# ASSESSING PRODUCTIVITY CHANGES IN UK HOSPITALS REFLECTING TECHNOLOGY AND INPUT PRICES

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## ABSTRACT

In this paper we use Malmquist productivity indexes to evaluate the performance of acute hospitals in the UK over the period after the introduction of the internal market in the National Health Service in 1991. The indexes are computed using non-parametric programming, known as Data Envelopment Analysis, and they are decomposed into multiple component measures to give insights into the trends in hospital performance. Overall we find that productivity regressed in the year after the reforms but progressed thereafter so that overall there was a net progress both as far as the inputs and costs are concerned. Productivity progress is mainly due to overall efficiency progress, which in turn is mostly attributed to allocative efficiency improvements. Technical change resulted in a small reduction in the amount of inputs used but also at higher production costs, because of a worsening in the match between input mixes and relative input prices. However, we suggest that the gains in productivity are not high enough to argue that the internal market has had a significant impact on productivity. Finally, it is argued that the methodologies employed here can be a valuable evaluative and managerial tool in the context of the new NHS reforms about to be introduced.

## I. INTRODUCTION

The measurement and analysis of productive performance either at firm, or at industry or finally at economy level has for long been a popular research area in economics and the related literature. Two concepts that have attracted considerable attention are *productivity* and *efficiency.* Although these are distinct concepts and they have developed separately, recently the two merged and the former incorporated the latter. Specifically, in early work in this field, *productivity change* was solely explained in terms of *technical (or technological) change*. However, the last two decades have seen the rapid development of a body of literature where it is acknowledged that productivity should account for (in)efficiency and that, in addition to technical change, *efficiency change* can also contribute to productivity change.

Grosskopf (1993) describes alternative approaches that can be used to measure and decompose productivity so that the contribution of efficiency is identified. One approach that has recently attracted considerable attention and is now becoming very popular is the Malmquist index approach. In this paper we employ it to study the performance of Scottish acute hospitals in the period after 1991. This is when a dramatic reform in the National Health Service took place with the introduction of the “internal market” that was created by means of a split between the providers and purchasers of health care services. It was thought that this system would gradually lead to efficiency and productivity gains. This would happen because of the competition that takes place as providers (ex NHS hospitals (now called Trusts) and private hospitals) try to attract the business of purchasers (General Practitioners, Health Authorities and the private sector). To be competitive and attract contracts hospitals now have no choice but to minimize the cost at which they provide their services relative to their competitors.

This paper is attempting to establish whether the reforms achieved their targets, i.e. whether they had a positive impact on hospital efficiency and productivity. To ascertain this we first use an input Malmquist index which we measure using non-parametric mathematical programming, know better as Data Envelopment Analysis (DEA). Thus, we base our analysis on minimum assumptions whilst we derive multiple decompositions of productivity into its component measures. Nonetheless, the input Malmquist productivity index reflects only input and output quantity data, whereas in the internal market it is the cost rather than the input quantities used in the production that matters. This is due to the fact that purchasers seek to find and contract with those hospitals which produce services at the lowest cost. Thus, a cost oriented approach would be more in line with the objectives of producers. Additionally, this is an industry where technical change is rapid and it mostly affects the cost at which output is delivered rather than the input quantities used to deliver it. Moreover, hospitals may diachronically improve their performance by changing their input mix rather than by changing the actual amount of inputs they employ. For these reasons we also use the cost Malmquist index developed recently by Maniadakis and Thanassoulis (1997). The two indices are complementary. The input index reflects input-output relationships and the cost index cost-output relationships. They are easy to compute, they are based on minimum assumptions and they provide multiple decompositions of productivity change into its root sources.

The paper unfolds as follows: section II lays out the basic concepts and illustrates the productivity measurement approach to be used; section III presents the empirical results; section IV summarises and discusses the results and section V concludes.

## II. METHODOLOGICAL BACKGROUND

### Production technology and the measurement of efficiency

Consider that in time period t, producers are using a vector of inputs $x^t \in \Re$ , to produce a vector of outputs $y^t \in \Re_+^m$. Define now the production technology of period t in terms of the *input requirement set*, which is:

$$L^t(y^t) = \{x^t : x^t \text{ can produce } y^t\}, \qquad (1).$$

$L^t(y^t)$ contains all input vectors that can produce the output $y^t$ in period t. Assume that $L^t(y^t)$ is non-empty, closed, convex, bounded, it satisfies strong disposability of inputs and outputs and it may exhibit either variable or constant returns to scale (VRS and CRS henceforth). The technology may also be defined in terms of the *input distance function* (Shephard, 1953, 1970) which is defined from the input set as:

$$D_I^t(y^t, x^t \mid cr) = \sup_\theta \{\theta : (x^t/\theta) \in L^t(y^t|cr\}, \theta > 0\} \qquad (2),$$

where the subscript I denotes input orientation and cr indicates that the distance function in (2) is defined under CRS, although, it may be defined under VRS in a similar fashion. $D_I^t(y^t, x^t \mid cr)$ measures the maximum factor required to deflate an input vector $x^t$ onto the CRS production boundary of the technology. $D_I^t(y^t, x^t \mid cr)$ is reciprocal to Farrell's (1957) input oriented measure of *technical efficiency,* which is defined as:

$$TE_I^t(y^t, x^t \mid cr) = \min_\phi \{\phi : (\phi x^t) \in L^t(y^t|cr), \phi > 0\}, \qquad (3).$$

$TE_I^t(y^t, x^t \mid cr)$ computes the maximum radial contraction of the vector $x^t$ within $L^t(y^t|cr)$. It may be defined under VRS in a similar fashion and in that case is often termed pure technical efficiency, $PTE_I^t(y^t, x^t \mid vr)$. The ratio of input technical to input pure technical efficiency gives an input oriented measure of scale efficiency, and so do their reciprocal distance functions, i.e.:

$$SE_I^t(y^t, x^t) = \frac{TE_I^t(y^t, x^t \mid cr)}{PTE_I^t(y^t, x^t \mid vr)} = \frac{D_I^t(y^t, x^t \mid vr)}{D_I^t(y^t, x^t \mid cr)} \qquad (4).$$

When input prices $w^t \in \Re_+^m$ are available, one may also define technology in terms of the *cost function*, which is:

$$C^t(y^t, w^t \mid cr) = \min_{x^t} \{w^t x^t : x^t \in L^t(y^t \mid cr), w^t > 0\} \qquad (5).$$

This function measures the minimum cost of producing a given output vector $y^t$ under the input prices $w^t$ and the technology of period t. With reference to some input - output correspondence $(x^t, y^t)$ define the input oriented measure of *overall (or cost) efficiency* ala Farrell (1957) as follows:

$$OE_I^t(y^t, x^t, w^t \mid cr) = \frac{C^t(y^t, w^t \mid cr)}{w^t x^t} \qquad (6),$$

where $w^t x^t \equiv \sum_{n=1}^{N} w_n^t x_n^t$. $OE_I^t(y^t, x^t, w^t \mid cr)$ indicates the extent to which observed cost can be reduced while being able to produce the observed output. When $OE_I^t(y^t, x^t, w^t \mid cr) < 1$, the observed production cost is in excess of the minimum required to secure the observed output. This may be due to using excess amounts of input or/and using the wrong input mix in light of input prices. The first form of inefficiency is captured by the technical efficiency measure in (3) and the second is captured residually by the input oriented measure of *allocative* (or *price*) *efficiency*, defined as follows:

$$AE_I^t(y^t, x^t, w^t \mid cr) = \frac{OE_I^t(y^t, x^t, w^t \mid cr)}{TE_I^t(y^t, x^t \mid cr)} = \frac{C^t(y^t, w^t \mid cr) D_I^t(y^t, x^t \mid cr)}{(w^t x^t)} \qquad (7).$$

Like the efficiency measures in (3), (4) and (6), $AE_I^t(y^t, x^t, w^t \mid cr)$ is bounded in (0,1] and if $AE_I^t(y^t, x^t, w^t \mid cr) = 1 \Leftrightarrow OE_I^t(y^t, x^t, w^t \mid cr) = TE_I^t(y^t, x^t \mid cr) = 1/D_I^t(y^t, x^t \mid cr)$. It should be finally noted that, like the distance function, all the above efficiency measures are radial.

