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## Abstract

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# 1 Introduction

The impact of institutions on economic performance is currently the subject of much debate among economists and policy makers. In this paper, we examine empirically a mechanism through which institutional and economic variables can affect a country's economic performance. It is generally accepted (see, for example, World Bank (1993)) that different countries operate at different distances from the frontier and that "catch up" can account for some of the differences in economic growth. Adkins, Moomaw and Savvides (2000) postulate that deviations from the production possibility frontier are functions of certain economic and institutional variables. Their results suggest that even among the members of the OECD, variations in human capital, economic freedom, and the tax burden are linked to efficiency. In this paper, propose a similar model and attempt to determine empirically whether these institutional differences extend to the regional level with countries.

Economists have demonstrated that institutions may have large effects on economic performance. For instance, Rodrik (1997) provides evidence that democracies are associated with: (1) more stable long-run growth rates, (2) greater short-run stability, (3) better ability to deal with adverse shocks; and (4) higher wages. He proposes three explanations of these empirical regularities. First, democracies may have greater stability because the preferences of the median voter inhibit radical policy actions that would yield extreme results. Second, voice in the political process reduces the amount of internal conflict. Finally, losers in political battles are more likely to avoid economic loss in a democracy than in other types of government.

Several recent studies have examined the role of institutions in promoting economic growth and productivity. For example, Dawson (1998) estimates cross-county growth and investment regressions and finds that economic growth is associated with economic freedom because of the latter's positive effect on investment and the level of total factor productivity (TFP). Aspects of political freedom are associated with higher investment, but there is no indication that they are associated with higher TFP. Using some of the same data as our study, Edwards (1998) first estimates a production function for a panel of 93 developed and developing countries and calculates TFP growth. He then estimates a relationship between the degree of trade openness and TFP growth and finds that initial per capita GDP, initial level of human capital and openness are important determinants of TFP growth.

Other research, more closely related to ours, indicates that planned economies are less efficient than unplanned ones. Bergson (1987, 1989, 1991), Marer (1981), Moroney and Lovell (1997) and others compare the performance of centrally planned economies to that of western market economies. Bergson (1987, 1989) estimates a constant-returns-to-scale production function via ordinary least squares and a dummy variable identifying planned economies. He finds that planned economies tend to use capital and land less efficiently than market economies. Moroney (1992) follows a similar approach and shows that planned economies used capital and energy less efficiently than West European economies during 1978-1980.

Moroney and Lovell (1997) were the first to use stochastic production frontier panel data techniques to compare the productive performance of market and planned economies. Their goal was to quantify the extent to which market economies are more efficient than planned ones. They find West European market economies have been much more productive than a group of seven East European planned economies during 1978-1980. They attribute most of the difference to the use of better technology in market economies. The Eastern European economies were no more than 76 percent as efficient as the Western European economies during this period.

None of the aforementioned studies account for the sources of technical inefficiency other than with the use of dummy variables indicating planned or market economies. In addition, they focus on OECD countries versus the former USSR or Eastern European economies. In this study, we use panel data to estimate a production frontier and examine the sources of inefficiency of regions within the European community. In the initial phases of this research we limit ourselves examining whether country specific factors affect technical inefficiency in a statistically significant way.

## 2 The Stochastic Frontier Model

A number of studies have estimated a stochastic production frontier and used the difference from the frontier (a measure of the predicted efficiencies) in a second stage regression to determine reasons for differing efficiencies. In the first stage, the predicted inefficiencies are estimated under the assumption that they are independently and identically distributed. Regressing other variables on the inefficiencies in a second stage is a clear violation of the independence assumption. According to Kumbhakar, Ghosh, and McGuckin (1991), there are at least two problems with such a procedure. First, inefficiency may be correlated with the inputs; if so the inefficiencies and the parameters of the second stage regression are inconsistently estimated. Second, the use of OLS in the second stage ignores the fact that the dependent variable (inefficiency) takes on values over the positive domain. Therefore, OLS may yield predictions that are inconsistent with this fact and is therefore not appropriate.

