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MEASURING PRODUCTIVE EFFICIENCY: AN ECONOMETRIC SURVEY

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PLAN

ABSTRACT

Although neglected by earlier economic literature, productive efficiency analysis has recently been the object of a number of theoretical and empirical studies in developed and developing countries with crucial implications for economic policy making. Inefficiency is costly, both to the individual producer and to society at large. The cost of inefficiency is basically an empirical question, but reliable answers to this question require an extensive econometric investigation at the theoretical level. This paper surveys in a brief but comprehensive way the most important recent econometric developments for the estimation of productive efficiency measures.

I. INTRODUCTION

The concept of efficiency is at the core of Economics, and is, in a broad sense, used to characterize the performance of productive processes transforming a set of inputs into a set of outputs. Although efficiency is an important characteristic of producer performance, it has not gained the proper share in economic literature. Earlier neoclassical theory typically ignored the possibility that producers might operate inefficiently, as one can see in the work of Carlson (1939), Hicks (1946), and Samuelson (1947), for example. Outside the main trend, Koopmans (1951, 1957) and Debreu (1951) were among the very few who investigated efficiency and its measurement. The most persuasive definition of productive or technical (in)efficiency was first given in 1957 by Farrell, who obtained a partial decomposition of private efficiency into technical and allocative components. However, until the late 1970's, the econometric methodology in this field was very rudimentary. Consequently, the empirical measurement of efficiency was limited. Since 1977, Farrell's conception became the tool for the econometric estimation of technical (in)efficiency of various sectors and industries in a number of studies of developed and developing economies[1]. These developments were due to the work of Aigner, Lovell, and Schmidt (1977), who proposed the stochastic frontier production function, and the work of Meeusen and Broeck (1977), who considered the Cobb-Douglas production function with a composed multiplicative disturbance term. Since then, and over the last ten years or so, the theoretical assumptions and empirical measures used in the analysis of efficiency have improved considerably.

The exposition of this paper is based on the concept of the production function. Let us consider an industry with m firms all producing a single homogeneous output, y, from a set of inputs, x. The production possibilities are described by a set of production functions,

$$y^i = f^i(x^i),\ y^i \in R_+,\ x^i \in \Omega,\ \Omega \subset R_+^n \qquad i=1,\ldots,m \qquad m<n \tag{1}$$

where R_+^n denotes the set of real positive numbers n.

These production functions can be conceived of as describing observed technologies of the m firms or hypothetical production possibilities. Consequently, we say that a firm is efficient if it maximizes its output with a given set of inputs, or, if it minimizes its inputs producing a given output (taking into account cost considerations as well).

[1] See the 1980, vol. 3, issue of the Annals of the *Journal of Econometrics*, Caves and Barton (1990), Caves (1992), the June 1992 issue of the *Journal of Productivity Analysis*, and Battese (1992).

Within this context, the development of the paper does not embrace organizational aspects of the production process. Efficiency is analyzed on the basis of a quantitative relationship between outputs and inputs, as well as their values expressed as revenues, profits and costs. It is well known since Adam Smith (1776, Ch. 1, 2, 3) and Karl Marx (1867, vol. 1 and vol. 3) that efficiency and organization of production are closely related. The weakness with this kind of analyses lies with the difficulty of quantifying this relationship. Morroni (1992) developed a model, his matrix of production elements, where he attempts to incorporate both quantitative and qualitative features of the production process. But from the empirical point of view, this model is rather weak in the sense of requiring very costly statistical surveys, if firms will be willing to release such detailed data.

The next section describes the notion of (in)efficiency. Section III presents and discusses the econometric approach to efficiency measurement and its developments so far. The fourth section discusses the empirical measures of (in)efficiency mostly used. Finally, the last section concludes the paper.

