input  $i$* ,  $g(x_{i,t}^k) \equiv (dx_{i,t}^k / dt) / x_{i,t}^k$  is the *growth rate of  $i$* , and  $g(a_t^k) \equiv (da_t^k / dt) / a_t^k$  is the *growth rate of TFP*, also known as the “Solow residual.” In words, the growth rate in GDP is the weighted average of growth rates in each input  $x_{i,t}^k$  weighted by the corresponding partial scale elasticity plus the growth rate in TFP. In addition, assuming *constant returns to scale* would allow normalizing each variable by one of the input variables, thus yielding:

$$\begin{aligned}
g(q_t^k / x_{j,t}^k) &\equiv \sum_{\substack{i=1 \\ i \neq j}}^N e_{i,t} \frac{\partial \ln(x_{i,t}^k / x_{j,t}^k)}{\partial t} + \frac{\partial \ln a_t^k}{\partial t}, \\
&= \sum_{i=1, i \neq j}^N e_{i,t} g(x_{i,t}^k / x_{j,t}^k) + g(a_t^k),
\end{aligned} \tag{3}$$

for  $k=1, \dots, n$ .

In our empirical analysis, input vector  $x_t^k$  consists of three elements—*labor*, *ICT-capital*, and *non-ICT-capital*. The normalizing variable is labor, so that we obtain decomposition of the growth in labor productivity into three sources of growth: (i) due to change in ICT-capital per worker, (ii) due to change in non-ICT-capital per worker, and (iii) due to change in other factors, attributed to the change in TFP. In practice, since data are observed discontinuously, we use the discrete version of (3), given by:

$$\Delta \ln(q_t^k / x_{j,t}^k) = \sum_{i=1, i \neq j}^N e_{i,t} \Delta \ln(x_{i,t}^k / x_{j,t}^k) + \Delta \ln(a_t^k), \tag{4}$$

for  $k=1, \dots, n$  where  $\Delta$  is the first-differences operator.

Upon computing the total growth rate for labor productivity and its sources according to decomposition given in (4), for each country  $k=1, \dots, n$  in a sample, we can analyze the contribution of each of the three sources to the change in the distribution of labor productivity in the entire population. Specifically, note first that from (4), we can obtain:

$$(q_t^k / x_{j,t}^k) = (q_{t-1}^k / x_{j,t-1}^k) \exp\left(\sum_{i=1, i \neq j}^N e_{i,t} \Delta \ln(x_{i,t}^k / x_{j,t}^k) + \Delta \ln(a_t^k)\right). \tag{5}$$

Expression (5) is describing the evolution of labor productivity from base to current period, depending on the sources of growth, and we call it the *contribution equation*. Using (5), we can analyse the contribution of change in the  $i$  th input (per unit of  $j$

th input) to the growth in GDP (per unit of  $j$  th input) for each country  $k$ . This is done by comparing the labor productivity estimates in the base period to the *fitted* values that account only for the change in the  $i$  th input (per unit of  $j$  th input)—obtained by setting all other changes in (5) to zero. Formally, the sample of such fitted values is defined by:

$$\left. \frac{q_t^k}{x_{j,t}^k} \right|_{\substack{\text{only change} \\ \text{in input } i \\ \text{per input } j}} = (q_{t-1}^k / x_{j,t-1}^k) \exp(e_{i,t} \Delta \ln(x_{i,t}^k / x_{j,t}^k)). \quad (6)$$

Similarly, the contribution to the change in GDP (per unit of input  $j$ ) due to the change in TFP only can be obtained by comparing the original sample to the sample of fitted values that account only for the change in TFP, i.e., setting all other changes in (5) to zero:

$$\left. \frac{q_t^k}{x_{j,t}^k} \right|_{\substack{\text{only change} \\ \text{in TFP}}} = (q_{t-1}^k / x_{j,t-1}^k)(a_t^k). \quad (7)$$

In the same fashion, we can analyze the contribution to change in GDP (per input  $j$ ) coming from any number of inputs with or without TFP by using (5) with all the other changes set to zero.