Kumbhakar, Ghosh, and McGuckin (1991) and Reifschneider and Stevenson (1991), have proposed models of technical inefficiency in the context of stochastic frontier models. In these cross-sectional models, the parameters of the stochastic frontier and the determinants of inefficiency are estimated simultaneously given appropriate distributional assumptions about the model's errors. Battese and Coelli (1995) proposed a stochastic frontier model in which the inefficiencies are expressed as specific functions of explanatory variables. The panel specification of this model can be expressed as follows:

$$y_{it} = x_{it}\beta + (V_{it} - U_{it}) \qquad i = 1, \dots, N \quad t = 1, \dots, T \tag{1}$$

where $y_{it}$ is the (logarithm) of output of country $i$ in time period $t$; $x_{it}$ is a $k \times 1$ vector of inputs; $\beta$ is a vector of unknown parameters; $V_{it}$ are random variables which are assumed to be independently and identically distributed $N(0, \sigma_V^2)$ and independent of $U_{it}$. The $U_{it}$ are non-negative random variables that account for technical inefficiency in production; they are assumed to be independently distributed as truncations at zero of the $N(m_{it}, \sigma_U^2)$ distribution. The mean inefficiency is a deterministic function of $p$ explanatory variables:

$$m_{it} = z_{it}\delta \tag{2}$$

where $\delta$ is a $p \times 1$ vector of parameters to be estimated. Following Battese and Corra (1977) we let $\sigma^2 = \sigma_V^2 + \sigma_U^2$ and $\gamma = \sigma_U^2/(\sigma_V^2 + \sigma_U^2)$.

Using this parameterization a test can be constructed to determine whether a production possibilities frontier (i.e., a one sided error term $U_{it}$) is supported by the data. If $U_{it}$ does not enter the model as a random variable then $\sigma_U^2 = 0$, $\sigma^2 =$

$\sigma_V^2$ and $\gamma = 0$. So, a hypothesis test of the null hypothesis that $\gamma = 0$ against the alternative that it is positive is used to test whether any form of stochastic frontier is required. Failure to reject the null suggests that the inefficiency term $U_{it}$ should be removed from (1), and then $\beta$ can be consistently estimated using ordinary least squares.

The inefficiencies, $U_{it}$, in equation (1) can be specified as:

$$U_{it} = z_{it}\delta + W_{it} \tag{3}$$

where $W_{it}$ is defined by the truncation of the normal distribution with mean zero and variance, $\sigma^2$. The parameters of the model ($\beta, \delta, \sigma^2$, and $\gamma$) are estimated using the maximum likelihood estimator (MLE); the likelihood function can be found in the Appendix. Then, the technical inefficiency of the $i$th country at time $t$ is

$$\mathrm{TE}_{it} = \exp\left(-U_{it}\right) = \exp\left(-z_{it}\delta - W_{it}\right) \tag{4}$$

The conditional expectation of $\mathrm{TE}_{it}$ is given in equation (13) of the Appendix and is used to produce predictions for each country in each time period, our measure of inefficiency. Computations were performed using the algorithm described in (Coelli 1996).

## Translog Production Function

We model the production function in (1) with the translog functional form because of its flexibility. The translog model can be interpreted as a second-order approximation to the unknown functional form. Most other contributions to this literature have adopted the constant returns to scale Cobb-Douglas model (e.g., Bergson (1987); Bergson (1989); Dawson (1998); Moroney and Lovell (1997); and Moroney (1992)). In the following section, we test the null hypothesis of the Cobb-Douglas specification versus the translog specification and reject the Cobb-Douglas at the 5% level in every instance. The translog specification of (1) is:

$$\begin{aligned}\ln Y_{it} = \beta_0 + \ln\left(L_{it}\right)\beta_1 + \ln\left(K_{it}\right)\beta_2 + .5[\ln\left(L_{it}\right)]^2\beta_3 +& \\ .5[\ln\left(K_{it}\right)]^2\beta_4 + \ln\left(L_{it}\right)\ln\left(K_{it}\right)\beta_5 + \left(V_{it} - U_{it}\right)&\end{aligned} \tag{5}$$

where $Y_{it}$ isoutput and $K_{it}$ and $L_{it}$ are physical capital and labor, respectively. Equation (5), however, ignores the role of technological change. This is normally modeled as a function of time introduced directly into the production function.

