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Efficiency and Input - and Output - Substitutability in English Higher Education 1996/97 to 2007/08: A Parametric Distance Function Approach

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A PARAMETRIC DISTANCE FUNCTION APPROACH

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Abstract

HEIs are likely to face tight fiscal constraints in the future. This paper uses random effects and stochastic frontier techniques to estimate an output distance function over the period 1997/97 to 2007/08 in order to investigate the efficiency of higher education institutions (HEIs) and to examine the opportunities for substitution between inputs. Mean efficiency across the whole sector is estimated to be 70%, and further investigation reveals that the pattern of production in the typical institution in the highest efficiency quartile is closest to the pattern of production of the average pre-1992 university. The Morishima elasticities calculated from the parameter estimates suggest that the main possibilities for substitution are out of undergraduates into other inputs and from administration into other inputs (except academic services). Opportunities for substitution are generally much more limited from postgraduate inputs, staff and academic services. A simple examination of the effects of merger activity reveals that it takes place amongst institutions which are typically performing at the same level as non-merging HEIs, and that it has beneficial effects in terms of efficiency.

JEL Classification: I23, C01, C33, D24

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1. INTRODUCTION

The recent financial crisis and the ensuing bail-out of banks by the government means that publicly funded sectors will face tight budgets. The cuts announced for the English higher education sector by the Higher Education Funding Council for England (HEFCE) in February 2010 came as no surprise: funding for 2010/11 would be £449 million lower than expected, and £518 million lower than last year's figure (Woolcock and Sugden 2010). However, recent reports suggest that a further £200 million will be taken from university budgets (Gray 2010). The precise effects on the sector of these cuts are unknown, but there is a fear that the severity of the cuts may cause some universities to close and some to merge (Griffiths 2010).

It has been suggested that there is scope for absorbing part of the cuts by increased efficiency (Mandelson 2009). Indeed, such efficiency savings could amount to £180 million (Woolcock and Sugden 2010). The efficiency of an organisation can be assessed by examining outputs produced in relation to either the costs incurred or inputs used. The former approach is relatively simple, and has been attempted in a number of studies; the latter approach is more complicated and there is no study, to date, of the production relationship of universities in England. Yet the production function approach can provide a rich analysis of interrelationships between inputs and outputs. A university, for example, uses capital, labour (both academic and administrative) and raw materials (students entering both undergraduate and postgraduate programmes) to produce its teaching and research outputs. Budget cuts are likely to affect the balance of inputs used. For example, the universities minister has called on universities to reduce the number of managers in order to make savings (Grimston 2010). Similarly, student places are likely to be affected by cuts: a proposed increase in university places of 20,000 is to be halved (Sherman *et al.* 2010). Whilst such policies may alleviate the financial situation, it is crucial to know before implementing the changes what the likely impact on the outputs of the sector will be. The purpose of this paper is therefore to estimate the production technology of higher education institutions (HEIs) in England over the period of 1997 to 2008 with a view to exploring efficiency and possibilities for substitution between inputs and between outputs, thus enabling an assessment of the likely consequences for higher education of the adverse fiscal situation.

There are various ways in which the relationship between inputs and outputs of firms can be explored. HEIs produce multiple outputs from multiple inputs, and so previous work has generally utilised the cost function to analyse how changing inputs (and hence cost) can affect output production (Cohn *et al.* 1989; Glass *et al.* 1995b; 1995a; Johnes 1996a; Hashimoto and Cohn 1997; Glass *et al.* 1998; Izadi *et al.* 2002; Cohn and Cooper 2004; Johnes *et al.* 2005; Stevens 2005; Johnes *et al.* 2008; Worthington and Higgs 2008; Johnes and Johnes 2009). The cost function, whilst a convenient tool of analysis in a multi-output, multi-input context, is not appropriate if input prices are not available, or if cost minimizing behaviour does not apply (Coelli and Perelman 1999). An alternative approach is to estimate the relationship between aggregate output and the multiple inputs, where aggregate output is a composite measure calculated using some pre-defined weights. The weights may be chosen arbitrarily or may be output prices, but estimates are biased if the weights chosen are incorrect, or if prices are used but revenue maximisation does not apply (Coelli and Perelman 1999).

The distance function approach offers an alternative which is not beset by any of these problems. The output- or input-oriented distance function approach allows for both multiple inputs and multiple outputs (Coelli and Perelman 2000; Rodríguez-Álvarez *et al.* 2004; Tonini 2004), does not assume any particular optimizing behaviour on the part of the firms, does not require a knowledge of prices of either inputs or outputs (Coelli and Perelman 1999; Coelli 2000; O'Donnell and Coelli 2003; Uri 2003a; 2003b; Rodríguez-Álvarez *et al.* 2004), and does not require prices to be exogenous (Baños-Pino *et al.* 2002). All of these points make the distance function approach particularly attractive in the context of higher education.

This paper uses a distance function approach to model the relationship between inputs and outputs in higher education in England. Frontier techniques are used to estimate the parameters of the distance function, and the technical efficiency of the individual HEIs and the sector as a whole. From the estimated parameters, Morishima elasticities of substitution (Blackorby and Russell 1989) can be calculated to assess the extent of substitutability between inputs (raw materials, capital and labour – both academic and non-academic) in the higher education production process. The performance measures of HEIs are examined to try to identify whether these vary by type of HEI (eg whether the HEI is a traditional pre-1992 university, a post-1992 university, a college of higher education or a London college). In addition, the characteristics of high and low-performing universities are examined and compared. The diversity of HEIs in, and the time period covered by the sample also allows a crude examination of the effect of merger activity on the performance measures. Such an analysis in the context of higher education is new to the literature and is particularly relevant if mergers are likely in the wake of financial cuts.

The paper is in six sections of which this is the first. Section 2 introduces the distance function methodology, whilst specification and estimation issues are presented in section 3. The data which form the basis of the analysis are described in section 4 and the results of estimating an output distance function are reported in section 5. Finally, conclusions are drawn in section 6.

2. METHODOLOGY

It is assumed that HEIs use a vector of inputs $x \in \mathbb{R}_+^K$ to produce a vector of outputs $y \in \mathbb{R}_+^M$. An output-oriented approach assumes that producers aim to maximize output from a given level of inputs whereas an input-oriented approach assumes the converse. In the case of higher education, inputs such as student intake are often pre-determined by government policy. For that reason, an output-oriented perspective is used here[1].

The production technology of the HEI is defined as

$$P(x) = \{y \in \mathbb{R}_{+}^{M} : x \text{ can produce } y\} \qquad (1)$$

The output distance function (Shephard 1970) is defined on the output set $P(x)$ as:

$$D(x, y) = min_{\theta}\{\theta : (y/\theta) \in P(x)\} \qquad (2)$$

It therefore seeks the largest possible proportional expansion (represented by the scalar θ) of the observed output vector (from a given input vector) given that the expanded vector must still belong to the original output set. The distance function $D(x, y)$ is non-decreasing, positively linearly homogeneous of degree +1, convex in *y*, and decreasing in *x* (Uri 2003a; 2003b). It therefore follows that

$$D(x, y) \leq 1 \Leftrightarrow y \in P(x) \qquad (3a)$$

$$D(x, y) = 1 \Leftrightarrow y \in \text{Bound}P(x) \qquad (3b)$$

where $\text{Bound}P(x)$ is the frontier of the output set (see Coelli *et al.* 2005). The distance function, like the production function, describes technology, but, in contrast to the production function, can handle both multiple outputs and multiple inputs without needing to know either input or output prices, and without making any of the usual optimizing assumptions about the firms under scrutiny (Grosskopf *et al.* 1995a; Tonini 2004). It is therefore particularly useful in the context of modelling university production. Moreover, $D(x, y)$ can be used as a measure of efficiency: if *y* is located on the boundary of the production possibility set, $D(x, y) = 1$ and this represents technical efficiency; if $D(x, y) < 1$, *y* lies inside the frontier and technical inefficiency exists (Uri 2003a).

Distance functions also provide useful information on shadow prices and the substitution properties of the production technology. If the output sets are convex, the duality between the output distance function and the revenue function[2] allows us to derive information on output shadow prices as follows (Grosskopf *et al.* 1995b):

$$\frac{\partial D(x,y)}{\partial y_m} = \frac{p_m^*}{R} = r_m^* \qquad (4)$$

where *R* is total revenue, p_m^* is the shadow price of the *m*th output (which under profit maximisation would equal output price (Paul *et al*. 2002)), and hence r_m^* is the revenue deflated shadow price of the *m*th output. The ratio of output shadow prices provides a measure of the marginal rate of transformation (*MRT*):

$$MRT_{mn} = \frac{r_m^*}{r_n^*} \qquad (5)$$

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[1] It should be noted, however, that in studies where both input- and output-distance functions are estimated, results are consistent across the two approaches (Coelli and Perelman 1999; Paul and Nehring 2005).

[2] It should be noted that the input distance function is the dual of the cost function. For more details, see (Grosskopf et al. 1995a).

