Growth and Convergence of the OECD countries: A Multi-Sector Production-Frontier Approach.*

Barnabé Walheer†

January 18, 2017

Abstract

Kumar and Russell (2002), Henderson and Russell (2005), and Badunenko, Henderson and Russell (2013) have proposed a production-frontier methodology to analyze the economic growth and the convergence of growth rates across countries. They see two main advantages to this methodology: (1) it reconstructs the world production frontier without relying on any particular (typically unverifiable) assumptions on any aspects of the growth process, and (2) it allows to decompose labor productivity growth into several parts. In this paper, I extend the previous approach by considering a multi-sector setting. This setting allows to propose a more realistic and complete country-level analysis, while keeping the same advantages as with the previous methodology. I also tackle the criticism of less reliable data at the sector level than at the country level by showing how the multi-sector approach can easily be adapted. I apply it to the OECD countries from 1995 to 2008. The results confirm the non-neutrality of technological change. I also find that capital accumulation plays the biggest role in the increase of output-labor productivity, while technological change and human capital accumulation also play an important role, but it is twice as small as capital accumulation. Interestingly, these results suggest the emergence of two groups: eastern and central European countries; and the EU15 and Korea. The two groups seem to diverge over time.

Keywords: growth, convergence, multi-sector, production-frontier analysis

*I wish to thank Antonio Estache, Bram de Rock, Laurens Cherchye, the Editor Robert Dyson, and two anonymous referees for their comments that substantially improved the paper.

†ECARES, Université Libre de Bruxelles. Avenue F.D. Roosevelt 50, CP 114/04, B-1050 Brussels, Belgium. Email: bwalheer@ulb.ac.be.

1 Introduction

In this introductory section, I motivate the theoretical and practical relevance of the multi-sector production-frontier approach to study the economic growth of countries, and I put my contributions in the context of the relevant literature.

Motivation. The current models used to analyze the economic growth of countries have two drawbacks: (1) they ignore sector heterogeneity, and (2) they are based on unverifiable assumptions on the growth process.

While economic growth analysis should be conducted at the country level since countries share common factors such as the government, the legal system, the education system, ignoring sector heterogeneity may give biased results.[1]

There is no guideline to choose the proper assumptions on the growth process. Indeed, assumptions on technology, market structure, technological change, and other aspects of the growth process are typically unverifiable. Growth analysis based on specific assumptions may lead to biased results.

These two drawbacks form the motivation to propose a new model taking sector heterogeneity into account, without resorting to any unverifiable assumptions on any aspects of the growth process. I also tackle the criticism of less reliable data at the sector level than at the country level (such as capital data in my application) by showing that the multi-sector approach can easily be adapted when some data are not perfectly measured.

Growth and convergence. Since the classic paper of Solow (1956), much effort has been put into better understanding economic growth and, especially, the existence or not of a tendency of world economies to converge over time (i.e. the poor catch up with the rich). Theoretical and empirical papers have been written on this subject (see Barro and Sala-i-Martin (1995), Temple (1999), Brock and Durlauf (2001), and Henderson, Parmeter and Russell (2008) for comprehensive literature

[1] There is already a large literature which has paved the way by considering regions instead of countries. See, for example, Neven and Gouyette (1995); Fagerberg and Verspagen (1996); Tondl (1999); Corrado, Martin and Weeks (2005); and Enflo and Hjertstrand (2009). The main difference with my analysis is that they do not aggregate region efficiency scores to obtain a country-specific efficiency score, i.e. they directly compare regions using the same methodology as Henderson and Russell (2005).

reviews[2]), which clearly increase our understanding of the growth and convergence issues, notwithstanding a certain amount of controversy. Indeed, much of the empirical papers use Baumol (1986)-Barro (1991) cross-sectional regressions and do not find the same conclusions.[3] This could be explained, as argued by Quah (1993, 1996, 1997) and others (e.g. Galor (1996), Jones (1997), Feyrer (2003), and Johnson (2005)) by the bimodal distribution of labor productivity, which implies that the world is divided into two categories[4] (the poor and the rich). As such, regressions focused on the first moment of the distribution cannot address the convergence issue.

Kumar and Russell (2002) use nonparametric efficiency analysis[5] to tackle the growth and convergence issues. They see two main advantages to this methodology. On the one hand, the world production frontier is reconstructed without relying on any particular (typically unverifiable) assumptions on technology, market structure, technological change, market imperfections or other aspects of the growth process (in contrast to most of the references cited above which are model driven). On the other hand, the methodology allows for a tripartite decomposition of labor productivity growth into that attributable to (1) technological change, i.e. shifts in the world production frontier, (2) technological catch-up, i.e. movements toward or away from the frontier, and (3) physical capital accumulation, i.e. movements along the frontier. This tripartite decomposition is especially used to explain the bipolarization of the distribution of labor productivity found by Quah and others. Kumar and Russell (2002) find that (*i*) technological change is decidedly non-neutral, (*ii*) both growth and bimodal polarization are driven primarily by physical capital accumulation, and (*iii*) the degree of technological catch-up is directly related to the initial distance from the frontier but not to initial productivity (i.e. no convergence).

Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013), inspired by the endogenous growth models of Lucas (1988) and Romer (1990), extend

[2]Also see the 1996 Economic Journal symposium; Bernard and Jones (1996); Durlauf (1996); Galor (1996); Quah (1996b); and Sala-i-Martin (1996).

[3]See, for example, Paap, Franses and Van Djik (2005), Higgins, Levy, Young (2006), Alfo, Trovato and Waldmann (2008), Battisti and Di Vaio (2008), and Owen, Viderasa and Davis (2009) for recent work using regression-based methodologies.

[4]The division of the world into two categories is a robust stylized fact that does not depend on the test used. See Henderson, Parmeter and Russell (2008) for more details.

[5]See Fare, Grosskopf and Lovell (1994), Cooper, Seiford and Zhu (2004), Cooper, Seiford and Tone (2007), Fried, Lovell and Schmidt (2008), and Cook and Seiford (2009) for reviews; and Gattou, Oral and Reisman (2004), and Emrouznejad, Parker and Tavares (2008) for extensive listings of papers.

the previous work of Kumar and Russell (2002) by incorporating human capital.[6] They use the human capital measure of Hall and Jones (1999), which is based on the summary of returns-to-education regressions by Psacharopoulos (1994). They obtain a quadripartite decomposition of the growth of labor productivity into (1) technological change, (2) technological catch-up, (3) physical capital accumulation, and (4) human capital accumulation. The results of Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013) confirm the non-neutrality of technology change found by Kumar and Russell (2002). They also find that about one-third of the productivity growth attributed by Kumar and Russell (2002) to physical capital accumulation should, instead, be attributed to the accumulation of human capital. Contrary to Kumar and Russell (2002), they separately analyze the effects of the components of the quadripartite decomposition on the change in mean productivity and the overall shift of the labor productivity distribution. They find that the primary cause of the bimodal polarization of labor productivity is efficiency change[7] (Badunenko, Henderson and Russell (2013) find that efficiency change is the only cause). Henderson and Russell (2005) confirm the results in Kumar and Russell (2002) by finding that the increased dispersion of productivity is primarily accounted for by physical capital accumulation (with some help from technological change and human capital accumulation). Badunenko, Henderson and Russell (2013) find that physical capital accumulation play a less important role, while technological change and human capital accumulation also significantly contribute to the shift of the distribution.