**The measurement of productivity**

Caves *et al.* (1982) have recently adapted to productivity measurement an index that was first proposed in the context of consumer theory by Sten Malmquist (1953), but it had laid unnoticed for three decades. Later, Färe *et al.* (1989) decomposed it into technical efficiency change and technical change and Maniadakis and Thanassoulis (1997) developed a cost Malmquist index which is also decomposed in price components. This section discusses the two complementary indexes in brief. Following Caves et al. (1982) and Färe *et al.* (1989) define the input Malmquist (IM) index as:

$$IM = \left[ \frac{D_I^t(y^{t+1}, x^{t+1} \mid cr)}{D_I^t(y^t, x^t \mid cr)} \frac{D_I^{t+1}(y^{t+1}, x^{t+1} \mid cr)}{D_I^{t+1}(y^t, x^t \mid cr)} \right]^{1/2} \qquad (8),$$

where $D_I^t(y^t, x^t \mid cr)$ is as in (2) and the rest of the distance functions in (8) are defined in a similar fashion. The index in (8) is in fact the geometric mean of two indices. The first, that is the first ratio inside the square brackets, compares $(x^t, y^t)$ to $(x^{t+1}, y^{t+1})$ by measuring their distance from the production technology of period t. The second index does the same but with reference to the production technology of period t+1. Thus, the production technology simply serves as a benchmark to compare certain input-output bundles and thus to define productivity. The index in (8) is defined under CRS but it captures productivity change irrespective of whether or not the underlying technology is CRS (Färe and Grosskopf, 1994), Färe, Grosskopf and Norris, 1997, and Maniadakis and Read, 1997). An index value less than 1 in (8) indicates productivity progress, in the sense that lower inputs are needed to secure certain output and similarly a value over 1 implies regress and a value of 1 indicates constant productivity.

In a multiple input-output production environment allocative efficiency is important as it too can contribute to productivity change. Thus, Maniadakis and Thanassoulis (1997) extended the Malmquist index approach illustrated above and developed a cost Malmquist index applicable to the case where, in addition to input-output quantities, input prices are known. The cost Malmquist (CM) productivity index is defined as follows:

$$CM = \left[ \frac{w^t x^{t+1} / C^t(y^{t+1}, w^t \mid cr)}{w^t x^t / C^t(y^t, w^t \mid cr)} \; \frac{w^{t+1} x^{t+1} / C^{t+1}(y^{t+1}, w^{t+1} \mid cr)}{w^{t+1} x^t / C^{t+1}(y^t, w^{t+1} \mid cr)} \right]^{1/2} \qquad (9).$$

In the way that the input distance function in (2) is reciprocal to the input measure of technical efficiency in (3), the cost ratios in (9) are reciprocal to the input measure of overall efficiency in (6). Thus, one can imagine them as 'cost distance functions', which can be decomposed into technical and allocative parts. The CM index has a similar interpretation to the IM index in (8). It is a geometric mean of two indices. The first (i.e. the first ratio in the brackets) compares the two production points under evaluation by measuring their distance from the cost technology of period t and the second index does the same but with reference to the cost technology of period t+1. Therefore, now the cost technology is used as a benchmark to define productivity instead of the production technology. The implication of this is that instead of comparing input vectors to technically efficient ones here we compare them to overall efficient ones. Thus, as with the input index in (8), the index in (9) is defined under CRS, thought it is not necessary to assume that this is the prevailing technology. An index value less than 1 in (9) indicates productivity progress because this implies that production is less costly in period t and similarly an index value over 1 implies regress, whereas constant productivity is signalled by a value of 1. Clearly, when allocative inefficiency does not exist, the index in (8) and that in (9) will give identical results (see (7)).

The two indices are illustrated graphically in Figure 1, where $y^t$ and $y^{t+1}$ have been standardised to the same level. The figure depicts a case where the technology moves closer to the origin in period t+1 and the producer moves from point G in period t and at point B in period t+1. In terms of the distances in Figure 1, the input Malmquist productivity index in (8) is: $IM = \left[ \frac{OB/OC}{OG/OE} \frac{OB/OA}{OG/OF} \right]^{1/2}$ and the cost Malmquist index in (9) is: $CM = \left[ \frac{OB/OZ}{OG/OM} \frac{OB/ON}{OG/OH} \right]^{1/2}$. This makes it clear that in the IM index contracts production points on the production boundary, whereas the CM index reflects them on the cost boundary. The most attractive feature of the two Malmquist indexes presented above is that they can be decomposed to provide insights into the root sources of productivity change. Their decompositions are graphically shown in Figure 2, where the subset of white boxes relates to the decompositions of the input Malmquist index, developed in Färe et al. (1989, 1994a,b). Their mathematical formulations are given in Appendix A. In summary, overall efficiency change (OEC) shows whether the producer becomes more cost efficient over time. Put in other words, whether it catches-up its cost frontier. In terms of the distances in

**Figure 1:** The input and the cost Malmquist index

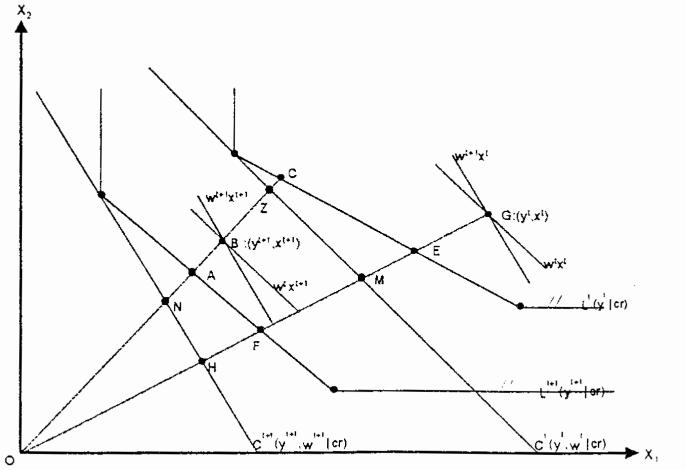

**Figure 2:** Productivity change and its decompositions

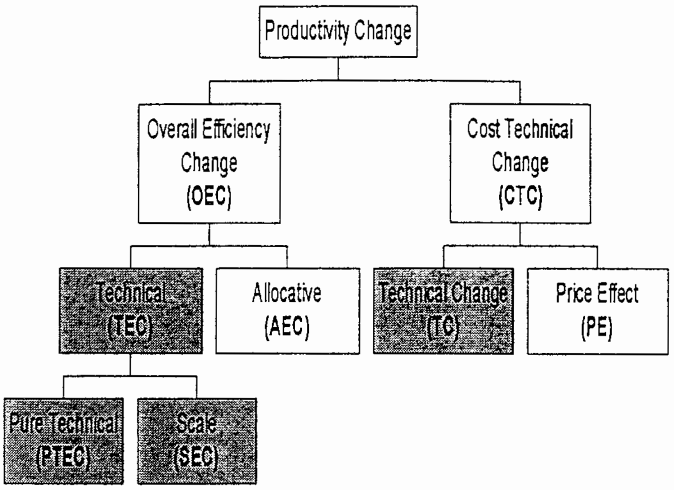

Figure 1, OEC is: (OB/ON)/(OG/OM). OEC can be then multiplicatively decomposed into technical efficiency change (TEC) and allocative efficiency change (AEC). Their interpretation is intuitive. In terms of the distances in Figure 1, AEC is: (OE/OM)/(OA/ON) and TEC is: (OG/OE)/(OB/OA). The last component can be further decomposed into pure technical efficiency change (PTEC) and scale efficiency change (SEC). Cost technical change (CTC) measures the shift in the cost boundary when moving from period t and t+1, evaluated at data from both periods. In terms of the distances in Figure 1 CTC reduces to:$[(OH/OM)\ (ON/OZ)]^{1/2}$. This term can be decomposed into a technical (TC) and a price (PE) component. TC captures the shift of the production boundary at data from both periods and in terms of the distances in Figure 1, TC reduces to: $[(OA/OC)(OF/OE)]^{1/2}$. PE captures the residual impact of relative input price (allocative) changes on the shift of the cost boundary. In other words, this term captures the contribution of relative input price changes on changes of the minimum cost at which output is produced when moving from the one period to the next. In terms of the distances in Figure 1, PE reduces to: $[(OC/OZ)/(OA/ON)(OE/OM)(OF/OH)]^{1/2}$.

