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R&D, TECHNOLOGICAL PROGRESS AND EFFICIENCY CHANGE IN INDUSTRIAL ACTIVITIES

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The objective of this paper is to estimate total factor productivity growth (TFP) in an international and sectoral setting using two alternative approaches based on the estimation of parametric stochastic frontiers and non-parametric production frontiers (DEA). The TFP is decomposed into two components, technological progress and efficiency change, that can also be interpreted as the results of the innovation and catching-up process, respectively. Finally their relationship is tested with a set of potential explanatory variables that includes R&D expenditures, international competition, and structural characteristics. It appears that the distinction between technological and efficiency performances does matter and must be taken into account in the design of industrial policy.

1. INTRODUCTION

In economics, the link between R&D outlays and productivity growth is one of the most difficult to observe and measure. The important pieces of work of the past decades, particularly by Zvi Griliches, have contributed to the understanding of mechanisms relating R&D to productivity change, but failed to give a clear and unambiguous measure of the importance of this relationship.[1]

One of the reasons explaining this difficulty is certainly the complexity of this relationship. First, as it is well known, only a small part of scientific and industrial research projects lead to technological innovations in process or in products. Second, from a dynamic point of view, even if this relationship exists, it is difficult to establish its lag structure. Third, R&D and innovative activities induce many externalities resulting from the diffusion process as is emphasized in the main conclusions of the OECD Programme on Technology and Economy (OECD, 1991a).

Another reason that has received a great deal of attention is the definition and the measurement problems concerning the involved variables. First of all, the borderline between R&D activities and expenditures, on the one hand, and industrial production and costs, on the other hand, is not clearly defined and requires a permanent methodological update.[2] Second, when one tries to obtain representative measures of productivity growth, specific measurement problems appear associated with each variable concerned, as is generally the case for output, capital and labor inputs.

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[1]See for instance Griliches (1979) and Griliches and Lichtenberg (1984).

[2]See OECD (1991b) and Griliches (1994).

Aside from these two major reasons explaining the difficulty of testing the relationship between R&D and productivity growth, traditional studies neglect the distinction between the two main sources of productivity growth: *technological progress* and *efficiency change*, respectively.

In 1982 Nishimizu and Page proposed for the first time a methodology to decompose productivity growth into these two components using the framework developed by the *frontier analysis* approach. They demonstrated that firms improving their productivity, achieve productivity gains either from technological progress or from efficiency gains. Therefore, if we are able to estimate the contribution of each one of these two sources of productivity growth, we will be able to test the impact of R&D on them.

Moreover, this distinction will be important for policy orientation if, as expected, R&D efforts are better translated into technological innovations than in efficiency gains. It will be also important if we try to identify other factors, such as competitive environment, that are expected to have a greater influence on efficient behavior than on technological improvements.

Nishimizu and Page (1982) measure and decompose TFP using a parametric frontier approach and aggregated panel data for several regions and industrial sectors in the former Yugoslavia. More recently Fecher and Perelman (1989, 1992) used a similar approach for OECD countries and industrial activities. An alternative approach, based on the estimation of non-parametric frontiers and Malmquist indexes of productivity, was proposed by Färe *et al.* (1992), and applied to national aggregated data for OECD countries [Färe *et al.* (1994)]. In these papers the authors were able to identify the paths of technological progress and efficiency change, the former being interpreted as the frontier shift due to *innovation* and the second as the result of technological *catching-up*.[3]

In this paper we use the OECD International Sectorial Data Base (ISDB) covering the period 1970–87, in order to estimate and decompose the productivity growth rates realized by eleven countries in eight different industrial sectors.[4] In section 2, we present two alternative parametric and non-parametric approaches to estimate productivity growth and to decompose it into technological progress and efficiency change. In the third section these methodologies are applied to the data and the main results are presented. Finally, in section 4, we present a series of tests concerning the relationship between the alternative measures of productivity growth estimated in section 3 and some factors expected to influence them, particularly R&D outlays.

Besides the high correlation observed between the parametric and non-parametric results, our main conclusion will be that technological change appears as the greater source of growth in OECD industrial activities. Moreover, even if productivity growth appears to be not significatively correlated with R&D activities, technological change is positively and significatively affected by R&D. This result confirms the fact that technological progress is not immediately available nor applied by all firms in all countries and that, in general, it is accompanied by

[3]For a complete survey on the theoretical and empirical literature on innovation and catching-up issues at the international level, see Fagerberg (1994).

[4]For a description of this data base see Meyer-zu-Schlochtern (OECD, 1988).

losses of efficiency for those firms that didn't have easy access to new technologies. This conclusion is similar to that we obtained in previous work [Fecher and Perelman (1989, 1992)], dealing with a slightly different data base and an alternative parametric frontier approach.

2. PRODUCTION FRONTIERS AND PRODUCTIVITY GROWTH

When we try to identify the most important difference between traditional *index numbers* and frontier analysis in terms of productivity measurement, we come to the conclusion that the difference relies on one assumption: the existence of an unobservable function, the production frontier, corresponding to the set of maximum attainable output levels for a given combination of inputs.[5] We represent this so-called "best-practice" function $g[\cdot]$ as follows:

$$y^F(t) = g[x(t), t] \tag{1}$$

where $y^F(t)$ is the potential output level on the frontier at time t, and $x(t)$ is a vector of inputs. Note that function $g[\cdot]$ directly depends on time, indicating that some of the shifts in the production frontier may occur independently of changes in inputs. In the terminology of Solow (1957), the time variable t is assumed to catch *neutral technological progress* in production.

