TECHNOLOGICAL CHANGE, EFFICIENCY GAINS AND CAPITAL ACCUMULATION IN LABOUR PRODUCTIVITY GROWTH AND CONVERGENCE: AN APPLICATION TO THE SPANISH REGIONS

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INDEX

ABSTRACT

The main objective of this paper is to analyse labour productivity growth and convergence in the Spanish regions between 1965 and 1995, decomposing total factor productivity (TFP) gains into technological progress and efficiency change by means of Malmquist productivity indices. On the basis of this decomposition, labour productivity growth is broken down into components attributable to technological change (shifts in the frontier), efficiency gains (movements toward the frontier) and capital accumulation (movements along the frontier). The approach followed in this study is based on work initiated by Färe *et al*. (1994), where a link between the economic growth and convergence literature and the production frontier approach was established. Furthermore, in the spirit of Quah's approach, the evolution of the whole distribution is considered. Thus, the analysis of the dynamics of the entire distribution of labour productivity and the factors behind it -technological progress, efficiency gains and capital accumulation- combine both approaches, yielding new insights into the process of productivity growth and convergence experienced by the Spanish regions over the last thirty years.

JEL classification: D24, O30, O47.

Key words: Total Factor Productivity, labour productivity growth and convergence.

I. INTRODUCTION

According to neoclassical growth theory, diminishing returns to accumulable factors constrain the possibilities of growth of an economy, pointing to exogenous technical progress as the source of long-run growth. At the same time, decreasing returns on capital appear to be driving force towards convergence since poorer economies experience higher returns on investment and consequently higher growth rates. On the other hand, endogenous growth theory provides a new perspective on the factors behind technology, and attribute differences in technology with being one of the sources of persistent differences between economies. Empirical research on economic growth has gained in interest in recent years and points to total factor productivity (TFP) growth as the main source of economic growth since factor accumulation alone can not explain the growth differences between economies.

In most empirical work, however, it is assumed that all units of production are efficient, so that TFP growth is identified with technological change. The possibility that part of this growth may have its origin in efficiency gains is therefore neglected, and biased estimates of technological progress will be obtained in the presence of inefficiencies (Grosskopf, 1993). In order to avoid such a bias, it becomes necessary to estimate a production frontier that shows the maximum technically attainable level of production. Inefficient behaviour could be measured by the difference between the actual level of production and the maximum possible level defined by the frontier. This in turn would allow us to decompose TFP growth into technological progress (shifts in the production frontier) and changes in efficiency (movements toward or away from the frontier).

Some recent studies have focused on the decomposition of TFP growth into efficiency change and technological progress, analysing their contribution to economic growth and, to a lesser extent, to economic convergence. In this sense, the results obtained by Färe *et al*. (1994), Perelman (1995), Taskin and Zaim (1997) and Maudos *et al*. (1999) for the OECD countries, or those of Beeson and Husted (1989), Domazlicky and Weber (1997) or Boisso *et al*. (2000) for the US, show the importance of taking into account the existence of inefficiencies. In the case of Spain, Gumbau and Maudos (1996), Maudos *et al.* (1998, 2000) and Gumbau (2000) find substantial differences in efficiency, both by regions and by sectors, and confirm the necessity of considering efficiency gains as a source of productivity growth.

In the context of this literature, we here analyse the productivity growth of the Spanish regions between 1965 and 1995, decomposing TFP gains into technological progress and efficiency change by means of Malmquist productivity indices. On the basis of this decomposition, labour productivity growth may be

broken down into components attributable to technological change (shifts in the frontier), efficiency gains (movements toward the frontier) and capital accumulation (movements along the frontier). This analysis is carried out at the aggregate level and for the main sectors of private activity.

Once the components of labour productivity growth have been analysed, we shall center on their relative contributions to convergence. A first approach to analysing convergence is based on the commonly used concept of β-convergence (introduced by Barro and Sala-i-Martin, 1992). However, following Quah's (1993, 1997) suggestion, the dynamics of the overall distribution is also analysed, both for the distribution of labour productivity and for each of its components.

Thus, the approach followed in this study is based on the work initiated by Färe *et al.* (1994), where a link between the economic growth and convergence literature, on the one hand, and the production frontier approach, on the other, was established. Furthermore, in the spirit of Quah's approach, the evolution of the whole distribution is considered. Consequently, the analysis of the dynamics of the entire distribution of labour productivity and the factors behind it - technological progress, efficiency gains and capital accumulation- combine both approaches, yielding new insights into the process of productivity growth and convergence experienced by the Spanish regions over the last thirty years.

The structure of the paper is as follows. Section II describes the approach followed to construct the production frontier and to break down labour productivity growth into technological progress, efficiency change and capital accumulation. The data and results for efficiency levels and labour productivity decomposition are presented in Section III. On the basis of these results, Section IV centres on the contribution of these factors to regional convergence, analysing the evolution of the entire distribution of productivity in terms of this decomposition. Finally, Section V presents the main conclusions.

2. A NON-PARAMETRIC APPROACH TO DECOMPOSING LABOUR PRODUCTIVITY GROWTH

In order to consider inefficient behaviour when studying productivity growth, we estimate a best practice frontier and the associated efficiency levels of individual regions (i.e. the distance of each region from the frontier). Measures of relative performance to this frontier are calculated by means of Malmquist productivity indices, which may be decomposed into technological progress and efficiency change[1]. Once the productivity indices have been estimated, we de-

[1] Malmquist productivity indices and their decomposition are presented in Appendix 1.

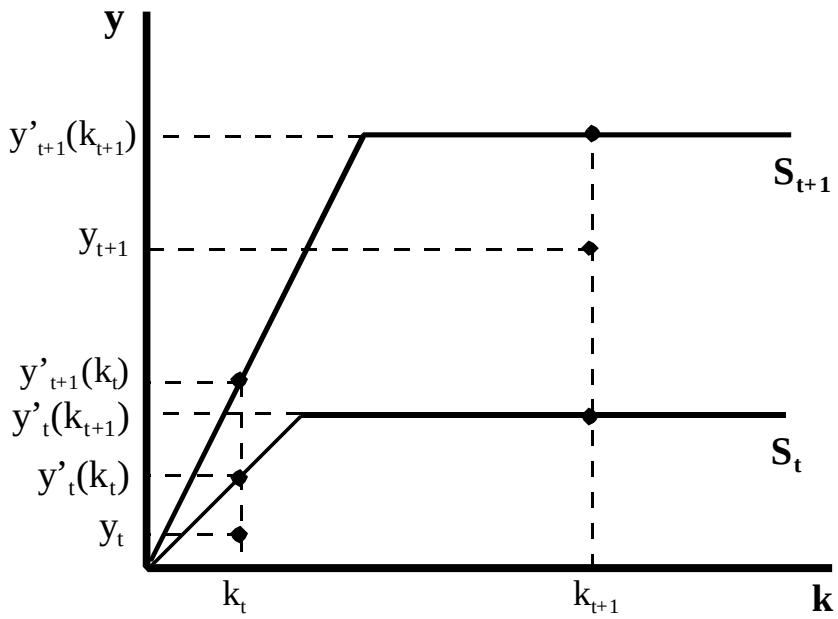
compose labour productivity growth into technological change (shifts in the production frontier), efficiency gains (movements toward the frontier) and capital accumulation (movements along the frontier).

In the case where only one output (Y) and two inputs, capital (K) and labour (L), are considered, the benchmark technology may be represented in the $\{k,y\}$-space, where $k = K/L$ and $y = Y/L$. Simple hypothetical technologies (S_t and S_{t+1}) are shown in Figure 1. The pairs (k_t, y_t) and (k_{t+1}, y_{t+1}) represent observed values while the potential output for this hypothetical economy in period t and $t+1$ is, by construction, $y'_t(k_t) = y_t / e_t$ and $y'_{t+1}(k_{t+1}) = y_{t+1} / e_{t+1}$, where e_t and e_{t+1} are the efficiency indices for the two periods. Therefore, the relative change in the output/labour ratio between these two periods is given by:

$$\frac{y_{t+1}}{y_t} = \frac{e_{t+1}}{e_t} \cdot \frac{y'_{t+1}(k_{t+1})}{y'_t(k_t)} \qquad (1)$$

Whereas the first factor in this expression (e_{t+1}/e_t) reflects the change in efficiency (change in the distance from the frontier), the second factor represents the shift in the frontier (technological change) and the effect of the change in the capital/labour ratio (movement along the frontier). Technological change can be measured by the shift in the frontier at period $t+1$, $y'_{t+1}(k_{t+1})/y'_t(k_{t+1})$, whereas capital accumulation would be measured along the period t frontier, $y'_t(k_{t+1})/y'_t(k_t)$. Alternatively, we could measure technological change relative to period t $y'_{t+1}(k_t)/y'_t(k_t)$, and capital accumulation as movements along the period $t+1$ frontier $y'_{t+1}(k_{t+1})/y'_{t+1}(k_t)$.

Figure 1



Since technological change and capital accumulation may be path dependent[2], which technology is used for normalization may condition the results of this decomposition. In order to avoid arbitrariness in the choice of the benchmark technology, the approach that we follow to measure technological change and capital accumulation is based on the geometric means of these changes relative to period t and $t+1$ technologies. Hence, multiplying the top and bottom of expression (1) by $[y'_t(k_{t+1}) \cdot y'_{t+1}(k_t)]^{1/2}$, we obtain the following identity:

$$\frac{y_{t+1}}{y_t} = \frac{e_{t+1}}{e_t} \cdot \left[\frac{y'_{t+1}(k_{t+1})}{y'_t(k_{t+1})} \cdot \frac{y'_{t+1}(k_t)}{y'_t(k_t)} \right]^{1/2} \cdot \left[\frac{y'_t(k_{t+1})}{y'_t(k_t)} \cdot \frac{y'_{t+1}(k_{t+1})}{y'_{t+1}(k_t)} \right]^{1/2}$$

$$= EC \cdot TC \cdot CA \qquad (2)$$

This shows how a relative change in the output/labour ratio is decomposed into efficiency change (EC), technological change (TC) and capital accumulation (CA).