The above components of the input and the cost Malmquist index have similar interpretations with the index itself. A score less than 1 indicates progress, greater than 1 indicates productivity regress and a unit score indicates that performance stayed constant. These decompositions are graphically summarized in Figure 2.

## III. ASSESSING UK HOSPITAL PRODUCTIVITY TRENDS

In most western countries, the costs of health care have shown substantial increase during the last four decades and it is generally expected that, under the pressure of cost increasing technological change and increases in demand due to epidemiological and demographic factors, this trend with continue. This led recently many countries to reorganise their health care systems. In most cases the main aim of the reforms in health care was to contain costs through increases in efficiency and productivity. In the UK it was thought that this could be achieved with the introduction of some competition in health care markets. This became possible by splitting the provision from the financing (purchasing) of health care services. To evaluate the impacts of the reforms we use here the approach outlined in the previous section. We compute productivity and its components using the non-parametric mathematical programming models, known better by the name Data Envelopment Analysis (DEA), presented in Appendix B.

### *Data*

The data set was provided by the Information and Statistics Division (ISD) of the NHS in Scotland and covers a sample of 75 Scottish hospitals over the financial years 1991/2 to 1995/6 inclusive. This period is immediately after the introduction of the internal market in the NHS in April 1991. All 75 hospitals in the set provide only acute services, so as to be homogenous producers and they were selected from a total of 400 hospitals.

The outputs we used are listed in Table 1, which also shows their descriptive statistics. The outputs reflect accident and emergency attendances, outpatient attendances, day cases and inpatient discharges, the last three having been adjusted for case-mix so as to reflect the fact that dissimilar cases have dissimilar resource implications. Details of the methods used for case-mix adjustment are given in Maniadakis and Thanassoulis (1998). All outputs are constantly increasing after 1991/2 and its is noticeable that day cases almost doubled in the period considered. It is also noticeable that there are large variations between hospitals.

**Table 1:** Descriptive statistics of output variables

| Variable | Statistic | 1991/2 | 1992/3 | 1993/4 | 1994/5 | 1995/6 |
|---|---|---|---|---|---|---|
| A&E attendances | Mean | 17,521 | 17,521 | 17,925 | 18,494 | 19,470 |
| | St.dev. | 22,733 | 22,733 | 22,803 | 22,650 | 23,177 |
| | Min | 0 | 0 | 0 | 0 | 0 |
| | Max | 88,771 | 88,771 | 90,372 | 90,953 | 91,626 |
| Adjusted inpatients | Mean | 7,129 | 7,428 | 7,667 | 7,991 | 8,396 |
| | St.dev. | 8,705 | 9,065 | 9,408 | 9,963 | 10,964 |
| | Min | 112 | 79 | 87 | 160 | 92 |
| | Max | 35,847 | 37,316 | 37,453 | 38,936 | 53,969 |
| Adjusted day cases | Mean | 4,646 | 4,932 | 6,054 | 6,814 | 7,371 |
| | St.dev. | 6,511 | 6,264 | 7,562 | 7,897 | 8,639 |
| | Min | 0 | 0 | 0 | 0 | 0 |
| | Max | 31,280 | 31,113 | 42,077 | 28,911 | 30,928 |
| Adjusted outpatients | Mean | 63,755 | 65,024 | 67,384 | 80,523 | 80,485 |
| | St.dev. | 76,291 | 80,275 | 81,356 | 94,956 | 91,676 |
| | Min | 0 | 0 | 0 | 0 | 0 |
| | Max | 317,623 | 315,930 | 338,673 | 353,978 | 356,608 |

As can be seen in the previous section we need input prices to compute the CM index. The price we used for each one of the three labour inputs is the mean annual salary for that professional group. As a proxy for the price of beds and hospital volume we used the capital charge per bed and per cubic metre respectively. The capital charge is an annual amount given by the government to each hospital, towards the maintenance and replacement of the capital lost due to use and depreciation.[1] The inputs we used are listed in Table 2, which also shows their descriptive statistics. The inputs reflect the number of doctors, nurses and other personnel (all in whole time equivalents), the number of hospital beds and the cubic metres of the hospital buildings.

Looking at Table 2, it can be seen that there is large variation between hospitals. Average hospital labour increased constantly after 1991/2. The relatively higher increase in the average administrative personnel in each hospital may reflect attempts at better hospital management. The volume of building infrastructure also increases but only marginally. In contrast, the number of staffed beds decreases, which may be the result of an effort to increase occupancy rates and also to transfer inpatient to day care cases.

Input prices generally differed between hospitals. Descriptive statistics on them are displayed in Table 3. We want to estimate net productivity trends and thus we deflated input prices to 1991/2, using the NHS Hospital and Community Health Price Index. Looking at Table 3 it is clear that net salaries stayed constant or even declined slightly over the five

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[1] A similar approach for valuing labour and capital input has been used by Byrnes and Valdmanis (1995) - salaries and the depreciation per bed - and Zuckerman *et al.* (1994).

year period considered. Capital input prices fluctuated but overall they stayed constant over the entire period considered.

**Table 2:** Descriptive statistics of input variables

| Variables | Statistics | 1991/2 | 1992/3 | 1993/4 | 1994/5 | 1995/6 |
|---|---|---|---|---|---|---|
| Doctors (WTE) | Mean | 56 | 59 | 60 | 64 | 67 |
| | St.dev. | 74 | 76 | 80 | 82 | 86 |
| | Min | 1 | 2 | 2 | 2 | 1 |
| | Max | 319 | 320 | 342 | 346 | 357 |
| Nurses (WTE) | Mean | 326 | 330 | 337 | 333 | 337 |
| | St.dev. | 337 | 341 | 348 | 345 | 357 |
| | Min | 12 | 12 | 12 | 13 | 13 |
| | Max | 1,220 | 1,249 | 1,327 | 1,285 | 1,315 |
| Other personnel (WTE) | Mean | 200 | 203 | 210 | 229 | 245 |
| | St.dev. | 217 | 218 | 224 | 257 | 285 |
| | Min | 5 | 6 | 8 | 5 | 5 |
| | Max | 1,016 | 1,026 | 1,053 | 1,164 | 1,173 |
| Beds (annual staffed) | Mean | 275 | 273 | 275 | 260 | 255 |
| | St.dev. | 272 | 270 | 273 | 257 | 258 |
| | Min | 10 | 11 | 11 | 11 | 11 |
| | Max | 1,016 | 1,019 | 1,015 | 1,036 | 1,054 |
| Cubic Meters (per 100) | Mean | 1030 | 1037 | 1062 | 1090 | 1080 |
| | St.dev. | 1217 | 1231 | 1283 | 1395 | 1393 |
| | Min | 12 | 12 | 5 | 16 | 13 |
| | Max | 5468 | 5468 | 5468 | 6220 | 6224 |

**Table 3:** Descriptive statistics of input price variables

| Variables | Statistics | 1991/2 | 1992/3 | 1993/4 | 1994/5 | 1995/6 |
|---|---|---|---|---|---|---|
| Doctor salary | Mean | 40,444 | 41,701 | 41,203 | 37,932 | 40,902 |
| | St.dev. | 8,793 | 9,851 | 10,531 | 9,194 | 9,730 |
| | Min | 13,111 | 12,075 | 11,524 | 12,245 | 23,587 |
| | Max | 65,146 | 74,042 | 84,363 | 65,763 | 88,744 |
| Nurse salary | Mean | 14,986 | 14,910 | 14,429 | 14,393 | 14,218 |
| | St.dev. | 1,300 | 1,284 | 1,326 | 1,184 | 1,172 |
| | Min | 12,378 | 12,606 | 11,479 | 11,934 | 11,623 |
| | Max | 22,403 | 20,633 | 20,112 | 20,112 | 20,112 |
| Other person. salary | Mean | 11,746 | 11,753 | 12,081 | 11,829 | 11,377 |
| | St.dev. | 1,296 | 1,484 | 2,123 | 1,676 | 1,443 |
| | Min | 9,102 | 7,923 | 8,467 | 7,322 | 9,146 |
| | Max | 14,904 | 15,797 | 23,459 | 18,956 | 16,020 |
| Capital charge/Bed (000s) | Mean | 2,660 | 2,594 | 2,881 | 3,064 | 2,697 |
| | St.dev. | 1,652 | 1,923 | 1,424 | 1,637 | 1,339 |
| | Min | 505 | 699 | 916 | 744 | 828 |
| | Max | 10,354 | 14,336 | 7,431 | 9,838 | 5,821 |
| Capital charge/100 $m^3$ (000s) | Mean | 1,156 | 1,096 | 1,499 | 1,366 | 1,114 |
| | St.dev. | 560 | 495 | 1,849 | 773 | 495 |
| | Min | 109 | 474 | 430 | 379 | 343 |
| | Max | 4,186 | 3,684 | 16,323 | 4,785 | 3,015 |