Then, for any observed output $y(t)$, using $x(t)$ for inputs, we can estimate the corresponding level of technical efficiency given by the distance output function:[6]

$$D_0^t[x(t), y(t)] = \frac{y(t)}{y^F(t)} \tag{2}$$

with $D_0^t[x(t), y(t)] = 1$ for technically efficient units, and $0 \leq D_0^t[x(t), y(t)] < 1$ for inefficient units.

Figure 1 illustrates for a one-output, one-input firm the estimation of such distance functions for two consecutive periods. Given the observed levels of production A and A' for periods t and $t+1$, respectively, technical inefficiency in the *output oriented side* is represented by the distance between the observed output and the frontier, that is the segment AQ for period t and the segment $A'R'$ for period $t+1$.

As can be seen in Figure 1, the observed firm radically improves its productivity between the two periods. In fact this change results from two different phenomena: on the one hand, the efficiency gain represented by the reduction in the distance function from the first to the second period ($PA/PQ < P'A'/P'R'$) and, on the other hand, the technological progress represented by the shift of the frontier function $g[\cdot]$ from period t to period $t+1$.

Two alternative approaches have been proposed to estimate productivity growth in this way.[7] The first one was proposed by Nishimizu and Page (1982) and is based on the estimation of a parametric frontier. The second one corresponds to

[5]The notion of "production frontier" is essentially due to Farell (1957) who was the first to give the scope of its applicability in empirical studies.

[6]See on this, Färe (1988).

[7]For a survey on these alternative approaches, see Grosskopf (1993).

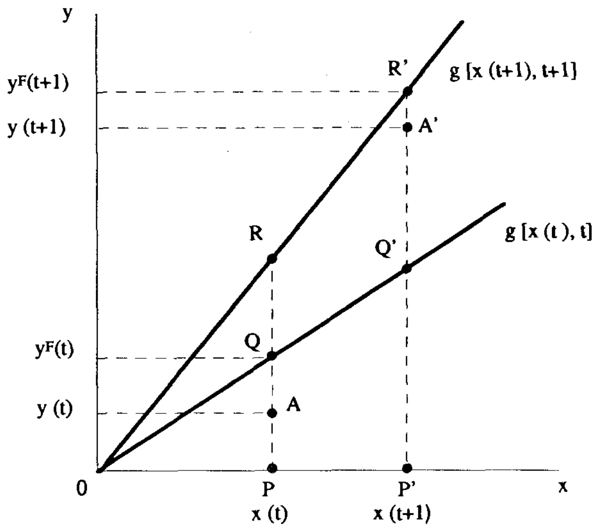

Figure 1. The Decomposition of Productivity Growth

the non-parametric case and was proposed by Färe *et al.* (1992). This approach relies on the estimation of Data Envelopment Analysis (DEA) frontiers by linear programming optimization.[8]

(a) *The parametric Approach*

For the parametric case we assume that the distance function (2) corresponds to:

(3) $$e^{u(t)}=\frac{y(t)}{y^F(t)},$$

where $t(t)\leq 0$ is the rate of technical efficiency.

Then, from equations (1) and (3), the observed output can be represented as:

(4) $$y(t)=g[x(t),\,t]\,e^{u(t)};$$

and the derivative of the logarithm[9] of equation (4) with respect to time is given by the following equation:

(5) $$\frac{\dot{y}(t)}{y(t)}=e_{g/x}\frac{\dot{x}(t)}{x(t)}+e_{g/t}+\dot{u}(t)$$

where $e_{g/x}$ and $e_{g/t}$ denote respectively the output elasticities of $g[x(t), t]$ with respect to $x(t)$ and t and dotted variables indicate time derivatives.

[8]For a methodological description of this approach, see Charnes, Cooper and Rhodes (1978) and Färe, Grosskopf and Lovell (1985).

[9]Note that parametric production frontiers are usually specified in logarithmic terms.

As indicated by equation (5), output changes can be decomposed into three components. The first one corresponds to input changes weighted by output elasticities (under constant returns to scale: $\sum e_{g/x}=1$), $e_{g/t}$ is the rate of technological progress corresponding to the shifts of the frontier and the last one, $\dot{u}(t)$, represents the technical efficiency change during period t.

Following Nishimizu and Page, we define the rate of total factor productivity change, TFP_p, as the variation in output not explained by input changes (the subscript p indicates the parametric approach). That is:

(6) $$\mathrm{TFP}_p(t)=\mathrm{TP}_p(t)+\mathrm{TEC}_p(t),$$

the sum of the rate of technological progress $[\mathrm{TC}_p(t)\equiv e_{g/t}]$ and of the rate of efficiency change $[\mathrm{TEC}_p(t)\equiv \dot{u}(t)]$.

(b) *The Non-parametric Approach*

For the non-parametric case the approach proposed by Färe *et al.* (1992) consists in estimating an *output based Malmquist productivity index* using distance functions derived from successive DEA frontiers.

Coming back to Figure 1, we assume now that both frontiers, $g[x(t), t]$ and $g[x(t+1), t+1]$, were estimated by DEA under the constant returns to scale hypothesis, then efficiency change can be defined as the product: $[P'A'/P'R \cdot PQ/PA]$, and technological progress as the geometrical mean of the frontier displacement measured at the observed inputs levels in periods t and $t+1$: $[PR/PQ \cdot P'R'/P'Q]^{1/2}$.