II. THE NOTION OF EFFICIENCY

Farrell (1957) explained inefficiency in terms of the following figure:

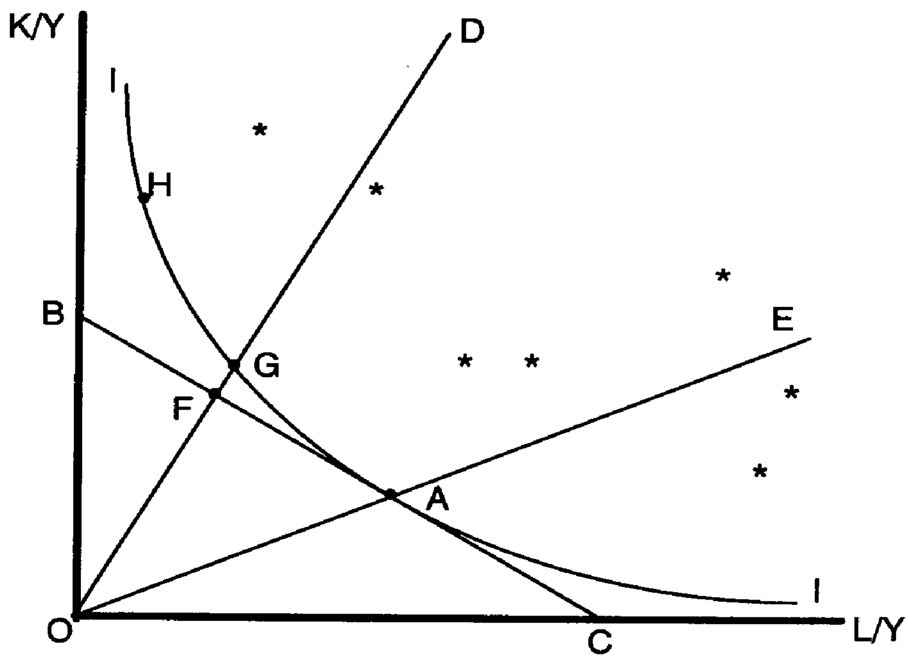

Figure 1

II is a unit isoquant of an economic activity X exhibiting constant returns to scale (CRTS). II is the locus of all minimum combinations of capital (K) and labor (L) per unit of output (Y) required to produce one unit of X's output, Y. Thus, II describes completely the technology of X. The relative prices of K and L are given by the line BC. The various points above II represent the various input-per-unit-of-output ratios, (K_i/Y, L_i/Y). A is the point of the least costly combination of inputs for producing the given quantity of output. The deviation of observed input-per-unit-of-output ratios from the unit isoquant, II, is considered to be associated with technical inefficiency of the firm involved.

If for example, the input combination was D instead of A, then DG/OD measures technical inefficiency defined as the proportional excess cost of inputs used over the feasible minimum cost G, using the input proportions indicated by OD. G is technically efficient, but it is not the least cost combination if factor prices are BC. The ratio GF/OG measures price inefficiency, which is also called "allocative inefficiency". It indicates the proportional excess cost due to the use of inappropriate input proportions.

The overall or economic efficiency of firm D is given by the ratio OF/OD which is the product of technical and price efficiency:

$$OF/OD = [1-(DG/OD)][1-(GF/OG)] \tag{2}$$

Farrell (1957) defined his measure of technical efficiency in terms of vector analysis. Recalling Fig. 1 and denoting the vectors OH and OA by x_1 and x_2, a convex linear combination of x_1 and x_2 is written as,

$$\lambda_1 x_1 + \lambda_2 x_2, \quad \lambda_2 = 1 - \lambda_1, \quad \text{for } 0 \leq \lambda_1 \leq 1 \tag{3}$$

It is easily shown by analytical geometry that G lies on the line segment from H to A and divides it in the ratio $\lambda_1 : \lambda_2$. (We assume here that the isoquant II is not a smooth curve but it consists of line segments. HA, for example, is such a line segment.) If $\lambda_1 + \lambda_2 > 1$, then D lies on the line segment OG but beyond G. If $0 \leq \lambda_1 + \lambda_2 < 1$, then D lies between O and G.