In order to identify whether there are country specific sources of inefficiency we have included dummy variables for each country. In addition, population density is also included as a determinant of efficiency.

# 3 Data

The data are constructed using the Eurostat database. The principle difficulty in this, as in many productivity studies, is the construction of a suitable capital stock series. This is particularly difficult for gathered at the regional level where time series on investment tend to be very short and contain missing observations.

In principle a series could be constructed based on the following equation:

$$K_t = \delta K_{t-1} + I_t \tag{6}$$

where $\delta$ represents the proportion of the capital stock remaining after depreciating in the prior period (one minus the depreciation rate), $K_t$ is real value of the capital stock in period $t$, and $I_t$ is real current investment. By recursive substitutions this becomes

$$K_t = \sum_{i=0}^{\infty} \delta^i I_{t-i} \tag{7}$$

Hence, if the depreciation rate is known and the investment series extends a long way into the past a reasonably accurate measure of the current period's capital stock can be obtained.

It is unlikely that regional investment data extend more that a few periods into the past. In our data series, a few of the regions have only 5 observations. In addition, there are several missing years in a few of the countries. The gaps in the data were filled by interpolation. For instance, no investment is reported for Denmark in 1991. To arrive at an estimate for that year's investment, investment for 1992 and 1990 were averaged. If the lapse in data is longer but no more than 3 periods, then a similar interpolation is performed. Again, in Denmark investment is missing in years 1984 and 1985. In order to obtain 1985 investment one third of the change in investment between 1986 and 1983 was added to 1983s investment to obtain data for 1984. Two thirds of the change is added to get the next year in the series.[1]

Another difficulty arises when the series are of different lengths. Some means of normalizing the depreciated sums of different length investment series. One method is to use the following:

$$K_t = \sum_{i=0}^{d} \delta^d I_{t-i}/(1 - \delta^{d+1}) \tag{8}$$

Once the last available periods capital stock is estimated then the previous periods are computed using equation (6). Several values of the depreciation parameter were tried and the results were not sensitive to the choice. The results below are based on $\delta = .85$ or an average depreciation rate of 15%. Giese and Schnorbus (1989) provide a good summary of the issues surrounding the difficulties of constructing regional capital stock series.

The other data consist of employment, gdp, land area, and population, all of which are from the Eurostat CD. Population density was computed by dividing population in various years by the most recently available measure of land area.

Although some of the regional series extend back to 1975 we decided to truncate our sample at 1982. This was done to reduce the level of error introduced into the computation of the imputed capital stock series. So, our sample consists of 14 years (1982-1996) and 80 regions in Europe. Each observation was disaggregated to its lowest available level. For instance, there were no regional data for Denmark and it is not disaggregated from the country level (NUTS 0). For Italy and France, on the other hand, some of the regions are reported at NUTS 2 while others only for NUTS 1. In the UK there is a small amount of data at the NUTS 1 level, but for some reason the NUTS 1 data are missing for 1991; in this instance the NUTS 0 country aggregate is available and is used. In the sample Denmark, Germany, Greece, Spain, France, Ireland, Italy, Netherlands, Luxembourg, Portugal and the UK are represented. There are no observations for Belgium, Austria, Finland, or Sweden.

A series of dummy variables were created for each of the countries in our sample and are included in the efficiency stage of the model in order to permit hypothesis tests to determine whether being in a country moves reduces inefficiency or increases inefficiency.

