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PRODUCTIVITY, TECHNOLOGY, AND EFFICIENCY:
An Analysis of the World Technology Frontier When Memory is Infinite

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Abstract: Using Data-Envelopment Analysis (DEA), a ‘world-technology frontier’ is constructed on the basis of data on 57 countries for the period 1980-90. Growth in total-factor productivity and its decomposition into technological progress and change in technical efficiency are analysed in this context. The paper shows that applying DEA in standard fashion results in a biased estimate of change in technical efficiency, due to an implausible loss of memory about production techniques. An amendment to DEA, called here Long-Memory DEA (LMDEA), is proposed in order to prevent technological regress and to achieve accurate measurement of technical-efficiency change. The application of LMDEA yields some new results that are largely in line with common perceptions of growth patterns.

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1 Introduction

A country's economic performance determines the standard of living of its population in the long run. How to measure economic performance and developmental progress comprehensively can be debated, but it appears that most of the important issues, such as life expectancy, child mortality or basic education, are correlated with income levels (Ray, 1998). Hence, income and its growth rate are useful starting points for an analysis of a country's development performance.

Theoretical models are built around the notion that there are two sources of income growth, factor accumulation and productivity growth. The first source can lead to high growth rates, but only for a limited time period. Thereafter, the law of diminishing returns inevitably sets in. Consequently, sustained growth can only be attained through productivity growth, that is, the ability to produce more and more output per unit of input (bundle of inputs). The Soviet Union of the 1950s and the 1960s, and to some extent the growth of the Asian 'Tigers', are usually quoted in the literature as examples of growth through factor accumulation (e.g. Krugman, 1994; Young, 1994, 1995). By contrast, growth in the industrialised countries appears to be based mainly on improved productivity (e.g. Färe *et al*, 1994).

The focus of this paper is on productivity measurement. More precisely, total-factor productivity (TFP) growth is measured by use of the Malmquist index, and its decomposition into change in technical efficiency and technological change. In this context, one may envisage a world-technology frontier with the most productive economies at or near this frontier and the less productive ones at some distance from it. Then, technological change relates to the shift of the frontier itself, while change in technical efficiency is reflected in how a country moves relative to the frontier.

Färe *et al* (1994) pioneered the use of data-envelopment analysis (DEA) for cross-country analyses of TFP growth. The same approach was adopted by Krüger, Cantner, and Hanusch (2000) as well as Rao and Coelli (1998). One common result of the latter two studies is that technological change is negative for some countries, i.e. countries seem to have experienced technological regress. No doubt, DEA is a suitable tool for analysing TFP growth at country level. However, the ensuing decomposition of productivity growth turns out to be problematic if ─ as in a standard application of this technique ─ the uncomfortable idea that countries can forget about past production techniques has to be accepted.

The present paper argues that memory loss at country level is highly implausible. First, why should a country experience technological regress? Once a "blueprint" is known, there is no reason why it would be forgotten over time. And while the notion of technological regress may be applicable at micro level (e.g. at plant-level), at the aggregate level there seem to be good reasons to exclude the possibility of technological regress altogether.

Second, leaving aside the purely conceptual problems of technological regress itself, an equally serious difficulty is that the estimated change in technical efficiency will be biased when technological regress is allowed for. This bias arises because in at least one of its segments the world technology frontier might recede towards some non-frontier countries. These countries not only face technological regress, but they will also have moved closer to the frontier. The latter means that such non-frontier countries will appear to have experienced an increase in technical efficiency ─ not due to any improvement in their performance, but, paradoxically, on account of a loss of knowledge about production. In this case, it cannot be argued that the countries have really caught-up with the front-runners, nor can it be credibly asserted that they have forgotten how they produced their output previously.

In order to eliminate this uncomfortable feature of DEA, this paper introduces a modification of the standard technique. The amendment proposed here is simply to prevent any segment of the world-technology frontier from receding. Put in terms of production techniques: once a technique has become available and learnt, it will be remembered forever and remain (at least potentially) utilisable. For obvious reasons, this version of the DEA will be dubbed the Long-Memory Data-Envelopment Analysis (LMDEA).

As an illustration of the LMDEA, the Malmquist productivity index is computed for a sample of 57 industrialised and developing countries for the time period 1980 to 1990. Data are taken from the Penn-World Tables Mark 5.6, providing the information to the simplest possible version of a production function: aggregate output (measured as real GDP) produced by use of the two inputs capital and labour. The analysis shows that standard DEA and LMDEA produce virtually identical estimates of TFP change. However, with LMDEA the (upward) bias of change in technical efficiency discussed previously is eliminated. The figures obtained with LMDEA suggest at least three observations. First, they are consistent with the divergence between industrialised countries and developing countries at large, as it is documented in the empirical literature. Second, the results also indicate that the factor-accumulation argument put forward as an explanation of the ‘Asian Miracle’ needs to be strongly qualified, since growth in ‘Tiger’ economies is to a large extent explained by TFP growth. Third, industrialised countries grew largely by means of technological progress, whereas productivity growth in developing countries, wherever and whenever it occurred, built on improvements in technical efficiency.

The rest of the paper is organised in the following way: Section Two discusses different ways of deriving estimates of TFP change and presents an argument for the use of DEA. The Malmquist-productivity index is discussed and so is the construction of a world-technology frontier by means of the DEA-technique. The section closes with a brief review of the empirical literature as a transition to the main contribution of this paper. In Section Three, the ‘memory-correction’ to the DEA called Long-Memory DEA (LMDEA) is introduced. Alongside a brief review of empirical studies applying DEA to macro data, the application of LMDEA to the data discussed above is presented in Section Four. The results obtained from standard DEA are compared with those of LMDEA. Section Five concludes the paper.