Thus, Farrell defines technical efficiency (TE) of any point to the right of II, by using the following linear equations system:

$$\lambda_1 x_{Hi} + \lambda_2 x_{Gi} = x_{Ai} \tag{4.1}$$

$$\lambda_1 x_{Hj} + \lambda_2 x_{Gj} = x_{Aj} \tag{4.2}$$

where $H(x_{Hi}, x_{Hj})$, $G(x_{Gi}, x_{Gj})$, and $A(x_{Ai}, x_{Aj})$. Then,

$$TE = 1/(\lambda_1 + \lambda_2) \tag{5}$$

The price line BC represents the total expenditures per unit of output at the most efficient factor combination. Any price line higher than BC represents higher average expenditures per unit of output. Thus, the economic efficiency of firm D is equivalent to the ratio of the average cost of production at A to the average cost of producing at D (Bressler, 1966). Note that G is technically efficient but price inefficient, while E is technically inefficient and price efficient.

Figure 2 presents in a more general way Farrell's concept of efficiency.

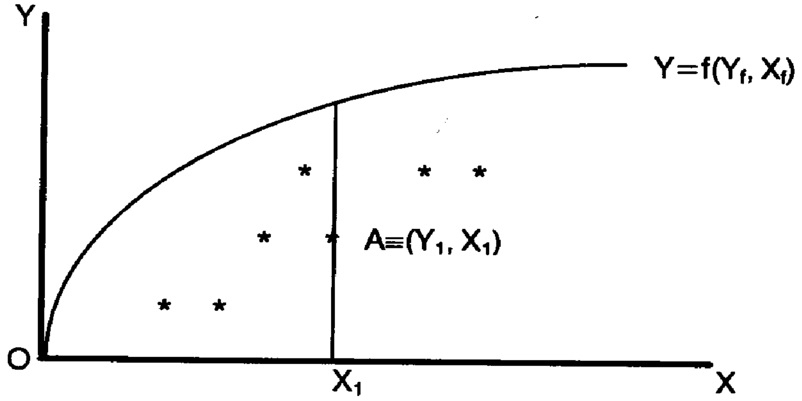

Figure 2

The observed input-output values are below the production frontier. A measure of the technical efficiency of the firm which produces output Y_1 with inputs X_1 (A in the figure) is given by the ratio Y_1/Y_f, where Y_f is the frontier output associated with the level of inputs X_f. Firms in the interior of the production frontier may be either technically or price inefficient or both. If it is not known whether interior points are only price or only technically inefficient, then these interior points may be referred to as X-inefficient (Leibenstein, 1966). Leibenstein considered his X-efficiency or non-allocative efficiency as a significant source of increased output. He distinguished it into three component-efficiencies:

(a) Intra-plant motivational efficiency,
(b) External-motivational efficiency, and
(c) Nonmarket input efficiency.

Another concept of (in)efficiency is the "scale (in)efficiency" which may take place if the CRTS assumption is removed. Thus, scale inefficiency appears when production takes place at scales either too small, or too large to minimize costs of production. The relationship between efficiency and firm size is frequently met in literature. Robinson (1962) discussed the reasons why efficiency might be expected to decline with increases in firm size, while Knight (1965) considered the cost-increasing inefficiency of large firms. Other studies which consinder the relationship between efficiency and scale are those of Yotopoulos and Lau (1973), Tyler (1979), Fare et al. (1984), Fare et al. (1985), and a rather recent one is that of Torii (1992).

There are two approaches to efficiency estimation: The deterministic and the stochastic. The deterministic approach uses mathematical programming techniques. Seiford and Thrall (1990) discuss recent developments in this approach, which is also called "Data Envelopment Analysis" (DEA)[2]. The stochastic approach uses econometric techniques to estimate frontier production functions. The stochastic approach has attracted more attention mainly because of its realistic specification which incorporates the random character of the input-output relationship.

The next section presents some of the most recent econometric advances in (in)efficiency measurement. Previous valuable discussions of relevant theoretical concepts are presented in Bauer (1990), Lovell and Schmidt (1988), Schmidt (1985), and Forsund et al. (1980).

III. ECONOMETRIC THEORY

The stochastic production frontier (SPF) is given by the following equation:

$$y = f(x,\beta)\ \exp(\varepsilon) \qquad \varepsilon = v-u,\ u \geq 0 \tag{6}$$

where y is output, f is the deterministic production function, or frontier production function (FPF), x is a vector of inputs, β is a vector of parameters, and ε is an error term.