Summary statistics appear in table 1. The symbols K2 and L2 represent $\ln^2(K)$ and $\ln^2(L)$, respectively and $KL = \ln(L)\ln(K)$. The summary statistics for the dummy variables are also included and yield some important information. Their means actually represent the proportion of the sample represented by each country. Thus, the relatively complete set of NUTS 2 regional observations for Italy accounted for about 37% of the observations. Portugal, having only 5 observations, is less than 1% of the sample.

# 4 Results

The maximum likelihood estimates for 2 specifications of the model are presented in table 2. In the first two columns are the estimates and t-ratios for a translog production function; in the last 2 columns are results for a Cobb-Douglas model.

Using a translog model we obtain reasonable estimates of both the capital and labor elasticities (which were measured at the center of the data). This is encouraging given the difficulties associated with construction of an adequate measure of capital stock. The capital elasticity is estimated to be .289 whereas labor's is estimated to be .735. Both are significantly different from zero at any reasonable testing level. The elasticities produced by the Cobb-Douglas model are less satisfactory, but within the range reported by others including Adkins et al. (2000) and many others using a variety of data sets. The Cobb-Douglas specification was tested against the translog using a likelihood ratio test. The resulting $\chi^2$ statistic, its critical value, and the degrees of freedom appear towards the bottom of the table in column (1). According to this test, the Cobb-Douglas specification is rejected in favor of the translog at the 5% level of significance. Since the Cobb-Douglas model may be misspecified, the specific results for it are not discussed further.

The t-ratios associated with the country effects are significantly negative for Denmark, Germany, and the Netherlands; this is evidence that these countries (or regions therein) have significantly less inefficiency or that they tend to lie closer to the production frontier. On the other hand, the regions in Greece, Spain, France, Ireland, Italy, and Portugal are farther from the frontier. Population density is not significant in the translog model.

To illustrate, we have produced estimated efficiencies for the regions and countries in the sample for the years 1990-1996. These appear in table 3. Note that regions in Germany are estimated to be 99% efficient while those of Portugal only 46% efficient.

```
Variable    N          Mean       Std Dev       Minimum       Maximum
---------------------------------------------------------------------
ID        748    37.5721925    21.2635374     1.0000000    80.0000000
TIME      748     7.6951872     3.4576231     1.0000000    14.0000000
ln(GDP)   748    10.2194277     1.1268205     6.9578800    13.5451000
ln(K)     748    10.4354554     1.0083178     8.1338400    13.1271000
ln(L)     748     6.7441643     1.0832673     4.0448000    10.1816000
K2        748    54.9570297    10.5866833    33.0797000    86.1602000
L2        748    23.3278255     7.2339815     8.1802200    51.8323000
KL        748    71.4260779    17.8929280    33.0829000   133.6540000
DK        748     0.0173797     0.1307688             0     1.0000000
DE        748     0.1804813     0.3848452             0     1.0000000
GR        748     0.0120321     0.1091019             0     1.0000000
ES        748     0.0066845     0.0815395             0     1.0000000
FR        748     0.2058824     0.4046155             0     1.0000000
IE        748     0.0173797     0.1307688             0     1.0000000
IT        748     0.3743316     0.4842737             0     1.0000000
NL        748     0.0173797     0.1307688             0     1.0000000
LU        748     0.1283422     0.3346943             0     1.0000000
PT        748     0.0066845     0.0815395             0     1.0000000
UK        748     0.0334225     0.1798573             0     1.0000000
DENSITY   748     0.0529849     0.1260000     0.0024579     1.9507200
```