2 Economic Performance and the World Technology Frontier

This section first compares three different ways of deriving TFP change: growth accounting, stochastic-frontier analysis (SFA), and DEA. Thereafter, it describes how the Malmquist-index of TFP change is calculated and decomposed into the two components of technological change and technical-efficiency change. DEA as the method used to obtain these growth figures is also discussed in some detail.

2.1 Growth accounting, SFA, and DEA

Arguably, the most widely used method for measuring TFP change is that of growth accounting. On the assumptions that output is produced using labour (L) and capital (K), and that the relative contributions to output growth of labour and capital are β_L and β_K, respectively, TFP change can be obtained as the residual of subtracting β_L*L + β_K*K from output change.[1] In principle, this accounting exercise can be conducted

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[1] Abramowitz (1956) succinctly called this residual component a “measure of our ignorance”. Solow (1957) showed for the case of the United States that TFP growth accounted for as much as 87

for any country using country-specific parameters.[2] While growth accounting is attractive — also on account of its simplicity — it requires several restrictive assumptions to hold. Among them is that of permanent technical and allocative efficiency. Product markets must be perfect so that the factor shares (β_L and β_K) reflect their respective marginal products. Agents are assumed to be maximising and production equilibrium is reached under an optimal allocation of resources.

But, why should equilibrium conditions hold permanently? For the analysis to work they need not because parameters can be obtained by estimating a parametric production function. However, the drawback from such an approach is that the parameters are average values for the entire sample. If there are country features that are heterogeneous and the analysis attempts at highlighting those (e.g. heterogeneous technological change), growth accounting seems to be an inappropriate tool.

One way to circumvent the averaging problem is to rely on SFA. The approach is attractive in that it constructs a frontier of efficient observations, which envelops the relatively inefficient observations. An important advantage of the method is that it is able to handle outliers and that hypotheses can be tested in the usual (econometric) way. However, there are several important drawbacks as well. The production function is assumed to be valid for all observations and technological change is the same for all observations. Whether technological change is continuous and smooth and common to all observations can be questioned. It is also somewhat disturbing that a distributional form of the error term as well as a functional form of the production function have to be assumed.

By contrast, DEA does not require any assumption about the functional form of the production function or economic agents' behaviour. Furthermore, there is no need to assume any specific distributional form of an "error term" (there is none!) and there is also no need to assume perfect factor markets or optimal resource allocation. A disadvantage of DEA is, of course, that it cannot handle noisy data in a satisfactory manner. Hence, in a dataset with many outliers or serious measurement errors, DEA

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per cent of output growth. Over time this number has decreased as measurement has been refined and the number of inputs being taken into account has increased. Still, a substantial amount of "unexplained" growth tends to remain as Hulten (2000) reports in his 'biography' of TFP.

[2] However, when studying several countries the parameter values for the United States (0.6 for β_L and 0.4 for β_K) are often assumed to hold for the whole sample.

may not be the best method to apply. On balance, and in view of a dataset comprised of country data, the present study considers DEA to be a more flexible and appropriate tool for the task at hand than the other methods outlined above.[3]

2.2 *The Malmquist TFP index and its decomposition*

TFP change is defined as the growth in output net of growth in inputs used. The measurement of TFP employed in this paper is based on the output-distance function and is due to Malmquist (1953).[4] In using the output-oriented version of DEA, the paper follows the approach of Färe *et al* (1994) for calculating productivity growth in different countries.

The DEA-approach is based on Farrell (1957) and on extensions of his work by Charnes et al. (1978), related work by Färe et al. (1983, 1985) and Banker et al. (1984). In this approach, efficiency of a production unit (in the present case a country) is measured relative to the efficiency of all other production units, and subject to the restriction that all units are on or below the best-practice frontier.

Let a country be denoted by c with $c=1,\ldots,C$, and where C also amounts to the number of observations in the sample. Assume that at every point in time there exists a production technology, which transforms $k=1,\ldots,K$ inputs x_k into $m=1,\ldots,M$ outputs y_m. The linear programming problem for a production point of a specific country c observed in period s with reference to the frontier function of period t is:

$$
\begin{aligned}
&\max_{\Phi,\lambda} \Phi_c \\
&s.t.\ \Phi_c\, y^s_{mc} - \sum_{i=1}^{C} \lambda_i\, y^t_{mi} \le 0 \qquad \forall m = 1,\ldots,M \\
&\qquad\qquad\qquad\qquad\qquad\qquad \Rightarrow D^t_c(x^s, y^s) = \Phi_c^{-1} \\
&\qquad \sum_{i=1}^{C} \lambda_i\, x^t_{ki} \le x^s_{kc} \quad \forall k = 1,\ldots,K \\
&\qquad \lambda_{1,\ldots,}\, \lambda_C \ge 0.
\end{aligned}
\tag{1}
$$

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[3] An innovative and interesting way to deal with a country frontier is that of Caselli and Coleman II (2000). However, while the approach has several advantages over traditional growth accounting, there is still need to specify a functional form of the production function.

[4] See also Caves, Christensen, and Diewert (1982), Nishimizu and Page (1982), and Färe et al (1994). Coelli, Rao, and Battese (1998) and Cooper, Seiford, and Tone ((2000) provide excellent introductions to the Malmquist TFP index.