This reflects the slope of the production possibility frontier and is therefore a measure of substitutability between outputs m and n, but is affected by the units in which outputs are measured. A normalized MRT corrects this problem and is defined as follows:

$$sub_{mn} = \frac{r_m^*}{r_n^*} \cdot \frac{y_m}{y_n} \tag{6}$$

If $sub_{mn} > 1$ ($sub_{mn} < 1$) then it is difficult (easy) to substitute out of output *m* and into output *n* (Paul *et al*. 2002). In the case of just two outputs, this measure of substitutability captures the curvature of the (two dimensional) production possibility frontier. When the number of outputs exceeds two, however, there are many directions in which the curvature of the production possibility frontier can be measured, and so sub_{mn} is an inadequate reflection of substitutability. It has been argued that the Morishima elastictity of substitution is an appropriate measure of substitutability in this case (Blackorby and Russell 1989). In the context of a distance function, the (indirect) Morishima elasticity of substitution is defined as (Grosskopf *et al*. 1995b):

$$M_{mn}(x,y) = -\frac{\mathrm{d}\ln[D_m(x,y)/D_n(x,y)]}{\mathrm{d}\ln[y_m/y_n]} = y_m \frac{D_{mn}(x,y)}{D_n(x,y)} - y_n \frac{D_{mm}(x,y)}{D_m(x,y)} \tag{7}$$

where $D_m(x,y)$ $\left(D_n(x,y)\right)$ is the partial derivative of the distance function $D(x,y)$ with respect to y_m (y_n) and $D_{mn}(x,y)$ ($D_{mm}(x,y)$) is the partial derivative of $D_m(x,y)$ with respect to y_m (y_n). It is therefore the percentage change in the ratio of output shadow prices (or the percentage change in the slope of the MRT) brought about by a percentage change in ratio of outputs. If y_m and y_n are highly substitutable values will be small (less than or equal to zero); the elasticity rises if substitutability possibilities between the outputs y_m and y_n are limited. The Morishima elasticity is asymmetric such that $M_{mn}(x,y)$ will not normally equal $M_{nm}(x,y)$ (Grosskopf *et al*. 1995a).

Analogous measures can be derived for the inputs. Thus shadow prices (or marginal products) of inputs are defined as

$$\partial D(x,y)/\partial x_k \tag{8}$$

and the marginal rate of technical substitution ($MRTS_{kl}$), which reflects the slope of the isoquant, is given by

$$MRTS_{kl} = \frac{\partial D(x,y)/\partial x_k}{\partial D(x,y)/\partial x_l} \tag{9}$$

The normalized $MRTS_{kl}$, which is unaffected by units of measurement of the inputs, is given by

$$sub_{kl} = \frac{\partial D(x,y)/\partial x_k}{\partial D(x,y)/\partial x_l} \cdot \frac{x_k}{x_l} \tag{10}$$

If $sub_{kl} > 1$ ($sub_{kl} < 1$) it is difficult (easy) to substitute out of input *k* into input *l*. Finally, the Morishima elasticity is defined as (Paul *et al*. 2002):

$$M_{kl}(x,y) = -\frac{\mathrm{d}\ln[D_k(x,y)/D_l(x,y)]}{\mathrm{d}\ln[x_k/x_l]} = x_k \frac{D_{kl}(x,y)}{D_l(x,y)} - x_k \frac{D_{kk}(x,y)}{D_k(x,y)} \tag{11}$$

where $D_k(x,y)$ $\left(D_l(x,y)\right)$ is the partial derivative of the distance function $D(x,y)$with respect to x_k (x_l) and $D_{kl}(x,y)$ ($D_{kk}(x,y)$) is the partial derivative of $D_k(x,y)$ with respect to x_l (x_k). It is therefore the percentage change in the ratio of input shadow prices (or the percentage change in the slope of the MRTS) brought about by a percentage change in ratio of inputs. If x_k and x_l are highly substitutable values will be small (less than or equal to zero); the elasticity rises if substitutability possibilities between the inputs x_k and x_l are limited. As in the case of outputs, the elasticity is asymmetric.

It is particularly appealing that these measures of substitutability can be calculated from the estimated distance function for each HEI in each year in which they appear in the data set (Grosskopf *et al*. 1995a). It is therefore possible to examine and compare patterns of change (if any) in the substitutability of inputs (and outputs) across different types of HEIs. It is also possible to establish how possibilities for substitution vary by size of institution.

3. SPECIFICATION AND ESTIMATION

Distance functions can be estimated using parametric or non-parametric methods. It is reassuring that studies which have compared efficiency values derived using both parametric and non-parametric methods suggest a high degree of correlation between them (Coelli and Perelman 1999; Whiteman 1999). The choice therefore depends on the aim of the study. The most common non-parametric method, data envelopment analysis (DEA), is useful because it does not require the specification of a functional form and it allows each firm to have its own set of weights. On the downside, DEA, in its basic form, makes no allowance for stochastic errors, and is sensitive to outliers. In addition, there are no estimates of the parameters of the function. Since the purpose of this study is to examine the estimated parameters and to derive from them measures of substitutability, this is a crucial shortcoming, and so parametric estimation is the method of choice.

A parametric distance function requires that a functional form be specified, the desirable properties of which are that it should be i) flexible; ii) easy to estimate; and iii) permit the imposition of homogeneity (Coelli and Perelman 2000). The translog fulfils all three criteria and has been used to estimate distance functions in the context of: telecommunications (Whiteman 1999; Uri 2003a; 2003b); railways (Coelli and Perelman 1999; Baños-Pino *et al*. 2002; Atkinson *et al*. 2003b; O'Donnell and Coelli 2003); electric utilities (Whiteman 1999; Atkinson and Primont 2002; Atkinson *et al.* 2003a); the water industry (Saal and Parker 2006); and agriculture (Paul *et al*. 2000; 2002; Karagiannis *et al*. 2004; Tonini 2004; Paul and Nehring 2005; Balcombe *et al*. 2007).

The translog distance function is defined below for N HEIs using inputs x_k ($k = 1,...,K$) to produce outputs y_m ($m = 1,...,M$):

$$\ln D_{it}(x,y) =$$

$$\alpha_0 + \sum_{m=1}^{M} \alpha_m \ln y_{mit} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \alpha_{mm} \ln y_{mit} \ln y_{nit} + \sum_{k=1}^{K} \beta_k \ln x_{kit} +$$

$$\frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} \ln x_{kit} \ln x_{lit} + \sum_{k=1}^{K}\sum_{m=1}^{M} \delta_{km} \ln x_{kit} \ln y_{mit} \qquad i = 1,2,\dots,N \qquad (12)$$

where subscript it refers to the ith HEI in the tth time period. Distance function restrictions require the following conditions to hold:

a) Homogeneity of degree +1 in outputs

$$\sum_{m=1}^{M} \alpha_m = 1 \quad \text{and} \qquad (13a)$$

$$\sum_{n=1}^{M} \alpha_{mn} = 0 \quad m = 1,2,\dots,M \quad \text{and} \qquad (13b)$$

$$\sum_{m=1}^{M} \delta_{km} = 0 \quad k = 1,2,\dots,K \qquad (13c)$$

b) Symmetry:

$$\alpha_{mn} = \alpha_{nm} \quad m,n = 1,2,\dots,M \quad \text{and} \qquad (14a)$$

$$\beta_{kl} = \beta_{lk} \quad k,l = 1,2,\dots,K \qquad (14b)$$

By the homogeneity restriction $D(x,\omega y) = \omega D(x,y)$ and so one output can be chosen arbitrarily, for example the Mth output, such that $\omega = 1/y_M$. Thus equation (13) can be written as:

$$\ln(D_{it}(x,y)/y_{Mit}) = \alpha_0 + \sum_{m=1}^{M-1} \alpha_m \ln\left(\frac{y_{mit}}{y_{Mit}}\right) + \frac{1}{2}\sum_{m=1}^{M-1}\sum_{n=1}^{M-1} \alpha_{mm} \ln\left(\frac{y_{mit}}{y_{Mit}}\right) \ln\left(\frac{y_{nit}}{y_{Mit}}\right) + \sum_{k=1}^{K} \beta_k \ln x_{kit} +$$

$$\frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} \ln x_{ki} \ln x_{lit} + \sum_{k=1}^{K}\sum_{m=1}^{M-1} \delta_{km} \ln x_{kit} \ln\left(\frac{y_{mit}}{y_{Mit}}\right) \qquad i = 1,2,\dots,N \qquad (15)$$

$$\Leftrightarrow -\ln y_{Mit} = \alpha_0 + \sum_{m=1}^{M-1} \alpha_m \ln\left(\frac{y_{mit}}{y_{Mit}}\right) + \frac{1}{2}\sum_{m=1}^{M-1}\sum_{n=1}^{M-1} \alpha_{mm} \ln\left(\frac{y_{mit}}{y_{Mit}}\right) \ln\left(\frac{y_{nit}}{y_{Mit}}\right) + \sum_{k=1}^{K} \beta_k \ln x_{kit} +$$

$$\frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} \ln x_{kit} \ln x_{lit} + \sum_{k=1}^{K}\sum_{m=1}^{M-1} \delta_{km} \ln x_{kit} \ln\left(\frac{y_{mit}}{y_{Mit}}\right) + \varepsilon_{it} \qquad i = 1,2,\dots,N \qquad (16)$$

where $\varepsilon_{it} = -\ln D_{it}(x,y)$

Additional variables to represent, for example, regulation changes, trends over time or differences between groups of firms can be captured by the inclusion into the above of dummy, trend and interaction variables.

Thus the distance $\ln D_{it}(x,y)$ is measured by the error term in equation (16), and the choice of estimation method depends on the assumptions made about this error term. On the assumption that ε_{it} is entirely stochastic, parameters in equation (16) can be estimated using fixed or random effects, and there are no inefficiency estimates (because these are assumed to be zero). An alternative assumption is that

$\varepsilon_{it} = v_{it} - u_i$ where v_{it} represents statistical noise and u_i represents technical inefficiency which varies by producer but not over time, and where there is no distributional assumption regarding u_i. In practice u_i is merged with the intercept α_0 and is estimated by first applying fixed or random effects and then, for each observation in the data set, subtracting the maximum individual effect. Both fixed and random effects estimation have the advantage that no distributional assumptions are imposed on the inefficiency term. Fixed effects estimation also allows the inefficiency and regressors to be correlated, but in practice require considerable degrees of freedom. Random effects estimation makes no such demands regarding degrees of freedom but is more restrictive in terms of assuming no correlation between inefficiency and regressors; this is a potentially serious drawback when inefficiency is likely to be related to usage of inputs (Sena 2003).