Multi-output multi-input nonparametric efficiency analysis. Recently, there have been attempts to increase the realism of nonparametric efficiency analysis, by proposing methodologies which take the link between inputs and outputs into account. This contrasts with standard nonparametric models which treat the conversion of inputs into outputs as a "black box", i.e. these standard nonparametric models do not assume any particular structure on how inputs are linked to outputs. The best known methodologies are Network DEA (see Färe and Grosskopf (2000) and Färe, Grosskopf

[6] Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013) use the same methodology. Badunenko, Henderson and Russell (2013) increase the sample (more countries and a longer time period) used in Henderson and Russell (2005).

[7] This result is also found by Badunenko, Henderson and Zelenyuk (2008), using the procedures developed in Kumar and Russell (2002), but increasing the data set by picking developed, newly industrialized, developing and transitional economies.

and Whittaker (2007)), the disaggregating output-input vector DEA (see Salerian and Chan (2005)) and the DEA-R (see Despic, Despic, and Paradi(2007)). These methodologies consider different ways of allocating inputs to outputs. Network DEA assumes that all inputs can be fully allocated to outputs, while the disaggregating output-input vector DEA and the DEA-R assume the opposite, i.e. inputs can only be partially allocated to outputs.

Inspired by these methodologies, Cherchye et al. (2013, 2014b, 2015) have proposed a unifying technique, which generalizes all these allocation procedures. Their method assumes output-specific production technologies, accounts for jointly used inputs in the production process, and incorporates specific information on how inputs are allocated to individual outputs. Interestingly, their definition of output-specific production technologies accounts for interdependencies between the different output-specific technologies (through jointly used inputs).

Contributions. I propose a multi-sector country-level analysis, based on the technique of Cherchye et al. (2013, 2014b, 2015a,b), which has the same features as the previous work of Kumar and Russell (2002), Henderson and Russell (2005), and Badunenko, Henderson and Russell (2013) (i.e. no assumption on the technology, one efficiency score for each country, and a quadripartite decomposition of labor productivity growth) and which has the added advantage of taking sector specificities into account (heterogeneity and interdependence). My multi-sector model may be adapted when some data (such as capital data in my application) are not perfectly measured. That is, in practice, I will compute the lower and upper bounds for the efficiency scores. I can thus easily tackle the criticism of less reliable data at the sector level than at the country level.

This methodology is applied to the OECD countries from 1995 to 2008.[8] My application can be seen as an analysis of the efficient frontier in the previous work of Kumar and Russell (2002), Henderson and Russell (2005), and Badunenko, Henderson and Russell (2013). Indeed, these authors analyze the world[9] and find that the efficient frontier is composed of OECD countries. My results confirm the non-

[8]My analysis could be seen as a pre-crisis analysis. It would be interesting, when the data are available, to see how the results change after 2008. In a similar setting, see also Cherchye, De Rock, Estache and Walheer (2014a) which analyzes eighteen European countries in three sectors during 2000-2007.

[9]Kumar and Russell (2002) analyze 57 countries, Henderson and Russell (2005) 65 countries; and Badunenko, Henderson and Russell (2013) 98 countries.

neutrality of technological change already found in this previous work. I also find that capital accumulation plays the biggest role in the increase of output-labor productivity, while technological change and human capital accumulation also play an important, if smaller, role. Interestingly, these results suggest the emergence of two groups among the OECD countries which seem to diverge over time: eastern and central European countries; and the EU15 and Korea.

Outline. The rest of the paper is structured as follows. In Section 2, I define the multi-sector output efficiency measurement and show how the labor productivity growth can be decomposed into four parts. In Section 3, I present the results. Section 4 concludes.

2 Methodology

This section is divided into two parts. In Section 2.1, I define and show how to use the multi-sector output efficiency measurement. In Section 2.2, I show how the productivity growth can be decomposed into four parts.

2.1 Multi-Sector Production-Frontier Approach

In this section, firstly I briefly explain the standard (country-level) approach introduced by Kumar and Russell (2002), Henderson and Russell (2005), and Badunenko, Henderson and Russell (2013). Then, I define the multi-sector (country-level) approach and explain its advantages compared to the standard one. Finally, I show how the multi-sector approach can easily be adapted when some data are not perfectly measured.

Multi-sector (country-level) production-frontier approach. The standard approach introduced by Kumar and Russell (2002) considers J countries, during T periods. Every country j at time t uses labor L_{jt}, physical capital K_{jt} to produce aggregate output Y_{jt}. Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013) consider a slightly modified setting by defining labor as $\hat{L}_{jt} = H_{jt}L_{jt}$ where H_{jt} stands for human capital. They argue that it is standard in macroeconomic theory to assume that human capital enters the technology as a multiplicative augmentation of the physical labor input.

That is, the following set S is observed:[10]

$$S = \{(Y_{jt}, \hat{L}_{jt}, K_{jt}) \mid j = 1, \ldots, J; t = 1, \ldots, T\}. \quad (1)$$

The data set S allows Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013) to characterize each country by its own production technology set.[11] Growth analysis should indeed be conducted at the country level since countries share common factors such as the government, the legal system, the education system, but the modeling of Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013) completely ignores sector heterogeneity.

I decompose each country in I sectors. That is, every sector i in country j at time t uses labor L_{ijt}, physical capital K_{ijt} and human capital H_{jt} to produce output Y_{ijt}. Capital and labor are completely allocated to the sectors since they are specific to each sector i. Human capital, which is computed with the average number of years of education in the country (see Section 3.1), is jointly used by the sectors to produce the output. As such, the sectors are interdependent since they share the country's education system, captured by human capital. Figure 1 summarizes this multi-sector setting.

Figure 1: Multi-sector setting of country j in period t

The set S can be redefined as

$$S = \{(Y_{ijt}, \hat{L}_{ijt}, K_{ijt}) \mid i = 1, \ldots, I; j = 1, \ldots, J; t = 1, \ldots, T\} \quad (2)$$

where $\hat{L}_{ijt} = H_{jt} L_{ijt}$, as explained previously.

The new formulation of the data set S allows to characterize each sector in every

[10]The approach can easily be modified to match the setting of Kumar and Russell (2002) by replacing $\hat{L}_{jt}$ by L_{jt} in the definition of S.

[11]Formally, using the sequential production set formulation of Diewert (1980), they construct the monotone (or free-disposal), convex and constant returns-to-scale technology set of every country j at time t. In particular, the set in period t for country j is defined as

$$T_t = \left(\begin{array}{c} (Y, \hat{L}, K) \mid Y \leq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} Y_{j\tau}, \\ \hat{L} \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} \hat{L}_{j\tau}, \\ K \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} K_{j\tau}, \\ \lambda_{j\tau} \geq 0 \ \forall j, \tau. \end{array} \right).$$

country by its own production technology set. Formally, using the sequential production set formulation of Diewert (1980), I construct monotone (or free-disposal), convex and constant returns-to-scale technology sets for every sector in each country for all periods. In particular, the technology set for sector i in country j at period t is given by[12]

$$T_t^i = \left(\begin{array}{c} (Y, \hat{L}, K) \mid Y \leq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{ij\tau} Y_{ij\tau}, \\ \hat{L} \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{ij\tau} \hat{L}_{ij\tau}, \\ K \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{ij\tau} K_{ij\tau}, \\ \lambda_{ij\tau} \geq 0 \ \forall i, \forall j, \forall \tau. \end{array} \right). \tag{3}$$

When assuming monotonicity, convexity, and constant return-to-scales of the country-specific technology set used by Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013), T_t is stronger than when assuming monotonicity, convexity, and constant return-to-scales of the sector-specific technology sets T_t^i (for $i = 1, \ldots, I$). Intuitively, assuming these technology axioms on the sectors do not imply that these axioms are fulfilled for the country since taking a convex combination of the sector technologies could give a convex or a non-convex technology for the country. See Cherchye et al. (2013) for a formal proof.