Table 1: Summary statistics for all variables

| | (1)<br>Coef | (2)<br>T-Ratio | (3)<br>Coef | (4)<br>T-Ratio |
|---|---|---|---|---|
| Constant | 1.6377 | 1.656 | 1.853 | 6.904 |
| $\ln(K)$ | 1.3998 | 3.454 | 0.511 | 11.959 |
| $\ln(L)$ | -0.6458 | -1.651 | 0.523 | 18.184 |
| $.5\ln^2(K)$ | -0.4085 | -4.258 | . | . |
| $.5\ln^2(L)$ | -0.5187 | -5.522 | . | . |
| $\ln(L)\ln(K)$ | 0.4674 | 4.922 | . | . |
| $Time$ | 0.0454 | 23.814 | 0.046 | 34.437 |
| | | | | |
| $\sigma^2$ | 0.0242 | 21.153 | 0.027 | 10.703 |
| $\gamma$ | 0.1297 | 8.119 | 0.087 | 6.110 |
| | | | | |
| Denmark | -0.2566 | -2.179 | -0.221 | -0.256 |
| Germany | -0.4594 | -19.113 | -0.392 | -12.003 |
| Greece | 0.2441 | 2.957 | 0.183 | 0.530 |
| Spain | 0.4986 | 5.974 | 0.243 | 0.347 |
| France | 0.1252 | 5.274 | 0.147 | 2.329 |
| Ireland | 0.1917 | 3.056 | 0.080 | 0.136 |
| Italy | 0.2941 | 28.880 | 0.276 | 11.300 |
| Netherlands | -0.4290 | -26.165 | 0.121 | 0.180 |
| Luxembourg | 0.0221 | 0.979 | -0.385 | -19.319 |
| Portugal | 0.7802 | 8.365 | 0.339 | 0.973 |
| UK | -0.0298 | -0.147 | -0.382 | -5.152 |
| Pop'l Density | 0.0002 | 0.077 | 0.034 | 1.632 |
| | | | | |
| Log Likelhihood | 358.7982 | | 333.965 | |
| Likehood Ratio | 49.6657 | | | |
| Degrees of Freedom | 3.0000 | | | |
| Critical value, 5% | 7.8100 | | | |
| | | | | |
| Elasticity | | | | |
| K | 0.289 | 10.0308 | 0.511 | 11.959 |
| L | 0.734 | 27.7134 | 0.523 | 18.184 |

Table 2: ML estimates of regional production functions and determinants of regional inefficiency

Table 3: Estimated efficiencies by country or region for 1990-1996

| Code | Name | 1996 | 1995 | 1994 | 1993 | 1992 | 1991 | 1990 |
|---|---|---|---|---|---|---|---|---|
| dk | Denmark | . | 0.989 | 0.989 | 0.989 | 0.989 | 0.989 | 0.989 |
| de1 | Baden-Wrttember | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| de2 | Bayern | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| de3 | Berlin | . | 1.000 | 1.000 | 0.994 | 0.994 | 0.993 | . |
| de5 | Bremen | . | 0.994 | 0.994 | 0.994 | 0.994 | 0.994 | 0.994 |
| de6 | Hamburg | . | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| de7 | Hessen | . | 0.994 | 0.994 | 0.994 | 0.994 | 0.994 | 0.994 |
| de9 | Niedersachsen | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| dea | Nordrhein-Westfa | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| deb | Rheinland-Pfalz | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| dec | Saarland | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| def | Schleswig-Holste | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| gr | Greece | . | . | . | . | . | 0.780 | 0.782 |
| es | Spain | . | . | . | . | . | 0.618 | 0.616 |
| fr1 | le de France | . | . | . | 0.900 | 0.898 | 0.898 | 0.900 |
| fr21 | Champagne-Ardenn | . | . | . | 0.885 | 0.886 | 0.892 | 0.888 |
| fr22 | Picardie | . | . | . | 0.883 | 0.883 | 0.885 | 0.884 |
| fr23 | Haute-Normandie | . | . | . | 0.892 | 0.893 | 0.894 | 0.896 |
| fr24 | Centre | . | . | . | 0.882 | 0.881 | 0.882 | 0.882 |
| fr25 | Basse-Normandie | . | . | . | 0.873 | 0.870 | 0.871 | 0.868 |
| fr26 | Bourgogne | . | . | . | 0.880 | 0.881 | 0.885 | 0.883 |
| fr3 | Nord - Pas-de-Ca | . | . | . | 0.885 | 0.885 | 0.886 | 0.887 |
| fr41 | Lorraine | . | . | . | 0.882 | 0.881 | 0.884 | 0.884 |
| fr42 | Alsace | . | . | . | 0.889 | 0.887 | 0.889 | 0.889 |
| fr43 | Franche-Comt | . | . | . | 0.883 | 0.882 | 0.886 | 0.886 |
| fr51 | Pays de la Loire | . | . | . | 0.878 | 0.874 | 0.879 | 0.880 |
| fr52 | Bretagne | . | . | . | 0.875 | 0.874 | 0.873 | 0.874 |
| fr53 | Poitou-Charentes | . | . | . | 0.877 | 0.875 | 0.877 | 0.876 |
| fr61 | Aquitaine | . | . | . | 0.883 | 0.881 | 0.885 | 0.886 |
| fr62 | Midi-Pyrnes | . | . | . | 0.873 | 0.873 | 0.876 | 0.877 |
| fr63 | Limousin | . | . | . | 0.873 | 0.870 | 0.872 | 0.869 |
| fr71 | Rhne-Alpes | . | . | . | 0.880 | 0.880 | 0.881 | 0.881 |