The percentage change of all outputs in period s required to attain the frontier function in period t (based on constant input levels) is represented by the maximum proportional augmentation factor Φ_c. Assuming that $s = t$, the country is on the frontier if $\Phi_c = 1$. On the other hand, if $\Phi_c > 1$, Φ_c measures the percentage level to which country c has to increase its output to reach the frontier. The real number $\lambda_i \geq 0$ corresponds to a virtual country on the frontier with which c is compared. For all $\lambda_i > 0$, this number indicates if and to what extent observation i $(i=1,\ldots,n)$ enters in the construction of the point of comparison for observation c. By way of calculation over all C observations, the productivity difference between the observations and the world-technology frontier for period $s = t$ is obtained.

Frontier functions and technical-efficiency measures can be compared across time by means of the Malmquist index. In turn, the Malmquist index can be decomposed into two parts: change in technical efficiency and change in best-practice. The latter component represents the movement of the world-technology frontier itself. The technical-efficiency component of the Malmquist index can be thought of as catching-up or convergence, i.e. over time countries move relative to the frontier. If a country moves closer to the frontier it is said to have caught up with (or converged to) the more advanced countries, if a country moves away from the frontier it is interpreted as diverging from the more advanced countries. If the frontier moves outward the interpretation is that of technological progress or innovation, given that the most advanced countries in the world are part of the sample. However, if the frontier moves inward this would have to be interpreted as technological regress, the implausibility of which was discussed above.

The (output-oriented) Malmquist TFP change between period s and period t can be written as

$$m_o(y_s, x_s, y_t, x_t) = \left[\frac{d_o^s(y_t, x_t)}{d_o^s(y_s, x_s)} \times \frac{d_o^t(y_t, x_t)}{d_o^t(y_s, x_s)} \right]^{1/2} \quad , \tag{2}$$

where $d_o^s(y_t, x_t)$ denotes the distance of the observation of period t from the technology frontier of period s. Now, equation (2) can be re-written in the following way:

$$m_o(y_s, x_s, y_t, x_t) = \frac{d_o^t(y_t, x_t)}{d_o^s(y_s, x_s)} \left[\frac{d_o^s(y_t, x_t)}{d_o^t(y_s, x_s)} \times \frac{d_o^s(y_s, x_s)}{d_o^t(y_s, x_s)} \right]^{1/2}, \tag{3}$$

where the ratio outside brackets is the change in the output-oriented measure of (Farrell) technical efficiency between periods *s* and *t*. The expression within the brackets of equation (3) is a measure of technological change. More precisely, it is the geometric mean of the shifts of the technology frontier between *s* and *t*, evaluated at x_t and at x_s, respectively. If m_o is greater than one, TFP change from period *s* to period *t* has been positive. A value of m_o less than one indicates TFP decline. Empirically, all four distance measures of equation (3) need to be calculated. In the case of one output and two inputs, *M* and *K* equal two (capital and labour) and one (real GDP), respectively.[5]

Figure 1 provides an illustration of the measurement concepts employed here. Quadrant I shows the technology frontier when there is only one country (B) on the frontier. For expository purposes only one country (A) out of the many positioned inside the frontier is shown. Country B on the frontier is technically efficient, while country A inside the frontier is technically inefficient. The degree of inefficiency of country A can be measured by drawing a vertical line through point A and up to the frontier. The ratio between A'D and A'A is a measure of the technical inefficiency of country A.

For the case of two time periods, with the bold line showing the frontier of year 1 and the dashed one representing the frontier of year 2, quadrant II shows how the frontier country has moved to the right due to attaining a higher K/L ratio. Again only one country (B) is assumed to be on the frontier. Furthermore, country A is supposed not to have moved at all between the two time periods.

The usual interpretation of what has happened is that there has been technological progress with the result of the dashed line moving above the bold one. However, for a whole segment of the frontier there has been technological regress,

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[5] It is worth noting here that a constant-returns-to-scale (CRS) technology needs to be assumed in order to properly measure TFP change by use of the Malmquist index (Grifell-Tatje and Lovell, 1995). However, when applying the Malmquist index at country level, the assumption of CRS seems to be appropriate, while in the case of plants such an assumption could be more problematic.

leaving the dashed line below the bold one. For country A, which is positioned under this segment, the interpretation would be that some previous relatively advanced production technique is no longer utilisable for A and similar countries, as if it had been ‘forgotten’. And since the frontier has receded towards country A’s location, the country has in effect come closer to the frontier, or in other words, country A appears to have caught up with the more advanced countries.

This paper maintains that on both accounts such an interpretation is erroneous. Technical efficiency is upwards biased because in one segment the frontier has been *allowed* to recede. Similarly, it can be argued that technological change has been measured with a downward bias. These biases, however, do not affect TFP change because the downward bias of technological change is fully compensated by the upward bias of technical-efficiency change. For that reason, if interest centres on TFP change alone the analysis can still produce useful results. However, if the sources of productivity change are to be identified and quantified, problems arise: Country A would erroneously be seen as improving its technical efficiency, while in fact nothing has changed for A.

While it was argued above that DEA is a useful tool for computing productivity change, it was also admitted that it has its flaws when applied to macro data. One may hold the view that DEA, by construction, is not well suited for application to macro data. Furthermore, allowing for technological memory loss might be defended on the grounds that there is a conflict between real data and theory as well as between real data and an interpretation of a best-practice frontier as one of world technology.