The non-parametric approach to efficiency and productivity measurement is easy to compute, it easily accommodates multiple inputs and outputs and it is based on minimum assumptions. However, unlike the econometric approach, it does not offer any tools that can aid researchers to specify the most appropriate model or to test the validity and robustness of the estimated results. There are various hypothesis and misspecification tests for DEA (see Banker, 1996), but these are in their infancy. To deal with this many authors (e.g. Valdmanis, 1992, Ozcan, 1992, Hollingsworth and Parkin, 1995) study the robustness of the results to different model specifications. This is a kind of sensitivity analysis in a DEA framework. Others use conventional statistical tools such as correlation analysis and regression analysis (e.g. Salinas-Jimenez and Smith, 1997, Morey et al., 1992) as a prelude to the DEA analysis. We used both of these approaches to validate our model.

In a simulation study, Smith (1997) argues that when correctly specified DEA models give accurate estimates of efficiency and that the dangers of misspecification are greater when sample sizes are small and models simple, which is not the case here. Also, he found that results from models where potential inputs exhibit high correlations are more robust. Thus, we used correlation analysis to find which input variables relate more to the output variables, but also to find how the input variables were correlated with each other, so as to drop some of them. Then, we used econometrics to find whether the model specified was a correct one (e.g. Salinas-Jimenez and Smith, 1996). DEA relates input to output quantities and thus a production function would be the preferred approach for such an analysis. However, given the multiproduct character of the hospital production process its dual cost function which accommodates multiple outputs was used instead. Our analysis indicated that the selected variables - which have been traditionally used in this type of analysis - were appropriate and reflected adequately the transformation of inputs into outputs within hospitals. Nonetheless, we also performed sensitivity analysis using different model specifications but the results staid constant.

## Hospital Productivity Trends After the NHS Reforms

Summary information of the values obtained for the IM index in (8) and the CM index in (9) in respect of the hospitals in the sample are displayed in Table 4. It is recalled that an index value less than one indicates progress and greater than one regress.

Table 4: Hospital productivity trends*

| | 1991/2 - 1992/3 | 1992/3 - 1993/4 | 1993/4 - 1994/5 | 1994/5 - 1995/6 | 1991/2 - 1995/6 |
|---|---|---|---|---|---|
| **Mean input index** | **1.060** | **0.902** | **0.992** | **0.977** | **0.928** |
| Max progress | 0.572 | 0.232 | 0.431 | 0.434 | 0.435 |
| Max regress | 2.712 | 1.350 | 4.794 | 2.969 | 4.204 |
| Hospitals progressed | 41 | 54 | 49 | 44 | 52 |
| Hospitals constant | 0 | 0 | 0 | 1 | 0 |
| Hospitals regressed | 34 | 21 | 26 | 30 | 23 |
| **Mean cost index** | **1.012** | **0.933** | **0.966** | **0.999** | **0.912** |
| Max progress | 0.718 | 0.509 | 0.503 | 0.742 | 0.549 |
| Max regress | 2.401 | 1.332 | 4.804 | 1.772 | 4.823 |
| Hospitals progressed | 42 | 53 | 53 | 40 | 59 |
| Hospitals constant | 0 | 0 | 0 | 1 | 0 |
| Hospitals regressed | 33 | 22 | 22 | 34 | 16 |

*Mean scores are geometric means of the entire hospital sample

Looking at Table 4 it is clear that overall the two indices indicate similar productivity trends although they also have some small differences. In particular, the input Malmquist index, IM, indicates that there was 6% productivity regress between 1991/2 and 1992/3, but a 9.8%, 0.8% and 2.3% progress between the succeeding pairs of years. Thus, overall there was a net productivity progress as far as input quantities are concerned. This is also indicated in the rightmost column. This displays the index values obtained by comparing

1991/2 to 1995/6, i.e. the first and the last year of the period under evaluation and indicates productivity progress of the order of 7.2%.[2]

These trends in productivity as captured by the input Malmquist index are also depicted in Figure 3, which also displays 95% confidence intervals computed using a bootstrap algorithm proposed by Atkinson and Wilson (1995) especially for constructing confidence intervals around Malmquist indices and their components (see appendix C). It is noticeable that the cost Malmquist index, CM, shows only 1.2% regress in the first year compared to 6% in the case of the IM index. The CM index then also shows progress in the succeeding pairs of years so that the overall net result suggests there has been productivity progress. This is also indicated in the rightmost column which displays the CM index value between the first and the last year of the period under evaluation and indicates productivity progress of the order of 8.8% compared to 7.2% in the case of the IM index. These trends are also depicted in Figure 4, where it is clear that the overall positive result in hospital performance is statistically significant. Thus in general, the two indices agree that after an initial regress there was productivity progress. The two indices also agree in broad terms on the maximum progress, maximum regress and the numbers of hospitals registering progress or regress. It is also noticeable that between 1991/2 and 1992/3 where there is regress the majority of hospitals are progressing. This implies that the minority of hospitals which led the overall industry result regressed by a substantial margin. For this reason, it is important to shift the focus of the analysis from the industry to the individual hospital level with the aim to identify and separate best from worst practice and study their organizational and managerial characteristics and practices.

**Figure 3:** Mean productivity change

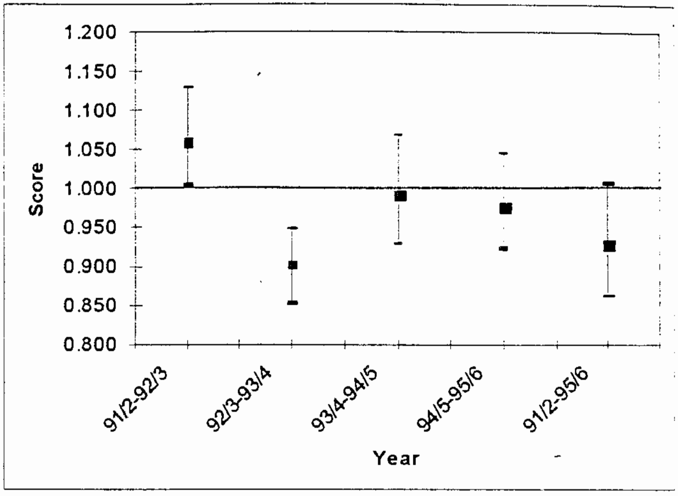
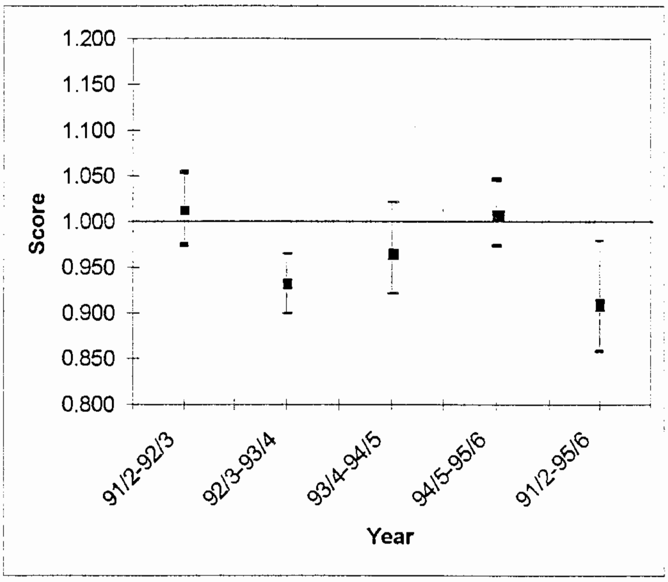


**Figure 4:** Mean cost productivity change



### The Components of Hospital Productivity Change

This section shows the results of the decomposition of the two indexes as summarised in Figure 2. Table 5 shows first the results of the decomposition of the CM index into the OEC and the CTC components. Looking at this table, it is seen that the CM index suggests

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[2] Note that this score is very close to the sum of the scores that relate to the four pair of years, which in this case is 6.9%. The same applies for the rest of the results given below and thus, for simplicity we shall stick to the results of the right foremost column.

progress or regress in concert with the CTC component in all succeeding pairs of years though the magnitude of the CM index is tempered by the OEC component.