| Code | Name | 1996 | 1995 | 1994 | 1993 | 1992 | 1991 | 1990 |
|---|---|---|---|---|---|---|---|---|
| fr72 | Auvergne | . | . | . | 0.874 | 0.874 | 0.875 | 0.875 |
| fr81 | Languedoc-Roussi | . | . | . | 0.880 | 0.880 | 0.881 | 0.880 |
| fr82 | Provence-Alpes-C | . | . | . | 0.888 | 0.887 | 0.888 | 0.889 |
| fr83 | Corse | . | . | . | 0.885 | 0.887 | 0.890 | 0.886 |
| ie | Ireland | . | 0.829 | 0.830 | 0.834 | 0.832 | 0.836 | 0.836 |
| it11 | Piemonte | 0.738 | 0.744 | 0.745 | 0.759 | 0.763 | 0.764 | 0.764 |
| it12 | Valle d'Aosta | 0.746 | 0.753 | 0.753 | 0.770 | 0.771 | 0.767 | 0.766 |
| it13 | Liguria | 0.754 | 0.761 | 0.760 | 0.774 | 0.779 | 0.776 | 0.772 |
| it2 | Lombardia | 0.745 | 0.752 | 0.753 | 0.767 | 0.772 | 0.772 | 0.771 |
| it31 | Trentino-Alto Ad | 0.733 | 0.740 | 0.739 | 0.754 | 0.758 | 0.754 | 0.750 |
| it32 | Veneto | 0.740 | 0.746 | 0.747 | 0.759 | 0.762 | 0.761 | 0.760 |
| it33 | Friuli-Venezia G | 0.751 | 0.756 | 0.756 | 0.766 | 0.768 | 0.767 | 0.764 |
| it4 | Emilia-Romagna | 0.747 | 0.753 | 0.755 | 0.768 | 0.771 | 0.770 | 0.768 |
| it51 | Toscana | 0.740 | 0.747 | 0.750 | 0.764 | 0.768 | 0.767 | 0.765 |
| it52 | Umbria | 0.734 | 0.740 | 0.742 | 0.757 | 0.761 | 0.759 | 0.757 |
| it53 | Marche | 0.736 | 0.744 | 0.746 | 0.758 | 0.762 | 0.760 | 0.757 |
| it6 | Lazio | 0.737 | 0.747 | 0.750 | 0.763 | 0.767 | 0.765 | 0.763 |
| it71 | Abruzzo | 0.732 | 0.739 | 0.740 | 0.755 | 0.755 | 0.752 | 0.750 |
| it72 | Molise | 0.725 | 0.731 | 0.730 | 0.743 | 0.747 | 0.742 | 0.741 |
| it8 | Campania | 0.724 | 0.729 | 0.731 | 0.743 | 0.747 | 0.748 | 0.746 |
| it91 | Puglia | 0.733 | 0.740 | 0.738 | 0.751 | 0.756 | 0.754 | 0.754 |
| it92 | Basilicata | 0.721 | 0.725 | 0.726 | 0.737 | 0.740 | 0.732 | 0.728 |
| it93 | Calabria | 0.714 | 0.719 | 0.721 | 0.732 | 0.737 | 0.733 | 0.735 |
| ita | Sicilia | 0.722 | 0.730 | 0.733 | 0.746 | 0.750 | 0.748 | 0.745 |
| itb | Sardegna | 0.723 | 0.732 | 0.736 | 0.747 | 0.750 | 0.745 | 0.741 |
| lu | Luxembourg | . | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 |
| nl11 | Groningen | . | . | . | . | 0.961 | 0.959 | 0.958 |
| nl12 | Friesland | . | . | . | . | 0.939 | 0.941 | 0.941 |
| nl13 | Drenthe | . | . | . | . | 0.935 | 0.939 | 0.937 |
| nl21 | Overijssel | . | . | . | . | 0.935 | 0.936 | 0.937 |
| nl22 | Gelderland | . | . | . | . | 0.931 | 0.931 | 0.932 |
| nl23 | Flevoland | . | . | . | . | 0.918 | 0.921 | 0.921 |
| nl31 | Utrecht | . | . | . | . | 0.943 | 0.945 | 0.945 |
| nl32 | Noord-Holland | . | . | . | . | 0.944 | 0.947 | 0.949 |