But there are counterarguments. First, on the construction side, DEA only needs a few amendments to be suitable for macro data. Second, by necessity the ‘estimated’ frontier is based on actual output and actual use of inputs, while a technological-knowledge frontier rather ought to be connected with potential output. It is known from the macro literature that even the best-performing countries do not produce up to their potential. And even if countries had the knowledge to produce at a higher level there may be circumstances that do not allow them to do so. This might sound like a serious drawback for trying to approximate the world-technology frontier with the world best-practice frontier. But on these two points the next section offers a solution.

3 The Long-Memory Data-Envelopment Analysis (LMDEA)

This section describes, with reference to Figure 1, how countries' technological memory can be preserved throughout the sample period. In quadrant II of the figure, the frontier country is seen to move from point B to B', where B' is located to the right of B. The movement of country B is such that a certain segment of the new world-technology frontier is positioned inside the previous year's frontier. For the likes of country A, this would entail technological regress. At the same time, this situation would be characterised by overestimation of technical-efficiency change.

Quadrant III shows how the problems of technological regress and consequent overestimation of technical-efficiency change can be rectified. That part of Figure 1 reflects the assumptions that the frontier country moves linearly from point B to B' and that, in order to prevent loss of knowledge, B is retained as a potential frontier point in all subsequent periods of the analysis. Hence, an 'artificial' frontier country (B) has been created in period 2. Country A is now at the same distance from the frontier in the second time period as it was in the first. Furthermore, the knowledge of production techniques that A had in the first period is retained in the second period. Quadrant IV shows the "new" world-technology frontier after points B and B' have been connected.

At this stage, a few remarks seem to be in place. First, measures of TFP-change using the original DEA or the LMDEA are nearly identical; numerical differences are negligible. Hence, if one is interested only in TFP change, and not in its decomposition, the original version of DEA can be used without problems. Second, since point B in the second period is an artificial frontier country it cannot play the role of a so-called peer country, i.e. a reference country from which to learn on policy issues. However, country B can still be used for policy discussions relating to the first period.

Third, in terms of production techniques, the area outlined by B, C and B' represents 'unknown' territory. For countries located between B and B' it can be argued that there is a risk of *under*estimating technical-efficiency change, or conversely, of overestimating technological progress. Could the line not be drawn from B to C and further to B' instead? The answer is no, as that would violate the concavity assumption needed for applying the DEA method. And also, why would the frontier country's move from B to B' pass through C? This is not to say that such a move is impossible, but only those data points that are actually observed are of interest. Furthermore, tracking the movement from B to B' has to do more with the dynamic path measured in smaller time intervals than that of a year. Therefore, approximating the (possibly non-linear) move from B to B' with a straight line seems as good as any other approximation.

4 An application of LMDEA

This section starts with a brief summary of three papers that have employed DEA to a set of countries. Thereafter, DEA and LMDEA are applied and the results obtained from these two methods are compared. Finally, the LMDEA results are compared with some of the results found in previous studies.

4.1 Literature review

Penn-World Tables Mark 5 provide the basis of the study by Färe *et al* (1994). The data cover 17 OECD countries over the years 1979-88. Output (real GDP) is assumed to be produced using labour and capital. The authors find that on average over the OECD countries TFP change was 0.7 per cent per year. Technological progress explained TFP change in all countries and showed an annual average change of 0.85 per cent. Hence, TFP growth in OECD countries was driven entirely by innovation resulting in technological progress. Technical efficiency, by contrast, deteriorated slightly over time. Using the same method as Färe *et al* (1994) the present paper obtains similar results for a slightly larger sample of industrialised countries, however with one important exception: for one country technological regress is detected.[6]

In Rao and Coelli (1998) the output variable is real GDP per capita with the inputs being labour and capital per capita. The data source from Penn-World Tables Mark 5.6 and cover 60 countries for the period 1965-90. For Latin America and North Africa/Middle East negative annual TFP growth is observed, while the highest TFP growth rate is that of Asia (0.99 per cent annually).

The paper reports several cases of technological regress. For instance, among OECD countries Denmark, Italy, and the Netherlands belong to this group, whereas Africa and Latin America exhibit the largest numbers of such cases. Even among the

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[6] This exception is Iceland, a country that was not included in the sample of Färe *et al* (1994).

Asian ‘Tigers’ there is one instance (Korea) of technological regress. Not surprisingly, change in technical efficiency is reported as being largest for those countries that experience negative technological change. Unfortunately, the authors do not comment on these cases, and they also refrain from questioning the occurrence of technological regress as such.

Krüger, Cantner, and Hanusch (2000) study the ‘East-Asian Miracle’ from 1960 to 1990, splitting their data into two time periods, namely 1960-73 and 1973-90. The paper is based on a fairly broad dataset covering 87 countries and drawing on Penn-World Tables Mark 5.6. Output is gross domestic product in international 1985 prices, labour is retrieved from the dataset, and while capital stock data are constructed from investment data by use of the perpetual inventory method. This increases the number of countries in the sample compared to other studies. The paper compares three groups of countries: the G7, Latin America, and a group of Newly Industrialised Countries (NICs). The authors find that the first period was characterised by factor accumulation, while in the second period, in addition to factor accumulation, there were effects of technology assimilation and learning along the lines of Nelson and Pack (1999). Over the second time period, three of the four NIC countries had positive TFP growth (the exception being Korea) where, on average, NIC productivity increased by 0.64 per cent annually. The corresponding figures for G7 countries and for Latin America were 0.76 and -0.70 per cent, respectively. Singapore had the fastest TFP growth (1.26 per cent) of all countries in the sample.