A third option is to assume that the error term of equation (16) comprises two components as in a stochastic production frontier approach (Aigner *et al*. 1977). One component of the error term is stochastic and the second measures inefficiency (and is therefore the distance measure). Specifically, in the context of a panel data set, the error term ε_{it} is specified in the stochastic frontier framework as:

$$\varepsilon_{it} = v_{it} - u_{it} \tag{17}$$

where v_{it} and u_{it} are independent of each other, are independently and identically distributed such that $v_{it} \sim N(0, \sigma_v^2)$, $u_{it} \sim N^+(\mu, \sigma^2)$ and N^+ represents a truncated-normal distribution truncated at 0. Thus $-u_{it} = -\ln D_{it}(x, y)$. The precise method of estimation depends on the assumption regarding the technical inefficiency component which has both a firm- and time-specific component. The simplest model is to assume that inefficiency varies by firm but is time-invariant i.e. $u_{it} = u_i$ where $u_i \sim N^+(\mu, \sigma_u^2)$, and where, for estimation purposes, u_i can be treated as a fixed parameter or random variable (Coelli *et al.* 2005). The fixed effects model has the disadvantage that efficiency is measured relative to the most efficient in the sample. An alternative is to assume a time-varying decay model for the inefficiency component such that $u_{it} = \{exp[-\eta(t - T_i)]\}u_i$ where T_i is the last period in the *i*th panel, η is a decay parameter to be estimated, and u_i is the base level of inefficiency which in this case is the inefficiency for the last period observed for unit *i* (Battese and Coelli 1992). Thus if $\eta > 0$ ($\eta < 0$) the level of inefficiency decreases (increases) towards the final period level and so inefficiency decreases (increases) over time. While this model can be estimated in both fixed and random effects frameworks, the recommendation is to use random effects using the method of maximum likelihood (Battese and Coelli 1992; Coelli *et al.* 2005). Thus, both time varying and time-invariant stochastic frontier models of equation (16) are estimated in a random effects framework by maximum likelihood methods in the sequel. For comparative purposes, the non-frontier random effects model of equation (16) is also estimated.

The precise specification of the distance function to be estimated is as follows:

$$-\ln y_{Mi} = \alpha_0 + \sum_{m=1}^{M-1} \alpha_m \ln\left(\frac{y_{mi}}{y_{Mi}}\right) + \frac{1}{2}\sum_{m=1}^{M-1}\sum_{n=1}^{M-1} \alpha_{mm} \ln\left(\frac{y_{mi}}{y_{Mi}}\right) \ln\left(\frac{y_{ni}}{y_{Mi}}\right) + \sum_{k=1}^{K} \beta_k \ln x_{ki} +$$
$$\frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} \ln x_{ki} \ln x_{li} + \sum_{k=1}^{K}\sum_{m=1}^{M-1} \delta_{km} \ln x_{ki} \ln\left(\frac{y_{mi}}{y_{Mi}}\right) + \tau t_i + v_{it} - u_{it} \qquad i = 1,2,\dots,N \qquad (18)$$

where y_3 (i.e. RESEARCH) is used as the numeraire[3] and t_i is a time trend variable (taking the values 1,…,12) included to capture changes in productivity over time[4]. The error u_{it} is estimated using, respectively, (non-frontier) random effects (RE), time-invariant (TI) SFA and time varying decay (TVD) SFA. All input and output variables are mean-corrected (Cuesta and Orea 2002; Cuesta and Zofío 2005). Shadow prices (see equations (4) and (8)) for each year of the sample, evaluated at the sample means, are therefore simply the first order coefficients (α_m and β_k).

Finally, it is worth discussing at this point the potential for simultaneous equations bias in the context of equation (16) since both inputs and outputs appear on the right hand side of equations (16). To counter this argument, note first that, in the context of the output distance function, inputs are given (exogenous) and outputs are endogenous. It is not, however, the outputs which appear as regressors in equation (17) but instead the normalised outputs (output ratios). The output distance function is defined for a proportional expansion of outputs given inputs and so output ratios are in fact held constant (Cuesta and Orea 2002; Tonini 2004)[5].

4. DATA

HEIs can be seen as using raw materials, capital and labour to produce teaching and research outputs. The diverse nature of the units included in this analysis make it difficult to define a uniform set of inputs and outputs; the parametric estimation of the function also demands that the number of inputs and outputs be kept at a reasonable number to ensure sufficient degrees of freedom. The inputs and outputs used here are therefore the same as those used in a previous (non-parametric) study of English higher education (Johnes 2008). The advantage of this is that results here can be compared with those from the earlier study.

All input and output variables are constructed from detailed annual statistics for all HEIs in England published by the Higher Education Statistics Agency (HESA). Five measures of inputs are used (see table 1

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[3] Note that there is evidence that results are insensitive to the choice of numeraire (Coelli and Perelman 2000; Paul and Nehring 2005). In fact all results presented in this paper have also been generated using respectively y_1 (PGOUTPUT) and y_2 (UGOUTPUT) as numeraire. Results are remarkably insensitive to choice of numeraire and all conclusions remain the same.

[4] Note that (following Paul and Nehring 2005) for estimation purposes the following is estimated using maximum likelihood methods to obtain, respectively, the random effects, the SFA time invariant and the SFA time varying model coefficients and efficiencies:

$$\ln y_{Mi} = -(\alpha_0 + \sum_{m=1}^{M-1} \alpha_m \ln\left(\frac{y_{mi}}{y_{Mi}}\right) + \frac{1}{2}\sum_{m=1}^{M-1}\sum_{n=1}^{M-1} \alpha_{mm} \ln\left(\frac{y_{mi}}{y_{Mi}}\right) \ln\left(\frac{y_{ni}}{y_{Mi}}\right) + \sum_{k=1}^{K} \beta_k \ln x_{ki} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} \ln x_{ki} \ln x_{li} +$$
$$\sum_{k=1}^{K}\sum_{m=1}^{M-1} \delta_{km} \ln x_{ki} \ln\left(\frac{y_{mi}}{y_{Mi}}\right) + \tau t_i) - v_{it} + u_{it} \qquad i = 1,2,\dots,N$$

[5] In the case of the input distance function outputs are exogenous and inputs are endogenous, but input ratios are held constant by definition.

for detailed definitions): undergraduate (UG) and postgraduate (PG) student numbers represent the raw materials; expenditure on academic services such as the library and computer services reflects capital input; the number of academic staff (STAFF) and the expenditure on administration and central services (ADMIN) reflect, respectively, academic and non-academic labour inputs. Finally, capital inputs are measured by expenditure on library, computing and other learning resources (ACSERV). In addition, three measures of outputs are included: output from undergraduate degree qualifications (UGOUTPUT) and from postgraduate degree qualifications (PGOUTPUT) measure the teaching output of HEIs; income received for research purposes (RESEARCH) is included to reflect research output.

Some shortcomings of the model specification should be presented at the outset. As in previous studies (Abbott and Doucouliagos 2003; Flegg and Allen 2007a; 2007b; Worthington and Lee 2008) raw material inputs and teaching outputs are not adjusted for quality (see Johnes 2008 for a discussion of this) mainly because of a lack of suitable published data, particularly in the context of input quality. This inevitably means that results regarding substitutability between inputs should be interpreted cautiously because the model ignores the potential effect on quality of such substitutions. In addition, the definitions of outputs make no allowances for subject differences – graduates at all levels and research are aggregated across all subject areas. Disaggregation of outputs even by broad subject areas would cause an unacceptable loss of degrees of freedom, and, for this reason, cost or production models in higher education tend to be estimated using aggregate definitions of outputs (Glass *et al.* 1995a; 1995b; Athanassopulos and Shale 1997; Glass *et al.* 1998; Avkiran 2001; Glass *et al.* 2002; Abbott and Doucouliagos 2003; Flegg *et al.* 2004; Glass *et al.* 2006; Flegg and Allen 2007a; 2007b; Johnes 2008). There are some exceptions where undergraduate teaching is split into broad subject categories (Johnes 1997; Izadi *et al.* 2002; Johnes *et al.* 2005; Stevens 2005; Johnes *et al.* 2008; Johnes and Johnes 2009; Thanassoulis *et al.* 2009) and a small number of studies where all three outputs (undergraduate, postgraduate and research outputs) are divided into arts and science categories (Johnes 1996b; 1998). Finally, the outputs included here encompass only the teaching and research functions of HEIs. Universities also produce ‘third mission’ or social output. This includes such services as the storage of knowledge, the provision of advice to business and of comment on issues of public interest. As is the case with most previous studies, no attempt is made here to find and include a measure of this output, and results may be biased as a consequence of the omission.

Table 1 here

A panel of data was collected for 12 years from 1996/97 to 2007/08. The sample is unbalanced for a number of reasons. Some HEIs merged during the study period. When this happened the merged institution was treated as a different entity from the HEIs which merged to form it (this approach is similar to Cuesta and Orea 2002). Some HEIs entered the higher education sector during the period. Finally, HEIs which produced a zero amount of any output or used a zero amount of any input during a given year were removed from the sample in that year. In addition, four HEIs have been removed entirely from the sample: Open University has been removed because of its large size and unique nature of teaching provision; the University of London (Institutes and activities) is also excluded on the grounds that the composition of the component HEIs recorded under this umbrella changes over time; University of Buckingham is deleted because it is not publicly funded, and Heythrop College because it only became publicly funded during the time period under consideration. The number of HEIs included in each year therefore varies from 118 to 126, and the panel includes 1462 observations in total. Descriptive statistics are provided in table 2 for all variables across the pooled sample. The typical HEI produces just over 1000 graduates from postgraduate degrees and nearly 2500 graduates from undergraduate degrees. In addition, it receives over £67million in research grants. The inputs used by the average HEI are nearly 2000 postgraduate students, 6700 undergraduate students, and nearly 850 academic staff. In addition it spends around £9million on academic services and £15.5million on administration. The plots of the inputs and outputs over time (see figures 1a and 1b) suggest that there has been an upward trend in all variables over the entire period with the exception of research income which has fallen slightly in the last year.