3. DATA AND RESULTS

The sample used in this study refers to the Spanish regions (Autonomous Communities), and covers the period 1965-1995. In each case, we consider one output (Gross Value Added at factor cost) and two inputs (private capital and labour). Data on GVA and employment was obtained from "*La renta nacional de España y su distribución provincial. Serie homogénea 1955 a 1993 y avances 1995 a 1997*", published by the Banco Bilbao-Vizcaya (BBV) in 1999, which supplies biennial information on these variables. The stock of (non-residential) private capital is obtained from the estimate by the Instituto Valenciano de Investigaciones Económicas (IVIE) and published by the BBV/IVIE Foundation -Mas *et al*. (1999): "*El stock de capital en España y su distribución territorial*". The BBV source provides information on GVA in 1986 pesetas for four sectors: agriculture, industry, construction and services. Deflators provided by this source allow the energy sector to be excluded from the industrial sector. Moreover, the public services sector is also excluded from the services sector. In both cases, the available data runs up to 1993. Thus, separate frontier production functions were estimated for the economy as a whole and for the agriculture, industry (excluding energy), construction and private services sectors.

The average efficiency levels estimated for the Spanish regions in the period 1965-1995 are given in Table 1. The average level of efficiency of the Spanish regions was around 81% between 1965 and 1995. Nevertheless, there are significant differences between both sectors and regions. For the aggregate of the economy, regions such as Madrid, the Basque Country or Catalonia, with efficiency levels above 90%, coexist

[2] Only if technological change is Hicks neutral will the proportional vertical shift in the frontier be independent of the capital/labour ratio.

with such other regions as Andalusia, Cantabria, Castilla y León, Galicia, Murcia, Castilla la Mancha and Extremadura, where efficiency levels do not reach 75%.

The agriculture sector presents the lowest results and the most variable evolution in terms of efficiency. In turn, the construction sector shows stable levels of efficiency –around 90%– over the whole period. Few differences between regions are observed in the latter sector, where the most inefficient region in 1995 (Extremadura) shows a level of efficiency of 80%. The most favourable evolution was observed in industry, where initial levels of inefficiency of around 20% were reduced to 6% in 1993, with this sector being the most efficient at the beginning of the nineties. This positive evolution in the industrial sector is common to all the regions, and it is noteworthy that at the end of the period all the regions present efficiency levels greater than 85%, reflecting the significant efficiency gains experienced by such regions as Murcia, Galicia, Andalusia, Extremadura, Castilla la Mancha and the Canaries, where efficiency levels were below 75% in 1965. Finally, the average level of efficiency in the services sector stayed in the range 80-85% over those thirty years. However, there were significant differences between regions in this sector, whith regions such as Madrid, Catalonia and the Canaries coming close to the frontier (Madrid was on the frontier throughout the period) whereas Castilla la Mancha, Castilla León, Extremadura and Galicia present efficiency levels of around 70-75% at the end of the period.

Table 1

AVERAGE EFFICIENCY LEVELS (1965-1995)*

	Total	Agriculture	Construction	Industry	Services
Andalusia	0.74	0.87	0.89	0.81	0.75
Aragón	0.80	0.76	0.87	0.86	0.83
Asturias	0.75	0.50	0.88	0.93	0.83
Balearic Islands	0.86	0.71	0.92	0.99	0.89
Basque Country	0.96	0.97	0.90	1.00	0.89
Canary Islands	0.85	0.85	0.99	0.80	0.87
Cantabria	0.74	0.58	0.90	0.93	0.83
C-la-Mancha	0.72	0.73	0.85	0.77	0.68
Cast. León	0.73	0.63	0.82	0.86	0.72
Catalonia	0.91	0.89	0.87	0.95	0.93
Extremadura	0.69	0.60	0.80	0.76	0.67
Galicia	0.73	0.45	0.85	0.82	0.76
La Rioja	0.89	0.94	0.99	0.83	0.86
Madrid	1.00	0.77	0.86	1.00	1.00
Murcia	0.73	0.87	0.96	0.71	0.78
Navarra	0.85	0.95	0.90	0.93	0.85
Valencia	0.80	0.96	0.97	0.88	0.83
Mean	0.81	0.77	0.90	0.87	0.82

(*) 1965-1993 for the industry and services sectors.

We decomposed labour productivity growth into TFP growth and capital accumulation, the latter being obtained residually. Also, the TFP growth was decomposed into efficiency gains and technological change, in view of the existence of different levels of efficiency between regions and sectors. Each of the three components of labour productivity growth for the Spanish economy over the 1965-1995 period is given in Table 2.

Table 2

DECOMPOSITION OF LABOUR PRODUCTIVITY GROWTH (base year = 1)

Total	**Out/L**	**Eff-change**	**Tech-change**	**TFP-growth**	**Cap-accumul.**
1965-1995	2.574	1.152	1.232	1.419	1.814
1965-1975	1.627	1.055	1.047	1.104	1.473
1975-1985	1.237	1.031	0.996	1.027	1.204
1985-1995	1.279	1.059	1.181	1.251	1.023
Agriculture	**Out/L**	**Eff-change**	**Tech-change**	**TFP-growth**	**Cap-accumul.**
1965-1995	4.611	1.115	2.291	2.554	1.805
1965-1975	1.500	0.943	1.301	1.227	1.222
1975-1985	1.769	1.094	1.298	1.419	1.247
1985-1995	1.738	1.080	1.357	1.466	1.185
Construction	**Out/L**	**Eff-change**	**Tech-change**	**TFP-growth**	**Cap-accumul.**
1965-1995	1.890	0.995	1.258	1.253	1.509
1965-1975	1.564	1.004	1.152	1.156	1.352
1975-1985	1.020	0.992	1.039	1.030	0.990
1985-1995	1.185	1.000	1.051	1.051	1.127
Industry	**Out/L**	**Eff-change**	**Tech-change**	**TFP-growth**	**Cap-accumul.**
1965-1993	3.159	1.166	1.996	2.327	1.358
1965-1975	1.965	1.027	1.659	1.703	1.154
1975-1985	1.276	1.040	1.185	1.232	1.035
1985-1993	1.260	1.091	1.015	1.108	1.137
Services	**Out/L**	**Eff-change**	**Tech-change**	**TFP-growth**	**Cap-accumul.**
1965-1993	1.729	1.032	1.220	1.260	1.372
1965-1975	1.376	1.014	1.179	1.195	1.151
1975-1985	1.104	1.019	0.984	1.003	1.101
1985-1993	1.138	0.998	1.052	1.050	1.083

The overall averages show that, for the aggregate of the economy, capital accumulation accounts for 63% of labour productivity growth, reflecting the intense process of capital accumulation undergone by the Spanish economy. On the other hand, efficiency gains explain around 40% of TFP growth for the aggregate of the economy, the other 60% being due to technological progress. Similarly, capital accumulation explains most of the productivity improvements in the services and construction sectors, whereas in the agriculture and industry sectors TFP growth is the main source of labour productivity change.

Most of the labour productivity growth over the period 1965-1995 took place between 1965 and 1975 (except in the agriculture sector), with technological progress and capital accumulation accounting for most of the observed growth in labour productivity. Finally, the efficiency change contribution was also important between 1975 and 1995 (with the exception of the construction sector), with a relative contribution to labour productivity growth of around 15-20% at both the aggregate and sector levels. Especially noteworthy is its contribution to productivity growth in industry between 1985 and 1993, where efficiency gains explain around 35% of labour productivity growth.

4. RELATIVE CONTRIBUTIONS TO CONVERGENCE

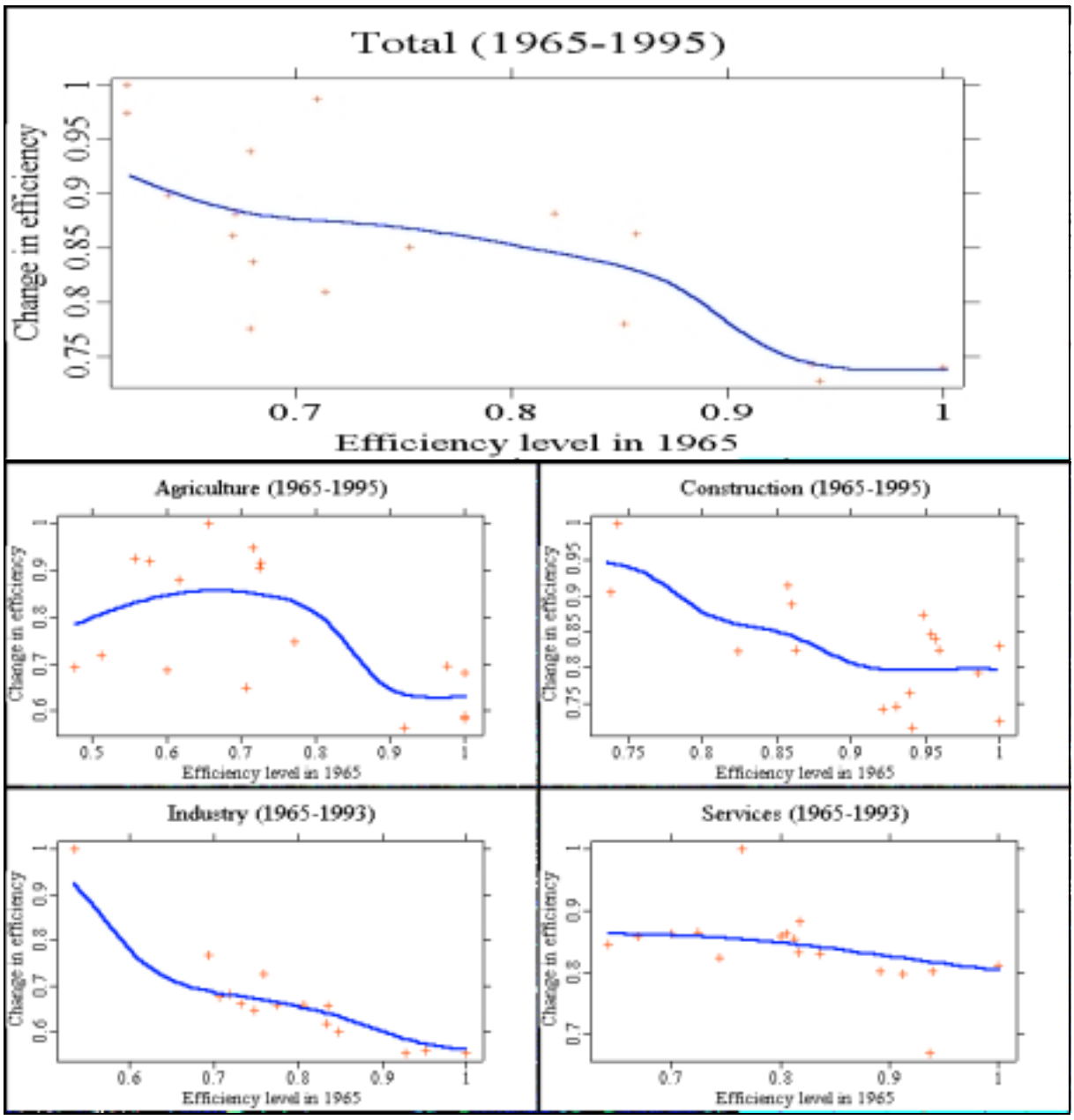
It has been often argued that slow technological catch-up is the main cause of slow convergence in labour productivity[3]. In the approach followed in this paper, a common technology is assumed for all regions, and technological catch-up is identified with movements toward the 'best-practice' production of the frontier (i.e. increases in efficiency). In order to analyse whether a process of technological catch-up and convergence has taken place among the Spanish regions between 1965 and 1995, Figure 2 shows the results of the non-parametric regression[4] between the efficiency growth rates and the initial levels of efficiency. On average, the less efficient regions of 1965 underwent greater efficiency gains than the more efficient ones, what indicates the existence of a process of convergence in the efficiency levels of the Spanish regions in these years.