Turning to the change in technical efficiency, the average annual rate for NIC countries was 2.55 per cent, an impressive figure suggesting rapid catching-up. G7 countries had on average a positive change amounting to 0.58 per cent (where Canada lost relative to the frontier), while Latin American countries increased technical efficiency by 0.91 per cent annually. Finally, all NICs experienced technological regress, amounting to an average of -1.86 per cent annually. With the exception of Venezuela, also all Latin American countries faced negative technological change. And among the G7 countries, only five progressed technologically (the exceptions being Japan and the UK) with an average rate of change of 0.18 per cent for the group as a whole.

The main argument of the presented paper is that the productivity figures presented above can be taken as correct and a change of method should result only in minor differences. However, for countries that are allegedly suffering from technological regress, change in technical efficiency reported in the aforementioned studies is likely to be exaggerated.

4.2 Results of LMDEA

The dataset used here covers 57 countries (including 22 OECD countries), where availability of capital-stock data is the limiting factor with respect to country coverage. The data, which are drawn from Penn World Tables Mark 5.6, span 11 years (1980-90). Values of output and capital are in international 1985 prices. Summers and Heston (1991) describe in detail how the variables have been created.

GDP (in chain index form) constitutes the output measure, while labour and capital are the only inputs.[7] Capital stock is non-residential capital only and is derived from capital stock per worker, while labour is derived from GDP per worker. On the basis of these data a world-technology frontier is constructed for each year and used to assess productivity change for individual countries.

Table 1 shows average annual growth rates of output, labour, and capital for all 57 countries as well as group averages for a few sub-groups of countries: OECD, the 'Tiger' economies of East Asia, a group of Sub-Saharan African countries, and other developing countries. For these country groups both unweighted and weighted averages are calculated with the weight being the size of the economy (real GDP). Among these groups of countries, the 'Tiger' economies have grown by close to eight per cent annually, with a high contribution coming from increases in capital. Capital accumulation was very fast in Taiwan and Korea, but also in Iran. Likewise, Thailand, Paraguay, Mauritius, Iceland, the Dominican Republic, and Chile experienced rapid capital accumulation with growth of more than five per cent per year. A similar pattern of capital accumulation dominating output growth emerges for the developing countries as a whole. But there are exceptions, like Zambia and Jamaica where the stock of capital decreased. The slowest growers on average are found in Africa, with the growth of labour outpacing capital accumulation. For instance, labour grew by 4.8 per cent or more per year in Kenya, Zimbabwe, and Nigeria.

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[7] There may be good reasons to disaggregate output for improved accuracy when measuring TFP change and its components (Forstner and Isaksson, 2002). However, in order to allow for comparison with other studies, aggregate output is used in the present exercise as well.

The country with the fastest growing output was Korea with an annual rate of nearly eight per cent. Other fast growers were Taiwan (7.5 per cent), Hong Kong (7.2 per cent), Thailand (6.8 per cent), and India (6.1 per cent). A rapid grower among the 'other' developing countries was Turkey with an annual rate of 4.6 per cent, while Japan and Portugal are two other countries with an average annual growth rate of more than four per cent. Among the African countries, Kenya, Mauritius, Morocco, and Zimbabwe grew by more than three per cent per year. In Latin America the fastest growing country was Paraguay (four per cent). By contrast, annual output growth was negative in a handful of countries in the sample, namely, Argentina, Côte d'Ivoire, Madagascar, and Sierra Leone.

In Table 2, the Malmquist-productivity indexes together with the indexes of technical-efficiency change and technological change are presented in two sets of columns: the first column shows the figures for the unmodified DEA, the second column the results obtained from the application of LMDEA. An index larger than one indicates improvement, a figure smaller than one deterioration of performance.

The standard DEA of OECD countries shows that on average TFP growth was nearly one per cent annually and was entirely driven by innovation. Only Iceland experienced technological regress, but the country showed unimpressive performance on all accounts. The 'Tiger' economies enjoyed very high TFP growth (over three per cent annually), an empirical fact that contrasts with the critique of the 'miracle' view. This critique, voiced by Paul Krugman and Alwyn Young among others, built on the assertion that the Asian 'Tigers' grew only by way of factor accumulation. The results provided here offer a different view and show that excellent TFP performance of these countries was entirely a catching-up affair. In the case of Hong Kong, for instance, the change in technical efficiency was over four per cent per year.

For Sub-Saharan African countries, TFP growth was negative on average, where Malawi, Mauritius, and Zimbabwe were the sole exceptions showing positive rates. All these countries experienced technological regress so that their positive change in technical efficiency comes as no surprise, according to what was discussed before. Malawi and Mauritius stand out with exceptional annual increases in technical efficiency of 3.8 and 2.7 per cent, respectively. As for the rest of the developing countries, it should be noticed that on average they experienced technological regress, positive change in technical efficiency, and slightly positive TFP growth when the average is GDP-weighted. Among these countries, India did exceptionally well, while several Latin American countries are among the worst performers.

Application of LMDEA produces a strongly modified picture. Since all OECD countries in the sample except one (Iceland) had positive technological change, there is not much difference for these countries between the results from both approaches. However, it is reassuring that the LMDEA results also square well with those of Färe *et al* (1994). Similar to OECD countries, the remarkable performance of the 'Tiger' economies is reflected also in the LMDEA figures. These figures are in stark contrast to what Krugman (1994) and Young (1994, 1995) have argued on the one hand, and to the results obtained by Krüger, Cantner, and Hanushek (2000) on the other. The chief factor behind these countries' growth has been improvement of technical efficiency, or catching-up.