Table 2 here
Figures 1a and 1b here

The inputs and outputs of the typical HEI conceal a substantial diversity across the HEIs contained in the sample. It is useful to examine, in figures 2a and 2b, the inputs and outputs of more homogeneous subgroups of HEIs. Pre-1992 HEIs are traditional universities which had university status prior to the Further and Higher Education Act of 1992.The typical pre-1992 university is characterised by production of both graduates from postgraduate degrees and research that exceed the corresponding levels produced by typical institutions in the other groups: the typical pre-1992 HEI produces around 1650 graduates from postgraduate degrees, 3000 graduates from undergraduate degrees and has research income of £123million. Post-1992 HEIs are former polytechnics which, by the provision of the Further and Higher Education Act, have, since 1992, been allowed to award their own degrees and use the title university. The typical post-1992 university produces approximately 1250 graduates from postgraduate degrees, 4350 graduates from undergraduate degrees and has £65million of research income. Production of graduates from undergraduate degrees therefore dominates the output of the typical post-1992 HEI. The third group of HEIs are institutions which are, or have recently been, colleges of higher education. These HEIs might be (but are by no means always) specialist institutions concentrating on a particular discipline. Since 2003, these colleges have been allowed to apply for university (and degree-awarding) status. The typical college of higher education is much smaller in size than the average university in other groups: it produces just over 300 graduates from postgraduate degrees, 1100 graduates from undergraduate degrees and has

£18million in research funding. The final group of universities are the colleges of the University of London which are recorded separately in the HESA data. These are separated out from other groups in the sample because they are a mix of institutions some of which concentrate on a particular discipline and all of which are administered under the umbrella of the University of London. The typical London HEI has slightly fewer graduates from postgraduate degrees and slightly more research funding than an average post-1992 HEI, and has a similar number of graduates from undergraduate degrees to a college of higher education.

Figures 2a and 2b here

5. RESULTS

The estimated parameters of the model defined in equation (18) are presented in table 3. All elasticities have the expected signs at the sample means. Returns to scale are measured by the (negative) sum of the marginal products of the inputs. Evidence regarding returns to scale (evaluated at the mean value of inputs and outputs) is mixed: the random effects model suggests returns are increasing, which is broadly in line with the finding of (ray) economies of scale in English higher education calculated from an estimated cost function for the period 2000/01 to 2002/03 (Johnes *et al.* 2005). The SFA estimation models, however, indicate that returns are decreasing. The contrast between the SFA findings and the earlier results from the estimated cost function may arise because of the difference between the studies in the definitions of outputs and the considerably longer time period covered by this study.

Table 3 here

5.1 Efficiency scores

The presence of technical inefficiency in the time invariant model is assessed using the test of H_0: $\sigma_u^2 = 0$ against the one-sided alternative, and in the time varying model by the test of H_0: $\mu = 0$[6] (Coelli *et al.* 2005). In both cases, H_0 is rejected and so inefficiency is significant. Mean efficiency over the whole period (reported in table 3) is around 70% and varies from around 37% in the worst-performing institutions to 97% at the top end (on the basis of the SFA results; RE results suggest a minimum of 47% and a maximum of 100%). Such variation in the performance of HEIs is worthy of further discussion. We will explore further the characteristics of the best- and worst-performing HEIs in section 5.3, but first it's worth examining the efficiency results found here in the context of previous studies of efficiency in higher education.

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[6] This tests for half-normal inefficiency effects at time period *T*.

It is difficult to make comparisons between this and previous studies because of differences in methodological approach and sample data. The level of efficiency found here is at the lower end of estimates found in previous studies which have also employed a production function approach to estimating efficiency (Athanassopulos and Shale 1997; Glass *et al.* 2002; Glass *et al.* 2006), and mean efficiency in these studies is in the range 85% to 95% (Flegg *et al.* 2004; Flegg and Allen 2007a; 2007b; Johnes 2008). However, mean efficiency of 70% is perfectly in line with estimates using a cost function approach (Johnes *et al.* 2005; Johnes *et al.* 2008). There are various explanations for the variation in results. First, this study differs from previous production function studies in terms of the diversity of institutions included in the sample (from colleges of higher education, through the more vocational post-1992 institutions to the pre-1992 traditional universities). From this perspective, it is much more similar to the sample sued in the cost function studies (Johnes *et al.* 2005; Johnes *et al.* 2008). Second, this study differs from all previous studies in terms of the long time period covered by the analysis. Third and most importantly, this study differs from the production function studies because it employs a parametric estimation method rather than a non-parametric approach (and in this sense, it is similar to the two cost function studies (Johnes *et al.* 2005; Johnes *et al.* 2008)). The distinction between parametric and non-parametric approach is an important one since SFA, in contrast to DEA, does not allow individual institutions to vary in their objectives, but instead applies the same parameters of the distance function to all HEIs. The effect of this distinction is illustrated by applying a constant returns to scale DEA model with the same 5 inputs and 3 outputs to the same HEIs: the result is a considerably higher average efficiency score of 86%. Given the diversity of the HEIs in this data set, perhaps a random parameter stochastic frontier distance function might be a more appropriate approach, but this is beyond the scope of the present paper[7].

Patterns of efficiency over time are indicated by the coefficient on the trend variable. *Evaluated at the mean of inputs and outputs*, technology has increased i.e. the frontier has been shifting outwards by 0.4 to 0.8% (per annum). The result is significant and is consistent with previous findings (using DEA) of positive technology change in English higher education over a similar period (Johnes 2008).

In the time varying decay model and *evaluated at the means of inputs and outputs*, technical efficiency has increased slightly by nearly 1% (per annum) over the period 1996/97 to 2007/08. The null hypothesis H_0: $\eta = 0$ is rejected at the 10% significance level offering some evidence of progress in technical efficiency in English higher education during the period under study. This differs from the clear finding, using DEA, of

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[7] The potential importance (in terms of efficiency estimates) of using a random parameter SFA rather than the SFA model used here is illustrated by the findings from two cost function studies. In the first, a SFA cost function is estimated across HEIs in England for a three-year period (2000/01 to 2002/03), and mean efficiency is found to be 69% (Johnes *et al.* 2008). In the second study, a SFA function with random parameters (i.e. the parameter on one of the outputs in the cost function, namely undergraduate science teaching, is allowed to vary by HEI) is estimated using the same data set, and in this case mean efficiency is found to be higher at 75% (Johnes and Johnes 2009).

technical efficiency regress over the period 1996/97 to 2004/05 (Johnes 2008). The complex functional form employed in the parametric estimation approach used here may well account for the differences between this study and the earlier one which took a non-parametric approach.

5.2 Measures of substitutability

The advantage of the parametric approach is that the estimated parameters of the distance function can provide information on substitution opportunities which are not available from the non-parametric DEA approach. The Morishima elasticities of substitution between outputs (M_{mn}), evaluated at the mean level of each input and each output are displayed in table 4a. All models suggest that, evaluated at the mean of inputs and outputs, there is scope to substitute out of postgraduate teaching output into research, since the Morishima elasticities are negative. There also appears to be some degree of substitutability from postgraduate into undergraduate teaching output. In contrast, opportunities for substitutability are much more limited between undergraduate teaching output and research (in both directions), from undergraduate into postgraduate teaching outputs, and from research into postgraduate teaching output.

Table 4a here

The Morishima elasticities of substitution between inputs (M_{kl}) are displayed in table 4b. Results are generally consistent across all estimation models. Specifically, substitution opportunities are limited (in both directions) between the following pairs of inputs: postgraduate students and staff; postgraduate students and academic services; undergraduate students and academic services; staff and academic services; academic services and administration. Substitution is relatively easy between undergraduate students and administration (in both directions). It is relatively easy to switch from undergraduates to postgraduates, from undergraduates to staff, from administration to postgraduates and from administration to staff, but not the other way around.

Table 4b here

While the values of the Morishima elasticities evaluated for an HEI using the mean level of inputs and producing the mean level of outputs are interesting, such an institution is purely hypothetical. Sensitivity of the results to evaluation at the mean is tested in two ways. First, the elasticities are evaluated at half of and twice the means of all the inputs and outputs. These results are shown in columns 4 to 9 of tables 4a and 4b. Generally speaking, substitution opportunities out of administration into other inputs are greater in smaller (half of mean) institutions than in larger (twice the mean) institutions.

Second, it is possible to evaluate the Morishima elasticities for each individual observation in the sample. From this, we can calculate mean values and test whether the mean is significantly different from zero. These values are shown in tables 5a and 5b. The results for outputs (table 5a) confirm the earlier findings that it is difficult to substitute undergraduate for postgraduate teaching output, and to substitute between undergraduate teaching output and research (in either direction).

Table 5a here

Table 5b here

The results for inputs are also consistent with those presented in the first three columns of table 4b: In summary, substitution is *generally* easier from undergraduates to postgraduates, to staff and to administration; and from administration to postgraduates, to undergraduates and to staff. Opportunities are much more limited in the context of the inputs postgraduates, staff and academic services. In making cuts, therefore, decision-makers should be aware of the limitation for substitution in the context of these inputs. A degree of caution should be exercised in developing policy from these results: where substitution appears possible, it should be remembered that the quality of teaching inputs and outputs has not been taken into account in the models estimated. Substitution between inputs may have adverse effects on quality which cannot be predicted from this model which accounts only for quantity.

5.3 Inter-institutional differences

Efficiency levels clearly differ by type of HEI (see table 6). Whilst the precise level of efficiency in each group differs by estimation method, the ranking does not. Pre-1992 universities and HEIs in London are the most efficient (with an average efficiency score of 71% to 76%) whilst post-1992 universities are typically less efficient (with an average of 67% to 69%). Colleges of higher education are the least efficient group of HEIs with an average efficiency of 60% to 67%. A test of the null hypothesis that means are the same for all groups is rejected. The lower level of efficiency amongst colleges of higher education is in line with earlier evidence based on a stochastic cost function (Johnes *et al.* 2008; Johnes and Johnes 2009) but conflicts with earlier evidence derived from a non-parametric output distance function (Johnes 2008). The earlier study, however, only includes 30 HEIs in the colleges of higher education category compared with between 38 and 43 included in each year of this study, and this may well account for the discrepancy.