As a final note, it is useful to once more emphasize the interdependencies between the different sectors. As mentioned before, the sectors are interdependent since they share the country's education system, captured by human capital (contained in $\hat{L}_{ijt} = H_{jt}L_{ijt}$). As such, my definition of technology sets T_t^i (for $i = 1, \ldots, I$) provides a formal statement of these sector interdependencies.[13]

Following Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013), I use a Debreu (1951)-Farrell (1957) output efficiency measure to compute the maximal expansion of the output (keeping the input constant). When adapting to my multi-sector setting (with I production sets T_t^i), I obtain the multi-sector output-oriented technical efficiency measure for each country j at time t

$$MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}) = \min \left\{ \theta \mid \forall i : \left(\frac{Y_{ijt}}{\theta}, \hat{L}_{ijt}, K_{ijt} \right) \in T_t^i \right\}. \tag{4}$$

[12]See Cherchye et al. (2015b) for a rigorous definition of the monotonicity (or free-disposability) and convexity of the production set T_t^i.

[13]See Cherchye et al. (2015a) for a detailed discussion on the interdependence of the sector-specific (named output-specific in their paper) production sets.

$MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ gives a 'benefit of the doubt' to the countries. Indeed, the common θ in the definition means that each country is evaluated by its least inefficient sector. In the absence of a known aggregation procedure, it is the most favorable way to aggregate the sector efficiencies in order to obtain the country efficiency scores, or in other words, my measure of efficiency represents the upper bound of the country-specific efficiency scores.[14] Attractively, this is in line with the usual nonparametric efficiency analysis, which typically adopts a similar 'benefit of the doubt' spirit by picking the most favorable aggregating procedure to obtain the country efficiency score.[15]

$MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ is the inverse of the maximal amount that output Y_{jt} can be expanded while keeping the input $(\hat{L}_{jt}, K_{jt})$ constant. $MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}) \leq 1$ and $MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}) = 1$ means that country j produces the maximal amount of output at time t. A smaller value of $MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ implies more inefficient behavior.

$MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ has the same advantage as the country-level efficiency measure used in Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013) (i.e. no assumption on the technology and one efficiency score for each country), but $MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ takes the multi-sector setting into account (i.e. heterogeneity and interdependence). Consequently, $MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ gives a more complete and more realistic analysis than the country-level efficiency measure used in Henderson and Russell (2005) and Badunenko, Henderson and Russell (2013), which is based on aggregated data.

The multi-sector output efficiency scores $MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ for $j_0 \in (1, \ldots, J)$

[14] Assuming the opposite, i.e. taking the most inefficient sector to evaluate the country efficiency, would give the worst favorable way to aggregate the sector efficiencies. Consequently, this aggregation procedure would give the lower bound of the country-specific efficiency scores.

[15] See, for example, Cherchye et al. (2007) for a detailed discussion of the 'benefit of the doubt' interpretation of nonparametric efficiency models and Cherchye et al. (2013, 2014b, 2015a,b) for measures close to mine which adopt this 'benefit of the doubt' spirit.

and $t_0 \in (1, \ldots, T)$ are easy to compute using a linear program **(LP-S)**:

$$MSTE_{j_0 t_0}(Y_{j_0 t_0}, \hat{L}_{j_0 t_0}, K_{j_0 t_0}) = \min_{\lambda_{ij\tau} \ (i \in \{1,\ldots I\}, j \in \{1,\ldots J\},, \tau \in \{1,\ldots t_0\})} \theta$$

$$\text{(S-1) } \forall i : \frac{Y_{ij_0 t_0}}{\theta} \leq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} Y_{ij\tau}$$

$$\text{(S-2) } \forall i : \hat{L}_{ij_0 t_0} \geq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} \hat{L}_{ij\tau}$$

$$\text{(S-3) } \forall i : K_{ij_0 t_0} \geq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} K_{ij\tau}$$

$$\text{(S-4) } \forall i, \forall j, \forall \tau : \lambda_{ij\tau} \geq 0$$

$$\text{(S-5) } \theta \geq 0.$$

Multi-sector production-frontier approach with imprecise data. I tackle the criticism of less reliable data at the sector level than at the country level by showing that the multi-sector approach can easily be adapted when some data are not perfectly measured. In my setting, the less reliable data is the capital data. Indeed, it is well known in applied macroeconomics that capital is difficult to measure, while labor and output are more easily computed. The following can easily be extended for labor L and/or output Y if needed. Let me assume that capital K_{ijt} is not well measured at the sector level, but well measured at the country level. Capital at the sector level can always be bounded and the sum over sectors must equal capital for the country. Formally, we have

$$\forall i, \forall j, \forall t : K_{ijt} \in [K_{ijt}^L, K_{ijt}^U] \text{ and } \forall j, \forall t : \sum_{i=1}^{I} K_{ijt} = K_{jt}. \tag{5}$$

Any value can be picked for the lower and upper bounds. Given my application, I choose to set an equiproportionate error level. Formally, α_{ijt} is defined as the error level on sector-level capital data. Consequently, $K_{ijt}^L = (1 - \alpha_{ijt})K_{ijt}$ and $K_{ijt}^U = (1 + \alpha_{ijt})K_{ijt}$. The two extreme cases are no confidence on sector-level capital data $\alpha_{ijt} = 1$, i.e. $K_{ijt}^L = 0$ and $K_{ijt}^U = 2 * K_{ijt}$, and full confidence on sector-level capital data $\alpha_{ijt} = 0$, i.e. $K_{ijt}^L = K_{ijt}^U = K_{ijt}$.

The previous linear program **(LP-S)** cannot be used with the modified setting since it is no longer linear (see constraint (S-3)). I suggest computing the lower and upper bounds for the multi-sector efficiency scores $MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$. The upper (lower) bound for the multi-sector efficiency score is computed by picking the most (least) favorable values for capital for the country under evaluation and the least (most) favorable values for the other countries.

Formally, the upper bound $MSTE^U_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ is computed, for $j_0 \in (1, \ldots, J)$ and $t_0 \in (1, \ldots, T)$, by the following linear program **(LP-SU)**

$$MSTE^U_{j_0t_0}(Y_{j_0t_0}, \hat{L}_{j_0t_0}, K_{j_0t_0}) = \min_{\lambda_{ij\tau}\ (i\in\{1,\ldots I\}, j\in\{1,\ldots J\})} \theta$$

$$\text{(SU-1) } \forall i : \frac{Y_{ij_0t_0}}{\theta} \leq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} Y_{ij\tau}$$

$$\text{(SU-2) } \forall i : \hat{L}_{ij_0t_0} \geq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} \hat{L}_{ij\tau}$$

$$\text{(SU-3) } \forall i : K^L_{ij_0t_0} \geq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} K^U_{ij\tau}$$

$$\text{(SU-4) } \forall i, j, \tau : \lambda_{ij\tau} \geq 0$$

$$\text{(SU-5) } \theta \geq 0.$$

Similarly, the lower bound $MSTE^L_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt})$ is computed, for $j_0 \in (1, \ldots, J)$ and $t_0 \in (1, \ldots, T)$, using the linear program **(LP-SL)**

$$MSTE^L_{j_0t_0}(Y_{j_0t_0}, \hat{L}_{j_0t_0}, K_{j_0t_0}) = \min_{\lambda_{ij\tau}\ (i\in\{1,\ldots I\}, j\in\{1,\ldots J\})} \theta$$

$$\text{(SL-1) } \forall i : \frac{Y_{ij_0t_0}}{\theta} \leq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} Y_{ij\tau}$$

$$\text{(SL-2) } \forall i : \hat{L}_{ij_0t_0} \geq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} \hat{L}_{ij\tau}$$

$$\text{(SL-3) } \forall i : K^U_{ij_0t_0} \geq \sum_{\tau=1}^{t_0} \sum_{j=1}^{J} \lambda_{ij\tau} K^L_{ij\tau}$$

$$\text{(SL-4) } \forall i, j, \tau : \lambda_{ij\tau} \geq 0$$

$$\text{(SL-5) } \theta \geq 0.$$

It directly follows from the previous definitions that:

$$\forall j, \forall t : MSTE^L_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}) \leq MSTE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}) \leq MSTE^U_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}). \quad (6)$$

I will demonstrate the usefulness of the lower and upper bounds in the application.