The question that naturally arises now is how to compare those samples. Perhaps the most popular way is to investigate the first moments of the distributions using the sample means. Another way is to analyze the dispersion or spread of the samples, using for example variance or the coefficient of variation. This would be in the spirit of sigma-convergence analysis of Abramovitz (1986) and Barro and Sala-i-Martin (1992). Yet another way is to use regression analysis of the growth rates on the base period GDP per worker, with possibly some conditioning variables hypothetically influencing the evolution of labor productivity. This would be in the spirit of (absolute or conditional) beta-convergence analysis of Barro and Sala-i-Martin (1992).

Finally, another approach that incorporates *all* moments of the distribution and allows for a visual impression of changes in the shape of the distribution is to estimate densities of the distributions and test for the equality of distributions as well as for multi-modality of the densities. This method is in the spirit of Quah (1996), Kumar and Russell (2002), and Badunenko et al. (2008), and we adapt it in our study. Specifically, we use the Li (1996) test and the Silverman (1981) test. P-values for the Li test we use here are bootstrapped (via 1-sample re-sampling) with 5000 replications. We use the Silverman normal adaptive (robust) rule of thumb (with Gaussian kernel) for selecting the bandwidth. For the Silverman test, we also use 5000 bootstrap replications, with Gaussian kernel, and the starting value for the bandwidth is obtained via the Sheather and Jones (1991) method.

### 3. Application

#### 3.1 Economic Growth and ICT Aspect

In this empirical part we are looking at the developed countries only. The main reason for this is the accuracy of the data on ICT capital. Another reason is that most of the wealth in the world is currently possessed by developed countries. Being accumulated over hundreds of years and invested into various types of capital, this wealth kept generating stable (although not very high, compared to some developing countries) economic growth, ensuring high and rising living standards for these nations. A particular type of capital, often referred to as ICT-capital, is claimed to have had a pronounced impact on the growth of these nations in the last quarter of the previous century. And so in this paper we try to quantify the effect of this type of capital relative to other major sources of economic growth in developed nations by synthesizing existing methodologies.

Research on economic growth and country productivity is one of the most popular topic in economics. Indeed, many researchers analyzed empirically the patterns of economic growth in the world. A major wave of the literature was inspired by the seminal works of Abramovitz (1986), Baumol (1986), Barro (1991, 2001), Mankiw et al. (1992), Quah (1993, 1996a, 1996b, 1997), Färe et al. (1994), Bernard and Jones (1996), Durlauf (1996), Jones (1997), Hall and Jones (1999), Sala-i-Martin (1996, 1997) and more recent works by van Ark (2002), Kumar and Russell (2002), Henderson and Russell (2005), Henderson and Zelenyuk (2006), Fagerberg et al. (2007), Badunenko et al. (2008), Castelacci (2008), Castelacci and Archibugi (2008), and Filippetti and Peyrache (2011) to mention a few.

The importance of ICT capital on economic growth and productivity was recorded and discussed in Brynjolfsson and Hitt (1998, 2000), Jorgenson (2000, 2001, 2003), Stiroh (2002), Timmer et al. (2003), and Piatkowski and van Ark (2003) to mention just a few. In our study, we use a different technique to statistically address this question. In particular, our study is fitting to the existing stream of literature by making a synthesis of methodologies from Solow (1957), Quah (1993, 1996a, 1996b, 1997), and Kumar and Russell (2002) and by applying it towards tackling the question about the main driving forces for the change in the (average) labor productivity distribution across developed countries during 1980–1995. A particular contribution of our study is that we attempt to statistically measure how large was the (direct) impact of changes in ICT-capital on the change in the distribution of labor productivity across countries within the Solow growth accounting framework.