Table 6 here

It is useful to see the characteristics of high- and low-performing HEIs (see table 7 and figures 3a and 3b). Those HEIs in the highest efficiency quartile have the largest number of postgraduate and research output (on average) of any other group, but have the *second lowest* undergraduate output. Inputs typically (with the exception of undergraduate inputs) are the highest. The plots illustrate the difference in size and mix of inputs in the most efficient HEIs compared to the lowest performing universities. Indeed, a comparison of figures 2a and 3a and figures 2b and 3b suggest that the pattern of production in the average pre-1992 HEI comes closest to the pattern of production in the average HEI in the top efficiency quartile: research in pre-1992 HEIs is a little lower and teaching output is a little higher than in the best performing universities. The Morishima elasticities presented earlier, however, suggest that there is some flexibility in terms of switching from postgraduate teaching (in particular) into research. In terms of inputs, pre-1992 universities use slightly more student inputs (particularly undergraduates) and fewer staff than the most efficient HEIs. The Morishima elasticities suggest that there is a degree of flexibility in terms of substituting out of undergraduate inputs into staff.

Table 7 here
Figures 3a and 3b here

The problem that the model does not include any kind of quality measure, particularly in the context of teaching inputs and outputs, has already been mentioned. As a crude measure of quality, the proportion of first and upper second class honours degrees achieved by the typical institution in each efficiency quartile is also included in table 7. There is no clear pattern. It is reassuring to note that the highest efficiency quartile also has the highest proportion of firsts and upper seconds, but there is little distinction between the highest and lowest quartiles in this respect. The null hypothesis that the mean proportion of first and upper second degrees is identical across efficiency quartiles cannot be rejected.

Finally, there has been some merger activity over the period[8], so we can see if efficiency differs between the pre-merger institutions and the merged entities. This can only be a crude analysis for two reasons. First, there is no control group with which to compare the pre- and post-merger institutions. Secondly, since the post-merger HEIs are inevitably later in the time period than the pre-merger HEIs, and since all models suggest that efficiency is slightly rising over time, there is an inbuilt tendency for the efficiency of post-merger HEIs to be slightly higher than the efficiency of pre-merger institutions. The main finding (see table 8 which displays the results from all models) is that average efficiency is considerably higher amongst post-merger than pre-merger (or non-merging) institutions. Moreover, the null hypothesis of identical means in the three groups is rejected. It should also be noted that pre-merger institutions typically have similar efficiency to non-merging HEIs. It appears, therefore, that the mergers which have taken place did not

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[8] There have been 20 instances during the period where institutions have merged into a new entity.

(typically) occur because of previously below-average performance. These results are interesting and point to the need for a more detailed analysis of the effect of merger activity.

Table 8 here

6. CONCLUSIONS

HEIs are likely to face tight fiscal constraints over the coming years. There has been some suggestion that cuts can be absorbed by increased efficiency. There is also a fear that cuts in budgets may increase the incidence of mergers in the sector. The purpose of this study is to estimate a multi-input multi-output distance function in order to provide a better understanding of possibilities for change in the sector. The results are derived from a panel data set of English HEIs over a period from 1996/97 to 2007/08. This is a period of rapid change (expansion) in terms of all inputs and outputs, in terms of the composition of the sector, and in terms of considerable merger activity. This study differs from previous ones which have examined efficiency in the English higher education sector in a number of ways. First, it uses a parametric rather than a non-parametric technique. This allows us to construct Morishima elasticities which signal the potential for substitutability between inputs and between outputs. Second, the merger activity which has taken place over the period allows us to explore what types of institutions (in terms of efficiency) are involved in mergers, and to examine the effect (in terms of efficiency) of the merger. Finally, the characteristics of HEIs in the lowest and highest efficiency quartiles are compared.

The first main finding from the study is that the English university sector is, on average, 70% efficient. Average efficiency varies significantly by type of HEI with the London and pre-1992 HEIs being more efficient than post-1992 universities, and these are in turn more efficient than colleges of higher education. The relatively low average efficiency found here for the sector as a whole contrasts strongly with that found in many other production function studies, and we speculate that this is caused by the estimation method which, unlike DEA, does not allow HEIs to have differing objectives but applies the same distance function across all observations. The results here therefore suggest that there is scope for efficiency improvements, especially in some HEIs. The Morishima elasticities indicate that, for a HEI using mean levels of inputs to produce mean levels of outputs, there is some degree of substitutability particularly from undergraduate inputs into other inputs and from administration into other inputs (except academic services). Advocates of reductions in administrative staff may therefore find some support for that policy in these results. Opportunities for substitution are generally much more limited from postgraduate inputs, staff and academic services. These conclusions are largely the same for HEIs which operate at half of and twice the mean levels of inputs and outputs.

An examination of the input and output composition of the highest and lowest performing HEIs suggests that the most efficient institutions tend to be the largest producers (on average) of postgraduate and research output, but not the largest producers of undergraduate outputs. The pattern of production in the typical institution in the highest efficiency quartile is closest to the pattern of production of pre-1992 universities (on average). Moreover, Morishima elasticities suggest that the changes in inputs and outputs which would make them more closely resemble the typical institution in the highest efficiency quartile are possible.

A strong caveat must accompany these results, however, since the model does not incorporate measures for quality particularly in the context of teaching inputs and outputs (at postgraduate and undergraduate levels). Thus, while changes may result in increased efficiency in the context of producing *output quantity*, this may well be at the expense of *output quality*. Clearly, possibilities fir modifying this model to take into account the quality of inputs and outputs should be considered in future work.

In the context of merger activity, the typical HEI involved in a merger has efficiency which is similar to the average non-merging HEI. The typical post-merger HEI is significantly more efficient than either pre-merger HEIs or non-merging HEIs. These results can only be a crude indicator as ideally there should be a control group of non-merging HEIs with similar characteristics to those of the merging HEIs with which to make comparisons. It does seem to suggest, however, that mergers of adequately performing institutions seem to have a beneficial effect on efficiency. This is an important result and should be followed up by a detailed investigation into the effect of institutional mergers on efficiency.