2.2 Quadripartite Decomposition of Labor Productivity Growth

In this section, I show how productivity growth can be decomposed into (1) efficiency change, (2) technological change, (3) capital deepening (increases in the capital−labor ratio), and (4) human capital accumulation, for each country. This section is directly inspired by the decompositions suggested by Kumar and Russell (2002) and extended by Henderson and Russell (2005). See their papers for more details. The only difference is that the efficient output levels are computed with the multi-sector country-level model instead of the standard country-level model used in their papers. In the rest of this section, I drop subscript j for better readability.

The technology is defined, for every country, under constant returns-to-scale, allowing to move from a representation in three dimensions $\langle Y, \hat{L}, K \rangle$ to a representation in two dimensions $\langle \hat{y}, \hat{k} \rangle$, by defining $\hat{y}_t = Y_t/\hat{L}_t$ and $\hat{k}_t = K_t/\hat{L}_t$. The technology is then characterized by the function $\hat{y}_t(\hat{k}_t)$.

The efficient output at time b and c (b and c denote the base and the current periods) is given by $\hat{y}_b(\hat{k}_b) = \hat{y}_b/\theta_b$ and $\hat{y}_c(\hat{k}_c) = \hat{y}_c/\theta_c$, where $\theta_t = MSTE_t(Y_t, \hat{L}_t, K_t)$ for $t = \{b, c\}$. It defines the following equality

$$\frac{\hat{y}_c}{\hat{y}_b} = \frac{\theta_c}{\theta_b} \frac{\hat{y}_c(\hat{k}_c)}{\hat{y}_b(\hat{k}_b)}. \quad (7)$$

Let $\tilde{k}_c = K_c/(L_c H_b)$ denote the ratio of capital to labor measured in efficiency units under the counterfactual assumption that human capital has not changed from its base period and let $\tilde{k}_b = K_b/(L_b H_c)$ denote the ratio of capital to labor measured in efficiency units under the counterfactual assumption that human capital is equal to its current-period level. The counterfactual assumptions allow, by keeping the other variables constant, to isolate the effect of capital-labor ratio and of human capital in productivity growth. Multiplying equation (7) by $\frac{\hat{y}_b(\hat{k}_c)}{\hat{y}_b(\hat{k}_c)}$ and $\frac{\hat{y}_b(\tilde{k}_c)}{\hat{y}_b(\tilde{k}_c)}$ gives

$$\frac{\hat{y}_c}{\hat{y}_b} = \frac{\theta_c}{\theta_b} \frac{\hat{y}_c(\hat{k}_c)}{\hat{y}_b(\hat{k}_c)} \frac{\hat{y}_b(\tilde{k}_c)}{\hat{y}_b(\hat{k}_b)} \frac{\hat{y}_b(\hat{k}_c)}{\hat{y}_b(\tilde{k}_c)}; \tag{8}$$

and by $\frac{\hat{y}_c(\hat{k}_b)}{\hat{y}_c(\hat{k}_b)}$ and $\frac{\hat{y}_c(\tilde{k}_b)}{\hat{y}_c(\tilde{k}_b)}$ gives

$$\frac{\hat{y}_c}{\hat{y}_b} = \frac{\theta_c}{\theta_b} \frac{\hat{y}_c(\hat{k}_b)}{\hat{y}_b(\hat{k}_b)} \frac{\hat{y}_c(\hat{k}_c)}{\hat{y}_c(\tilde{k}_b)} \frac{\hat{y}_c(\tilde{k}_b)}{\hat{y}_c(\hat{k}_b)}. \tag{9}$$

Productivity growth, $y_t = Y_t/L_t$ for $t = \{b, c\}$, can be decomposed into the growth of output per efficiency unit of labor and the growth of human capital.

$$\frac{y_c}{y_b} = \frac{H_c}{H_b} \frac{\hat{y}_c}{\hat{y}_b}. \tag{10}$$

Combining all the previous equations gives

$$\frac{y_c}{y_b} = \frac{\theta_c}{\theta_b} \frac{\hat{y}_c(\hat{k}_b)}{\hat{y}_b(\hat{k}_b)} \frac{\hat{y}_c(\hat{k}_c)}{\hat{y}_c(\tilde{k}_b)} \left(\frac{\hat{y}_c(\tilde{k}_b)}{\hat{y}_c(\hat{k}_b)} \frac{H_c}{H_b} \right) \tag{11}$$

$$= EFF \times TECH^b \times KACC^c \times HACC^c. \tag{12}$$

and

$$\frac{y_c}{y_b} = \frac{\theta_c}{\theta_b} \frac{\hat{y}_c(\hat{k}_c)}{\hat{y}_b(\hat{k}_c)} \frac{\hat{y}_b(\tilde{k}_c)}{\hat{y}_b(\hat{k}_b)} \left(\frac{\hat{y}_b(\hat{k}_c)}{\hat{y}_b(\tilde{k}_c)} \frac{H_c}{H_b} \right) \tag{13}$$

$$= EFF \times TECH^c \times KACC^b \times HACC^b. \tag{14}$$

Equations (12) and (14) decompose productivity growth over the two periods b and c into the change in efficiency (EFF), i.e. shifts in the world production frontier; technological change ($TECH$), i.e. movements toward or away from the frontier; the change in the capital-labor ratio ($KACC$); and human capital accumulation ($HACC$), i.e. movements along the frontier.

These two decompositions do not yield the same results.[16] To overcome the path dependence of the decomposition, Kumar and Russell (2002) and Henderson and

[16] The two decompositions are equal only if the neutrality of technological change is assumed (as in Solow (1957) and in the many studies building on his pioneering article).

Russell (2005) have suggested adopting the Fisher Ideal decomposition introduced by Caves et al. (1982) and Fare et al. (1993). In particular, top and bottom of Equation (7) are multiplied by $\left(\hat{y}_b(\hat{k}_c)\hat{y}_b(\tilde{k}_c)\right)^{1/2}\left(\hat{y}_c(\hat{k}_b)\hat{y}_c(\tilde{k}_b)\right)^{1/2}$ which yields

$$\frac{y_c}{y_b} = EFF \times \left(TECH^b TECH^c\right)^{1/2} \times \left(KACC^b KACC^c\right)^{1/2} \times \left(HACC^b HACC^c\right)^{1/2} \tag{15}$$

$$= EFF \times TECH \times KACC \times HACC. \tag{16}$$

The productivity change can be decomposed into the efficiency change (EFF), the geometric averages (over the base and current periods) of technological change ($TECH$), the change in the capital-labor ratio ($KACC$), and human capital accumulation ($HACC$).