| Code | Name | 1996 | 1995 | 1994 | 1993 | 1992 | 1991 | 1990 |
|---|---|---|---|---|---|---|---|---|
| nl33 | Zuid-Holland | . | . | . | . | 0.941 | 0.944 | 0.944 |
| nl34 | Zeeland | . | . | . | . | 0.943 | 0.945 | 0.949 |
| nl41 | Noord-Brabant | . | . | . | . | 0.939 | 0.940 | 0.942 |
| nl42 | Limburg (NL) | . | . | . | . | 0.935 | 0.938 | 0.940 |
| pt | Portugal | . | . | . | . | . | 0.464 | 0.464 |
| uk | United Kingdom | . | . | . | . | . | 0.967 | . |
| uke | Yorkshire and Th | . | . | . | . | 0.967 | . | 0.966 |
| ukf | East Midlands | . | . | . | . | 0.967 | . | 0.968 |
| ukg | West Midlands | . | . | . | . | 0.968 | . | 0.967 |
| ukh1 | East Anglia | . | . | . | . | 0.968 | . | 0.968 |
| ukk | South West | . | . | . | . | 0.968 | . | 0.963 |
| ukl | Wales | . | . | . | . | 0.963 | . | 0.967 |
| ukm | Scotland | . | . | . | . | 0.968 | . | 0.961 |
| ukn | Northern Ireland | . | . | . |  | 0.964 | . | 0.961 |

Population density is not significant in the translog model.

## 5 Conclusion

## Notes

[1] The computation $I_{1985} = (I_{1986} - I_{1983})2/3 + I_{1983}$ was performed.

# Appendix

This appendix reproduces key results from Battese and Coelli (1993) and is intended to aid the reader in interpreting and using the results contained in the paper. See (Battese and Coelli 1993) for additional details.

The pdf of $v_{it}$ is

$$f_V(v) = \frac{\exp(-\frac{1}{2}v^2/\sigma_V^2)}{\sqrt{2\pi}\sigma_V} \qquad -\infty < v < \infty \tag{9}$$

The pdf of the truncated normal density is

$$f_U(u) = \frac{\exp(-\frac{1}{2}(u - z\delta)^2/\sigma_U^2)}{\sqrt{2\pi}\sigma_U\Phi(z\delta/\sigma_U)} \qquad u \geq 0 \tag{10}$$

where the subscripts, $i$ and $t$, have been omitted for convenience, and the function $\Phi()$ is the distribution function for the standard normal random variable.