It is also instructive to consider African countries again. Technical-efficiency improvement of 3.8 per cent for Malawi and 2.7 per cent for Mauritius measured by the standard DEA technique decreases to 1.1 and 1.6 per cent, respectively, when LMDEA is applied. For Kenya and Zimbabwe the latter method assesses deterioration in technical efficiency, whereas the former suggested a one-per cent improvement. Two other African countries, Sierra Leone and Mauritius, display even significant differences in TFP growth, pointing out that measurement problems may not be confined to the components of TFP change alone.

For the 'other' developing countries as a group, LMDEA shows no signs of technical-efficiency improvement and results for individual countries provide more detail to this picture. India's 4.3 per cent increase in technical efficiency per year is now down to 2.6 per cent, nevertheless a figure that is still impressive. And many of the remaining countries in the group for which DEA produces positive technical-efficiency change exhibit negative change under LMDEA.

5 Conclusions

This paper has argued that DEA is an acceptable tool for analysing economic performance at country level when compared with the growth accounting and stochastic-frontier approaches. Among the most important advantages of DEA is that no behavioural assumptions need to be made. Moreover, no assumptions about the functional form of the production function or distributional form of the error term are required. In computing the Malmquist-TFP index, DEA allows for a useful decomposition of TFP change into technological change and change in technical efficiency. Such decomposition appears most valuable for the assessment of economic performance and can also inform policy discussions.

One drawback of the standard DEA is that the method allows countries to lose knowledge about production techniques. This kind of memory loss is implausible and causes inaccurate measurement of technological change and technical-efficiency change. As a consequence, a country appears as performing exceptionally well in technical efficiency without actually having improved at all. This bias occurs when the country is located in a region where the world technology frontier is receding.

The amendment to DEA proposed here and called Long-Memory DEA (LMDEA) imposes on countries infinite technological memory in concordance with the nature of knowledge. The virtues of this amendment are twofold: First, LMDEA, by retaining all previous frontier points, prevents the technology frontier from moving inwards and thus preserves knowledge about production techniques. Second, it avoids overestimation of technical-efficiency change due to memory loss. The figures for TFP-change are in principle identical for DEA and LMDEA with occasional small differences. The view taken here is that if the focus is on productivity alone, standard DEA is viable.

In order to illustrate the risks of using standard DEA, and the virtues of using LMDEA for the purpose of evaluating various countries' growth performance, TFP change and changes in technology and technical efficiency were computed using both methods. Among the most striking results of this comparison is the fact that for African countries technical-efficiency change is grossly exaggerated in DEA estimates. And for countries like Kenya or Zimbabwe an improvement in technical efficiency suggested by DEA figures is actually turned into deterioration when using LMDEA. Similar examples are found among 'other' developing countries, where several instances of positive technical-efficiency change assessed by DEA turn negative with LMDEA. The results of the present paper also largely corroborate the findings of Färe *et al* (1994) that for OECD countries TFP growth was based on innovation. Finally, as an important by-product, the paper refutes the idea that the Asian 'Tiger' economies grew only by means of factor accumulation. It shows that, to the contrary, there was considerable TFP growth involved in the growth of these economies, and that this component was mainly the result of improvements in technical efficiency.

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Table 1. Average annual growth of output and input (per cent), 1980-90

OECD	**Output**	**Labour**	**Capital**
AUSTRALIA	3.06	1.88	3.86
AUSTRIA	2.20	0.80	4.06
BELGIUM	2.11	0.55	2.22
CANADA	2.88	1.31	5.22
DENMARK	1.82	0.61	2.32
FINLAND	3.35	0.74	3.81
FRANCE	2.14	0.94	3.11
GREECE	1.81	0.55	2.52
ICELAND	3.08	1.60	6.53
IRELAND	3.27	0.71	3.28
ITALY	2.43	0.68	3.07
JAPAN	4.17	0.78	6.10
LUXEMBOURG	3.53	0.76	4.21
NETHERLANDS	1.91	1.34	2.60
NEW ZEALAND	1.72	1.46	3.05
NORWAY	2.61	1.03	2.43
PORTUGAL	4.29	0.50	4.33
SPAIN	2.92	0.91	4.41
SWEDEN	2.00	0.69	3.77
SWITZERLAND	2.35	0.87	3.50
U.K.	2.39	0.51	3.02
U.S.A.	2.33	1.24	3.56
Unweighted mean	***2.65***	***0.93***	***3.68***
Weighted mean	***2.79***	***1.00***	***4.07***

TIGERS	**Output**	**Labour**	**Capital**
HONG KONG	7.23	1.80	3.21
KOREA	7.95	1.98	8.69
TAIWAN	7.51	2.03	8.97
Unweighted mean	***7.57***	***1.94***	***6.95***
Weighted mean	***7.71***	***1.98***	***8.26***

AFRICA	**Output**	**Labour**	**Capital**
CÔTE D'IVOIRE	-1.61	2.77	3.19
KENYA	3.68	5.22	2.42
MADAGASCAR	-0.54	2.11	1.90
MALAWI	2.78	2.64	1.40
MAURITIUS	3.98	1.74	5.73
NIGERIA	0.22	4.80	1.91
SIERRA LEONE	-0.03	1.69	4.14
ZAMBIA	0.72	3.44	-2.34
ZIMBABWE	3.52	5.13	0.22
Unweighted mean	***1.41***	***3.28***	***2.06***
Weighted mean	***1.34***	***4.36***	***1.52***