#### 3.2 Data and Summary of Estimation Results

As an input to our statistical analysis, we use the growth accounting results obtained by Timmer et al. (2003) for 15 developed countries. For a description of the data used we refer to Timmer et al. (2003). Here we will focus on the visualization and formal statistical testing of the changes in distributions of labor

productivity across the countries (from 1980 to 1995). In particular, we will consider the impact of three sources: (i) change in ICT-capital per unit of labor, (ii) change in non-ICT-capital per unit of labor, and (iii) change in other factors, attributed by convention to changes in TFP. Although our sample exhausts most of the population of developed countries in the world, it is still a fairly small sample. For this reason, a bootstrap for the Li (1996) test statistic would be particularly useful.

Figure 1 visualizes the estimated densities, while Table 1 presents the results of the bootstrapped p-values for the Li (1996) test, where the null hypothesis is that the distribution of labor productivity in 1980 is equal to another distribution of interest. The solid lines in Figure 1 visualize distributions of labor productivity in 1980 and 1995 by plotting the kernel-based estimates of the corresponding true densities. We see that a very dramatic change has occurred over 15 years: in Table 1, the Li test suggests very significant change, with p-value of 0.0062 (i.e., reject the hypothesis of equality of these two distributions at less than 1% significance level).

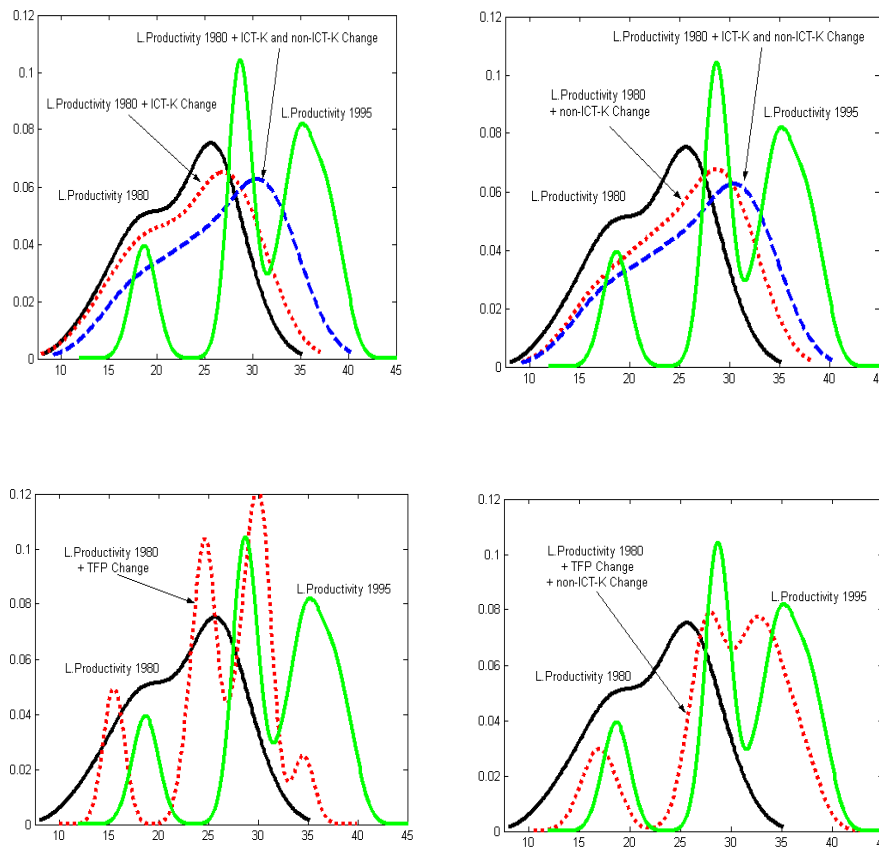
From the figure we also see a three-modal distribution of labor productivity in 1995—suggesting that three distinct “clubs” of countries have emerged within the set of developed countries by 1995. The “richest club” consist of Belgium, Denmark, France, Germany, Italy, the Netherlands, and the US, with the Netherlands being the leader (in terms of labor productivity) among these seven. The “middle club” of our sample of developed countries consists of Austria, Finland, Spain, Sweden, and the UK, with Austria being the leader among these five. Finally, the “poorest club” in our sample of developed countries consist of Greece and Portugal, having similar labor productivity, with Greece being slightly in the lead. Application of the Silverman (1981) smooth-bootstrap-based test for multi-modality of the distribution of labor productivity in the developed countries in 1995 yields a p-value of 0.0414, thus *rejecting* the hypothesis of uni-modality at less than 5% level. This finding is coherent with theoretical justification for a multi-peak convergence offered by Quah (1996) and Basu and Weil (1999) and with empirical evidence (for twin-peak *world* convergence) found in Kumar and Russell (2002).