[3] In this sense, Mankiw *et al*. (1992) or Barro and Sala-I-Martin (1995) point to slow diffusion of technology as the reason for the slowness of convergence (aproximately 2% per year).

[4] See Appendix 2.

Figure 2

NON-PARAMETRIC REGRESSION ON EFFICIENCY



However, this fact does not mean that technological catch-up tends to reduce the differences in labour productivity between the Spanish regions, since regions with relatively high labour productivity could present significant levels of inefficiency and consequently take advantage of efficiency gains as much as regions with relatively low levels of productivity per worker. Likewise, we should also study whether regions with initially lower levels of labour productivity have greater observed rates of technological progress and capital accumulation, with these factors contributing to convergence (or divergence) in output per worker.

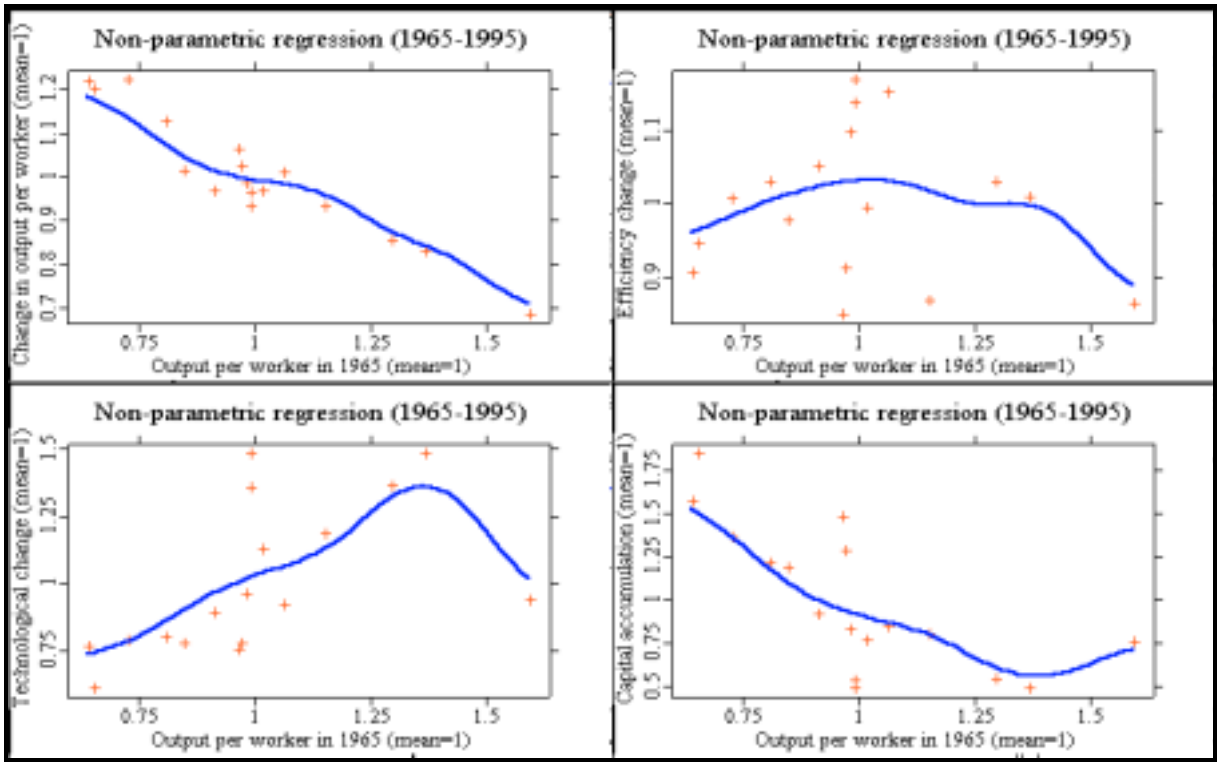
Figure 3 shows the dependence of the growth rate of labour productivity and each of its components (efficiency gains, technological change and capital accumulation) on the initial levels of output per worker in 1965. On the basis of this information, various conclusions may be drawn:

1) There is an inverse relationship between the growth rates of labour productivity and the initial level of this variable: on average, the less productive regions have tended to grow faster than the more productive ones, thus leading to the process of convergence pointed in so many studies.
2) However, in analysing the relationship between efficiency change and the initial level of productivity, we observe no clear pattern, at least at the aggregate level and for the services sector, suggesting that efficiency gains benefited the relatively more productive regions as much as the relatively less productive ones. In contrast, in the agriculture, construction, and industrial sectors, technological catch-up appears to be a source of convergence, since regions with initially low levels of labour productivity underwent greater gains in efficiency, thus contributing to the process of convergence in labour productivity.
3) While technological change played an important role in productivity growth, this was not the case with respect to convergence. The positive regression slope suggests that the more advanced regions benefited more from technological progress than the less productive regions. This tendency is common to the aggregate of the economy and sectorially, with the exception of the construction sector which presents no clear pattern.
4) On the other hand, capital accumulation seems to have contributed positively to labour productivity convergence. A strong inverse relationship between capital accumulation and the initial level of labour productivity appears at the aggregate level, pointing to capital accumulation as an important source of convergence among the Spanish regions. Similar results are found for the industry and services sectors and, to a lesser degree, for the agriculture sector. In the construction sector, however, capital accumulation shows no significant contribution to the convergence observed in labour productivity.