The Malmquist index of productivity change, M, is obtained as the product of these two components:

(7) $$M(t)=\left[\frac{P'A'}{P'R}\cdot\frac{PQ}{PA}\right]\cdot\left[\frac{PR}{PQ}\cdot\frac{P'R'}{P'Q}\right]^{1/2}.$$

And in terms of distance functions:[10]

(8) $$M(t)=\frac{D_0^{t+1}[x(t+1), y(t+1)]}{D_0^t[x(t), y(t)]}\cdot\left\{\frac{D_0^t[x(t+1), y(t+1)]}{D_0^{t+1}[x(t+1), y(t+1)]}\cdot\frac{D_0^t[x(t), y(t)]}{D_0^{t+1}[x(t), y(t)]}\right\}^{1/2},$$

where each distance function can be obtained from the estimation of non-parametric DEA frontiers for periods t and $t+1$. Note that in (8) some distance functions are estimated on the basis of different time periods frontiers and observations. This implies that in some cases these distances may take values greater than one.

Furthermore, in order to present the results in a form which allows comparison with the parametric results, we adopt a presentation of equation (8) in terms of rates of growth. That is:

(9) $$M(t)=[1+\mathrm{TP}_{np}(t)]\cdot[1+\mathrm{TEC}_{np}(t)]\equiv 1+\mathrm{TFP}_{np}(t),$$

where TFP_{np}, TP_{np} and TEC_{np} are, respectively, defined as the rates of total

[10]For more details and proofs, see Färe *et al.* (1992a, b).

productivity growth, technological progress and efficiency change under the non-parametric approach (indicated by the subscript *np*). Equation (9) can be rewritten as follows:

$$(10) \qquad \mathrm{TFP}_{np}(t) = \mathrm{TP}_{np}(t) + \mathrm{TEC}_{np}(t) + [\mathrm{TP}_{np}(t) \cdot \mathrm{TEC}_{np}(t)].$$

Comparing equation (10) to equation (6), we see that an additional term, the combination of both rates of growth, appears in equation (10) under the non-parametric approach. As we will later show the value of this term is in fact rather small for current rates of growth and may then be neglected in most cases.

In the next section we will use these two alternative approaches to estimate productivity growth in OECD industrial sectors. These results will also be compared with those obtained from the estimation of a traditional productivity index proposed by Meyer-zu-Schlochterm (1988) on a first issue of the ISDB data base. This index is defined as the net difference between the output growth rate and the sum of input growth rates weighted by their shares in total production. Following Meyer-zu-Schlochterm (1988) these shares are assumed to be constant and equal to 0.25 and 0.75, respectively, for labor and capital.

3. Data Description and Estimation

As indicated before, the data we use in this study is the OECD-ISDB data base which the basic information on output, labor and capital needed for the estimation of production frontiers. Output is defined as value added (GDP) at constant prices and in U.S. dollars corresponding to 1980 purchasing power parities.[11] This variable, like capital formation, is obtained on a national accounts basis and corresponds to sectoral aggregates in accordance with the International Standard Industrial Classification (ISIC). Labor is defined as total employment, including self-employment, and is measured by the number of individuals. Capital is estimated by means of a perpetual inventory model. The data source for the estimation of the capital stock is gross fixed capital formation, assumed to have service lives and scrapping rates specific to each sector and country.[12]

Table 1 gives a first view of the framework we choose for the analysis. There are eight manufacturing sectors. Among them, some sectors can be considered as traditional: 'food', 'wood' and 'textiles', and others can be identified as rather modern: 'machinery and equipment' or 'chemicals'. The countries were selected under the sole criteria of availability of data, this explains why three countries (Australia, Netherlands and Finland) also present in the ISDB data base were dropped in this study. Finally, we distinguish six periods of three years. In this respect two particular periods can be distinguished; they correspond to the two oil crises of 1973–75 and 1979–81.

In order to estimate production frontiers we consider each industrial sector separately. The production process is always represented by a one-output–two-inputs technology corresponding to GDP, total employment and capital stock,

[11]GDP is given in market prices. The rate of indirect taxes is also included in the ISDB database, but in many cases this information is missing. In previous work we estimated production frontiers with GDP net of indirect taxes, but with data coming from a first issue of the ISDB [Fecher and Perelman (1989, 1992)].

[12]See Meyer-zu-Schlochtern (1988) for more specific assumptions.

TABLE I

SCOPE OF THE STUDY

Industrial Sectors	Countries	Periods
Food, drink, and tobacco	Belgium	1970–72
Textiles	Canada	1873–75
Wood, cork, and furniture	Denmark	1976–78
Paper and printing	France	1979–81
Chemicals	Germany	1982–84
Nonmetallic mineral products	Italy	1985–87
Basic metal products	Japan	
Machinery and equipment	Norway	
	Sweden	
	U.K.	
	U.S.	

Source: OECD, International Sectoral Data Base (ISDB), Paris, 1991.

respectively. To obtain comparable results from the alternative parametric and non-parametric frontiers approaches we assume constant returns to scale (CRS) in both cases.

(a) *Stochastic frontier estimation*

The parametric frontiers we estimate are stochastic. Following Aigner, Lovell and Schmidt (1977) and Meeusen and Van den Broeck (1977) we rewrite equation (4) in the form:

$$y(i, t) = g[x(i, t), t]\, e^{\varepsilon(i,t)} \tag{4'}$$

where $\varepsilon(i, t) = \mu(i, t) + v(i, t)$ is a composed error term for country i and period t, combining a technical efficiency term, $\mu(i, t)$, assumed to be half-normally distributed with standard error σ_μ and a random term, $v(i, t)$ assumed to have the usual properties, that is, normal distribution, zero mean and standard error σ_v.