3 Application

To present my application, I first explain how the sector-level data is selected. Subsequently, I present the results of the empirical analysis.

3.1 Data

I use the data of output (Y), capital (K) and labor (L) from the OECD Detailed National Accounts database. Output is proxied by the Gross Added Value measured in millions of the current national currency. Capital is proxied by the Gross Capital Formation measured in millions of the current national currency. Output and capital are corrected by inflation and by purchasing power parity (PPP) to obtain comparable data. As such, output and capital are measured in constant PPP prices (I choose 1995 as reference year). Labor is measured in thousands of people employed. For human capital (H), I follow the construction of Hall and Jones (1999)

$$H_{jt} = e^{\phi(e_{jt})}. \tag{17}$$

where ϕ is a piecewise-linear function, with a zero intercept and a slope of 0.134 through the fourth year of education, 0.101 for the next 4 years, and 0.068 for education beyond the eighth year; and e_{jt} is the average number of years of education of the adult population in country j at time t given by Barro and Lee (2013).

I select 20 OECD countries: Austria, Belgium, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Korea, Luxembourg, the Netherlands, Norway, Poland, Slovakia, Slovenia, Spain, and Sweden. The time period is 1995-2008. The application can be seen as an analysis of the efficient frontier of the previous work of Kumar and Russell (2002), Henderson and Russell (2005), and Badunenko, Henderson and Russell (2013) analyzing the world.[17] Since I am interested in the decomposition of the growth of the output per labor, I analyze the more output-per-labor-intensive sectors: Mining, Manufacturing (which is also the most labor-intensive sector), Electricity, Gas and Water, Transport, Financial Intermediation, and Real Estate (which is also the most output-intensive sector).[18] See Table 1 for more details.

3.2 Results

This section is divided into three parts. In the first part, I present the results of the efficiency measures. Next, I give the quadripartite decomposition. Finally, I discuss the emergence of two groups in the OECD countries.

Multi-sector efficiency scores. I calculate efficiency for the endpoint years 1995 and 2008 using the benefit of the doubt procedure explained in Section 2.1.[19] The results are available in Table 2. The efficient countries in 1995 were: Belgium, Finland, France, Ireland, Italy, Korea, Luxembourg, the Netherlands, Norway, Slovenia, Spain, and Sweden. In 2008, they were: Italy, Luxembourg, and Sweden. The median is 1

[17]Färe et al. (1994) also analyze the OECD countries (from 1979 to 1988). The main difference with my analysis is that they ignore sector specificities.

[18]For the sake of completeness, I redid the computation exercise of Section 3.2 taking all the sectors into account. The quadripartite decomposition is very similar to what is obtained with the most output-per-labor-intensive sectors. For the efficiency scores, they are bigger than or equal to what was obtained previously. This is expected since taking more sectors puts more constraints on the country-level efficiency scores. More details can be found in Tables 6 and 7 in the Appendix, which must be compared to Tables 2 and 3.

[19]As explained in Section 2.1, the benefit of the doubt is the best case scenario, i.e. it evaluates the country in the best light by taking the upper bound of the sector-specific efficiency scores. I redo all the computations assuming the opposite, i.e. countries are evaluated by the lower bound of the sector-specific efficiency scores (the worst case scenario). The results are available in Table 8 and confirm the main conclusions: non-neutrality of technological change, the important roles of capital accumulation and technological change in the increase of output-labor productivity; and the emergence of two groups: eastern and central European countries; and EU15 and Korea.

Table 1: Relative shares of output, labor and output/labor (%)

Sector	Output	Labor	Output/Labor
Agriculture	2.41	5.71	2.52
Fishing	0.11	0.149	3.66
Mining	0.91	0.38	23.21
Manufacturing	19.81	18.81	5.23
Electricity, gas and water	2.17	0.78	15.50
Construction	6.04	7.29	3.95
Wholesale	11.30	15.01	3.76
Hotels and restaurants	2.75	4.60	2.73
Transport	6.80	5.98	5.59
Financial intermediation	5.01	2.85	9.03
Real estate	20.60	10.46	8.43
Public administration	6.65	6.84	4.52
Education	4.90	6.39	3.63
Health	6.37	8.22	3.35
Other community services	3.65	4.61	3.64
Private households	0.45	1.84	1.19
Total	100	100	100

in 1995 and 0.73 in 2008, which indicates a decrease of the level of efficiency between the two periods. Table 2 indicates that the biggest drops are in central and eastern European economies (due perhaps to disorganization and instability) and in Korea (probably due to the East Asian crisis). I also compute the lower and upper bounds for an error level of 10% (see Section 2.1 for more details).

Quadripartite decomposition. The decomposition per country is available in Table 3.[20] The median productivity change is 14.19%, which is attributed to efficiency change; i.e. shifts in the world production frontier (-19.86%); technical change, i.e. movements toward or away from the frontier (12.27%); capital accumulation (20.14%); and human capital accumulation (8.91%), i.e. movements along the frontier. The median efficiency change is negative, that of capital accumulation is positive and almost twice that of technological change. The median human capital accumulation is half that of capital accumulation. It implies that capital accumulation plays the biggest role in the increase of output-labor productivity, while technological change

[20]Percentages are obtained by subtracting 1 from the index and multiplying by 100. The contributions of individual components do not sum to the total productivity change.

Table 2: Efficiency scores in 1995 and 2008

	1995			2008		
Country	$MSTE$	$MSTE^L$	$MSTE^U$	$MSTE$	$MSTE^L$	$MSTE^U$
Austria	0.80	0.80	0.91	0.75	0.75	0.82
Belgium	1	0.98	1	0.79	0.70	0.89
Czech Republic	0.71	0.58	0.86	0.55	0.50	0.66
Denmark	0.74	0.67	0.87	0.74	0.67	0.82
Estonia	0.41	0.33	0.49	0.35	0.32	0.39
Finland	1	1	1	0.75	0.72	0.83
France	1	0.96	1	0.95	0.95	1
Germany	0.89	0.89	1	0.89	0.89	0.89
Hungary	0.67	0.61	0.75	0.67	0.61	0.75
Ireland	1	1	1	0.72	0.67	0.80
Italy	1	1	1	1	1	1
Korea	1	0.98	1	0.53	0.53	0.53
Luxembourg	1	1	1	1	0.93	1
Netherlands	1	1	1	0.71	0.64	0.79
Norway	1	0.95	1	0.71	0.63	0.79
Poland	0.90	0.74	1	0.69	0.57	0.85
Slovakia	0.69	0.57	0.85	0.53	0.43	0.65
Slovenia	1	0.90	1	0.57	0.52	0.70
Spain	1	1	1	0.82	0.82	0.82
Sweden	1	1	1	1	1	1
Median	1	0.95	1	0.73	0.67	0.82

and human capital accumulation play an important, if smaller, role.

The labor productivity growth of the Scandinavian economies (Denmark, Finland, Norway, and Sweden) and the Netherlands is higher, as explained by Scarpetta, Hemmings, Tressel, and Woo (2002), probably because of fewer labor market rigidities, which allows lower costs to adopt or develop a new technology. Fare, Grosskopf and Margaritis (2007) argue that the great performance of Ireland is due to the high-tech manufacturing sector. Luxembourg also performed very well because of a high capital-labor ratio. Korea has a high labor productivity growth because it has a high technological catch-up and capital accumulation; this stylized fact for Asian countries has already been found by Kim and Lau (1994) and Young (1995). Three central and eastern European economies (Austria, Estonia, and Slovakia) also have great growth performance, which could be due to successfully passed key economic and political reforms, while the others (the Czech Republic, Hungary, Poland, and Slovenia) performed poorly. The much weaker performance of the other OECD countries could be explained by two reasons. Firstly, changes in the composition of the economy and, secondly, as argued by Fare, Grosskopf and Margaritis (2006), the growth of the service sector, which seems to be less productive over time.