Figure 1 suggests that the changes in the distribution of labor productivity were not “uniform” over countries—some grew faster than others—and we are interested in learning what sources have contributed the most to this type of distributional “divergence.” Let us focus on the dotted curve in the upper left panel of Figure 1, which is the estimated density of labor productivity in 1995 under the condition that only the change in ICT-capital per unit of labor is accounted for, i.e., other changes in (5) are set to zero. We see that a relatively small change has occurred, relatively “uniformly” over all the countries in the sample—in the sense that the totally different shape of distribution observed in 1995 was *not* caused by the change in ICT-capital per unit of labor. Given the p-value of 0.9040 (see Table 2), the Li test suggests that this contribution was statistically insignificant. One of course should be careful interpreting this result, since statistical insignificance might have occurred because our asymptotic test might have not reached a desired power for our small sample to be able to reject the null hypothesis. More data is needed to check the robustness of this conclusion. Moreover, statistical insignificance of a contribution

does not always imply economic insignificance of the same contribution, especially if this insignificance is due to a small sample. This evidence is also consistent with earlier studies, e.g., van Ark (2002) summarizing many studies in the field, noted that "... [i]n the rest of the advanced world the evidence of acceleration in productivity growth due to ICT is weaker [than in the US] though not wholly absent."

Let us now focus on the dashed curve in the upper left panel of Figure 1, which is the estimated density of labor productivity in 1995 under the condition that the change in TFP in (5) is set to zero, i.e., only changes in ICT-capital and non-ICT-capital per unit of labor are accounted for. When these two changes are jointly accounted for, the shape of the distribution is not changed dramatically (as when all changes are accounted for). It only skews the distribution in base period (1980) to the right in a somewhat "uniform" fashion. This time, the power of the Li test was enough to identify significance of the contribution only with p-value of 0.2480.

**Figure 1. Estimated Densities of Labor Productivity Accounting for Various Factors, 1980 and 1995**



**Table 1. Bootstrap Estimated P-Values for the Li Test for Various Hypotheses**

<b>Null Hypothesis:</b> Distributions of labor productivity in 1980 is equal to F, where	<b>p-value</b>
F is the distribution of labor productivity in 1995	0.0062
F is the distribution of labor productivity in 1995 accounting only for ICT-capital per unit of labor change, i.e., changes in TFP and in non-ICT-capital per unit of labor in (5) are set to zero	0.9040
F is the distribution of labor productivity in 1995 accounting only for non-ICT-capital per unit of labor change, i.e., changes in TFP and ICT-capital per unit of labor in (5) are set to zero	0.6606
F is the distribution of labor productivity in 1995 accounting only for ICT-capital and non-ICT-capital per unit of labor change, i.e., change in TFP in (5) is set to zero	0.2480
F is the distribution of labor productivity in 1995 accounting only for TFP change, i.e., changes in ICT-capital and non-ICT-capital per unit of labor in (5) are set to zero	0.2938
F is the distribution of labor productivity in 1995 accounting only for TFP and ICT-capital per unit of labor change, i.e., change in non-ICT-capital per unit of labor in (5) is set to zero	0.5776
F is the distribution of labor productivity in 1995 accounting only for TFP and non-ICT-capital per unit of labor change, i.e., change in ICT-capital per unit of labor in (5) is set to zero	0.0330

Notes: p-values were estimated using 5000 bootstrap replications for the original Li statistic. Results were robust to different bandwidth choices.