The specification of equation (4′) we adopt here is a log-linear (Cobb–Douglas) approximation. For each of the eight industrial sectors we estimate a frontier of the form:

$$\ln y(i, t) = \alpha + \sum_{k=1}^{2} \beta_k \ln x_k(i, t) + \gamma T + \mu(i, T) + v(i, t), \tag{11}$$

with $i = 1, \ldots, 11$ indicating the countries, $t = 1, \ldots, 18$, the years 1970 to 1987 and $T = 1, \ldots, 6$, the three-year periods 1970–72 to 1985–87; x_2 correspond to labor and capital inputs respectively and α, β_1, β_2 and γ are the parameters to be estimated. Note that β_1 and β_2 are the elasticities of output with respect to labor and capital respectively that are assumed to verify the CRS hypothesis, that is $\beta_1 + \beta_2 = 1$. Finally, the coefficient γ, associated with the trend variable, indicates the frontier shifts over time (periods) that are assumed to represent (neutral) technological progress in production.

Given the panel nature of the data, equation (11) will be estimated by a maximum likelihood technique particularly adapted for this case [see Battese and

Coelli (1988)]. The hypothesis we adopt is that technical efficiency is country and period specific $[\mu(i, T)]$, with periods defined as indicated before.[13]

Once equation (11) is estimated,[14] we will be able to estimate for each country and sector the corresponding rate of productivity growth as in equation (6), summing up the estimated rate of technological change within the sector ($\hat{\gamma}$) and the estimated rate of change in technical efficiency:

$$\text{TFP}_p(i, T) = \hat{\gamma} + \left[\frac{\hat{u}(i, T)}{\hat{u}(i, T-1)} - 1 \right], \tag{12}$$

where $\hat{u}(i, T) = e^{\hat{\mu}(i,T)}$ and $\hat{u}(i, T-1) = e^{\hat{u}(i,T-1)}$ are, respectively, the estimated rates of technical efficiency reached by country i in periods T and $T-1$.

(b) *DEA estimation*

Under the non-parametric approach we estimate one production frontier for each sector and each (three-year) period using the DEA approach. For these estimations we choose the Charnes, Cooper and Rhodes (1978) model that assumes constant returns to scale. The dual of the linear programming algorithm that allows the construction of these DEA frontiers and the estimation of the corresponding output-oriented measures of technical efficiency, $z(r, s)$, for country r at time s, are of the form:

$$\begin{aligned} &\min z(r, s) = \omega_1^T x_1(r, s) + \omega_2^T x_2(r, s), \\ &\text{s.t. } \omega_1^T x_1(i, t) + \omega_2^T x_2(i, t) - \theta^T y(i, t) \geq 0, \forall i, \forall t, \\ &\quad \theta^T y(r, s) = 1, \\ &\quad \omega_1^T, \omega_2^T, \theta' \geq 0, \end{aligned} \tag{13}$$

where ω_1^T, ω_2^T and θ^T are the variables to be estimated as the solution of the LP problem that has to be solved for each observation. More intuitively, the same problem can be presented in an output ratio form:[15]

$$\begin{aligned} &\min z(r, s) = \frac{\omega_1 x_1(r, s) + \omega_2 x_2(r, s)}{\theta y(r, s)}, \\ &\text{s.t. } \frac{\omega_1 x_1(i, t) + \omega_2 x_2(i, t)}{\theta y(i, t)} \geq 1, \forall i, \forall t, \\ &\quad \omega_1, \omega_2, \theta \geq 0. \end{aligned} \tag{14}$$

Technical efficiency for country r and year s is therefore calculated as the ratio between the weighted inputs and the weighted output, subject to the condition that for all the observations this ratio is equal or greater than one. Note that the main difference between this presentation and the LP model (13) lies in the fact that the last problem accepts an infinite number of solutions (any positive

[13]In a recent paper Battese and Coelli (1992) propose an alternative time-varying efficiency model in order to relax the assumption of technical efficiency constancy.

[14]In order to estimate the parametric frontier described by equation (10) we use the program FRONTIER developed by Coelli (1992).

[15]See Seiford and Thrall (1990)

transformation) for ω_1, ω_2 and θ, unless these variables were normalized as in the LP problem (ω_1^T, ω_2^T and θ^T) under the condition that $\theta^T y(r, s) = 1$.

Other than the distance functions $z(r, s)$, obtained from the estimation of these DEA frontiers, the estimation of the Malmquist index requires the estimation of other efficiency measures across-periods as indicated in equation (8). For instance, if we want to calculate the distance function for observations in period 2 with respect to the frontier estimated for period 1, we solve problem (13) for each observation of period 2 subject to the frontier built in period 1.

Finally, proceeding as indicated in equations (9) and (10) of section 2, we calculate for each country, within each industrial sector, the average growth of productivity by period, as well as its decomposition between technological progress and efficiency change. The results of these estimations are presented in Tables 2 to 6 together with those obtained from the alternative parametric and index numbers approaches.