Table 3: Quadripartite decomposition

Country	Productivity change	EFF	TECH	KACC	HACC
Austria	18.51	-6.39	11.13	9.59	9.83
Belgium	2.68	-20.02	18.87	1.06	13.93
Czech Republic	-6.58	-22.50	14.98	-10.57	31.13
Denmark	24.14	-0.04	9.67	7.05	6.79
Estonia	33.15	-13.44	33.69	131.15	-45.13
Finland	27.92	-24.91	15.40	47.62	6.45
France	4.45	-4.80	2.49	7.92	9.77
Germany	7.27	0	-3.45	8.18	24.41
Hungary	-35.19	-0.04	0.26	27.64	-45.48
Ireland	27.56	-27.22	17.21	45.65	6.20
Italy	-1.82	0	0	-1.82	7.79
Korea	19.52	-46.25	73.68	47.07	-6.10
Luxembourg	20.47	0	0	20.47	3.88
Netherlands	26.81	-28.09	34.97	10.66	21.98
Norway	83.74	-28.76	23.56	84.38	25.97
Poland	-8.13	-22.88	16.68	77.59	-39.91
Slovakia	9.88	-22.88	3.82	19.82	18.01
Slovenia	-0.45	-42.28	-0.29	48.56	19.38
Spain	-9.26	-17.70	13.42	-9.76	24.27
Sweden	25.44	0	0	25.44	8.06
Median	14.19	-18.86	12.27	20.14	8.91

It is important to compare these results to what was found previously in the literature for the OECD. I compare my results to those of Henderson and Russell (2005), Badunenko, Henderson, Zelenyuk (2008), and Badunenko, Henderson and Russell (2013) for the OECD.[21] These papers compare countries of different continents, while I compare the OECD countries. Nevertheless, all these papers confirm my results:

[21]For the sake of completeness, I redid the computation exercise with my sample of countries and time period, considering the standard country-level methodology (i.e. without the multi-sector setting). For the productivity change, I obtain EFF, TECH, KACC and HACC: 14.65, -12.20, 15.67, 9.53 and 31.59 for the decomposition with human capital; and 20.61, -3.55, 5.13 and 19.19 for the decomposition without human capital. These results are in line with what was found previously (see Table 4).

capital accumulation and technological change have played an important role in the increase of output-labor productivity and human capital accumulation cannot be skipped since it also plays an important role. Moreover, as discussed previously, my application can be seen as an analysis of the efficient frontier in the previous work analyzing the world.

Table 4 gives the median for the quadripartite (tripartite for Badunenko, Henderson and Zelenyuk (2008)) decomposition for three previous papers for the OECD countries. Henderson and Russell (2005), who consider an earlier sample, also find that capital accumulation is the main driver, while technological change and human capital play a smaller role. Badunenko, Henderson and Zelenyuk (2008), who consider a period close to the period in this paper, find that efficiency change contributes negatively and that the main role is played by technological change. Finally, Badunenko, Henderson and Russell (2013), who consider a bigger sample, find that technological change contributes more significantly, while technological change and human capital accumulation are equal to approximately two-thirds of capital technological change.

Table 4: Median for the quadripartite decomposition

	Period	Productivity change	EFF	TECH	KACC	HACC
This paper	1995-2008	14.19	-18.86	12.27	20.14	8.91
HR	1965-1990	83.3	0.4	14.3	39.5	14.8
BHZ	1992-2000	20.25	-4.88	22.33	3.34	/
BHR	1965-2007	142.8	9.4	36.2	26.1	25.7

HR: Henderson and Russell (2005), BHZ: Badunenko, Henderson and Zelenyuk (2008), BHR: Badunenko, Henderson and Russell (2013).

Table 5 gives the median for the quadripartite decomposition for central and eastern Europe, EU12, EU15, and Korea. These numbers highlight the existence of two groups (central and eastern Europe and EU15+Korea). Central and eastern European countries have a negative productivity change over the period, while the others have a positive productivity change. This could be explained by the disorganization and the instability in central and eastern European countries. The negative change is due to a disaccumulation of human capital and a negative efficiency change. The accumulation of capital is bigger than in the EU12 and EU15 groups.

Technological change has the biggest contribution for the EU12, EU15 and Korea, but the proportions are very different. For the EU12 and EU15 groups, technological change increases by around 10%, while capital and human capital accumulation are around 9%. For Korea, technological change increases by around 75%, while capital is around 50% and human capital accumulation decreases by about 6%. These results are in line with those of Henderson and Russell (2005), Badunenko, Henderson and Zelenyuk (2008); and Badunenko, Henderson and Russell (2013).

Table 5: Quadripartite decomposition: median per group

Group	Productivity change	EFF	TECH	KACC	HACC
Central and eastern Europe	-3.52	-22.69	9.40	38.10	-10.95
EU12	12.89	-12.04	12.27	8.88	9.80
EU15	19.49	-5.59	10.40	8.88	8.91
Korea	19.52	-46.25	73.68	47.07	-6.10
OECD	14.19	-18.86	12.27	20.14	8.91

The emergence of two groups. The output and capital per efficiency unit of labor are plotted for the selected sectors in Figure 2.[22] Contrary to the standard production-frontier approach, the frontier cannot be seen on this graph since I do not assume monotonicity, convexity, and constant return-to-scales of the technology set (T_t), but monotonicity, convexity, and constant return-to-scales of the sector-specific technology sets (T_t^i) (se the discussion in Section 2.1). Clearly, two groups are present in the graph. The first group on the lower left has levels of output and capital similar in 1995 and 2008. It is composed of central and eastern European countries. The second group on the upper right has higher levels of output and capital in 2008 than in 1995. It is composed of the EU15 and Korea. The presence of two groups confirms the non-neutrality of technological change.[23] This result was found for the world by Kumar and Russell (2002), Henderson and Russell (2005), and Badunenko, Henderson and Russell (2013). The non-neutrality of technological change could be explained, as suggested by Allen (2012), by two reasons. On the one hand, almost no technological change occurs at low levels of capitalization and, on the other hand,

[22]The two-dimension representation, output and capital per efficiency unit of labor $\langle \hat{y}, \hat{k} \rangle$, contains the four variables since the constant returns-to-scale assumptions of the sector technologies and the modeling of human capital as a multiplicative augmentation of the physical labor input allow to move from a representation in four dimensions $\langle Y, K, L, H \rangle$ to one in two dimensions $\langle \hat{y}, \hat{k} \rangle$. See Section 2 for more details.

[23]Technological change would be Hicks neutral if the production frontier in $\langle \hat{y}, \hat{k} \rangle$ space shifted vertically by the same proportional factor; it would be Harrod neutral if it shifted radially by a constant proportional factor. Neither one of these two definitions of neutrality hold for the scatter plot drawn in Figure 2.

most innovation occurs in advanced economies with high levels of capitalization, and these innovations would be aimed at expanding the frontier at those high levels.