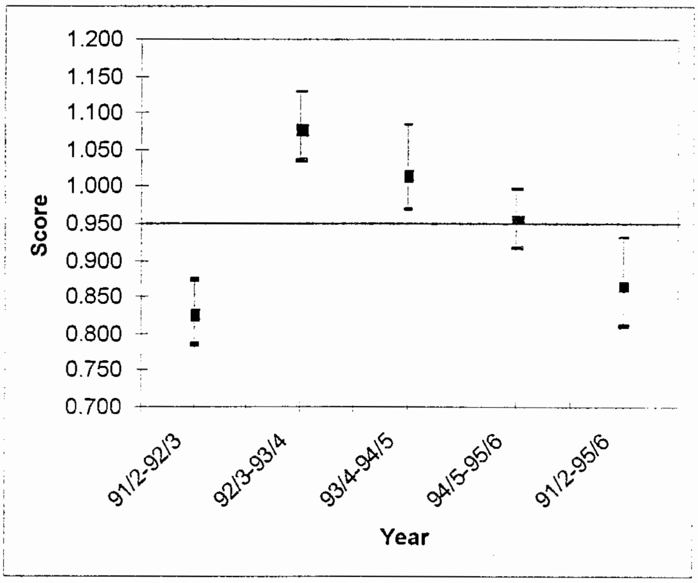
The rightmost column suggests that between the first and the last year after the NHS reforms the progress in productivity reflected in the CM index was due to improvements in overall efficiency, captured in the OEC component which takes a value of the order of 13.3%. This implies that on average hospitals come closer to their cost frontier during the period considered. These trends in overall efficiency are also depicted in Figure 5, where it is clear the progress in overall efficiency is statistically significant.

**Table 5:** The decomposition of hospital productivity change*

| | 1991/2 - 1992/3 | 1992/3 - 1993/4 | 1993/4 - 1994/5 | 1994/5 - 1995/6 | 1991/2 - 1995/6 |
|---|---|---|---|---|---|
| **Cost Malmquist Index** | **1.012** | **0.933** | **0.966** | **0.999** | **0.912** |
| Overall Efficiency Change | 0.827 | 1.079 | 1.016 | 0.956 | 0.867 |
| Cost Technical Change | 1.225 | 0.865 | 0.950 | 1.045 | 1.052 |

*Scores displayed are geometric means of the entire hospital sample

**Figure 5:** Mean overall efficiency change



The improvement in overall efficiency reflects mainly improvements in allocative efficiency across most hospitals as the decomposition results in Table 6 indicate. This table shows the decomposition of the OEC component into PTEC, SEC and AEC defined in (A4). It is seen that the large improvement in overall efficiency was mainly the result of improvement in allocative efficiency (8.9% between 1991/2 - 1995/6) and secondly the result of an improvement in pure technical efficiency (4.2%). Scale efficiency did not change overall. These trends in the components of productivity are also depicted in Figures 6,7 and 8 together with confidence intervals around them. It should be noted that the IM index does not capture the AEC but only the PTEC and SEC components. Thus, it does not reflect this large improvement in the performance of the hospitals.

**Table 6:** The decomposition of hospital overall efficiency change*

| | 1991/2 - 1992/3 | 1992/3 - 1993/4 | 1993/4 - 1994/5 | 1994/5 - 1995/6 | 1991/2 - 1995/6 |
|---|---|---|---|---|---|
| **Overall Efficiency Change** | **0.827** | **1.079** | **1.016** | **0.956** | **0.867** |
| Allocative Efficiency Change | 0.908 | 1.076 | 1.012 | 0.921 | 0.911 |
| Pure Technical Efficiency Change | 0.929 | 0.988 | 1.042 | 1.002 | 0.958 |
| Scale Efficiency Change | 0.980 | 1.015 | 0.964 | 1.036 | 0.993 |

*Scores displayed are geometric means of the entire hospital sample

Let us now focus on the CTC component and its decomposition into the TC and PE components. The trends in these components of productivity are displayed in Table 7 and Figures 9 to 11.