(c) *The Main Results*

Reading Table 2 we observe a close concordance between the alternative approaches. Pooling together the results for all the industrial sectors, countries

TABLE 2

CORRELATION TABLES BETWEEN ALTERNATIVE INDICATORS OF TECHNICAL EFFICIENCY AND PRODUCTIVITY GROWTH

	Alternative Approaches		
	Non-parametric	Parametric	Index Numbers
Technical efficiency levels			
Non-parametric	1.0	0.925	
Parametric		1.0	
TFP growth			
Non-parametric	1.0	0.829	0.833
Parametric		1.0	0.943
Index numbers			1.0
Efficiency change			
Non-parametric	1.0	0.577	
Parametric		1.0	
Technological progress			
Non-parametric	1.0	0.146	
Parametric		1.0	

Note: Pearson correlation coefficiencts calculated on the basis of 415 (three-year) periodic observations. All the coefficients are significatively different from zero.

and periods, we remark that parametric and non-parametric frontier estimations lead to very similar technical efficiency scores: the correlation coefficient is equal to 0.925. It is a very satisfying result if we consider the number of methodological differences that distinguish them, even if we use the same variables and assume constant returns to scale in both cases.[16]

A similar conclusion can be drawn when we look at productivity growth rates. The alternative measures estimated by parametric and non-parametric frontier

[16]In Appendix (Table A.1), we reproduce the estimated parameters corresponding to the sectorial parametric frontiers.

approaches present a correlation coefficient of 0.829. Particularly high is the correlation between TFP changes estimated either by a simple index numbers technique or through the estimation of stochastic frontiers. In this case the correlation coefficient is 0.943.

As we turn to the results obtained by the decomposition of TFP growth into technological and efficiency changes, the comparison between the parametric and non-parametric approaches yields contradictory results. For efficiency change the correlation coefficient reaches 0.577, whereas for technological progress the correlation is 0.146. We know, by construction, that technological progress is differently specified and estimated under the parametric and the non-parametric approaches. In the first we assumed that, for each industrial sector, technological progress corresponds to a regular and general frontier shift, caught by a trend variable. On the contrary, in the non-parametric approach technological change can differ over time and across countries.

TABLE 3

MAIN INDICATORS OF PRODUCTIVITY GROWTH BY INDUSTRIAL SECTOR
Average growth rates by year (in %)

	Efficiency Change		Technological Change		TFP Growth		
Industrial Sector	Non-parametric $[TEC_{np}]$	Parametric $[TEC_p]$	Non-parametric $[TP_{np}]$	Parametric $[TP_p]$	Non-parametric $[TFP_{np}]$	Parametric $[TFP_p]$	Index Numbers
Food, drink, and tobacco	0.06	−2.01	0.46	4.04	0.52	2.03	1.10
Textiles	−0.23	−0.56	2.64	2.35	2.39	1.80	2.51
Wood, cork, and furniture	0.07	−0.03	1.22	1.95	1.29	1.92	1.36
Paper and printing	0.26	0.56	−0.01	0.60	0.25	1.15	0.95
Chemicals	−1.37	−0.85	3.70	2.74	2.05	1.89	2.86
Non-metallic mineral products	−0.02	0.02	0.31	0.91	0.27	0.93	1.31
Basic metal products	−1.57	−0.92	1.88	2.35	0.21	1.43	2.05
Machinery and equipment	0.38	0.60	1.89	1.77	2.24	2.36	3.50
All sectors	−0.14	−0.17	1.80	2.14	1.60	1.98	2.59

Note: Average values are weighted by GDP in 1980 prices and US$ PPP equivalences.

In Tables 3 to 5 we present the detailed results corresponding respectively to sectors, countries and periods. In each table the average growth rates per year were obtained as weighted means, using GDP as the weight variable. Note that as anticipated in section 2, equation (10), the decomposition of the non-parametric productivity growth score into the sum of technological and efficiency growth rates is not exact. However, in more than 415 cases analyzed, only 13 cases were the differences greater than 0.5 per cent and, within them, in only 4 cases greater than 1 percent.

General results are given at the bottom of Table 3. We remark that, on the average, both approaches present very similar results for the two components of productivity growth. The rates of change in technical efficiency appear as close to zero while technological progress approximates an average growth rate of 2 percent per year. These results accept different explanations and we will come back to them in the next section when we test the potential influence some selected factors may have on them. Nevertheless, let us note that they confirm the fact that technological progress appears as the main source of productivity growth among OECD industrial activities.

In the last columns of Table 3 we can observe that, on the average, Malmquist (non-parametric) indexes give lower estimations of TFP growth (1.60 percent by year), compared with the parametric results (1.98 percent), and the index number estimations (2.59 percent).

If we now examine the results by sector it appears that, except for the "food" sector in which we obtain very different results under the alternative approaches, all sectors present rather homogeneous figures: the highest rates of productivity growth are observed for the "chemical" and "machinery and equipment" sectors, and the lowest rates correspond to the "non-metallic mineral products" industry. As expected, the gains derived from innovation are the most important in the "chemical" industry (about 3.0 percent by year on average), but it is also one of the sectors in which the losses in technical efficiency are significant. Another result that merits emphasis is that obtained by a rather traditional sector: "textiles," essentially due to technological progress.

In Table 4 we present the same results by country. As expected, there are not great differences among them in terms of technological progress. By construction, we assume that all countries share the same technology. The main differences appear in the way each country takes advantage of this technology. Not surprisingly, Japanese industry shows the best rates of efficiency growth, followed by Belgium. On the other extreme we note the case of Norway, with efficiency losses greater than 1.5 percent per year.