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OTHER DEVELOPING COUNTRIES	Output	Labour	Capital
ARGENTINA	-1.14	0.96	1.01
BOLIVIA	0.64	2.51	0.06
CHILE	3.42	2.47	5.77
COLOMBIA	3.30	2.52	3.32
DOMINICAN REP.	2.66	3.24	5.93
ECUADOR	1.54	2.77	4.63
GUATEMALA	1.15	2.88	2.26
HONDURAS	2.43	3.90	1.64
INDIA	6.07	2.25	4.90
IRAN	1.45	3.95	8.17
ISRAEL	3.87	2.37	2.49
JAMAICA	1.21	2.31	-0.75
MEXICO	2.53	2.77	2.49
MOROCCO	3.95	3.44	1.05
PANAMA	1.91	2.81	2.59
PARAGUAY	4.01	3.22	5.45
PERU	0.37	2.56	2.35
PHILIPPINES	2.08	2.56	2.85
SRI LANKA	4.35	1.45	3.73
SYRIA	3.03	3.24	4.63
THAILAND	6.81	2.36	6.70
TURKEY	4.63	2.38	4.05
VENEZUELA	0.14	3.29	1.73
Unweighted mean	***2.63***	***2.70***	***3.35***
Weighted mean	***3.38***	***2.54***	***3.95***

ALL DEVELOPING COUNTRIES, UNWEIGHTED	Output	Labour	Capital
TIGERS	7.57	1.94	6.95
AFRICA	1.41	3.28	2.06
OTHER DEVELOPING COUNTRIES	2.63	2.70	3.35
Unweighted mean	***2.74***	***2.78***	***3.33***

ALL DEVELOPING COUNTRIES, WEIGHTED	Output	Labour	Capital
TIGERS	7.71	1.98	8.26
AFRICA	1.34	4.36	1.52
OTHER DEVELOPING COUNTRIES	3.38	2.54	3.95
Weighted mean	***4.03***	***2.54***	***4.58***

Note: Weighted means are computed with real GDP as the weight. For ease of reference, brief names are used for the following three ‘Tiger’ economies.

Table 2. DEA and LMDEA index numbers, annual averages 1980-90

	DEA				LMDEA		
OECD	**ΔTE**	**ΔTC**	**ΔTFP**	**OECD**	**ΔTE**	**ΔTC**	**ΔTFP**
AUSTRALIA	0.995	1.015	1.010	AUSTRALIA	0.995	1.016	1.010
AUSTRIA	0.994	1.006	1.000	AUSTRIA	0.993	1.009	1.002
BELGIUM	0.998	1.015	1.013	BELGIUM	0.998	1.016	1.013
CANADA	1.002	1.016	1.018	CANADA	1.001	1.016	1.018
DENMARK	1.003	1.004	1.007	DENMARK	1.001	1.007	1.008
FINLAND	1.006	1.017	1.023	FINLAND	1.006	1.017	1.023
FRANCE	0.997	1.015	1.012	FRANCE	0.997	1.015	1.012
GREECE	1.003	1.002	1.005	GREECE	1.002	1.003	1.005
ICELAND	0.987	0.996	0.983	ICELAND	0.985	1.002	0.988
IRELAND	1.015	1.002	1.017	IRELAND	1.014	1.003	1.017
ITALY	1.000	1.001	1.001	ITALY	0.998	1.004	1.001
JAPAN	1.006	1.004	1.010	JAPAN	1.006	1.005	1.011
LUXEMBOURG	1.011	1.018	1.029	LUXEMBOURG	1.011	1.018	1.029
NETHERLANDS	0.996	1.005	1.000	NETHERLANDS	0.994	1.007	1.001
NEW ZEALAND	0.991	1.010	1.001	NEW ZEALAND	0.989	1.012	1.001
NORWAY	0.997	1.017	1.015	NORWAY	0.997	1.017	1.015
PORTUGAL	1.011	1.002	1.013	PORTUGAL	1.011	1.004	1.015
SPAIN	1.002	1.001	1.003	SPAIN	1.000	1.003	1.003
SWEDEN	0.998	1.016	1.013	SWEDEN	0.997	1.016	1.013
SWITZERLAND	0.993	1.018	1.011	SWITZERLAND	0.993	1.018	1.011
U.K.	1.010	1.001	1.011	U.K.	1.009	1.003	1.012
U.S.A.	1.000	1.008	1.008	U.S.A.	1.000	1.010	1.010
Unweighted mean	***1.001***	***1.009***	***1.009***	***Unweighted mean***	***1.000***	***1.010***	***1.010***
Weighted mean	***1.001***	***1.008***	***1.009***	***Weighted mean***	***1.001***	***1.009***	***1.010***
TIGERS	**ΔTE**	**ΔTC**	**ΔTFP**	**TIGERS**	**ΔTE**	**ΔTC**	**ΔTFP**
HONG KONG	1.042	1.005	1.048	HONG KONG	1.042	1.005	1.048
KOREA	1.035	1.000	1.034	KOREA	1.034	1.001	1.035
TAIWAN	1.022	1.001	1.023	TAIWAN	1.021	1.003	1.024
Unweighted mean	***1.033***	***1.002***	***1.035***	***Unweighted mean***	***1.032***	***1.003***	***1.036***
Weighted mean	***1.031***	***1.001***	***1.031***	***Weighted mean***	***1.030***	***1.002***	***1.032***
AFRICA	**ΔTE**	**ΔTC**	**ΔTFP**	**AFRICA**	**ΔTE**	**ΔTC**	**ΔTFP**
IVORY COAST	0.990	0.982	0.973	IVORY COAST	0.970	1.002	0.972
KENYA	1.010	0.983	0.992	KENYA	0.988	1.002	0.990
MADAGASCAR	0.987	0.985	0.972	MADAGASCAR	0.970	1.002	0.973
MALAWI	1.038	0.975	1.012	MALAWI	1.011	1.000	1.011
MAURITIUS	1.027	0.988	1.014	MAURITIUS	1.016	1.003	1.019
NIGERIA	0.986	0.977	0.964	NIGERIA	0.961	1.002	0.963
SIERRA LEONE	1.000	0.968	0.968	SIERRA LEONE	0.973	1.000	0.973
ZAMBIA	0.998	0.987	0.984	ZAMBIA	0.979	1.002	0.981
ZIMBABWE	1.010	0.995	1.005	ZIMBABWE	0.999	1.003	1.002
Unweighted mean	***1.005***	***0.982***	***0.987***	***Unweighted mean***	***0.985***	***1.002***	***0.987***
Weighted mean	***0.997***	***0.983***	***0.981***	***Weighted mean***	***0.977***	***1.002***	***0.979***