The upper right panel of Figure 1 is similar to the upper left panel, except that the dotted curve is the estimated density of labor productivity in 1995 when we only account for the change in non-ICT capital per unit of labor, and the other curves are the same as in Figure 1. From both figures, we see that non-ICT-capital deepening alone was also not substantial in dramatically changing the distribution of labor productivity (p-value 0.6606) but slightly larger than the ICT-capital deepening. Again, the small sample size might be a reason for inability to identify statistical significance of the contribution.

The lower left panel of Figure 1 is similar to the upper left and upper right panels, but the dotted curve here is the estimated density of labor productivity in 1995 under the condition that all changes except TFP in (5) are set to zero, i.e., no changes in ICT-capital and non-ICT-capital per unit of labor are accounted for. The figure clearly suggests that the changes in TFP were responsible for the dramatic change in the shape of the distribution of labor productivity across countries over 15 years. The Li test for comparing it with the base period distribution gives a p-value of 0.2938, which is lower than for other single factors yet higher than conventional significance levels. On the other hand, the application of the Silverman (1981) test



for multi-modality of this distribution (when only changes in TFP are accounted for) gives a p-value of 0.0422, thus suggesting we reject the hypothesis of uni-modality (at the 5% significance level) in favour of multi-modality and supporting the conclusion that TFP change is responsible for the change from a uni-modal to a multi-modal distribution in labor productivity.

Finally, in the lower right panel of Figure 1, the dotted curve is the estimated density of labor productivity in 1995 under the condition that the change in ICT-capital per unit of labor in (5) is set to zero, i.e., only changes in TFP and in non-ICT-capital are accounted for. The Li test suggests significance of the contribution, giving a p-value 0.0330. To save space, we dropped a panel presenting the estimated density of labor productivity in 1995 under the condition that the change in non-ICT capital per unit of labor in (5) is set to zero, i.e., only changes in TFP and ICT-capital deepening are accounted for, but the p-value for the comparison with the base level is 0.5776 (Table 1). Thus, one can see that the contribution from the change in non-ICT-deepening was, overall, relatively larger than from the change in ICT-deepening with or without accounting for TFP change.

#### 4. Concluding Remarks

In this paper we adopted the Solow growth accounting methodology towards statistical testing of significance of the contribution from each source of a decomposition of productivity growth. We applied this methodology to investigate significance of the contributions from change in TFP, in ICT-capital, and in non-ICT-capital. Using a sample covering nearly the entire population of developed countries, we have discovered quite interesting results.

First, we found no evidence that, from 1980 to 1995, ICT-capital deepening was a statistically significant force of change in the distribution of labor productivity of the developed countries. This is, however, not a surprising result. One should just recall the famous debate about the productivity paradox (e.g., see Griliches, 1994, 1997; Brynjolfsson and Hitt, 1998, 2000; Triplett, 1999; van Ark, 2002), which has been succinctly described by one of the founders of the growth literature: “You can see the computer age everywhere but in the productivity statistics” (Solow, *New York Review of Books*, July 12, 1987).

Another explanation could be that we had relatively a small sample size; however, we used nearly the entire population of developed countries. We also had a relatively short time span (e.g., Kumar and Russell, 2002, had 25 year-span for about 60 countries to make their conclusion), while the long-run effect could be very important here. So, we fully concur with van Ark (2002) that “... there is still good reason to believe that ICT will have a longer lasting impact on the potential for economic growth ... [because] ICT may be characterized as a typical general purpose technology” (van Ark, 2002, p. 1). Our conjecture is that the evidence can and will be found with this methodology for larger data sets and more likely for longer time horizons.