TABLE 4

MAIN INDICATORS OF PRODUCTIVITY GROWTH BY COUNTRY

Average growth rates by year (in %)

	Efficiency Change		Technological Change		TFP Growth		
Country	Non-parametric $[TEC_{np}]$	Parametric $[TEC_p]$	Non-parametric $[TP_{np}]$	Parametric $[TP_p]$	Non-parametric $[TFP_{np}]$	Parametric $[TFP_p]$	Index Numbers
Belgium	0.79	0.97	1.37	2.33	2.14	3.30	3.89
Canada	−0.90	−0.79	2.14	2.08	1.13	1.29	1.49
Denmark	0.04	−0.59	0.97	2.27	0.98	1.68	1.86
France	−0.65	−0.76	2.07	2.23	1.31	1.47	1.93
Germany	−0.78	−1.16	1.12	2.20	0.27	1.04	1.45
Italy	0.36	0.16	2.87	2.12	3.15	2.28	3.09
Japan	1.18	1.64	0.58	2.19	1.72	3.82	5.05
Norway	−1.57	−1.51	1.88	2.09	0.23	0.58	0.91
Sweden	−0.40	−0.49	2.50	1.96	2.01	1.46	1.64
U.K.	−0.72	−1.05	2.06	2.24	1.29	1.19	1.68
U.S.	−0.34	−0.36	2.19	2.07	1.78	1.71	2.21
All countries	−0.14	−0.17	1.80	2.14	1.60	1.98	2.59

Note: Average values are weighted by GDP in 1980 prices and US$ PPP equivalences.

Finally, in Table 5 we present, once again, the same indicators but on an intertemporal basis. Particularly interesting are the results corresponding to the rates of productivity growth. As we can see in the last columns of this table, the results obtained under the three alternative approaches confirm a positive productivity growth path with rates higher than 2 percent in average for all the periods but the oil crisis of 1979–81. Another interesting fact to be noted is that for the period going from 1976–78 to 1979–81 the parametric and non-parametric approaches give a very different explanation of productivity decline. Under the parametric approach it is probably due to a loss in efficiency, while for the non-parametric approach it corresponds mainly to a stop in technological progress.

TABLE 5

MAIN INDICATORS OF PRODUCTIVITY GROWTH BY PERIOD
Average growth rates by year (in %)

	Efficiency Change		Technological Change		TFP Growth		
Period	Non-parametric $[TEC_{np}]$	Parametric $[TEC_{p}]$	Non-Parametric $[TP_{np}]$	Parametric $[TP_{p}]$	Non-parametric $[TFP_{np}]$	Parametric $[TFP_{p}]$	Index Numbers
1973–75/1970–72	−0.55	0.003	2.06	2.16	1.48	2.16	2.63
1976–78/1973–75	−0.71	−0.53	2.03	2.16	1.15	1.63	2.21
1979–81/1976–78	1.20	−0.81	−0.16	2.15	0.98	1.34	1.59
1982–84/1979–81	−1.28	−0.63	2.55	2.14	1.19	1.52	2.39
1985–87/1982–84	0.46	0.95	2.43	2.10	2.90	3.05	3.88
All periods	−0.14	−0.17	1.80	2.14	1.60	1.98	2.59

Note: Average values are weighted by GDP in 1980 prices and US$ PPP equivalences.

Another way to look at these results is to investigate the rates of technical efficiency reached by each country over time in the different sectors. Table 6 presents the results corresponding to the non-parametric case and for the two extreme periods. Remember that they are highly correlated with those obtained under the alternative parametric approach.

What we can learn from Table 6?

(i) The U.S. industries that appeared in the earlier 1970s as the most efficient in all sectors are still the best performers in six activities at the end of the period. The two exceptions are "chemicals" and "basic metals" industries. In the first case Japanese and British industries push the frontier up and in the second case Japanese alone.

(ii) Two other Japanese industries show spectacular efficiency improvements over the period: "paper" and "machinery." For the paper industry, Canada and Italy show similar paths as well as France in the "non-metallic" sector.

(iii) Surprisingly, most of the German and Scandinavian industries show rates of technical efficiency generally less than 70 percent. Furthermore, the lowest rates of efficiency are observed in both "chemicals" and "basic metals" sectors.

Summing up, even if some evidence of convergence in industrial activities appears over the 1970s and the 1980s, it was limited to a few sectors and countries. These results confirm that efficiency growth opportunities are substantial, even among the most industrialized countries. In the following section we try to identify some of the factors that may influence this evolution.

4. R&D AND OTHER DETERMINANTS OF PRODUCTIVITY GROWTH

The aim of this section is to test the relationship between productivity growth and some variables assumed to be potential explanatory factors of production

TABLE 6

TECHNICAL EFFICIENCY BY SECTOR AND COUNTRY
Non parametric approach (*DEA*)

Country	Period	Food	Textiles	Wood	Paper	Chemicals	Non-metallic	Basic Metal	Machinery
Belgium	1970–72	0.946	0.650	—	0.743	0.363	0.363	0.361	0.990
	1985–87	0.993	0.679	—	0.743	0.643	0.452	0.451	0.924
Canada	1970–72	0.798	0.798	0.933	0.732	0.620	0.893	0.921	0.837
	1985–87	0.669	0.896	0.984	0.911	0.326	0.793	0.532	0.769
Denmark	1970–72	0.445	0.495	0.458	0.658	0.330	0.510	0.626	0.577
	1985–87	0.601	0.596	0.489	0.610	0.380	0.450	0.426	0.471
France	1970–72	0.657	0.906	0.598	0.855	0.746	0.643	0.412	0.587
	1985–87	0.654	0.844	0.703	0.731	0.522	0.949	0.366	0.531
Germany	1970–72	0.670	0.757	0.694	0.657	0.665	0.642	0.670	0.734
	1985–87	0.669	0.695	0.544	0.633	0.559	0.607	0.643	0.625
Italy	1970–72	0.630	0.913	—	0.714	0.491	0.700	0.749	0.656
	1985–87	0.795	0.890	—	0.931	0.517	0.773	0.454	0.652
Japan	1970–72	0.986	0.595	—	0.770	0.928	0.990	0.974	0.740
	1985–87	0.899	0.529	—	0.929	0.891	0.753	0.960	0.980
Norway	1970–72	0.320	0.745	0.697	0.490	0.350	—	0.579	0.745
	1985–87	0.250	0.637	0.658	0.526	0.286	—	0.482	0.468
Sweden	1970–72	0.557	0.842	0.789	0.528	0.464	0.600	0.297	0.529
	1985–87	0.503	0.679	0.813	0.650	0.374	0.632	0.280	0.466
U.K.	1970–72	0.873	0.702	—	0.965	0.989	0.740	0.367	0.534
	1985–87	0.911	0.644	—	0.787	0.961	0.715	0.292	0.438
U.S.	1970–72	0.965	0.971	0.947	0.968	0.946	0.961	0.975	0.965
	1985–87	0.984	0.968	0.975	0.997	0.656	0.979	0.571	0.988