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OTHER	**ΔTE**	**ΔTC**	**ΔTFP**	**OTHER**	**ΔTE**	**ΔTC**	**ΔTFP**
ARGENTINA	0.971	1.003	0.975	ARGENTINA	0.971	1.004	0.974
BOLIVIA	1.002	0.998	1.000	BOLIVIA	0.995	1.003	0.998
CHILE	0.983	1.000	0.983	CHILE	0.981	1.004	0.985
COLOMBIA	0.998	1.003	1.001	COLOMBIA	0.997	1.004	1.001
DOMINICAN REP.	0.974	0.996	0.970	DOMINICAN REP.	0.968	1.003	0.971
ECUADOR	0.975	1.003	0.978	ECUADOR	0.974	1.003	0.977
GUATEMALA	0.993	0.993	0.986	GUATEMALA	0.983	1.003	0.985
HONDURAS	1.006	0.994	1.000	HONDURAS	0.996	1.003	0.999
INDIA	1.043	0.984	1.027	INDIA	1.026	1.002	1.029
IRAN	0.970	1.005	0.975	IRAN	0.970	1.004	0.974
ISRAEL	1.010	1.002	1.012	ISRAEL	1.009	1.003	1.012
JAMAICA	1.016	0.992	1.008	JAMAICA	1.004	1.003	1.007
MEXICO	0.990	1.006	0.996	MEXICO	0.990	1.004	0.994
MOROCCO	1.025	0.990	1.015	MOROCCO	1.009	1.002	1.011
PANAMA	0.977	1.003	0.980	PANAMA	0.977	1.003	0.980
PARAGUAY	1.000	0.977	0.977	PARAGUAY	0.979	1.001	0.980
PERU	0.971	1.001	0.972	PERU	0.968	1.004	0.971
PHILIPPINES	1.000	0.992	0.992	PHILIPPINES	0.989	1.003	0.992
SRI LANKA	1.012	1.000	1.013	SRI LANKA	1.010	1.004	1.013
SYRIA	0.981	1.000	0.981	SYRIA	0.981	1.003	0.983
THAILAND	1.035	0.994	1.028	THAILAND	1.026	1.003	1.030
TURKEY	1.018	0.999	1.017	TURKEY	1.013	1.004	1.017
VENEZUELA	0.981	1.003	0.984	VENEZUELA	0.980	1.003	0.983
Unweighted mean	***0.997***	***0.997***	***0.994***	***Unweighted mean***	***0.991***	***1.003***	***0.994***
Weighted mean	***1.005***	***0.997***	***1.003***	***Weighted mean***	***0.999***	***1.003***	***1.003***

ALL DEVELOPING COUNTRIES, UNWEIGHTED

	ΔTE	**ΔTC**	**ΔTFP**		**ΔTE**	**ΔTC**	**ΔTFP**
TIGERS	1.033	1.002	1.035	TIGERS	1.032	1.003	1.036
AFRICA	1.005	0.982	0.987	AFRICA	0.985	1.002	0.987
OTHER	0.997	0.997	0.994	OTHER	0.991	1.003	0.994
Unweighted mean	***1.002***	***0.994***	***0.996***	***Unweighted mean***	***0.993***	***1.003***	***0.996***

ALL DEVELOPING COUNTRIES, WEIGHTED

	ΔTE	**ΔTC**	**ΔTFP**		**ΔTE**	**ΔTC**	**ΔTFP**
TIGERS	1.031	1.001	1.031	TIGERS	1.030	1.002	1.032
AFRICA	0.997	0.983	0.981	AFRICA	0.977	1.002	0.979
OTHER	1.005	0.997	1.003	OTHER	0.999	1.003	1.003
Weighted mean	***1.017***	***1.005***	***1.014***	***Weighted mean***	***1.011***	***1.011***	***1.014***

Note: All figures have been produced using Tim Coelli's software (Coelli, 1996). Weighted means are computed with real GDP as the weight. For ease of reference, brief names are used for the following three 'Tiger' economies. ΔTE stands for change in technical efficiency, ΔTC for technological change, and ΔTFP for change in total factor productivity.

Figure 1. Illustration of the long-memory frontier (LMDEA)

Assumptions:
Y-axis = Y/L, X-axis = K/L.
One country (B) on the frontier and one country A inside (*), the frontier country “moves” over time while country A does not change from year 1 to year 2.