Let the overall equation error of the linear model be denoted, $E$, and note that $V = E + U$. Given the statistical independence of $V$ and $U$, the joint density of $E$ and $U$ is obtained by multiplication. This yields:

$$f_{E,U}(e, u) = \frac{\exp(-\frac{1}{2}[(e + u)^2/\sigma_V^2] + [(\mu - z\delta)^2/\sigma_U^2])}{2\pi\sigma_U\sigma_V\Phi(z\delta/\sigma_U)} \qquad u \geq 0 \tag{11}$$

Using the reparameterization $\mu_* = (\sigma_V^2 z\delta - \sigma_U^2 e)/(\sigma_V^2 + \sigma_U^2)$ and $\sigma_*^2 = \sigma_U^2\sigma_V^2/(\sigma_V^2 + \sigma_U^2)$ yields

$$f_{E,U}(e, u) = \frac{\exp(-\frac{1}{2}[(u - \mu_*)^2/\sigma_*^2] + [(e + z\delta)^2/(\sigma_U^2 + \sigma_V^2)])}{2\pi\sigma_U\sigma_V\Phi(z\delta/\sigma_U)} \qquad u \geq 0 \tag{12}$$

The marginal density of $E$ is then obtained by integrating $U$ out of the joint density. This yields:

$$f_E(e) = \frac{\exp(-\frac{1}{2}[(e + z\delta)^2/(\sigma_U^2 + \sigma_V^2)])}{\sqrt{2\pi}(\sigma_U + \sigma_V)^{\frac{1}{2}}[\Phi(z\delta/\sigma_U)/\Phi(u_*/\sigma_*)]} \qquad u \geq 0 \tag{13}$$

The density function for production, $Y_{it}$, is then

$$f_{Y_{it}}(y_{it}) = \frac{\exp\left(-\frac{1}{2}\{\frac{(y_{it}-x_{it}\beta+z_{it}\delta)^2}{\sigma_V^2+\sigma_U^2}\}\right)}{\sqrt{2\pi}(\sigma_U+\sigma_V)^{\frac{1}{2}}[\Phi(d_{it})/\Phi(d_{it}^*)]} \tag{14}$$

where $d_{it} = z_{it}\delta/\sigma_U$, $d_{it}^* = u_{it}^*/\sigma_*$, and $u_{it}^* = [\sigma_V^2 z_{it}\delta - \sigma_U^2(y_{it}-x_{it}\beta)]/(\sigma_V^2+\sigma_U^2)$.

Defining $\sigma_S^2 \equiv \sigma_V^2 + \sigma_U^2$ and $\gamma \equiv \sigma_U^2/\sigma_S^2$, it follows that the log-likelihood is

$$\begin{aligned} L(\beta,\delta,\gamma,\sigma_S^2) = &-\frac{1}{2}\sum_{i=1}^{N} T_i\{\ln 2\pi + \ln\sigma_S^2\} \\ &-\frac{1}{2}\sum_{i=1}^{N}\sum_{t=1}^{T_i}\{(y_{it}-x_{it}\beta+z_{it}\delta)^2\sigma_S^2\} \\ &-\sum_{i=1}^{N}\sum_{t=1}^{T_i}\{\ln\Phi(d_{it}) - \ln\Phi(d_{it}^*)\} \end{aligned} \tag{15}$$

where $d_{it} = z_{it}\delta/(\gamma\sigma_S^2)^{\frac{1}{2}}$, $d_{it}^* = \mu_{it}^*/[\gamma(1-\gamma)\sigma_S^2]^{\frac{1}{2}}$, $\mu_{it}^* = (1-\gamma)z_{it}\delta - \gamma(y_{it}-x_{it}\beta)$, and $\sigma_* = [\gamma(1-\gamma)\sigma_S^2]^{\frac{1}{2}}$.

To predict efficiencies, the following conditional expectation is used:

$$E(e^{-U}|E=e) = \{\exp[-\mu_* + \frac{1}{2}\sigma_*^2]\}\{\Phi[(\mu_*/\sigma_*) - \sigma_*]/\Phi(\mu_*/\sigma_*)\} \tag{16}$$

For additional details, see Battese and Coelli (1993).

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