Note: The — indicate missing data.
Average values are weighted by GDP in 1980 prices and US$ PPP equivalences.

improvement. Among them, R&D activities will especially retain our attention. As explained in the introduction, we expect that once we have succeeded in decomposing productivity growth into technology change (innovation) and technical efficiency changes (catching up), we will be able to identify the way in which R&D efforts (i.e.) reflect each one of these main sources of growth.

We shall not be exhaustive in the explanation of productivity growth for two main reasons. On the one hand, the complexity of the relationships that we test and particularly those leading the process of innovation and, on the other hand, the availability of data that considerably limits the scope of the analysis.

In Table 7 we present the results obtained by weighted OLS regressions performed on the whole sample. The dependent variables are the indicators of growth estimated and presented in section 3.

Besides R&D that is represented here by the ratios of lagged research and development spending[17] to total output $[(\mathrm{R\&D/GDP})_{T-1}]$, we introduce four variables that are expected to influence, either innovation or the catching-up process, or both of them. To identify these explanatory factors, we heavily borrow from Caves and Barton (1990) and Fecher and Perelman (1992).

The first variable is the lagged level of technical efficiency $[\mathrm{TEC}_{T-1}]$ estimated as indicated in section 3. This variable is assumed to represent the dynamics of the *catching-up process*. As is known, a crucial source of growth in productivity is obtained by imitation—applying existing knowledge. In the framework of our analysis that effect, if it exists, will be translated into a source of efficiency improvements towards the frontier. This means that countries which showed a low level of efficiency in the previous period are those that can most increase their productivity in the following one.

The second variable is a proxy for international competitive conditions. In the absence of reliable and complete data on effective protection, we calculate for each sector and country an indicator of international trade given by the rate of total imports (M) and exports (X) with respect to the total value of production (TPV), augmented of imports. This variable[18] is introduced, like R&D, with a lag of one period $[((X+M)/\mathrm{TPV}+M)_{T-1}]$.

The openness of the economy is expected to be a factor that improves productivity. The industrial sectors more exposed to external competition are at the same time stimulated to innovate and to be productively efficient. Furthermore, international trade may be also an indirect source of growth if traded goods are a mean of R&D diffusion[19].

The third variable is the rate of growth of capital formation that is represented by the change in the ratio of new investments to capital $[(\dot{I}/K)_T]$. This variable may affect productivity growth in different manners.[20] If new technology is embodied in new vintages of capital, an increase in capital formation can speed

[17]Historical statistics on research and experimental development activities in OECD member countries are collected every two years through international surveys and stored in the OECD Science and Technological Databank. Missing information for intermediate years was replaced by interpolated ones.

[18]Annual data on imports, exports and total production values come from the OECD Compatible Trade and Production Data Base (COMTAP).

[19]On technological spillovers, see i.e. Griliches (1992).

[20]Data on investments also come from the ISDB data base.

TABLE 7

THE DETERMINANTS OF PRODUCTIVITY GROWTH
Weighted OLS regressions

	Efficiency Change		Technological Change		TFP Growth		
Expanatory Variables	Non-parametric [TEC_{np}]	Parametric [TEC_p]	Non-parametric [TP_{np}]	Parametric [TP_p]	Non-parametric [TFP_{np}]	Parametric [TFP_p]	Index Numbers
Constant	4.03*	−0.600	0.019	2.19*	−0.845	3.17*	−0.001
	(3.6)	(0.6)	(0.04)	(19.2)	(0.8)	(4.4)	(0.004)
R&D $\left(\frac{R\&D}{GDP}\right)_{T-1}$	−0.300*	−0.267*	0.457*	0.061*	0.156*	−0.049	0.100
	(4.8)	(4.2)	(6.0)	(3.0)	(2.7)	(1.0)	(1.9)
Catching-up $(TEC)_{T-1}$	−4.76*	−0.085	—	—	0.196	−2.87	—
	(5.8)	(0.09)	—	—	(0.2)	(4.0)	—
Trade $\left(\frac{X+M}{TPV+M}\right)_{T-1}$	−0.026*	−0.004	0.021*	−0.004	0.018	−0.012	0.016*
	(2.9)	(0.4)	(2.3)	(1.5)	(2.1)	(1.9)	(2.4)
Capital $(I/K)_T$	0.102*	0.100*	−0.052*	−0.010	0.052*	0.039*	0.009
formation	(5.8)	(5.5)	(2.4)	(1.7)	(3.2)	(3.0)	(0.6)
Output $(GDP)_{T-1}$	0.350*	0.351*	−0.009	−0.028*	0.350*	0.396*	0.482*
growth	(11.1)	(10.8)	(0.2)	(2.7)	(11.9)	(16.6)	(17.6)
R^2	0.365	0.329	0.118	0.064	0.318	0.467	0.472
n	356	356	356	356	356	356	356

Note: t-statistics are indicated in brackets.
Average values are weighted by GDP in 1980 prices and US$ PPP equivalences, t-tests are given into brackets.
[1]All the variables are expressed in average values by (three-years) periods indicated by the suffix p. For the definition and sources, see the core of the text.
*Indicates that the coefficient is statistically significant at the 1 percent level.

up the rate of introduction of a new technology and then positively affect technological progress and efficiency change. However, they can also have a negative effect if, as has been the case in the past years, a part of these new investments have been made to comply with safety and environmental regulations.