Figure 2: Output-capital graph

The previous results clearly indicate the existence of two groups, but the remaining question concerns convergence. Do the two groups converge or diverge? The distribution of output per worker in 1995 and 2008 is plotted in Figure 3. Two important observations can be made with this graph. Firstly, the distribution seems bimodal for the two years, but the two modes are more present in 2008 than in 1995. Secondly, the right tail seems bigger in 2008 than in 1995. These two facts speak in favor of a divergence of the two groups.

To confirm these two observations, I resort to the Silverman test and skewness. I use the test proposed by Silverman (1981) to formally test the existence of two modes in 1995 and 2008. The null hypothesis of the Silverman test is that a kernel distribution has n modes and the alternative hypothesis is that it has more than n modes. Using this test, I find that the 1995 distribution contains two modes (p-value = 0.001), but no more than three (p-value = 0.7518). Similarly, the 2008 distribution contains two modes (p-value = 0.001), but no more than three (p-value = 0.4464). Skewness is used to confirm the bigger right tail in 2008. The 1995 distribution has a Skewness of -0.0663, while the 2008 distribution has a Skewness of 0.0188. All these results confirm the previous observations.

Furthermore, one can expect that the two modes will increase with time. Different reasons could explain the divergence of the two groups: namely, the disorganization and the instability in central and eastern European countries compared to the EU15 and Korea. Also, central and eastern European countries have a greater decrease in efficiency and disaccumulate human capital (Table 4). The technical catch-up is similar to the EU15. The divergence between the two groups is compensated for by the greater physical capital accumulation of central and eastern European countries.

Figure 3: Distribution of output per worker in 1995 and 2008

Figure 4: Output growth against initial output level

Figure 4 plots the growth against the initial level of output per work. Clearly, the (significantly different from zero) positive slope speaks against a β-convergence, which confirms the conclusion of Figure 3. Indeed, β-convergence, which postulates that initially poorer countries will reach a more dynamic growth, is characterized by a negative slope in the regression growth against the initial level of output per work.

Figure 5 looks at which component of the quadripartite decomposition plays a role in the divergence of the two groups. The slopes (significantly different from zero, except for human capital) show that efficiency change plays a role in the convergence between the two groups, while technological change, capital accumulation, and human capital accumulation play a role in the divergence between the two groups.

Figure 5: Role of the quadripartite decomposition in the divergence of the two groups

4 Conclusion

In this paper, I have extended the dynamic production-frontier methodology proposed by Kumar and Russell (2002), Henderson and Russell (2005), and Badunenko, Henderson and Russell (2013) to analyze the economic growth and the convergence of growth rates across countries. The new multi-sector dynamic production-frontier methodology keeps the same features as previous work (i.e. no assumption on the technology, one efficiency score for each country, and a quadripartite decomposition of labor productivity growth), but has the added advantage of taking sector specificities into account (heterogeneity and interdependence). I also demonstrate the usefulness of the new multi-sector approach when some data (such as capital in my application) are not perfectly measured.

I apply this methodology to the OECD countries from 1995 to 2008. The results confirm the non-neutrality of technological change and highlight that capital accumulation plays the biggest role in the increase of output-labor productivity. Technological change and human capital accumulation also play an important, if smaller, role in the increase of output-labor productivity. Interestingly, the results suggest the emergence of two groups: eastern and central European countries; and EU15 and Korea. The two groups seem to diverge over time.

References

[1] Alfo M, Trovato G, Waldmann R, 2008, "Testing for country heterogeneity in growth models using a finite mixture approach", *Journal of Applied Econometrics* 23, 487-514.

[2] Allen R C, 2012, "Technology and the great divergence", *Explorations in Economic History* 49(1), 1-16.

[3] Badunenko O, Henderson D J, Russell R R, 2013, "Polarization of the worldwide distribution of productivity", *Journal of Productivity Analysis* 40, 153-171.

[4] Badunenko O, Henderson D J, Zelenyuk V, 2008, "Technological change and transition: relative contributions to worldwide growth during the 1990s", *Oxford Bulletin of Economics and Statistics* 70(4), 61-92.

[5] Banker R, Emrouznejad A, Lopes A L M, Rodrigues de Almeida M, 2014 "Data Envelopment Analysis in the public sector", *Socio-Economic Planning Sciences* 48(1), 1-104.

[6] Baumol W, 1986, "Productivity Growth, Convergence, and Welfare: What the Long-run Data Show", *American Economic Review* 76(5), 1072-1085.

[7] Barro R, 1991, "Economic growth in a cross section of countries", *Quarterly Journal of Economics* 106, 407-443..

[8] Barro R., Sala-i-Martin X, 1995, "Economic Growth", *McGraw-Hill*.

[9] Battisti M, Di Vaio G, 2008, "A spatially-filtered mixture of β-convergence regressions for EU regions", *Empirical Economics* 34(1), 105121.

[10] Bernard, A, Jones C, 1996, "Technology and Convergence", *Economic Journal* 106(6), 1037-1044.

[11] Brock W A , Durlauf S N, 2001, "Growth Empirics and Reality", *University of Wisconsin, Madison, Working Paper* 2024.

[12] Caves D W, Christensen L R, Diewert W E, 1982, "The Economic Theory of Index Numbers and the Measurement of Input, Output, and Productivity,", *Econometrica* 50, 1392-1414.

[13] Cherchye L., De Rock B., Dierynck B., Roodhooft F., Sabbe J., 2013, "Opening the Black Box of Efficiency Measurement: Input Allocation in Multi-Output Settings", *Operations Research* 61, 1148-1165.

[14] Cherchye L, De Rock, Estache A, Walheer B, 2014a, "Reducing Energy Use Without Affecting Economic Objectives: A Sectoral Analysis", in *The Next Generation of Economic Issues in Energy Policy in Europe*, CEPR Press.

[15] Cherchye L, De Rock, Walheer B, 2015a, "Multi-output efficiency with good and bad outputs", *European Journal of Operational Research* 240(3), 872-881.

[16] Cherchye L, De Rock, Walheer B, 2015b, "Multi-Output Profit Efficiency And Directional Distance Functions", *OMEGA* forthcoming.

[17] Cherchye L, Moesen, W, Rogge, N and Van Puyenbroeck, T, 2007, "An introduction to 'benefit of the doubt' composite indicators", *Social Indicators Research* 82, 111-145.

[18] Cook W D, Seiford L M, 2009, "Data Envelopment Analysis (DEA) - Thirty years on", *European Journal of Operational Research* 192, 1-17.

[19] Cooper W W, Seiford L M, Tone K, 2007, "Data Envelopment Analysis: A Comprehensive Text with Models, Applications, References and DEA-Solver Software, Second Edition", *Springer Edition.*

[20] Cooper W W, Seiford L M, Zhu, 2004, "Handbook on Data Envelopment Analysis, Second Edition", *Springer Edition.*

[21] Corrado L, Martin R, Weeks M, 2005, "Identifying and interpreting regional convergence clusters across Europe", *Economic Journal* 115, 133-160.

[22] Debreu G, 1951, "The Coefficient of Resource Utilization", *Econometrica* 19(3), 273-292.

[23] Despic O, Despic M, and Paradi J, 2007, "DEA-R: ratio-based comparative efficiency model, its mathematical relation to DEA and its use in applications", *Journal of Productivity Analysis* 28, 33-44.

[24] Diewert W, 1980, "Capital and the theory of productivity measurement.", *American Economic Review* 70(2), 260-267.

[25] Durlauf S, 1996, "On Convergence and Divergence of Growth Rates: An Introduction.", *Economic Journal* 106(6), 1016-1018.