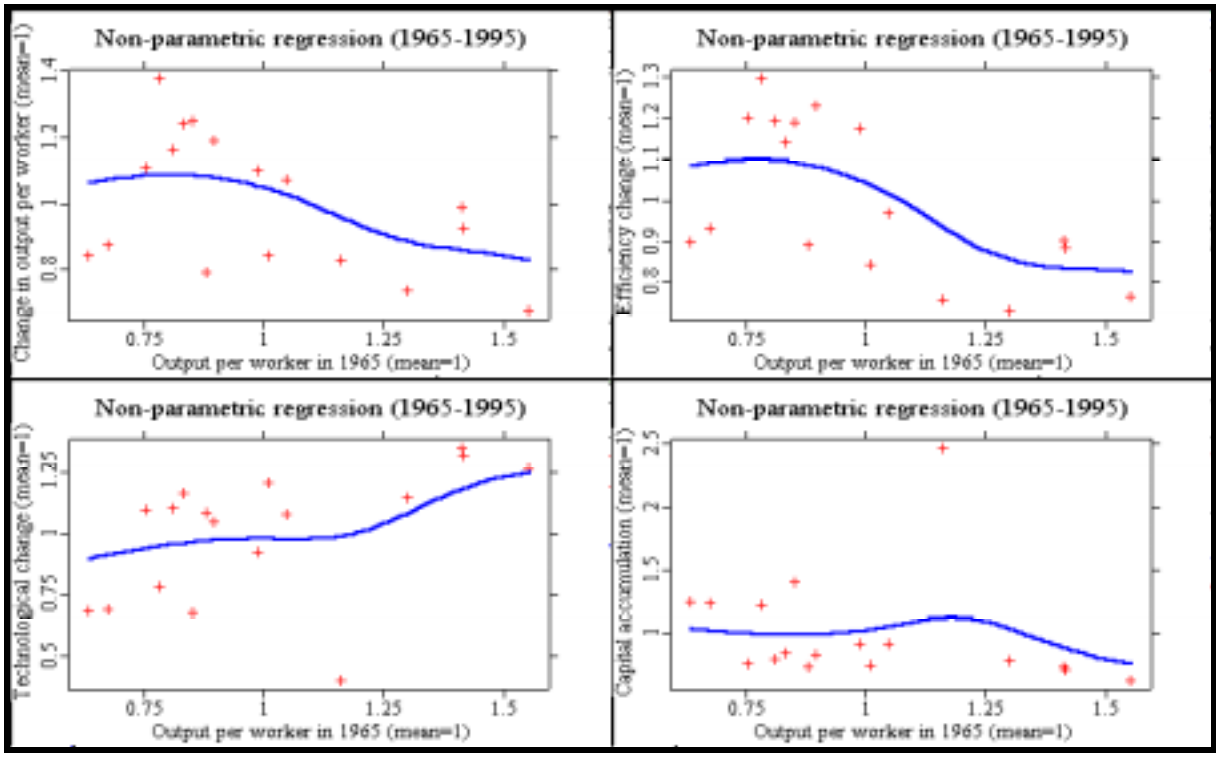
Figure 3

RELATIVE CONTRIBUTIONS TO LABOUR PRODUCTIVITY CONVERGENCE

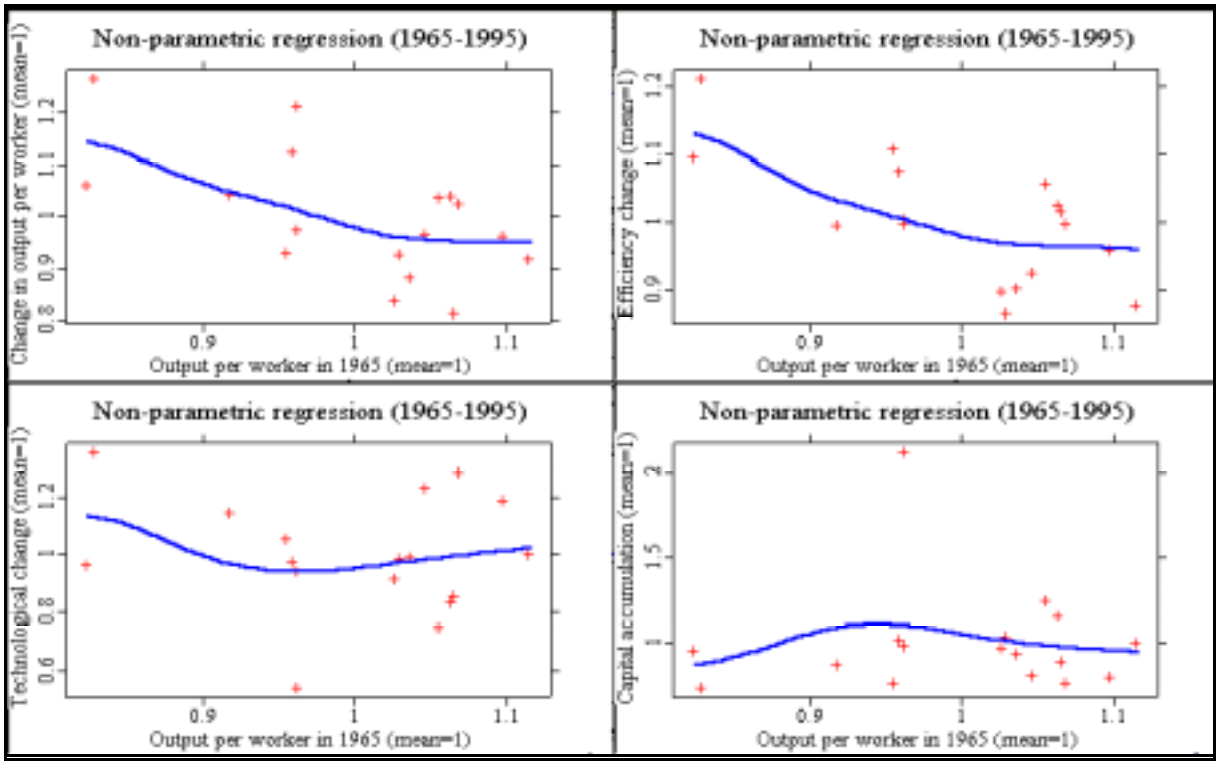
Total



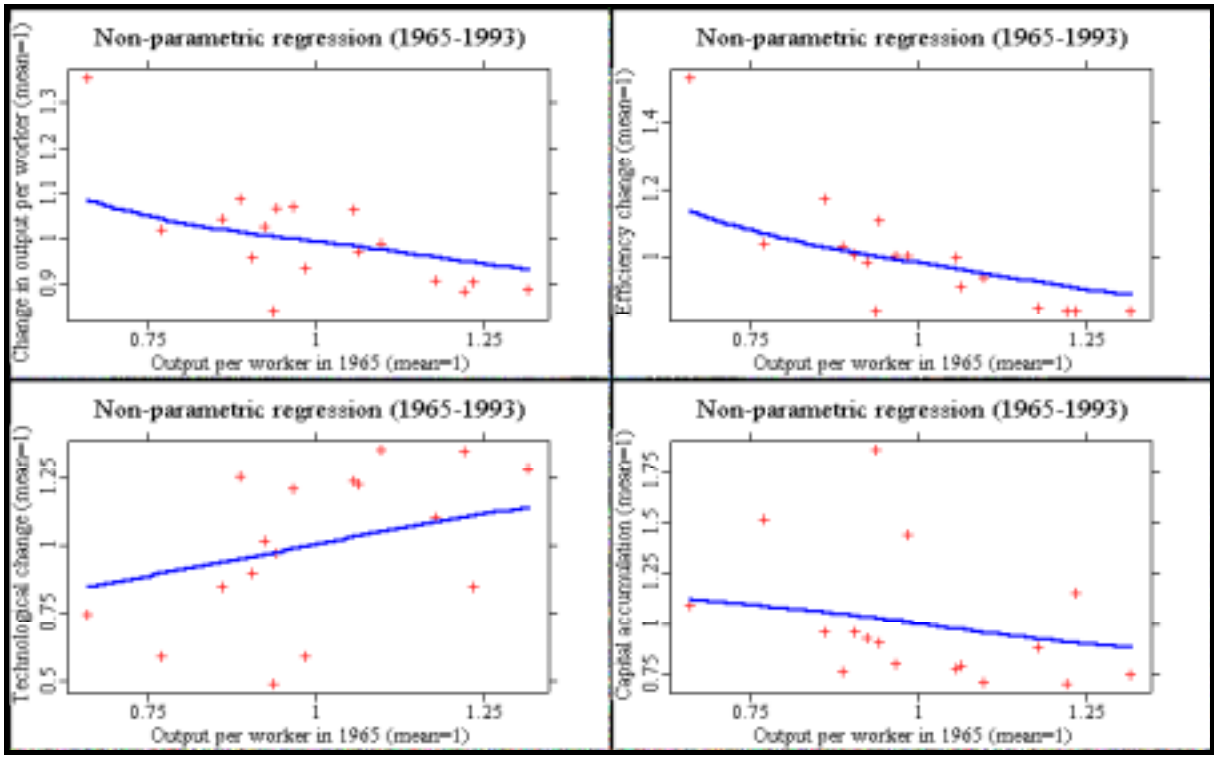
Agriculture



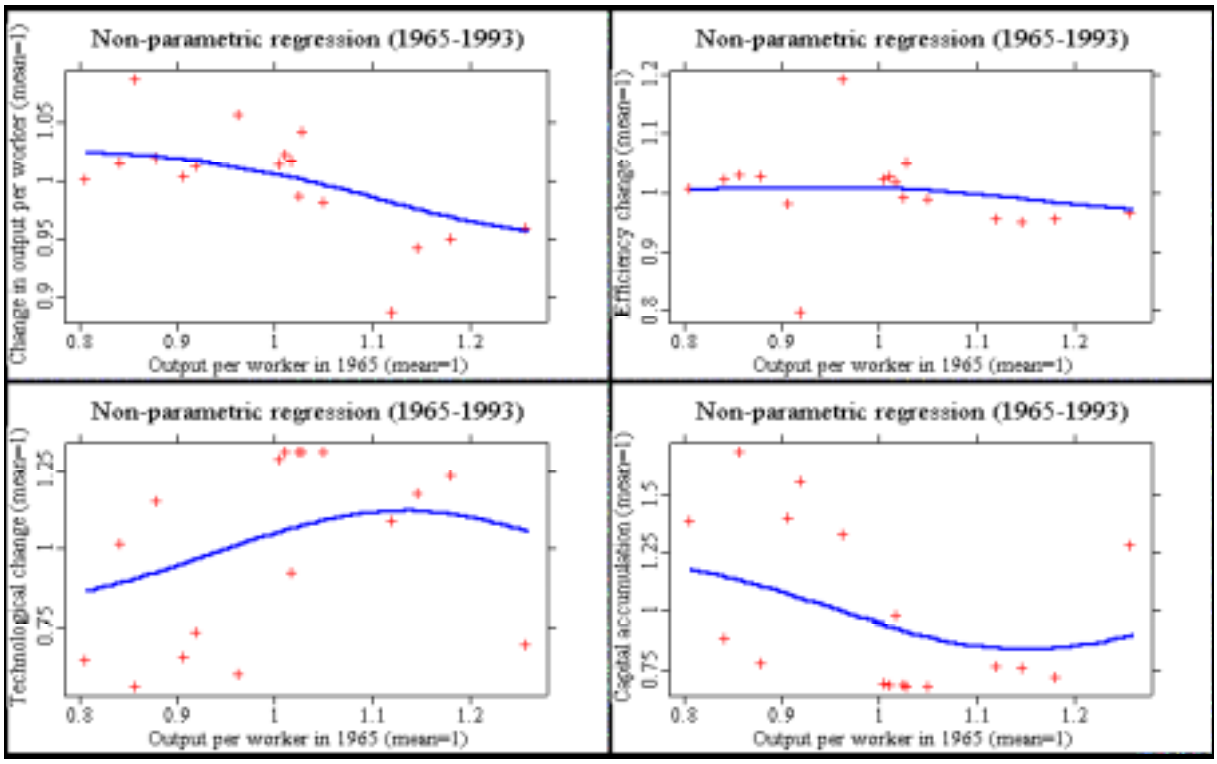
Construction



Industry



Services



The above analysis, based on regressions of average growth rates, is aimed at explaining the behaviour of the conditional mean, but it provides little information about the cross-sectional distribution of labour productivity and its evolution. In the spirit of Quah's approach (Quah, 1993, 1997), we shall therefore analyse the entire distribution of labour productivity and efficiency levels of the Spanish regions between 1965 and 1995. This analysis will provide information not only about the relative behaviour of the different regions, but also about the dynamics of the convergence process observed in this period.