Another important issue is that we considered only the *direct* effect of ICT-capital on the change in labor productivity. However, much of the change in TFP, which was the largest source among the three, might have resulted from *indirect* influence of the ICT: due to enormous technological change experienced by the ICT industry itself and to innovations that became possible in other industries because of ICT use (e.g., see discussion of van Ark, 2002, on different channels of ICT impact).

Perhaps the most interesting finding in our empirical illustration is that the distribution of labor productivity across countries has changed dramatically during 1980–1995: from a uni-modal to multi-modal distribution, a change that is supported by statistical tests. Moreover, the estimated density plots suggest that TFP was the only driving force (among the three in our decomposition) that caused such multi-modality, and this again was supported by statistical tests, with fairly high confidence. One might recall that, in his seminal study, Solow (1957) also found that the effect of changes in TFP was the largest. On the other hand, for a broader sample of countries (that also included developing countries) and using different methodology, Kumar and Russell (2002) found that it was the capital deepening that caused the shift toward a multi-modal distribution from 1965 to 1990. Henderson and Russell (2005) also found that efficiency change, not considered in our study, was important for such a shift. Note, however, that the time span for these studies stops in 1990—before the boom in high-tech industries. Similar methodology applied to the period 1992–2000 by Badunenko et al. (2008) gave strong evidence that the technological change (an analog of TFP in our study) was the major source of growth and further (distributional or twin-peak) divergence.

Finally, we admit that our approach is far from perfect. Besides extending the data set or its time span, one improvement can be made towards modelling the aggregate production function more accurately by considering other crucial inputs, especially human capital, and/or relaxing assumptions of constant returns to scale. The developed methodology can handle many of these and other extensions. Another natural avenue for further research would be to try more rigorous approaches for the separation of different drivers of economic growth (e.g., see Growiec, 2012). More rigorous treatment of statistical aspects would be another natural extension of this work. This may include allowing for spatial correlation across observations (countries), which is not explicitly dealt with in this paper but can be approached with other econometric techniques. Overall, we hope that our study and its limitations, together with other studies, would provoke further works on these and other interesting research questions.

## References

- Abramovitz, M., (1986), “Catching Up, Forging Ahead, and Falling Behind,” *Journal of Economic History*, 46(2), 385-406.
- Badunenko, O., D. J. Henderson, and V. Zelenyuk, (2008), “Technological Change and Transition: Relative Contributions to Worldwide Growth during the 1990s,” *Oxford Bulletin of Economics and Statistics*, 70(4), 461-492.