Figure 1a: Mean levels of outputs over time

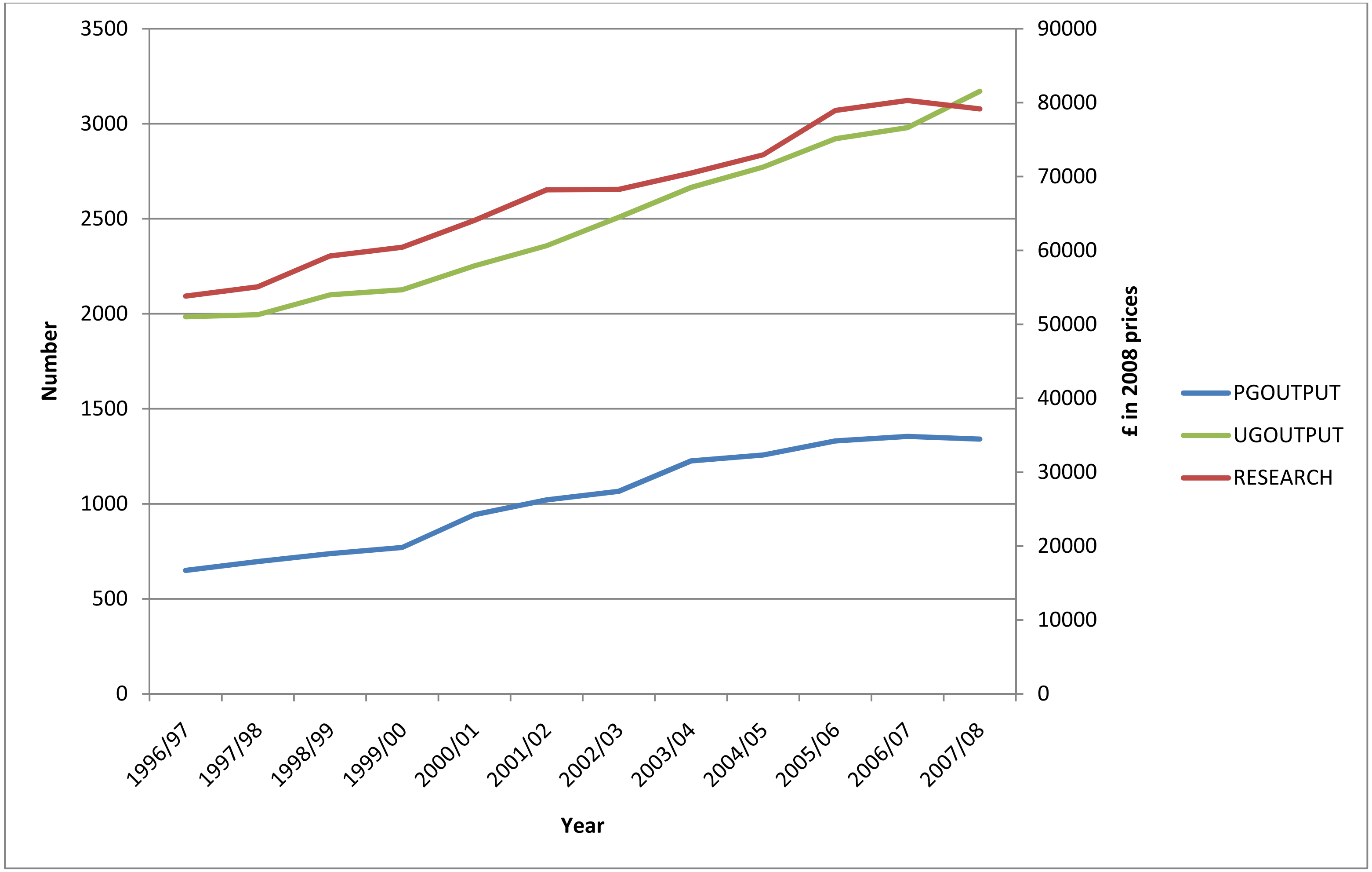


Figure 1b: Mean levels of inputs over time

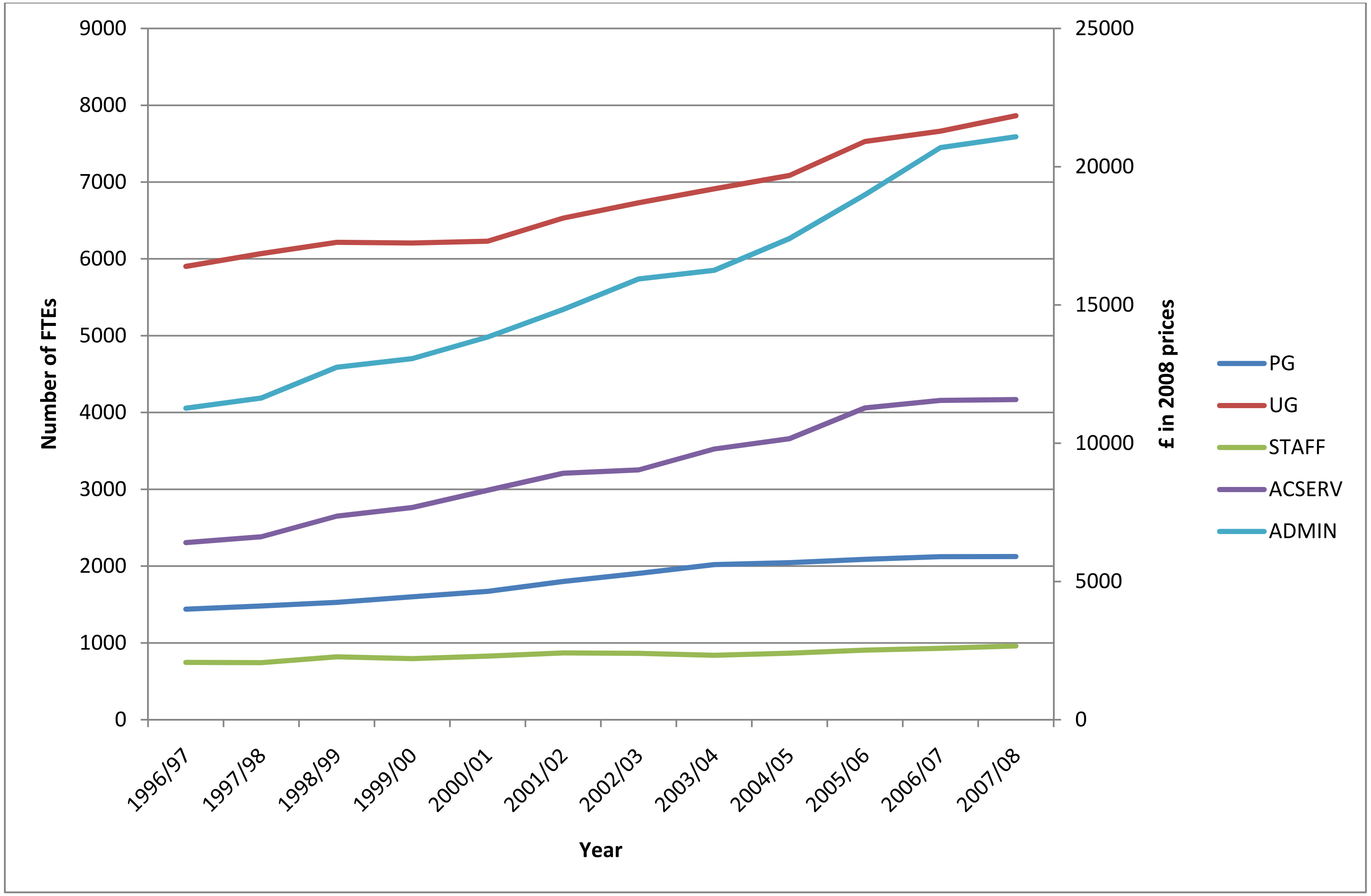


Figure 2a: Mean outputs by HEI type

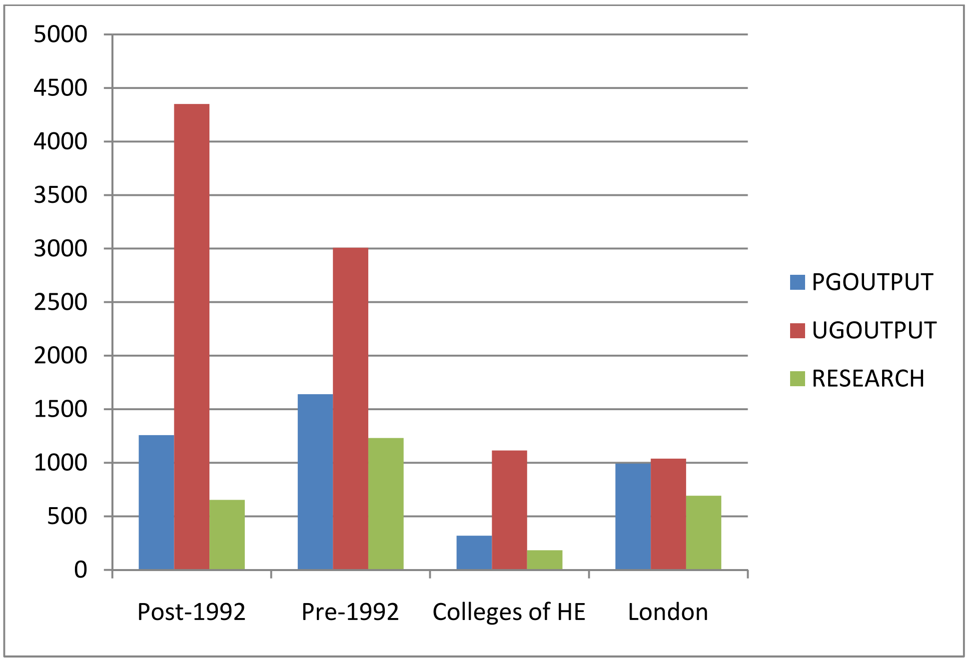
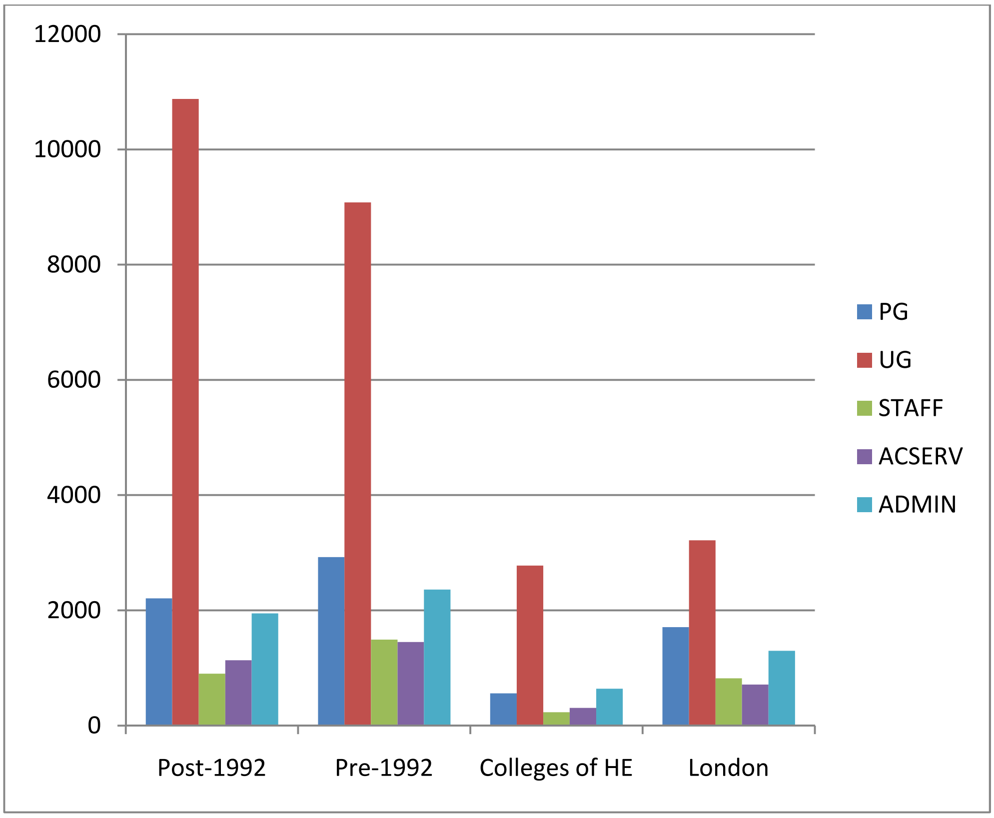


Figure 2b: Mean inputs by HEI type



Note: In order to plot inputs and outputs on the same axes, RESEARCH is in £00000s and ACSERV and ADMIN are in £0000s. See table 1 for units of measurement of remaining variables.