[26] Emrouznejad A, Parker B R, Tavares G, 2008, "Evaluation of research in efficiency and productivity: A survey and analysis of the first 30 years of scholarly literature in DEA.", *Socio-Economic Planning Sciences,* 42(3), 151-157.

[27] Enflo K, Hjertstrand P, 2009, "Relative Sources of European Regional Productivity Convergence: A Bootstrap Frontier Approach", *Regional Studies* 43(5), 643-659.

[28] Fagerberg J, Verspagen B, 1996, "Heading for divergence? Regional growth in Europe reconsidered", *Journal of Common Market Studies* 34, 431-448.

[29] Färe R, Grosskopf S, Lovell C A K, 1985, "Measurement of Efficiency of Production", *Kluwer-Nijhoff Publishing.*

[30] Färe R, Grosskopf S, Lovell C A K, 1994, "Production Frontier", *Cambridge University Press.*

[31] Färe R, Grosskopf S, Norris M, Zhang Z 1994, "Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries", *American Economic Review* 84 (1), 66-83.

[32] Färe R, and Grosskopf S, 2000, "Network DEA", *Socio-Economic Planning Sciences* 34, 35-49.

[33] Färe R, Grosskopf S, Margaritis D, 2006, "Productivity Growth and Convergence in the European Union", *Journal of Productivity Analysis* 25(1), 111-141.

[34] Färe R, Grosskopf S, Margaritis D, 2007, "Productivity, convergence and policy: a study of OECD countries and industries", *Journal of Productivity Analysis* 28(1-2), 87-105.

[35] Färe R, Grosskopf S, Whittaker G, 2007, "Network DEA", *Modeling Data Irregularities and Structural Complexities in Data Envelopment Analysis, J. Zhu and W. Cook, Eds. Springer.*

[36] Farrell M, 1957, "The Measurement of Productive Efficiency", *Journal of the Royal Statistical Society* Series 1, General, 120, Part 3, 253-281.

[37] Feyrer J, 2003., "Convergence by parts", *Working paper, Dartmouth College.*

[38] Fried, H, Lovell C A K, Schmidt S, 2008, "The Measurement of Productive Efficiency and Productivity Change", *Oxford University Press.*

[39] Galor O, 1996, "Convergence? inferences from theoretical models", *Economic Journal* 106, 1056-1096.

[40] Gattou S, M. Oral M and Reisman A, 2004 "Data envelopment analysis literature: A bibliography update (1951-2001)", *Socio-Economic Planning Sciences,* 38, 159-229.

[41] Hall R, Jones C, 1999, "Why do some countries produce so much more output per worker than others", *Quarterly Journal of Economics* 114(1), 83-116.

[42] Henderson D J, Russell R R, 2005, "Human capital and convergence: a production-frontier approach", *International Economic Review* 46(4),1167-1205.

[43] Henderson D J, Parmeter C F, Russell, R R, 2008 , "Modes, weighted modes, and calibrated modes: Evidence of clustering using modality tests", *Journal of Applied Econometrics* 23, 607-638.

[44] Higgins J, Levy D, Young A T, 2006 "Growth and Convergence across the U.S.: Evidence from County-Level Data", *Review of Economics and Statistics* 88(4): 671681.

[45] Johnson P, 2005 "A continuous state space approach to convergence by parts. ", *Economics Letters* 86, 317-321.

[46] Jones C, 1997, "On the Evolution of theWorld Income Distribution.", *Journal of Economic Perspectives* 11(3),19-36.

[47] Kim J-I, Lau L J, 1994, "The sources of economic growth of the East Asian newly industrialized countries", *Journal of the Japanese and International Economies* 8, 235-271

[48] Kumar S, Russell R, 2002, "Technological change, technological catch-up, and capital deepening: relative contributions to growth and convergence.", *American Economic Review* 92(3), 527-548.

[49] Neven D, Gouyette C, 1995, "Regional convergence in the European Community", *Journal of Common Market Studies* 33, 47-65.

[50] Owen A, Videras J, Davis L, 2009, "Do all countries follow the same growth process?", *Journal of Economic Growth* 14(4), 265286.

[51] Paap R, Franses P H, Van Djik D, 2005, "Does Africa grow slower than Asia, Latin America and the Middle East? Evidence from a new data-based classification method", *Journal of Development Economics* 77(2), 553-570.

[52] Psacharopoulos G, 1994, "Returns to investment in education: a global update.", *World Dev* 22, 1325-1343.

[53] Quah D, 1993, "Galtons fallacy and tests of the convergence hypothesis", *Scandinavian Journal of Economics* 95(4), 427-443.

[54] Quah D, 1996, "Twin peaks: growth and convergence in models of distribution dynamics", *Economic Journal* 106(437), 1045-1055.

[55] Quah D, 1997, "Empirics for growth and distribution: stratification, polarization, and convergence clubs", *Journal of Economic Growth* 2(1), 27-59.

[56] Sala-i-Martin X, 1996, "The Classical Approach to Convergence Analysis", *Economic Journal* 106(6), 1019-1036.

[57] Salerian, J. and Chan C., 2005, "Restricting multiple-output multiple-input DEA models by disaggregating the output-input vector", *Journal of Productivity Analysis* 24, 5-29.

[58] Scarpetta S, Hemmings P, Tressel T, and Woo J, "The Role of Policy and Institutions for Productivity and Firm Dynamics: Evidence from Micro and Industry Data", *OECD Economics Department Working Papers* 329.

[59] Silverman B W, 1981, "Using Kernel Density Estimates to Investigate Multimodality", *Journal of the Royal Statistical Society* Series B 43, 97-99.

[60] Solow R, 1956, "A Contribution to the Theory of Economic Growth", *Quarterly Journal of Economics* 70(1), 65-94.

[61] Temple J, 1999, "The New Growth Evidence", *Journal of Economic Literature* 37(1), 112-156.

[62] Tondi G, 1999, "The changing pattern of regional convergence in Europe", *Jahrbuch fur Regionalwissenschaft* 19, 1-33.

[63] Young A, 1995, "The tyranny of numbers: confronting the statistical realities of the East Asian growth experience", *Quarterly Journal of Economics* 110(3), 641-680.

Appendix

Table 6: Efficiency scores in 1995 and 2008 with all sectors

	1995	2008
Country	*MSTE*	*MSTE*
Austria	1	0.87
Belgium	1	0.94
Czech Republic	0.71	0.55
Denmark	0.91	0.85
Estonia	0.41	0.35
Finland	1	0.88
France	1	1
Germany	0.89	0.89
Hungary	1	0.86
Ireland	1	1
Italy	1	1
Korea	1	1
Luxembourg	1	1
Netherlands	1	0.90
Norway	1	1
Poland	0.96	0.80
Slovakia	1	1
Slovenia	1	0.80
Spain	1	1
Sweden	1	1
Median	1	0.9173

Table 7: Quadripartite decomposition with all sectors

Country	Productivity change	EFF	TECH	KACC	HACC
Median	14.65	-3.10	2.97	10.07	12.26

Table 8: Quadripartite decomposition for the worst case scenario: median per group

Group	Productivity change	EFF	TECH	KACC	HACC
Central and eastern Europe	-3.52	-75.47	159.58	159.93	-37.28
EU12	12.89	-68.16	103.32	68.45	6.07
EU15	19.49	-66.47	122.06	53.35	6.07
Korea	19.52	-33.55	76.33	5.52	4.25
OECD	14.19	-67.81	131.34	76.74	4.96