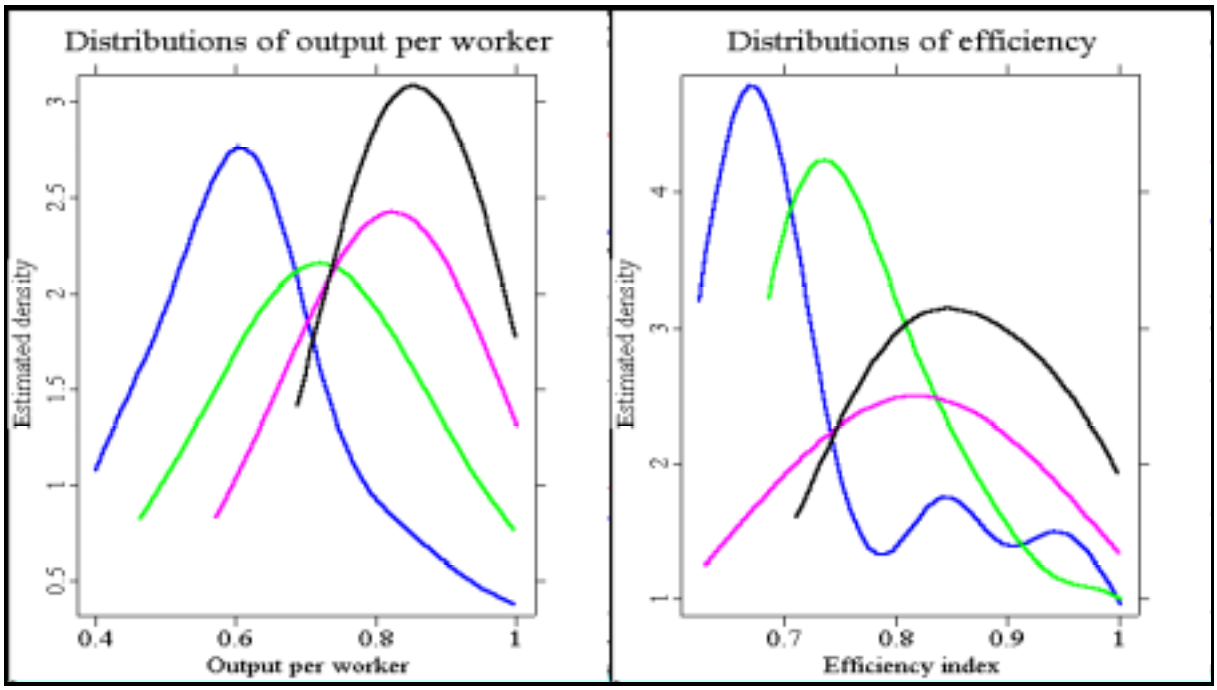
Figure 4 shows the distributions of output per worker and efficiency levels of the Spanish regions for the aggregate of the economy and by sectors. With regard to the estimated densities of labour productivity at the aggregate level, the dispersion of the regions in the distribution has progressively narrowed as more regions concentrate at relatively higher levels of output per worker. A similar pattern of convergence is observed in industry from 1975 onwards, although there was no convergence in the distribution of labour productivity in this sector between 1965 and 1975. On the other hand, the convergence in the services sector took place mainly in the first decade, with few changes in the distribution of labour productivity between 1975 and 1993. Finally, the dispersion of output per worker between regions remained relatively stable throughout the period in the agriculture and construction sectors. It is noteworthy that, in the last decade, the distribution of labour productivity in the agriculture sector changed from a unimodal distribution to a multimodal one.

With respect to the distributions of efficiency levels, there is an overall shift in the probability mass towards unity between 1965 and 1995 at both the aggregate and the sector levels (with the only exception being the construction sector, where the mean of the distribution was already close to unity at the beginning of the period). This indicates how the Spanish regions have tended to move towards the frontier over time. For the aggregate of the economy, it is also worthnoting the evolution undergone from an initial multimodal to a unimodal distribution, a transformation which took place between 1965 and 1975. Multimodal distributions also appear in the agriculture sector, although the final distribution is clearly unimodal. The dispersion in efficiency levels in this sector remained high throughout the period, given that the least efficient regions still present inefficiency levels of around 0.5 in 1995. Finally, a significant process of convergence in efficiency levels is observed in industry, especially between 1985 and 1993, with most regions approaching the technological frontier by the end of the period.