Figure 3a: Mean outputs by efficiency quartile

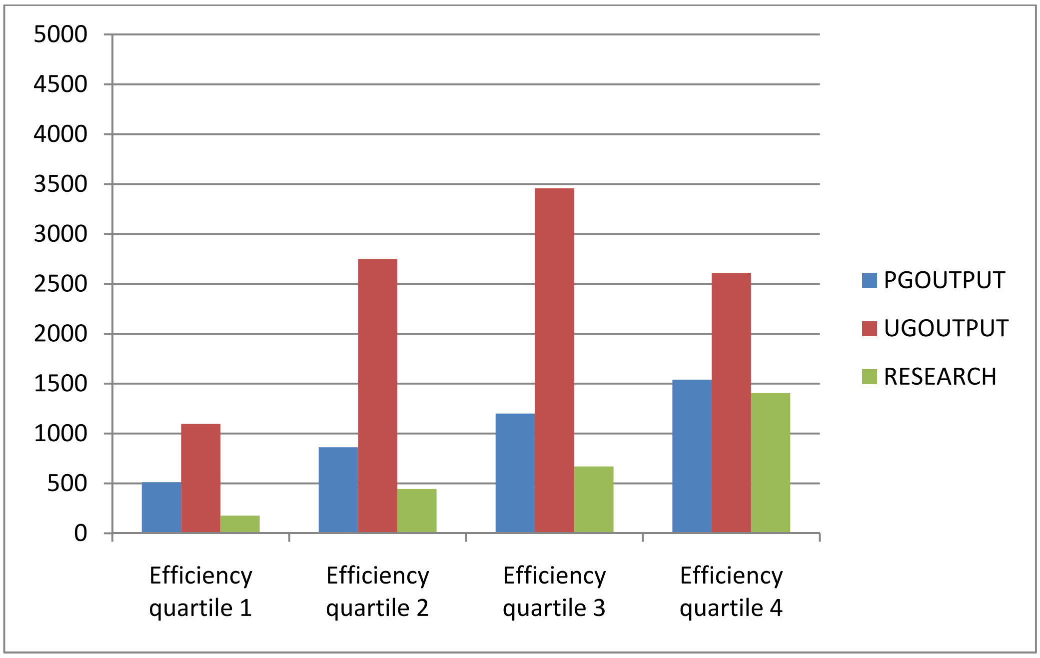
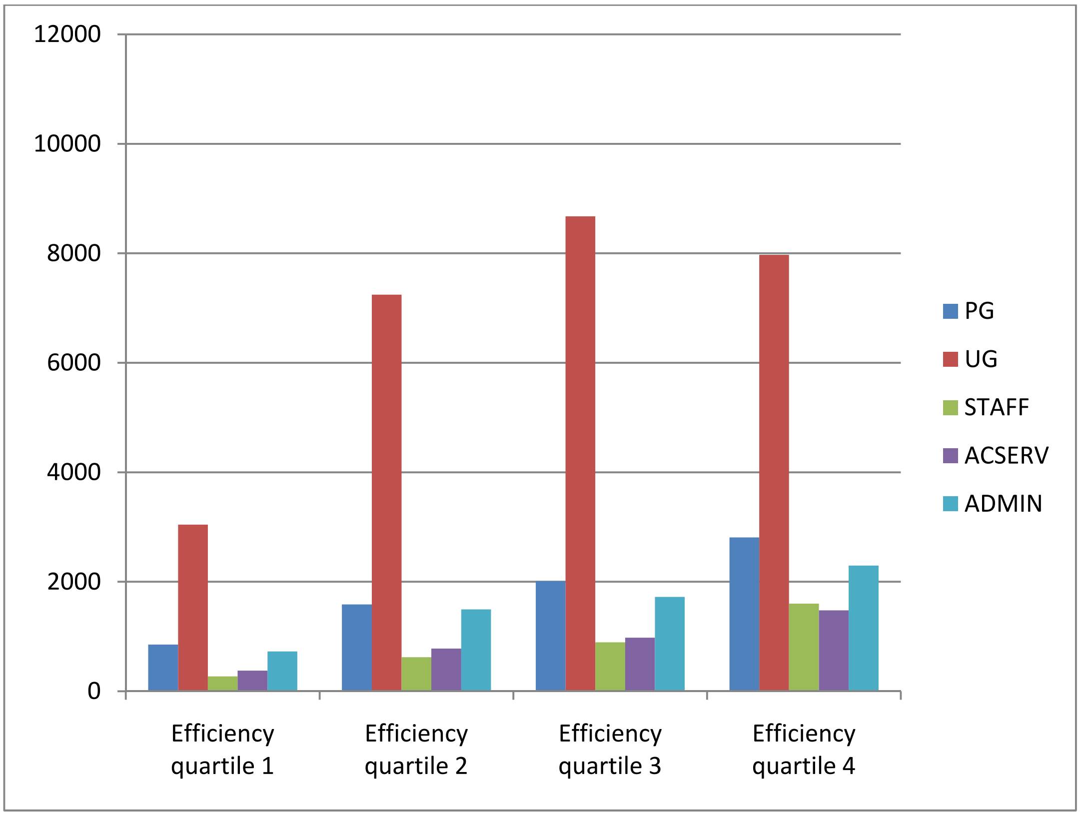


Figure 3b: Mean inputs by efficiency quartile



Note: In order to plot inputs and outputs on the same axes, RESEARCH is in £00000s and ACSERV and ADMIN are in £0000s. See table 1 for units of measurement of remaining variables.

Table 1: Definitions of inputs and outputs

Variable name		Definition
Inputs:		
PG	x_1	**The total number of FTE postgraduate students (i.e. students on programmes of study leading to higher degrees, diplomas and certificates, including Postgraduate Certificate of Education (PGCE) and professional qualifications)**
UG	x_2	**The total number of FTE first degree and other undergraduates. The 'other undergraduates' category includes qualification aims below degree level such as Foundation Degrees and Higher National Diploma (HND)[2]**
STAFF	x_3	**The number of full-time academic staff plus 0.5 times the number of part-time academic staff**
ACSERV[1]	x_4	**Expenditure incurred on centralised academic services such as the library and learning resource centres, central computer and computer networks, centrally run museums, galleries and observatories, and any other general academic services (in £000s)**
ADMIN[1]	x_5	**Expenditure on total administration and central services including expenditure on staff and student facilities (including, for example, Careers Advisory Service, all grants to student societies, emoluments to wardens of halls of residence, accommodation office, athletic and sporting facilities, excluding maintenance, and the institution's health service) and general educational expenditure (in £000s)**
Outputs		
PGOUTPUT	y_1	**The number of higher degrees plus total other postgraduate qualifications awarded (including doctorate, other higher degrees, PGCEs and other postgraduate qualifications)**
UGOUTPUT	y_2	**The number of first degree and other undergraduate degrees awarded (see definition of UG)**
RESEARCH[1]	$\mathbf{y_3}$	**Income received in funding council grants plus income received in research grants and contracts (in £000s)**

Notes:

1. These variables are deflated to July 2008 values using the higher education pay and prices index (http://www.universitiesuk.ac.uk/statistics/heppi/default.asp).
2. A full description of students included in these categories can be found in the HESA data documentation.
3. Source of data:(HESA 1994/95a; 1994/95b; 1995/96a; 1995/96b; 1996/97a; 1996/97b; 1997/98a; 1997/98b; 1998/99a; 1998/99b; 1999/00a; 1999/00b; 2000/01a; 2000/01b; 2001/02a; 2001/02b; 2002/03a; 2002/03b; 2003/04a; 2003/04b; 2004/05a; 2004/05b; 2005/06a; 2005/06b; 2006/07a; 2006/07b; 2007/08a; 2007/08b).

Table 2: Descriptive statistics

Variable	N	Mean	SD
Outputs:			
PGOUTPUT	1462	1028.27	891.85
UGOUTPUT	1462	2479.00	1854.48
RESEARCH	1462	67407.54	76124.40
Inputs:			
PG	1462	1814.39	1481.25
UG	1462	6732.87	4785.30
STAFF	1462	846.24	845.64
ACSERV	1462	9022.21	8244.26
ADMIN	1462	15584.14	12048.31

Table 3: Parameter estimates of the translog output distance function

		RE		TI		TVD	
		coeff	P-value	coeff	P-value	coeff	P-value
CONSTANT		0.055	0.000	-0.295	0.000	-0.339	0.000
PGOUTPUT	α_1	0.111	0.000	0.093	0.000	0.096	0.000
UGOUTPUT	α_2	0.281	0.000	0.229	0.000	0.225	0.000
RESEARCH[1]	α_3	0.608		0.678		0.679	
PGOUTPUT*PGOUTPUT	α_{11}	0.109	0.000	0.099	0.000	0.103	0.000
UGOUTPUT*UGOUTPUT	α_{22}	-0.117	0.000	-0.104	0.000	-0.107	0.000
RESEARCH*RESEARCH	α_{33}	-0.003		-0.023		-0.026	
PGOUTPUT*UGOUTPUT	α_{12}	0.002	0.890	-0.009	0.512	-0.011	0.424
PGOUTPUT*RESEARCH[1]	α_{13}	-0.111		-0.090		-0.092	
UGOUTPUT*RESEARCH[1]	α_{23}	0.115		0.114		0.118	
PG	β_1	-0.169	0.000	-0.164	0.000	-0.161	0.000
UG	β_2	-0.289	0.000	-0.276	0.000	-0.278	0.000
STAFF	β_3	-0.284	0.000	-0.233	0.000	-0.224	0.000
ACSERV	β_4	-0.140	0.000	-0.135	0.000	-0.133	0.000
ADMIN	β_5	-0.137	0.000	-0.152	0.000	-0.155	0.000
PG*PG	β_{11}	-0.010	0.534	-0.019	0.187	-0.016	0.267
UG*UG	β_{22}	-0.237	0.000	-0.219	0.000	-0.224	0.000
STAFF*STAFF	β_{33}	0.006	0.899	-0.043	0.319	-0.038	0.378
ACSERV*ACSERV	β_{44}	0.011	0.654	-0.003	0.915	-0.008	0.735
ADMIN*ADMIN	β_{55}	-0.172	0.002	-0.145	0.004	-0.141	0.005
PG*UG	β_{12}	0.164	0.000	0.122	0.000	0.124	0.000
PG*STAFF	β_{13}	-0.139	0.000	-0.082	0.001	-0.081	0.001
PG*ACSERV	β_{14}	0.025	0.197	0.018	0.318	0.013	0.479
PG*ADMIN	β_{15}	-0.009	0.761	-0.006	0.837	-0.007	0.787
UG*STAFF	β_{23}	0.039	0.159	0.050	0.074	0.050	0.074
UG*ACSERV	β_{24}	-0.011	0.644	-0.015	0.518	-0.008	0.734
UG*SADMIN	β_{25}	0.116	0.011	0.146	0.000	0.150	0.000
STAFF*ACSERV	β_{34}	-0.006	0.766	0.021	0.307	0.021	0.305
STAFF*ADMIN	β_{35}	0.060	0.132	0.008	0.820	-0.002	0.963
ACSERV*ADMIN	β_{45}	-0.058	0.035	-0.064	0.012	-0.060	0.018
PG*PGOUTPUT	δ_{11}	-0.066	0.000	-0.051	0.000	-0.052	0.000
PG*UGOUTPUT	δ_{12}	-0.013	0.493	0.005	0.769	0.008	0.638
PG*RESEARCH[1]	δ_{13}	0.079		0.046		0.044	
UG*PGOUTPUT	δ_{21}	-0.162	0.000	-0.138	0.000	-0.141	0.000
UG*UGOUTPUT	δ_{22}	0.162	0.000	0.144	0.000	0.146	0.000
UG*RESEARCH[1]	δ_{23}	0.000		-0.006		-0.005	
STAFF*PGOUTPUT	δ_{31}	0.171	0.000	0.138	0.000	0.137	0.000
STAFF*UGOUTPUT	δ_{32}	-0.100	0.000	-0.107	0.000	-0.108	0.000
STAFF*RESEARCH[1]	δ_{33}	-0.071		-0.031		-0.028	