**Figure 6:** Mean allocative efficiency change

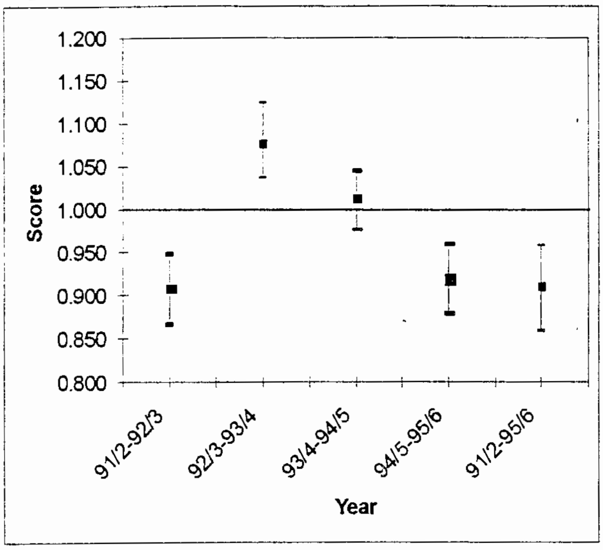


**Figure 7:** Mean pure technical effic. change

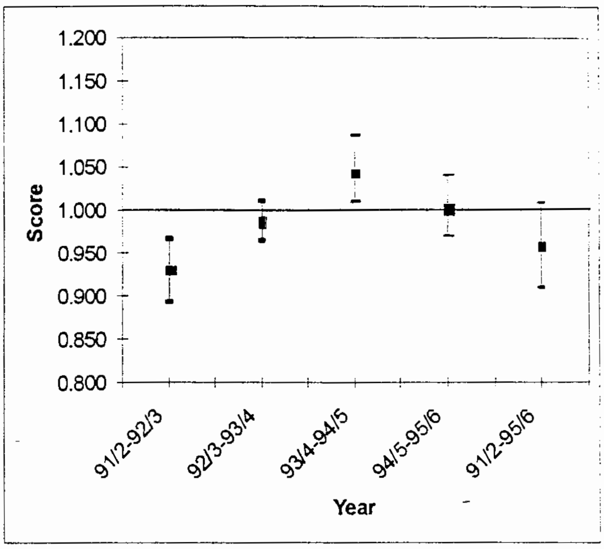


**Figure 8:** Mean scale efficiency change

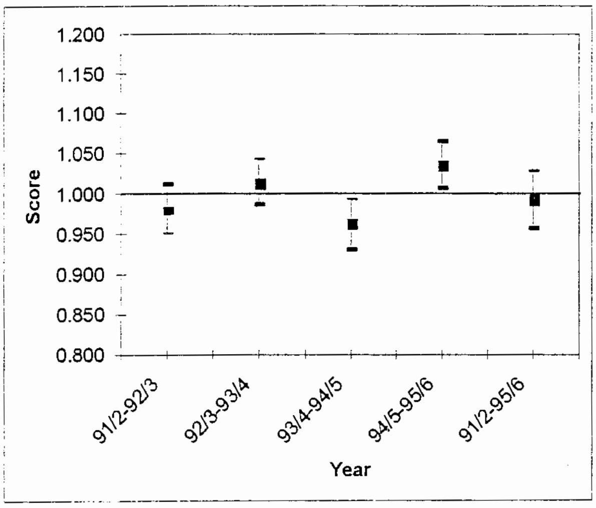


**Figure 9:** Mean cost technical change

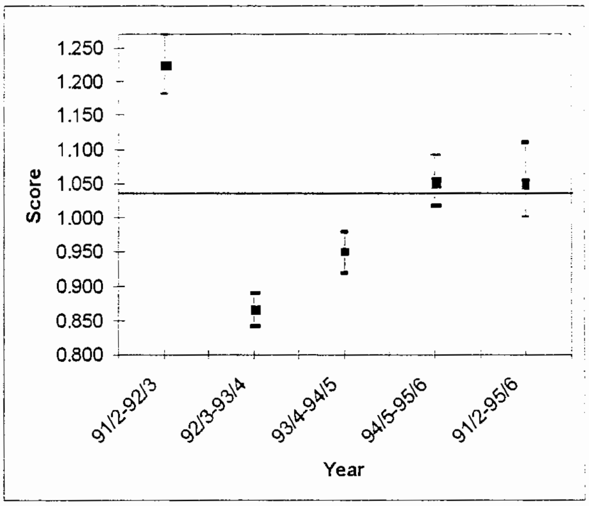


**Figure 10:** Mean technical change

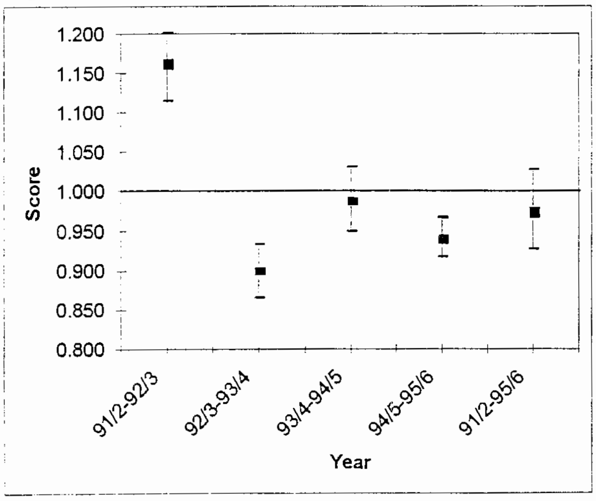
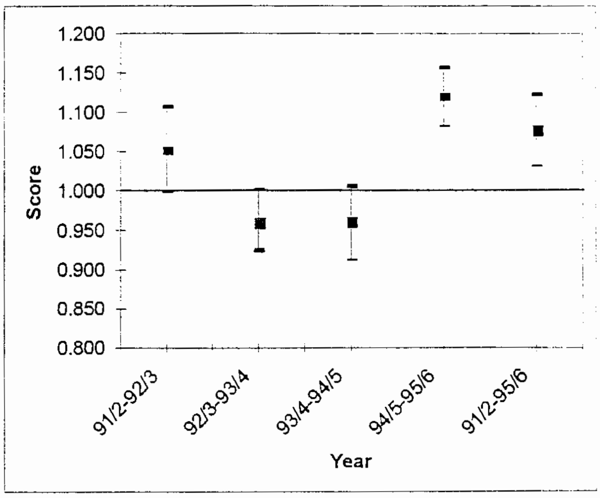


**Figure 11:** Mean price effect



The rightmost column in Table 7 suggests that between the first and last years of the assessment period there was a regress of the order of 5.2% in the minimum cost at which a given output is delivered (CTC component). This is the net result of an improvement as far as input quantities are concerned (TC = 2.5%) and a deterioration in the match between input prices and input mixes used in production (PE = 7.8%).

These imply that, eliminating inefficiency, a given output quantity was on average produced at 5.2% higher cost in the last relative to the first year of the period considered. Despite the fact that in the last period less input quantities were necessary to produce certain output than in the first, frontier production shifted to such input mixes that led to increases in production cost. Thus, as it is usually the case in this industry, technical change led to marginal savings in input quantities but also at higher production costs. This is a very interesting finding which would be missed by an approach focused only on quantities. Some more insights into the diachronic performance of hospitals can be gained by looking the results of Table 8 which includes average efficiency scores over the period studied. It is clear there that, although hospitals improved their relative efficiency over time, a lot of inefficiency still exists. Given the current levels of the NHS hospital budget in the UK elimination of this inefficiency would generate savings up to £9 billion.

**Table 7**: The decomposition of hospital (cost) technical change*

| | 1991/2 - 1992/3 | 1992/3 - 1993/4 | 1993/4 - 1994/5 | 1994/5 - 1995/6 | 1991/2 - 1995/6 |
|---|---|---|---|---|---|
| **Cost Technical Change** | **1.225** | **0.865** | **0.950** | **1.045** | **1.052** |
| Technical Change | 1.164 | 0.900 | 0.987 | 0.941 | 0.975 |
| Price Effect | 1.052 | 0.962 | 0.962 | 1.111 | 1.078 |

*Scores displayed are geometric means of the entire hospital sample

**Table 8**: Overall efficiency and its components

| | 1991/2 | 1992/3 | 1993/4 | 1994/5 | 1995/6 |
|---|---|---|---|---|---|
| **Overall efficiency** | **0.60** | **0.71** | **0.66** | **0.67** | **0.69** |
| ♦ Allocative | 0.77 | 0.84 | 0.79 | 0.78 | 0.84 |
| ♦ Technical | 0.77 | 0.84 | 0.84 | 0.84 | 0.81 |
| • Pure technical | 0.86 | 0.91 | 0.92 | 0.90 | 0.89 |
| • Scale | 0.90 | 0.92 | 0.91 | 0.93 | 0.90 |

## IV. SUMMARY AND DISCUSSION

Overall, the analysis showed that there was productivity regress in the first year after the 1991 reforms but progress thereafter so that there was a net gain as far as input quantities and costs are concerned. The decomposition of productivity change showed that technical change led to a reduction in input usage but at higher production costs due to the effect of input prices. Hospitals became more cost efficient over time. Their efficiency gains are mainly due to allocative efficiency improvements and secondly due to pure technical efficiency improvements in the first year after the reforms. As the period studied was relatively short, scale efficiency did not change significantly. It is noticeable though that in recent years scale and pure technical efficiency have been regressing slightly.

An overall finding was that the magnitude of the changes in hospital performance diminishes over time and that there are substantial differences between individual hospitals. Some hospital showed substantial losses and others substantial gains in productivity. Thus, it would be interesting to study the possible causes of such differences, with a view to identifying best practice and its root sources.

The results indicate that both the opponents and the supporters of the 1991 NHS reforms might have after all exaggerated their effects on hospital productivity. Clearly, the progress found here is not strong enough to argue that the reforms resulted in substantial improvements in hospital productive performance. The finding that productivity gains were moderate is consistent with the results of the assessment in English hospitals conducted by Söderlund *et al.* (1997). The fact that the magnitude of hospital efficiency and productivity changes diminished over time supports the argument that policies aimed at creating incentives for increases in efficiency of hospitals have a one-time effect on efficiency, instead of a steady effect until inefficiency is eliminated (Burgess and Wilson, 1995).

Also, the fact that productivity trends were mostly led by technological trends, which in turn were cost increasing, supports the argument that it is easier for hospitals to improve performance by introducing new technologies rather than by making better use of the existing ones. Burgess and Wilson (1995), Färe *et al* (1989), Magnuessen (1994)) and Tambour (1998), all found that technical change rather than technical efficiency change dominate productivity in health care delivery. This finding is also in line with the notion that changes in technology rather than hospital efficiencies drive health care expenditure, as argued by Newhouse (1993) and Schwartz and Mendelson (1994), among others.

It is recalled that, in the framework of the present evaluation, productivity change reflects changes over time in the amount and costs of the inputs used to deliver certain output. Productivity change was decomposed into two component measures, one reflecting the performance of efficient producers (technical change) and one reflecting the performance of inefficient producers (efficiency change). During the entire period studied productivity progressed approximately by 8.8% and this was the combined effect of a 5.2% cost technical regress and a 13.3% overall efficiency progress. Put another way, this is saying that cost efficient hospitals became less cost efficient by the end of the period considered, whereas cost inefficient hospitals became more efficient. As there was a regress in the industry cost frontier, the gains in productivity are entirely due to the fact that some inefficiency has been eliminated.

It was asserted by the Government before the reforms that the hospital sector was very inefficient and that the internal market would result in reductions of the inefficiencies and indeed that happened. However, as a lot of inefficiency still exists one may argue that performance did not improve to the extent which would have been possible. Average overall efficiency rose from 60% in 1991/2 to 69% in 1995/6, an increase of 9 percentage points. These gains are mainly due to the allocative efficiency factor, which rose from 77% in 1991/2 to 84% in 1995/6, and secondly due to technical efficiency which rose from an average of 77% to 81%. Despite this improvement, hospitals were still highly inefficient and they could improve their performance substantially by eliminating the remaining inefficiency. It was estimated earlier that about £9 billion could be saved by eliminating inefficiency in the UK NHS.