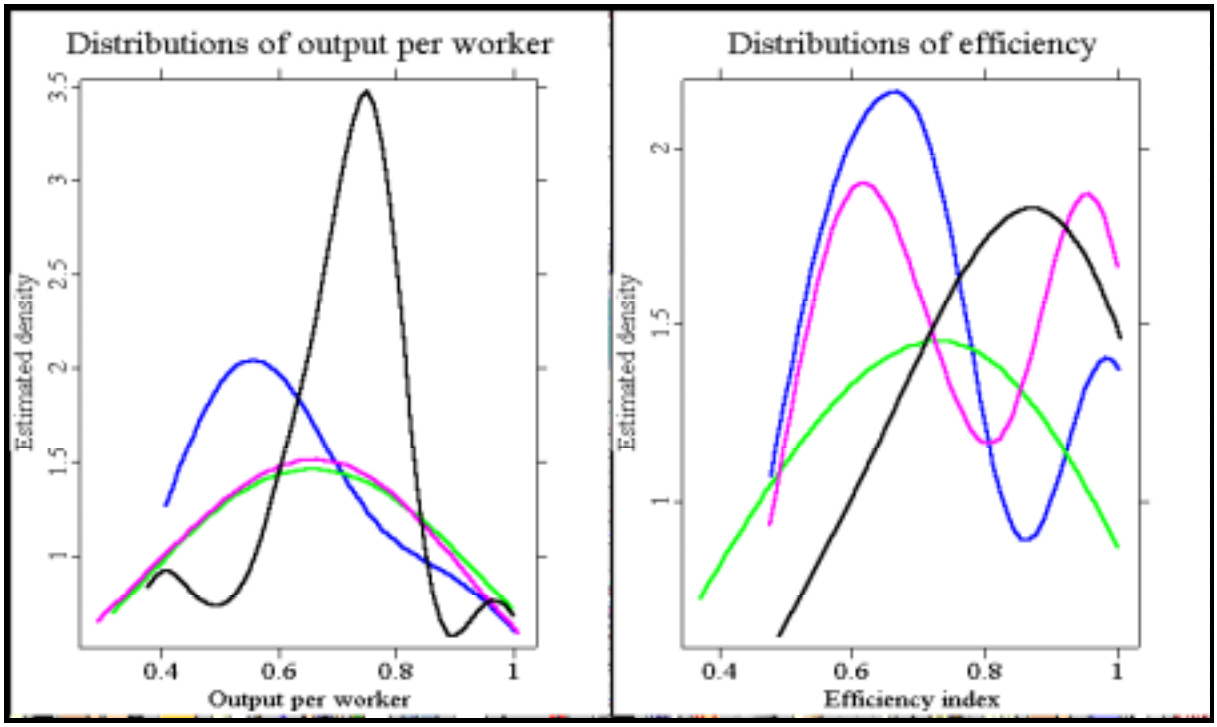
Figure 4

DISTRIBUTIONS OF OUTPUT PER WORKER AND EFFICIENCY LEVELS

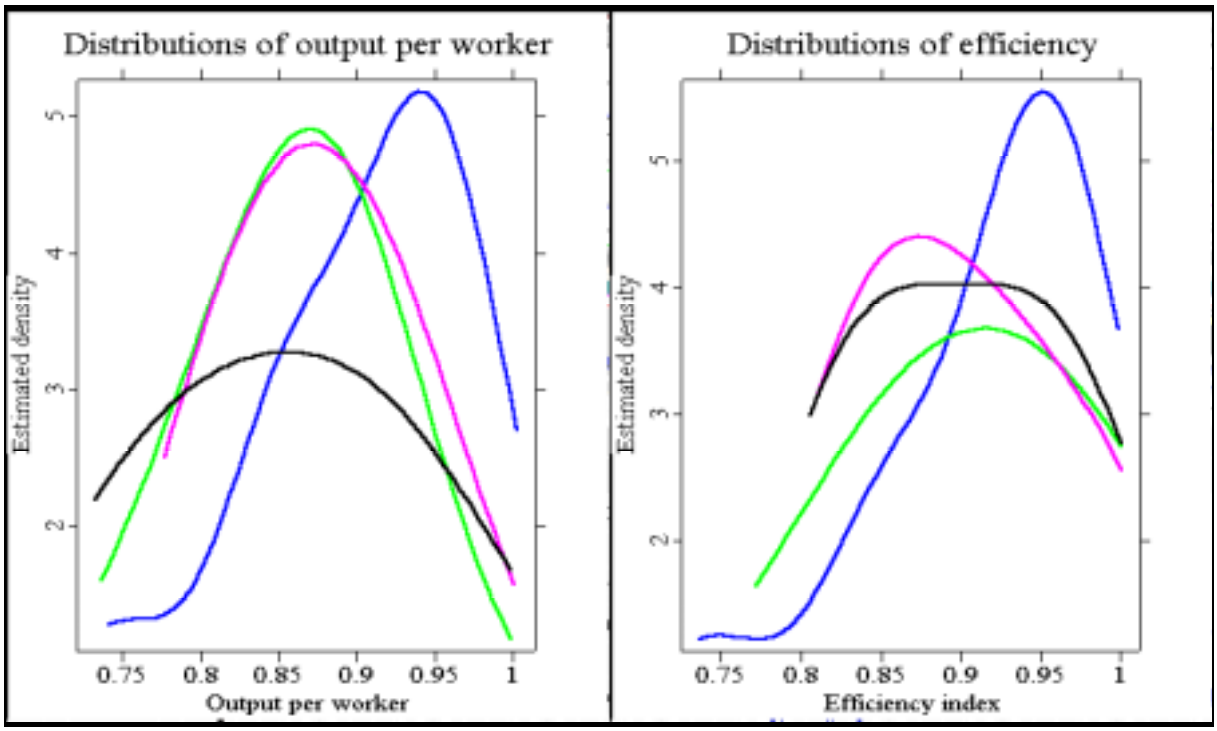
Total



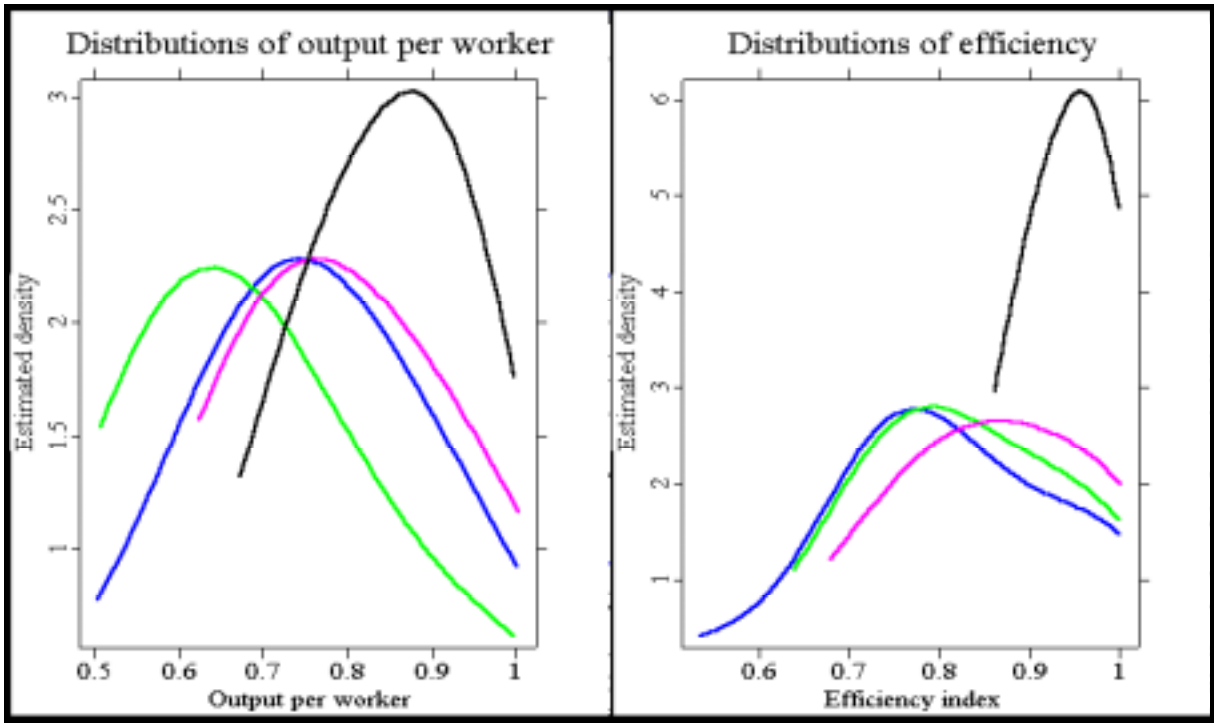
Agriculture



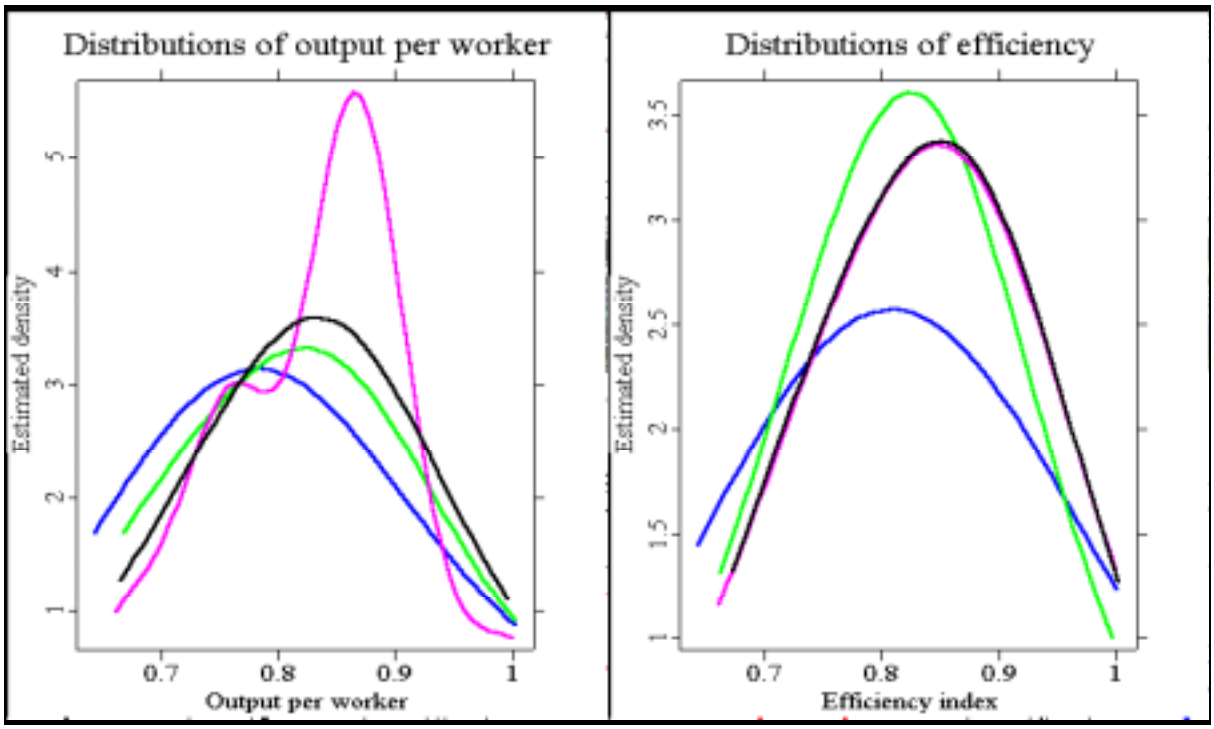
Construction



Industry



Services



1965	1975	1985	1995 (1993 for Ind. and Serv.)

We shall now analyse the evolution of the distribution of output per worker in terms of its components. On the basis of our labour productivity decomposition, we carried out a simulation in order to assess how efficiency change, technological progress and capital accumulation contribute to the evolution of the labour productivity distribution. To answer the question of what the labour productivity distribution would have been in 1995 if the labour productivity of each region had changed due only to one of its components, we have to calculate the theoretical productivity corresponding to each region by isolating that component.

Re-writing the labour productivity growth decomposition in expression (2) as

$$y_{t+1} = (EC \cdot TC \cdot CA) \cdot y_t \qquad (3)$$

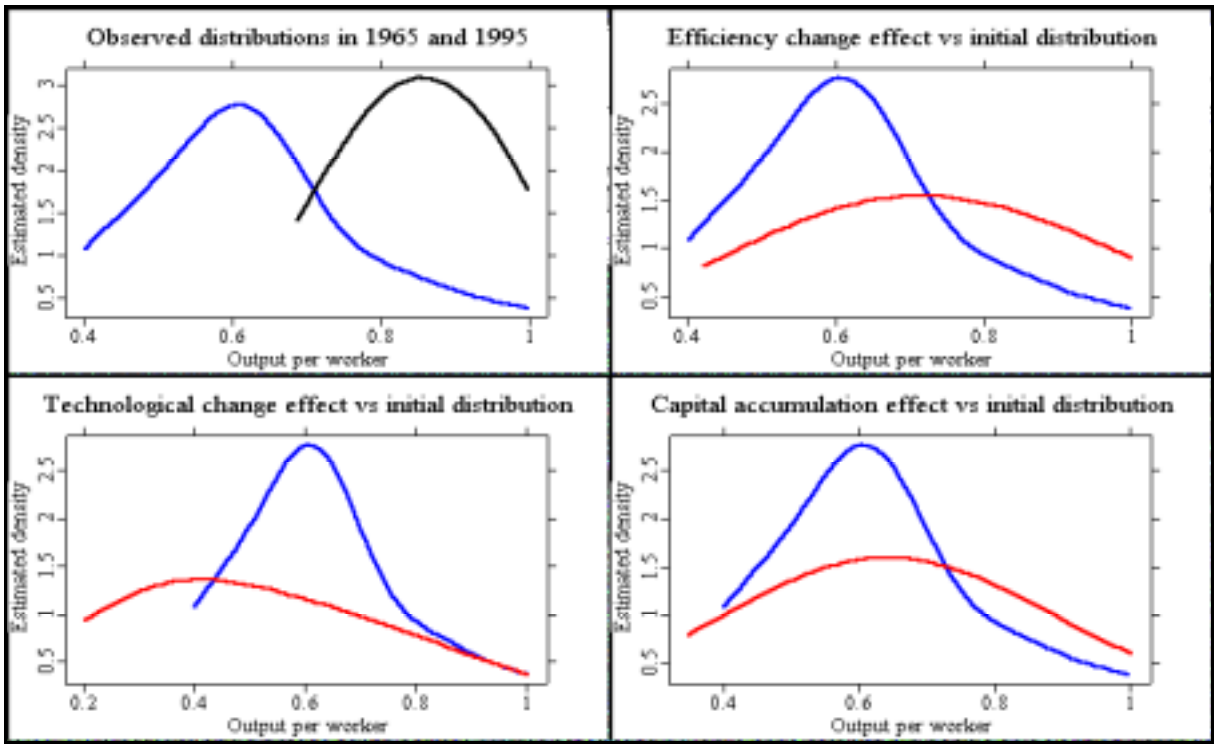
it can be observed that the labour productivity in 1995 may be constructed by multiplying the initial labour productivity by all the components of labour productivity growth. Similarly, we can construct counterfactual distributions by introducing just one of these three components, thus isolating its effect from those of the other components (i.e. if we construct the variable $y^e = EC \cdot y_t$ we isolate the effect of changes in efficiency, assuming a stationary production frontier and no capital accumulation). We then estimate the corresponding densities. Figure 5 shows the initial distribution of output per worker and the densities estimated by isolating the effect of each component (estimated densities for initial and final years are also presented for comparison).

Although the overall evolution of the labour productivity distribution can not be explained by any of the three components of productivity change separately, one observes how efficiency changes and capital accumulation have contributed to the observed convergence in productivity at the aggregate level since they move the curve towards higher levels of labour productivity. On the other hand, the effect of technological progress alone is to shift the probability mass towards the low tail of the distribution, indicating that technological change has contributed negatively to the process of convergence in labour productivity.