ACSERV*PGOUTPUT	δ_{41}	-0.016	0.237	-0.013	0.274	-0.011	0.355
ACSERV*UGOUTPUT	δ_{42}	0.029	0.090	0.028	0.085	0.029	0.066
ACSERV*RESEARCH[1]	δ_{43}	-0.013		-0.014		-0.018	
ADMIN*PGOUTPUT	δ_{51}	0.044	0.037	0.038	0.047	0.042	0.029
ADMIN*UGOUTPUT	δ_{52}	-0.066	0.036	-0.060	0.045	-0.062	0.035
ADMIN*RESEARCH[1]	δ_{53}	0.022		0.021		0.020	
YEAR	τ	0.004	0.000	0.004	0.000	0.008	0.000
	σ^2			0.044	0.000	0.043	0.000
	σ_u^2			0.039	0.000	0.038	0.000
	σ_v^2			0.006	0.000	0.005	0.000
	μ			0.358	0.000	0.369	0.000
	η					0.009	0.067
Mean Technical Efficiency		0.699		0.691		0.676	
Log Likelihood				1413.76		1415.23	
N		1462		1462		1462	
No. of groups		164		164		164	
Returns to scale[2]		1.019		0.959		0.951	

Notes:

1. RE=random effects estimation model; TI=time invariant SFA model; TVD=time varying decay SFA model
2. Estimated parameters without P-values are calculated using the homogeneity conditions (see equations (13a) to (13c) and (14a) to (14b)).
3. Returns to scale are evaluated at the mean of inputs (and outputs).

Table 4: Morishima's elasticties evaluated at the mean, half of the mean and twice the mean of inputs and outputs

	Mean			**0.5*Mean**			**2*Mean**		
	1	2	3	4	5	6	7	8	9
	RE	TI	TVD	RE	TI	TVD	RE	TI	TVD
a) Outputs									
M_{12}	0.021	-0.110	-0.121	0.172	0.065	0.042	-0.197	-0.372	-0.358
M_{21}	1.434	1.357	1.357	1.443	1.388	1.394	1.426	1.318	1.313
M_{13}	-0.169	-0.203	-0.207	-0.022	-0.028	-0.043	-0.384	-0.464	-0.444
M_{31}	0.000	0.064	0.084	0.154	0.225	0.232	-0.222	-0.175	-0.129
M_{23}	1.603	1.623	1.648	1.619	1.641	1.669	1.588	1.606	1.628
M_{32}	1.413	1.531	1.563	1.425	1.548	1.584	1.402	1.515	1.542
b) Inputs									
M_{12}	0.376	0.444	0.454	0.465	0.534	0.551	0.250	0.309	0.303
M_{21}	-0.790	-0.541	-0.576	-0.559	-0.312	-0.329	-1.103	-0.873	-0.947
M_{13}	1.431	1.240	1.264	1.490	1.310	1.342	1.379	1.179	1.200
M_{31}	1.842	1.320	1.332	1.750	1.228	1.239	1.962	1.424	1.438
M_{14}	0.764	0.752	0.805	0.728	0.729	0.790	0.785	0.757	0.806
M_{41}	0.934	0.871	0.859	0.971	0.879	0.852	0.899	0.856	0.857
M_{15}	1.008	0.923	0.950	1.045	0.951	0.980	0.984	0.896	0.924
M_{51}	-0.198	0.083	0.137	-0.790	-0.279	-0.204	0.112	0.292	0.337
M_{23}	0.041	-0.011	-0.029	0.146	0.093	0.083	-0.116	-0.195	-0.242
M_{32}	0.884	0.634	0.650	0.906	0.636	0.653	0.854	0.608	0.618
M_{24}	0.258	0.318	0.256	0.396	0.487	0.425	0.076	0.088	0.002
M_{42}	1.120	1.037	0.968	1.134	1.022	0.945	1.114	1.055	0.988
M_{25}	-0.664	-0.754	-0.772	-0.939	-0.976	-0.977	-0.629	-0.758	-0.810
M_{52}	-0.653	-0.481	-0.450	-1.180	-0.746	-0.683	-0.433	-0.416	-0.420
M_{34}	1.067	0.657	0.668	1.080	0.584	0.592	1.057	0.708	0.720
M_{43}	1.105	0.890	0.843	1.127	0.870	0.809	1.089	0.904	0.867
M_{35}	0.583	0.760	0.841	0.380	0.710	0.814	0.687	0.794	0.861
M_{53}	-0.463	0.012	0.098	-1.072	-0.350	-0.235	-0.142	0.221	0.290
M_{45}	1.506	1.400	1.326	1.725	1.551	1.451	1.390	1.313	1.255
M_{54}	0.164	0.521	0.544	-0.321	0.295	0.336	0.399	0.640	0.655

Columns 1, 4 and 7 are calculated from the RE model (see section 3).Columns 2,5 and 8 are calculated from the time invariant SFA model (see section 3). Columns 3,6 and 9 are calculated from the time varying decay SFA model (see section 3). Columns 1, 2 and 3: values are evaluated at means of all inputs and all outputs. Columns 4, 5 and 6: values are evaluated at 0.5*means of all inputs and all outputs. Columns 7, 8 and 9: values are evaluated at 2*means of all inputs and all outputs.

Table 5: Morishima elasticities averaged across all HEIs

	1	2	3
a) Outputs			
M_{12}	-0.092	-1.603	-0.689
M_{21}	1.470*	1.204*	1.314*
M_{13}	-0.292	-1.701	-0.786
M_{31}	-0.115	-1.290	-0.416
M_{23}	1.647*	1.615*	1.685*
M_{32}	0.933*	1.033*	1.087*
b) Inputs			
M_{12}	0.434*	0.224	1.377*
M_{21}	-0.758*	-0.948*	5.878
M_{13}	1.257*	1.495*	2.015*
M_{31}	1.882*	1.196*	-2.698
M_{14}	0.720*	0.720*	1.581*
M_{41}	0.944*	0.864*	1.496*
M_{15}	0.995*	0.917*	1.747*
M_{51}	-0.016	0.178*	-0.424
M_{23}	0.178	-0.558	0.239
M_{32}	0.892*	0.410*	0.721*
M_{24}	0.365*	-0.047	0.508*
M_{42}	1.135*	1.060*	0.953*
M_{25}	-0.454*	-1.050*	-0.730*
M_{52}	-0.430*	-0.646*	-0.477
M_{34}	1.070*	0.488*	0.667*
M_{43}	1.116*	0.819*	0.846*
M_{35}	0.638*	0.632*	0.860*
M_{53}	-0.210	0.081*	-0.094
M_{45}	1.465*	1.354*	1.400*
M_{54}	0.440*	0.722*	0.402
RTS	1.044*	0.224*	1.377

Note:

* The H_0: mean elasticity is equal to 0 is rejected at the 5% significance level (2-sided test). In the case of RTS the H_0: mean is equal to unity is rejected at the 5% significance level.

Table 6: Efficiency by type of HEI

	RE	TI	TVD	N
Post-1992 HEIs	0.693	0.681	0.666	366
Pre-1992 HEIs	0.714	0.752	0.739	435
Colleges of HE	0.672	0.619	0.599	485
London	0.745	0.760	0.752	176

Note:

RE=random effects estimation model; TI=time invariant SFA model; TVD=time varying decay SFA model

Table 7: Characteristics of HEIs by efficiency quartile

Quartile	1	2	3	4
N	366	365	366	365
Efficiency score	0.534	0.629	0.709	0.832
RTS	0.978	0.981	0.987	1.048
a) Outputs				
PGOUTPUT	511.333	862.655	1200.402	1539.638
UGOUTPUT	1097.511	2750.937	3458.363	2610.271
RESEARCH	17794.620	44406.290	66953.230	140613.200
b) Inputs				
PG	853.150	1584.671	2013.079	2808.745
UG	3044.063	7244.819	8676.478	7970.893
STAFF	271.973	621.053	892.713	1600.648
ACSERV	3748.379	7792.715	9786.895	14773.220
ADMIN	7257.000	14943.220	17214.200	22940.500
c) Quality				
Proportion of 1st and 2is	0.542	0.508	0.537	0.568

Note:

Quartiles are based on the SFA TVD model.

Table 8: Efficiency by merger activity

	RE	TI	TVD	N
Pre-merger HEIs	0.704	0.693	0.671	154
Post-merger HEIs	0.739	0.802	0.794	122
All other HEIs	0.694	0.679	0.664	1186

TI=time invariant estimation model; TVD=time varying decay model

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