The productivity trends observed here are similar to those at hospitals operating in other countries, markets and health systems (Färe *et al*, 1989, Magnuessen, 1994, Burgess and Wilson, 1995 and Tambour, 1998). Thus it could be argued that our results may have occurred irrespective of the internal market reforms in 1991. Therefore, the overall conclusion is that, despite the progress achieved, the reforms did not necessarily generate the improvements in hospital performance that could have been possible and possibly not those expected by their supporters.

There are many reasons why the internal market may have failed so far to deliver the full benefits expected. Economic theory postulates that competition in the short run may lead to lower product prices, lower production costs, higher efficiency and better quality. In the long run it may manifest itself through changes in the size of institutions, degree of specialisation, exit of unsuccessful players and entry of new ones. The NHS internal market was built on the foundation of a centrally planned system, where extensive efforts went into avoiding duplication of services and thus one could expect that in many cases there may be oligopolistic or monopolistic markets where competition is limited or non existent.

Moreover, the existence of competition does not always guarantee cuts in production costs or increases in efficiency and service quality. Evidence from USA studies, reviewed by Rosko (1996), suggests that to be more competitive hospitals often introduce new technologies and thus competition results in increasing instead of decreasing hospital production costs. As hospitals try to attract customers by introducing sophisticated technologies and by increasing the scope of the services provided, often there is under-utilisation and higher inefficiency and these increase costs further. This is the "medical arms race" hypothesis, for which some evidence was found here as we have observed cost increasing technical change trends.

Competition requires full information between the players in the market and implies that providers have the incentives and the managerial competence to respond to competition by increasing efficiency and cutting production costs. Clearly this does not always happen in health care. Information is often limited and the hospital management as well as doctors are not subject to strong incentives to be efficient. Competition also implies that buyers are price sensitive and shop around, which is more applicable for the case of General Practitioners rather than for the District Health Authorities and in any case it happens only when several Trusts exist in one area. In conclusion, there are many reasons that can explain why the full benefits of competition could not be realised in the internal market.

## IV. CONCLUSION

In this paper we used a non-parametric mathematical programming approach to compute Malmquist productivity indexes which were used to evaluate hospital productive performance after the reforms of the early 90s. We found moderate productivity gains and we identified their sources and we also concluded that further gains are still feasible. The Government is now about to introduce some new NHS reforms (Department of Health, 1997), where the internal market is to be abolished but many elements of it will be retained. It is believed now that the continuous measurement, monitoring, analysis and benchmarking of performance in the context of an integrated system will lead to increases in efficiency, productivity and service quality and reductions in production costs. Thus, Health Authorities will now only monitor and co-ordinate the system. The primary care sector will be organised into Primary Care Groups that will provide primary care services and will commission secondary health care services provided by autonomous Trusts. These bodies will collaborate to set up local health and performance targets and then they will try to achieve these. All parties will be assessed against these targets and this is why the new system will be performance driven. Therefore, performance measurement will now be more important than ever before as those who perform well will be eligible for extra cash and those who do not comply with certain performance standards will be sanctioned.

Due to its importance, it is acknowledged that performance measurement should be undertaken with new reliable, rigorous, sophisticated and broader measures of performance, which will be based on greater use of comparative information than existing ones (i.e. the NHS efficiency index) (Department of Health, 1997). Clearly, the methodologies employed here can be used to achieve these objectives. These methodologies are sophisticated enough to model multiproduct and complex institutions such as those providing health care. However, despite their sophistication, they are based on simple assumptions, they are easy to understand and implement in the empirical context and to present their results. In addition, such methodologies can be ultimately used for other purposes. In particular, at industry level they can be employed to set overall performance targets; to construct success indicators and league tables; to evaluate health policies and reforms and to demonstrate value for money and to perform cross industry comparisons. At hospital level they can be used to set production targets; to benchmark best practice with the view to disseminating it and to improve hospital management. These capabilities make the approach used here a worthwhile management tool in the provision of health services.

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## APPENDIX A: DECOMPOSITIONS OF THE INPUT AND THE COST MALMQUIST INDEX

Consider that in time period t, producers are using a vector of inputs $x^t \in \Re_+^n$, available at prices $w^t \in \Re_+^n$, to produce a vector of outputs $y^t \in \Re_+^m$ and define the technology of production as in section I. Following Fare et al. (1989), the input Malmquist index (IM) in (8) can be decomposed into technical efficiency change (TEC) and technical change (TC) as follows:

$$IM = \frac{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)}{D_i^t(y^t,x^t\,|\,cr)}\left[\frac{D_i^t(y^{t+1},x^{t+1}\,|\,cr)}{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)}\,\frac{D_i^t(y^t,x^t\,|\,cr)}{D_i^{t+1}(y^t,x^t\,|\,cr)}\right]^{1/2} \qquad \text{(A1).}$$

Then, following Fare et al. (1994ab), TEC, the term outside the brackets in A1, can be further decomposed into pure technical efficiency change (PTEC) and scale efficiency change (SEC) as follows:

$$TEC = \frac{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,vr)}{D_i^t(y^t,x^t\,|\,vr)}\left(\frac{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)}{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,vr)}\Big/\frac{D_i^t(y^t,x^t\,|\,cr)}{D_i^t(y^t,x^t\,|\,vr)}\right) \qquad \text{- (A2),}$$

where vr denotes VRS. In a similar fashion, following Maniadakis and Thanassoulis (1997), the cost Malmquist index in (9) can be then decomposed into overall efficiency change (OEC) and cost technical change (CTC) as follows:

$$CM = \frac{w^{t+}x^{t+1}/C^{t+1}(y^{t+1},w^{t+1}\,|\,cr)}{w^t x^t/C^t(y^t,w^t\,|\,cr)}$$

$$\left[\frac{w^t x^{t+1}/C^t(y^{t+1},w^t\,|\,cr)}{w^{t+1}x^{t+1}/C^{t+1}(y^{t+1},w^{t+1}\,|\,cr)}\,\frac{w^t x^t/C^t(y^t,w^t\,|\,cr)}{w^{t+1}x^t/C^{t+1}(y^t,w^{t+1}\,|\,cr)}\right]^{1/2} \qquad \text{(A3).}$$

OEC can be decomposed into PTEC, SEC and allocative efficiency change (AEC) as follows:

$$OEC = \frac{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,vr)}{D_i^t(y^t,x^t\,|\,vr)}\left(\frac{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)}{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,vr)}\Big/\frac{D_i^t(y^t,x^t\,|\,cr)}{D_i^t(y^t,x^t\,|\,vr)}\right)$$

$$\frac{w^{t+1}x^{t+1}/C^t+1(y^{t+1},w^{t+1}\,|\,cr)D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)}{w^t x^t/C^t(y^t,w^t\,|\,cr)D_i^t(y^t,x^t\,|\,cr)} \qquad \text{(A4).}$$

Finally, CTC can be decomposed into TC and the price effect (PE) as follows:

$$CTC = \left[\frac{D_i^t(y^{t+1},x^{t+1}\,|\,cr)}{D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)}\,\frac{D_i^t(y^t,x^t\,|\,cr)}{D_i^{t+1}(y^t,x^t\,|\,cr)}\right]^{1/2}$$

$$\left[\frac{w^t x^{t+1}/C^t(y^{t+1},w^t\,|\,cr)D_i^t(y^{t+1},x^{t+1}\,|\,cr)}{w^{t+1}x^{t+1}/C^{t+1}(y^{t+1},w^{t+1}\,|\,cr)D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)}\right. \qquad \text{(A5).}$$

$$\left.\frac{w^t x^t/C^t(y^t,w^t\,|\,cr)D_i^t(y^t,x^t\,|\,cr)}{w^{t+1}x^t/C^{t+1}(y^t,w^{t+1}\,|\,cr)D_i^{t+1}(y^t,x^t\,|\,cr)}\right]^{1/2}$$