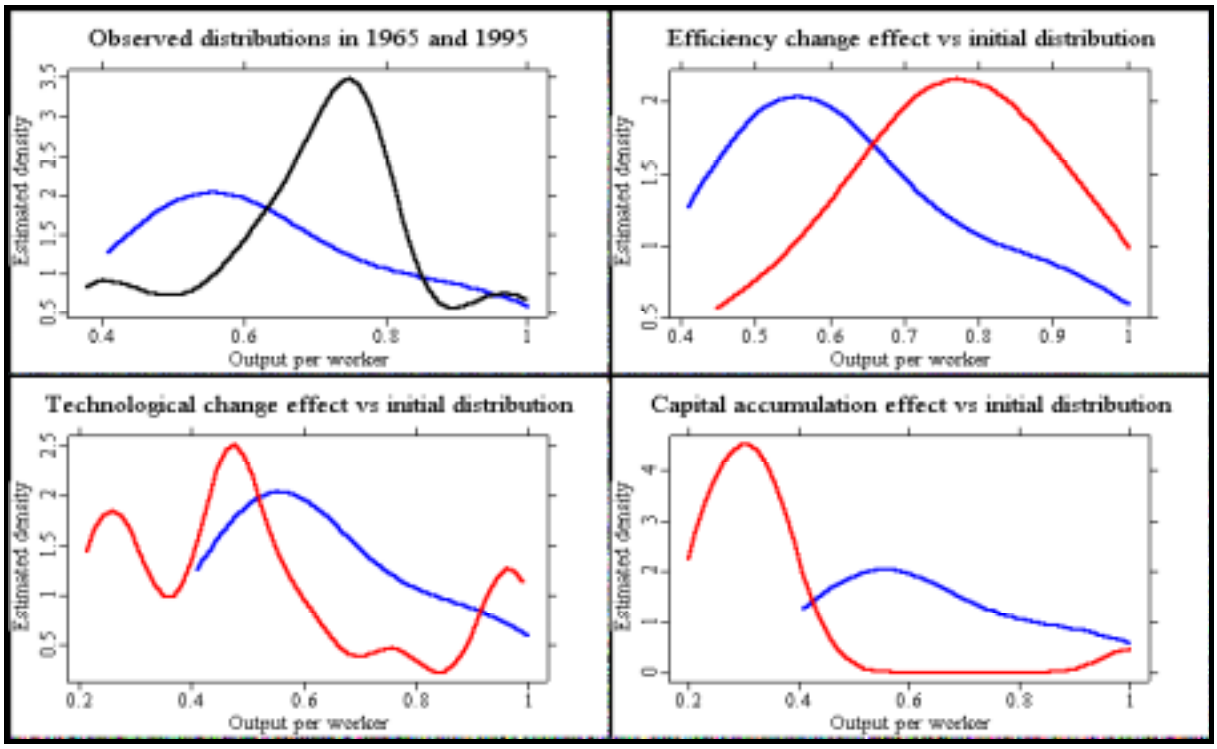
Figure 5

COUNTERFACTUAL DISTRIBUTIONS

Total



Agriculture



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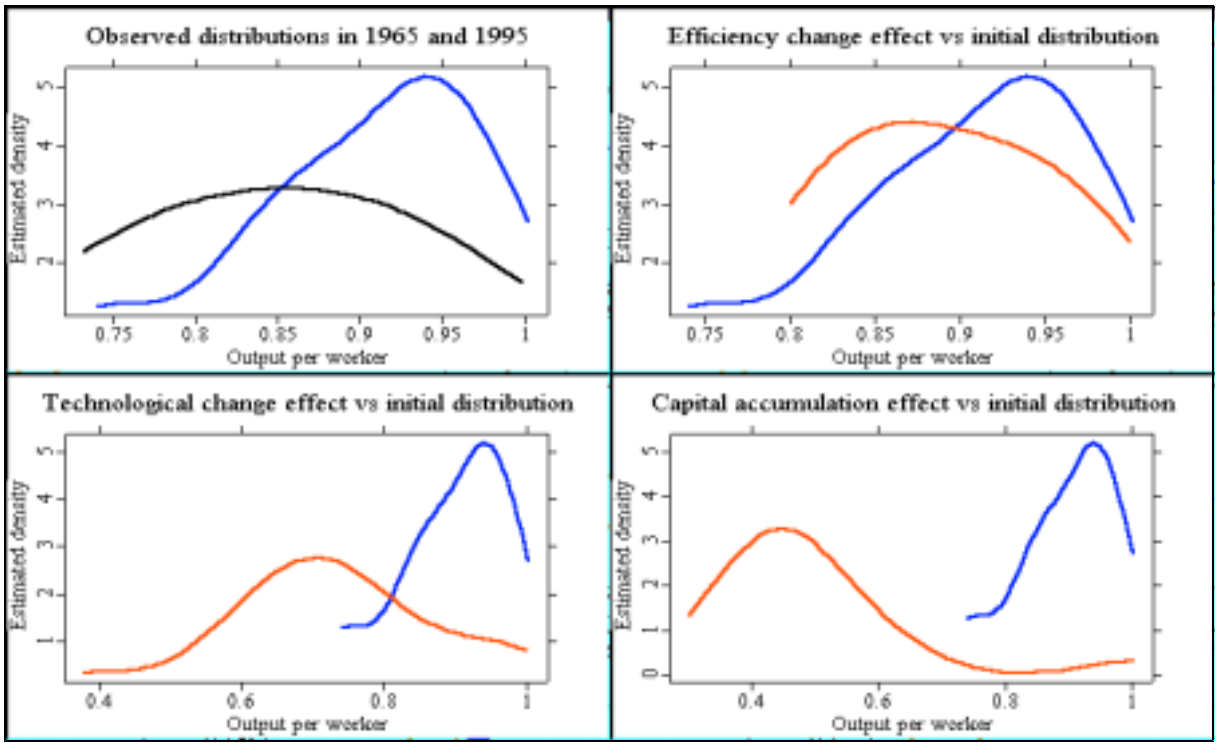

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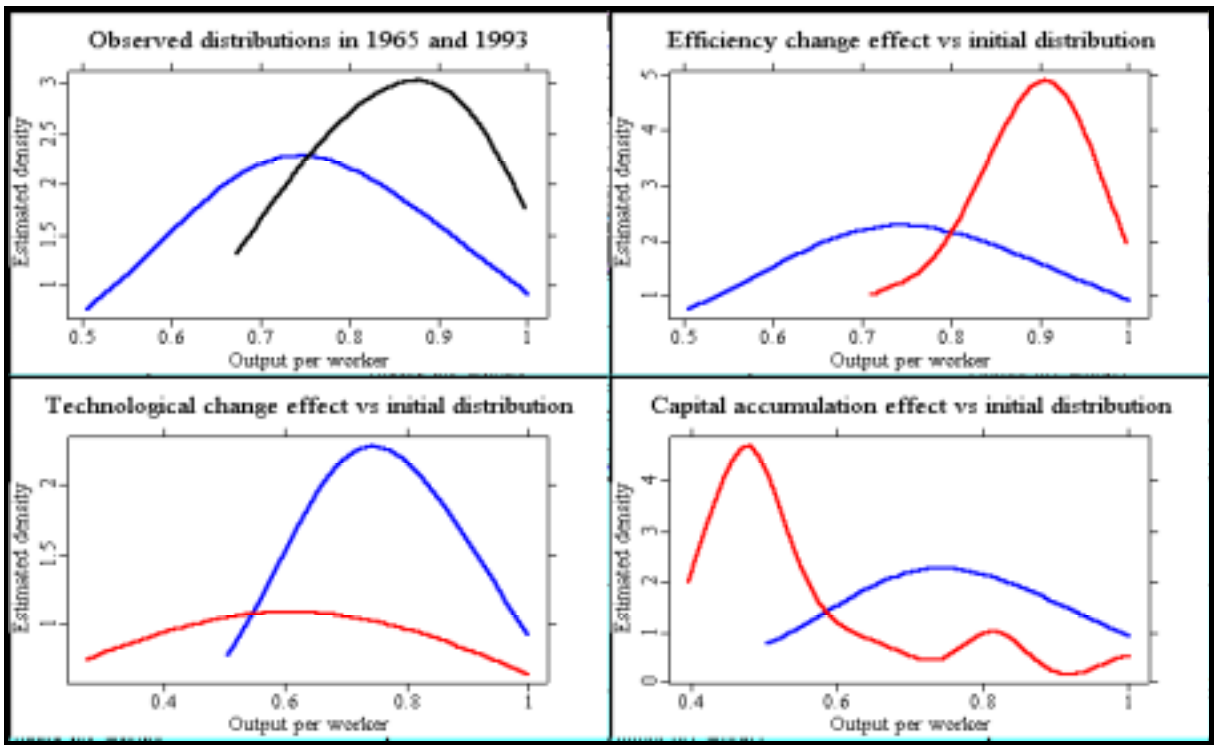

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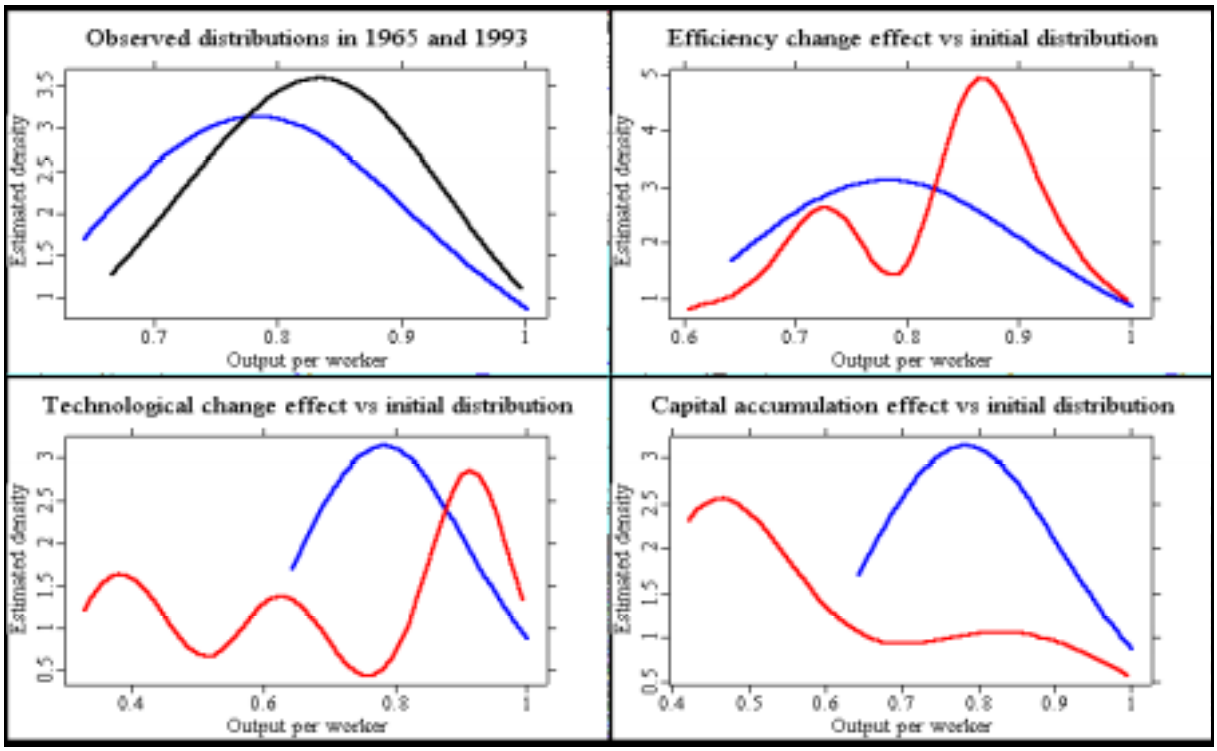

At the sector level, while efficiency gains stand out as a driving force in the evolution of the labour productivity distribution, the regions would tend to concentrate at lower levels of output per worker as the result of technological change and capital accumulation. It is also worthwhile noting that multimodal distributions arise in some cases (mainly as the result of technological progress in the agriculture and services sectors, or due to capital accumulation in the industry and services sectors), indicating that the Spanish regions would have tended to cluster into groups of regions with different levels of output per worker as the result of different paths of technological progress and capital accumulation. However, the overall distribution of output per worker remains unimodal after being adjusted by all three components of labour productivity growth, without there emerging any polarization in productivity levels between the Spanish regions[5].