The last variable is the lagged rate of grwoth in output [$\dot{GDP}_{T-1}$]. This variable is assumed to represent the exogeneous growth of demand. The expected interaction between this variable and the rate of productivity growth is known as the Kaldor–Verdoom relationship.[21] The expansion of the market can be seen as the start of a cumulative process in which new products will be created and new production processes will be applied. In this case, the effect of the output growth variable is expected to be positive on both the technological and the efficiency components of productivity growth.

The results presented in Table 7 are mainly those expected:

(i) First, even if R&D activities do not have an unambiguous effect on TFP growth evaluated by the three alternative approaches, it appears to be a crucial factor in favor of the innovation process, particularly under the non-parametric frontier approach. On the contrary, its effect on efficiency change is negative and significant in both models. This result can be explained by the fact that when R&D results in a positive shift of the frontier, at the same time it is the source of efficiency losses for those countries and sectors that are not able to follow this path.

(ii) Second, the catching-up factor presents the expected sign but, paradoxically, for the non-parametric case the effect on efficiency change is not present on TFP growth and the inverse result is obtained for the parametric case.

(iii) Concerning competitive conditions represented by international trade, we obtain contradictory but not significant effects.[22]

(iv) Finally, for the two variables representing the capital formation and the Kaldor–Verdoon relationship we derive, in both cases, positive and significant coefficients on technical efficiency changes and TFP growth indicating that new investments and exogeneous demand have a crucial role on the catching-up process.

5. Conclusions

In this paper we have estimated total productivity growth for eleven OECD countries and eight industrial sectors over the period 1970–87 using two alternative, parametric and non-parametric, frontier approaches. The results obtained from the estimation of stochastic and DEA frontiers were highly correlated and showed that technological change was the main source of growth within the panel, even if some expected discrepancies appeared between the two approaches when analysing the detailed results by country, sector or period.

[21]On the Kaldor–Verdoon relationship, see Dosi (1984) and Boyer and Petit (1991).

[22]A similar result was obtained in Fecher and Perelman (1992) testing with an alternative variable representing the degree of protection.

It also appeared clearly that the sectors that experienced the most important technology progress are "chemicals" and "textiles" and that which showed the greater losses in efficiency is the "basic metal products" sector. Within countries, Japan and to a lesser extent Belgium, appeared as those that realized the best results in efficiency terms. These results can be interpreted, without doubt, as a catching-up process. In terms of productivity growth, the best period is 1985–87 and the worst 1979–81.

The last step of our study tested the impact of different potential explanatory variables on productivity growth and its components. It appeared clearly that R&D outlays have a positive and significant influence on technological change and that, in addition, other variables that represent the dynamics of investments and the exogeneous demand seem to have a positive effect on efficiency gains, that is on the catching-up process.

These results are certainly partial and must be seen as provisional. The availability of new and more complete data, especially on the market structures, will allow us to improve them in the future. Nevertheless, they illustrate the interest and the possibilities offered by the frontier analysis approach to the identification of the two sources of growth which are technological progress and efficiency change.

APPENDIX

TABLE A.1

PARAMETRIC FRONTIER ESTIMATORS

Industrial Sector	Constant $\hat{\alpha}$	Labor Elasticity[1] $\hat{\beta}_1$	Technological Progress[2] $\hat{\gamma}$	Share of Inefficiency Variance $\hat{\sigma}^2_\mu/\hat{\sigma}^2_{\mu+v}$	Number of Observations
Food, drink, and tobacco	10.3	−0.028	0.126	0.200	198
	(0.99)	(0.316)	(0.918)	(0.230)	
Textiles	5.61*	0.380*	0.072*	0.185*	198
	(0.59)	(0.053)	(0.010)	(0.035)	
Wood, cork, and furnitures	9.70*	0.007	0.060*	0.170*	126
	(0.64)	(0.065)	(0.012)	(0.040)	
Paper and printing	8.33*	0.178*	0.018	0.225*	198
	(0.60)	(0.057)	(0.010)	(0.023)	
Chemicals	4.76*	0.505*	0.084*	0.508*	198
	(0.32)	(0.032)	(0.017)	(0.050)	
Nonmetallic mineral products	6.61*	0.325*	0.028*	0.259*	180
	(0.77)	(0.071)	(0.011)	(0.050)	
Basic metal products	2.14	0.737*	0.072*	0.721*	198
	(1.31)	(0.118)	(0.026)	(0.124)	
Machinery and equipment	5.28*	0.461*	0.054*	0.218*	198
	(0.48)	(0.047)	(0.010)	(0.023)	

Note: The estimation were performed under the maximum likelihood approach proposed by Battese and Coelli (1988) using the FRONTIER program developed by Coelli (1992). In all the cases the efficiency term is assumed to follow a half-normal distribution.

[1]Estimated under the CRS assumption: $\hat{\beta}_1 + \hat{\beta}_2 = 1$.

[2]The trend variable is represented by six (three-years) periods.

Standard errors are given in brackets. *indicates that the coefficient is statistically significant at the 1% level (*t*-test).

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