## APPENDIX B: COMPUTATION OF PRODUCTIVITY AND ITS COMPONENTS

Let us have in each time period j = 1...J production units. In period t, the $k^{th}$ unit employs amounts $x^t_{kn}$ of input n (n = 1...N), available at prices $w^t_{kn}$ (n = 1...N), to produce amounts $y^t_{km}$ of output m, (m = 1...M). For the decomposition of the index one has simply to compute the distance functions as shown by Färe *et al.,* (1989), whose models for period t are as follows:

$$\begin{array}{lll} \left[D_i^t(y^t,x^t\,|\,cr)\right]^{-1} = & \min\limits_{z,\theta} \ \theta & \\ \text{Subject to} & \sum\limits_{j=1}^{J} z_j y^t_{jm} \ge y^t_{km} & \\ & \sum\limits_{j=1}^{J} z_j x^t_{jn} \le \theta\, x^t_{kn} & \\ & z_j \ge 0 & \text{(B1),} \end{array}$$

$$\begin{array}{lll} \left[D_i^t(y^{t+1},x^{t+1}\,|\,cr)\right]^{-1} = & \min\limits_{z,\theta} \ \theta & \\ \text{Subject to} & \sum\limits_{j=1}^{J} z_j y^t_{jm} \ge y^{t+1}_{km} & \\ & \sum\limits_{j=1}^{J} z_j x^t_{jn} \le \theta\, x^{t+1}_{kn} & \\ & z_j \ge 0 & \text{(B2),} \end{array}$$

where $z_j$ (j = 1...J) is an intensity variable used to form convex linear combinations of observed inputs and outputs. For the calculation of $D_i^{t+1}(y^{t+1},x^{t+1}\,|\,cr)$ and $D_i^{t+1}(y^t,x^t\,|\,cr)$ one has to use models (B1) and (B2) after first swapping round the superscripts t and t+1. To compute $D_i^t(y^t,x^t\,|\,vr)$ one has simply to incorporate $\sum_{j=1}^{J} z_j = 1$ in (B1). $D_i^{t+1}(y^{t+1},x^{t+1}\,|\,vr)$ is computed in a similar manner.

The cost Malmquist index is measured in terms of cost ratios. For unit k the cost denoted $w^tx^t$ is: $w^tx^t \equiv \sum_{n=1}^{N} w^t_{kn} x^t_{kn}$. Similarly the costs denoted $w^{t+1}x^{t+1}$, $w^{t+1}x^t$ and $w^tx^{t+1}$ are respectively $\sum_{n=1}^{N} w^{t+1}_{kn} x^{t+1}_{kn}$, $\sum_{n=1}^{N} w^{t+1}_{kn} x^t_{kn}$, $\sum_{n=1}^{N} w^t_{kn} x^{t+1}_{kn}$. Following Maniadakis and Thanassoulis (1997), for unit k, the terms $C^t(y^t, w^t|cr)$ and $C^t(y^{t+1}, w^t|cr)$ can be computed the following models:

$$\begin{array}{lll} C^t(y^t, w^t|cr) = & \min\limits_{x,z} \ w^t_{kn}\, x_n & \\ \text{Subject to} & \sum\limits_{j=1}^{J} z_j y^t_{jm} \ge y^t_{km} & \\ & \sum\limits_{j=1}^{J} z_j x^t_{jn} \le x_n, & \\ & z_j \ge 0,\ x_n \ge 0 & \text{(B3),} \end{array}$$

$$\begin{array}{lll} C^t(y^{t+1}, w^t|cr) = & \min\limits_{x,z} \ w^t_{kn}\, x_n & \\ \text{Subject to} & \sum\limits_{j=1}^{J} z_j y^t_{jm} \ge y^{t+1}_{km} & \\ & \sum\limits_{j=1}^{J} z_j x^t_{jn} \le x_n, & \\ & z_j \ge 0,\ x_n \ge 0 & \text{(B4).} \end{array}$$

The terms $C^{t+1}(y^{t+1}, w^{t+1}|cr)$ and $C^{t+1}(y^t, w^{t+1}|cr)$ can be computed using models (B3) and (B4) after first swapping round the superscripts t and t+1.

## APPENDIX C: THE BOOTSTRAP

The process used will be illustrated here with reference to the input Malmquist index IM and is reproduced in Table C1. Recall that in period t (e.g. 1991/2) we have j = 1...75 producers using inputs $x^t$ to produce outputs $y^t$ and similarly for period t+1 (e.g. 1992/3). DEA was used to compute j = 1...75 scores for the Malmquist index of the two adjacent years, so that a sample of $IM_j$ (j=1...75) productivity scores were obtained. Geometric mean productivity for the entire hospital sample was then computed as: $GIM = \left(\prod_{j=1}^{J=75} IM_j\right)^{1/j}$. Hospital identifiers and productivity scores together with the geometric mean of the original sample are depicted in the first and second columns of Table C1. Then J (75) productivity scores were re-sampled with replacement from the original sample and their geometric means were calculated in a similar fashion. This was done 1,000 times. Table C1 displays 3 such re-samples and their means. The deviation of the mean of the 1,000 means from the original sample mean indicates whether there is any bias, but in our case this was very trivial. Thus, to compute confidence intervals we used the simple percentile method. Hence, for the 95% confidence intervals, values for the confidence limits were chosen so as to exclude 2.5% of the values on either side of the rank ordered vector of bootstrapped geometric means. With respect to the scores obtained for the IM index between 1991/2 and 1992/3 (see Table 4 and Figure 3), geometric mean productivity was 1.060, indicating 6% regress between 1991/2 and 1992/3. The geometric mean of the 1,000 bootstrapped means in this case was 1.059, and the 95% lower and upper confidence limits were 1.005 and 1.127 (see Figure 3), and they indicate that the null hypothesis of no regress is rejected at 95% significance.

Table C1: The bootstrap

| Original sample | | Re-sample 1 | | Re-sample 2 | | Re-sample n | | Re-sample 1000 | |
|---|---|---|---|---|---|---|---|---|---|
| Unit | $IM_j$ | Unit | $B\hat{M}I_j$ | Unit | $B\hat{M}I_j$ | Unit | $B\hat{M}I_j$ | Unit | $B\hat{M}I_j$ |
| 1 | 1.332 | 54 | 1.000 | 21 | 0.998 | | | 30 | 0.948 |
| 2 | 0.972 | 35 | 1.092 | 17 | 0.892 | | | 17 | 0.892 |
| n | | | | | | | | | |
| 74 | 1.559 | 5 | 0.922 | 49 | 0.964 | | | 10 | 0.911 |
| 75 | 0.940 | 34 | 1.000 | 62 | 1.055 | | | 49 | 0.964 |
| **GMI** | **1.060** | | | | | | | | |
| $B\hat{I}M_j^n$ | | | **1.036** | | **1.056** | | | | **1.077** |

As depicted in Figure C1, the frequency distribution of the 1,000 bootstrapped geometric mean scores approximates a perfectly normal distribution.

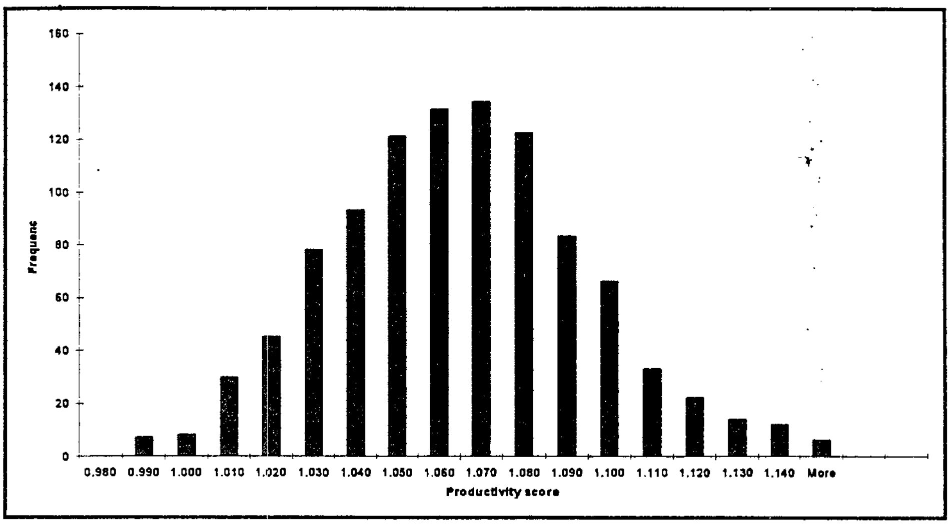

Figure C1: Frequency distribution of the bootstrapped mean Malmquist productivity scores, 1991/2-1992/3