[5] This analysis was also carried out for each ten-year interval. The common pattern was that changes in efficiency tend to account for most of the observed evolution in the distributions of output per worker in each of these subperiods. However, in industry, technological progress appeared to be the main driving force explaining changes in the distribution of labour productivity between 1965 and 1985.

V. CONCLUSIONS

In this paper we have studied the labour productivity growth and convergence processes undergone by the Spanish regions between 1965 and 1995. By taking into account the different levels of efficiency of the regions, labour productivity changes were decomposed into capital accumulation, technological progress and efficiency gains. Furthermore, the dynamics of the overall distribution of labour productivity and the relative contribution of each of its components to convergence were analysed. The following conclusions may be drawn from the analysis.

Firstly, regarding the estimated levels of efficiency, between 1965 and 1995 the Spanish regions operated, on average, at efficiency levels of around 80%, indicating that efficiency gains are a potential source of productivity growth. In this sense, efficiency changes accounted for around 15% of growth in output per worker, although capital accumulation and technological progress were the main driving forces of labour productivity growth.

Secondly, there has been a process of technological catch-up and convergence in efficiency levels among the Spanish regions, since the less efficient regions in 1965 underwent greater efficiency gains than the more efficient ones. Capital accumulation also appeared to be an important source of labour productivity convergence among the Spanish regions, whereas the benefits of technological change tended to be greater in regions with high initial levels of output per worker, and thus contributed negatively to convergence in labour productivity.

Thirdly, in analysing the dynamics of the overall distribution of output per worker and the relative contribution of each of its components, we found that none of these components alone was able to explain the evolution of the labour productivity distribution. However, the results pointed to changes in efficiency being the main driving force explaining the change in the distribution of output per worker.

Finally, it has to be noted that our analysis was based on the decomposition of labour productivity growth into technological change, efficiency gains, and capital accumulation, but it does not provide the reasons behind the behaviour of these components. This indicates that the study carried out is not yet closed. Consequently, it seems interesting to look at the question of such variables as human capital or efforts devoted to research activities as potentially important factors affecting the processes of technological change and efficiency gains.

APPENDIX 1

Let S^t be the technology of production at period t $(t = 1, \ldots T)$:

$$S^t = \{(X^t, Y^t) : X^t \text{ can produce } Y^t\} \qquad (A.1)$$

where X^t and Y^t are the vectors of inputs and outputs, respectively.

Following Shephard (1970), the distance function at period t is defined as[6]:

$$D_o^t(X^t, Y^t) = \min\{\theta : (X^t, Y^t/\theta) \in S^t\} \qquad (A.2)$$

what allows a perfect characterization of the technology, since $(X^t, Y^t) \in S^t$ if, and only if, $D_o^t(X^t, Y^t) \leq 1$.

In order to define the Malmquist productivity index, we need to relate the input and output vectors at period t to the technology of the next period, S^{t+1}:

$$D_o^{t+1}(X^t, Y^t) = \min\{\theta : (X^t, Y^t/\theta) \in S^{t+1}\} \qquad (A.3)$$

Similarly, we could define $D_o^t(X^{t+1}, Y^{t+1})$, where the input and output vectors at period $t+1$ would be related to the period t technology.

On the basis of the above concepts, Färe *et al*. (1994) define the following Malmquist productivity index:

$$M_o^{t+1}(X^{t+1}, Y^{t+1}, X^t, Y^t) = \left[\frac{D_o^t(X^{t+1}, Y^{t+1})}{D_o^t(X^t, Y^t)} \frac{D_o^{t+1}(X^{t+1}, Y^{t+1})}{D_o^{t+1}(X^t, Y^t)} \right]^{1/2} \qquad (A.4)$$

As it can be observed, this index is the geometric mean of two Malmquist indices, the first related to the technology of period *t*, and the second to the technology of period $t+1$.

This is in fact an index of productivity change between period t and $t+1$ and can be decomposed into efficiency change (EC) –change in relative efficiency between periods t and $t+1$– and technological change (TC) –the geometric mean of the shift in the frontier between these two periods:

$$M_o^{t+1} = EC \cdot TC$$

where $EC = \dfrac{D_o^{t+1}(X^{t+1}, Y^{t+1})}{D_o^t(X^t, Y^t)}$ and $TC = \left[\dfrac{D_o^t(X^{t+1}, Y^{t+1})}{D_o^{t+1}(X^{t+1}, Y^{t+1})} \dfrac{D_o^t(X^t, Y^t)}{D_o^{t+1}(X^t, Y^t)} \right]^{1/2}$ (A.5)

In order to estimate the component distance functions of the Malmquist index, we use the data envelopment analysis (DEA)[7] non-parametric technique of

[6] The subscript *o* refers to output based distance functions.

[7] Method developed by Charnes, Cooper and Rhodes (1978), based on Farrell (1957) technical efficiency measures.

linear programming. By assuming constant returns to scale and exploiting the fact that the distance functions can be estimated as reciprocals of Farrell efficiency measures[8], the specific problem to calculate $D_o^t(X^t, Y^t)$ can be expressed as:

$$\left[D_o^t(X_t, Y_t)\right]^{-1} = \max_{\phi\lambda} \phi$$

$$\text{s.t.} \quad -\phi\, y_{i,t} + Y_t\lambda \geq 0 \qquad (A.6)$$
$$x_{i,t} - X_t\lambda \geq 0$$
$$\lambda \geq 0$$

The other three distance functions are calculated similarly, substituting the appropriate period index (i.e.t or $t+1$).

[8] Specifically,

$$D_o^t(X^t, Y^t) = \min\{\theta : (X^t, Y^t/\theta) \in S^t\}$$
$$= \left[\max\{\theta : (X^t, \theta Y^t) \in S^t\}\right]^{-1}$$
$$= 1/F_o^t(X^t, Y^t)$$

where, $F_o^t(X^t, Y^t)$ is the Farrell output based measure of technical efficiency.

APPENDIX 2

Most empirical analyses of convergence have been based on regression analyses of cross-section growth of the type $y_i = m(X_i) + \varepsilon_i$, where y is some measure of the growth of each economic unit during a given time period, X a matrix of variables which explains this growth, ε a random perturbation (zero mean and unknown variance $\sigma^2(X)$) representative of specific shocks, and m a pre-set function which depends on a set of unknown parameters that are to be estimated, $m(X) = m(X,\beta)$. Given the nature of these regression analyses, it is obvious that the function m is to be understood as the expectation value (average) of growth for certain values of the explanatory variables $E[y \mid X = X_i]$ and, in the absence of any a priori evidence to the contrary, the function m is usually assumed to be linear, i.e., $m(X,\beta) = X\beta$.

In this study, we use non-parametric estimation techniques from a double perspective. Firstly, these techniques are used to estimate the functional relationship between the variable y and the regressors X, i.e., the conditional expectation $E[y \mid X] = m(X)$. This manner of determining the regression function is more flexible than the parametric approach since it does not require the function m to belong to a given family of functions. It only requires that the function $m(\bullet)$ satisfies certain regularity conditions. Secondly, in the analysis of the output per capita and efficiency level distributions, we use kernel estimates to approximate the probability density function ($f(\bullet)$) of the random variables.

Without going into too many technical details[9], we shall describe in the following lines the essential fundamentals of the non-parametric approach. Suppose that there are n independent observations available, $y_1, y_2, ..., y_n$, of the random variable Y. The kernel estimator of the value of the density function of that variable at a point y, $f(y)$, will be given by

$$\hat{f}_h(y) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{y_i - y}{h}\right) \qquad \text{(B.1)}$$

where $K(\bullet)$ is the so-called kernel function, and h is the bandwidth (or smoothing parameter) which controls the regularity of the estimated curve.

The statistical properties (bias, variance, consistency, etc.) of the proposed estimator depend on the choice of kernel function and bandwidth, although in practice the choice of the kernel is less important than that of the parameter h since the kernel functions can be rescaled so that the difference between two

[9] A number of specialized books and articles provide technical details. Examples are Härdle and Linton (1994), Silverman (1986), or the more recent surveys of Cao *et al*. (1997) and Delgado and Robinson (1995).

estimates based on different kernels will be practically negligible (Marron and Nolan, 1988).

In our case we used Gaussian-type kernel functions ($K(u) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}u^2\right)$) in all the calculations, and chose the bandwidth on the basis of the least-squares cross-validation (LSCV) criterion[10].

With respect to the use of the non-parametric approach to estimate the functional relationship between a response variable (y) and a set of *p* explanatory variables (X) given by $E[y \mid X] = m(X)$, in the present work we used the Nadaraya-Watson estimator, which in the multivariate case takes the form

$$\hat{m}_h(X) = \frac{\sum_{i=1}^{n} \hat{K}\left(\frac{x_{i1} - x_1}{h_1}, \frac{x_{i2} - x_2}{h_2}, \ldots, \frac{x_{ip} - x_p}{h_p}\right) y_i}{\sum_{i=1}^{n} \hat{K}\left(\frac{x_{i1} - x_1}{h_1}, \frac{x_{i2} - x_2}{h_2}, \ldots, \frac{x_{ip} - x_p}{h_p}\right)} \qquad \text{(B.2)}$$

where $\hat{K}(u) = \hat{K}(u_1, \ldots, u_p) = K(u_1) \ldots K(u_p)$ is a multi-dimensional multiplicative kernel function, with K denoting the univariate kernel function, and the bandwidth is now a *p* -dimensional vector given by $h = (h_1, h_2, \ldots, h_p)$.

[10] For further details on different methods of bandwidth selection, see Härdle (1991), Marron (1989), Park and Turlack (1992), or Sheater and Jones (1991).

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