- Barro, R. and X. Sala-I-Martin, (1992), "Convergence," *Journal of Political Economy*, 100(2), 223-251.
- Basu, S. and D. N. Weil, (1998), "Appropriate Technology and Growth," *Quarterly Journal of Economics*, 113(4), 1025-1054.
- Baumol, J. W., (1986), "Productivity Growth, Convergence, and Welfare: What the Long-Run Data Show," *The American Economic Review*, 76(5), 1072-1085.
- Brynjolfsson, E. and L. M. Hitt, (2000), "Beyond Computation: Information Technology, Organizational Transformation and Business Performance," *Journal of Economic Perspectives*, 14(4), 23-48.
- Brynjolfsson, E. and L. M. Hitt, (1998), "Beyond the Productivity Paradox: Computers are the Catalyst for Bigger Changes," *Communications of the ACM*, 41(8), 49-55.
- Färe, R., S. Grosskopf, M. Norris, and Z. Zhang, (1994), "Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries," *American Economic Review*, 84(1), 66-83.
- Filippetti, A. and A. Peyrache, (2011), "The Patterns of Technological Capabilities of Countries: A Dual Approach Using Composite Indicators and Data Envelopment Analysis," *World Development*, 39(7), 1108-1121.
- Griliches, Z., (1994), "Productivity, R&D, and the Data Constraint," *American Economic Review*, 84(1), 1-23.
- Griliches, Z., (1997), "Plenary Session: Perspectives on the Productivity Paradox," Centre for the Study of Living Standards, Conference on Service Sector Productivity and the Productivity Paradox, Ottawa, Transcription.
- Growiec, J., (2012), "The World Technological Frontier: What Can We Learn from the US States?" *Oxford Bulletin of Economics and Statistics*, 74(6), 777-807.
- Henderson, D. J. and R. R. Russell, (2005), "Human Capital and Convergence: A Production-Frontier Approach," *International Economic Review*, 46(4), 1167-1205.
- Henderson, D. J. and V. Zelenyuk, (2007), "Testing for (Efficiency) Catching-up," *Southern Economic Journal*, 73(4), 1003-1019.
- Jones, C., (1997), "On the Evolution of World Income Distribution," *The Journal of Economic Perspectives*, 11(3), 19-36.
- Jorgenson, D. W., (2001), "Information Technology and the US Economy," *American Economic Review*, 91(1), 1-32.
- Jorgenson, D. W., (2003), "Information Technology and the G7 Economies," *World Economics*, 4(4), 139-169.
- Jorgenson, D. W., (2000), *Econometric, Volume 3: Economic Growth in the Information Age*, The MIT Press, Cambridge, Massachusetts, London, England.
- Kumar, S. and R. R. Russell, (2002), "Technological Change, Technological Catch-up, and Capital Deepening: Relative Contributions to Growth and Convergence," *American Economic Review*, 92(3), 527-548.
- Li, Q., (1996), "Nonparametric Testing of Closeness between Two Unknown Distribution Functions," *Econometric Reviews*, 15(3), 261-274.

- Li, Q., (1999), "Nonparametric Testing the Similarity of Two Unknown Density Functions: Local Power and Bootstrap Analysis," *Journal of Nonparametric Statistics*, 11(1-3), 189-213.
- Los, B. and M. B. Timmer, (2005), "The 'Appropriate Technology' Explanation of Productivity Growth Differentials: An Empirical Approach," *Journal of Development Economics*, 77(2), 517-531.
- Pagan, A. and A. Ullah, (1999), *Nonparametric Econometrics*, Cambridge University Press.
- Piatkowski, M. and B. van Ark, (2004), "Productivity, Innovation and ICT in Old and New Europe," Research Memorandum GD-69.
- Quah, D., (1996), "Twin Peaks: Growth and Convergence in Models of Distribution Dynamics," *Economic Journal*, 106(437), 1045-1055.
- Rosenblatt, M., (1956), "Remarks on Some Nonparametric Estimates of a Density Function," *Annals of Mathematical Statistics*, 27(3), 832-837.
- Sheather, S. and M. Jones, (1991), "A Reliable Data-Based Bandwidth Selection Method for Kernel Density Estimation," *Journal of the Royal Statistical Society*, 53(3), 683-690.
- Silverman, B. W., (1981), "Using Kernel Density Estimates to Investigate Multimodality," *Journal of the Royal Statistical Society*, 43(1), 97-99.
- Simar, L. and V. Zelenyuk, (2006), "On Testing Equality of Two Distribution Functions of Efficiency Scores Estimated from DEA," *Econometric Reviews*, 25, 497-522.
- Solow, R. W., (1957), "Technical Change and the Aggregate Production Function," *The Review of Economics and Statistics*, 39(3), 312-320.
- Stiroh, K., (2002), "Are ICT Spillovers Driving the New Economy?" *Review of Income and Wealth*, 48(1), 33-57.
- Timmer, M., G. Ypma, and B. van Ark, (2003), "IT in the European Union: Driving Productivity Divergence?" Research Memorandum GD-67 (Groningen Growth and Development Centre).
- Triplett, J., (1999), "The Solow Productivity Paradox: What Do Computers Do to Productivity?" *Canadian Journal of Economics*, 32(2), 309-334.
- van Ark, B., (2002), "Measuring the New Economy: An International Comparative Perspective," *Review of Income and Wealth*, 48(1), 1-14.