The stochastic frontier or composed-error model was introduced in 1977 by Aigner, Lovell and Schmidt, as well as by Meeusen and Van de Broeck. According to their model, the error term ε in equ.(6) has two components: v is a symmetrical random error. It is the conventional normal distribution of random elements, including measurement errors, minor omitted variables, and other exogenous factors beyond the plant's, firm's, or industry's control. The second component of ε is the one-sided error term $-u$, which represents technical inefficiency. The elements of $-u$ indicate shortfalls of the industry's production units from the efficient frontier, or from the maximum possible value of industry's output given by the stochastic frontier $[f(x,\beta)\exp(v)]$. Technical inefficiency is shown in the skewness of the residuals around the fitted production function.

The economic logic behind the composed-error specification is that the production process is subject to two economically distinguishable random disturbances with different characteristics. The non-positive disturbance u reflects the fact that each firm's output must lie on or below its stochastic frontier

[2] Empirical applications of this approach (DEA) are included in the *Journal of Productivity Analysis, Special issue: International Applications of Productivity and Efficiency Analysis,* vol. 3, Nos 1/2, June 1992.

$f(x,\beta)\exp(v)$. Any such deviation is the result of factors under the firm's control, such as technical and economic efficiency, the will and effort of the producer and his employees, or probably such factors as defective and damaged products. But the frontier itself can vary randomly across firms, or over time for the same firm. In this interpretation, the frontier is stochastic, with random disturbance $v \gtreqless 0$, being the result of favorable or unfavorable external events, such as luck, climate, machine performance, topography, as well as errors of observation and measurement on y.

Taking into account the above structure of the error term ε, we can estimate the variances of v and u, which will give evidence on their relative sizes. But we can also measure productive efficiency by the following ratio:

$$y/[f(x,\beta)\ \exp(v)] \tag{7}$$

As an illustration, we can assume that,

(a) v is normally distributed $(0,\sigma_v^2)$, (8.1)

(b) u is derived from a normal distribution $(0, \sigma_u^2)$ truncated from above, and (8.2)

(c) u and v are independent. (8.3)

Then, by using a distribution function for the sum of a symmetric normal random variable and a truncated random variable, we can derive a loglikelihood function for which the parameters can be estimated by using the Maximum Likelihood method (ML)(Aigner et al., 1977). For n observations we can have the following equation:

$$\ln L(y/\beta, \lambda, \sigma) = n\ln(\sqrt{2}/\sqrt{\pi}) + n\ln\sigma^{-1} + \sum \ln[1-F^*(y-x\beta)\,\lambda\sigma^{-1})] - \\ -1/2\sigma^2 \sum (y-x\beta)^2 \tag{9}$$

where $\sigma=\sigma_u^2+\sigma_v^2$, $\lambda=\sigma_u/\sigma_v$, and F^* is the standard normal distribution function.

Coming to equ. (7), if we assume a Cobb-Douglas production function,

$$Q=AK^{\alpha}L^{\beta}e^{u}e^{v} \tag{10}$$

then, the measure of technical efficiency for each firm is the following:

$$e^{u} = Q/AK^{\alpha}L^{\beta}e^{v} \tag{11}$$

Note that equ. (11) measures productive inefficiency due to factors which are under the firm's control only. Also, equ. (10) includes an unobserved variable, v. Since v is unobservable, we cannot estimate an efficiency measure for each firm separately, but we can estimate the mean technical efficiency, which is given by the $E(e^u)$. Under assumptions(8.1)–(8.3),

$$E(e^{u}) = 2e^{\sigma/2}\,[1\text{-}F^{*}(\sigma_u)] \qquad (12)$$

From the above we can conclude that given a parametric functional form for f(x) and distributional assumptions on u and v, the model (6) can be estimated by the ML method. For the asymptotic properties of the ML estimators, see Aigner et al. (1977) and Olson et al. (1980). Another method which is more frequently used is the so called corrected OLS or COLS. The COLS was first proposed by Richmond (1974), and Forsund et al. (1980) have named it. Olson et al. (1980) showed that the COLS estimators have statistical properties at least as desirable as those of the ML estimators. The COLS may be described as follows: Equation (6) can be written as,

$$\ln(y) = \ln[f(x)] + v - u = -\mu + \ln[f(x)] + (v - u + \mu) \qquad (13)$$

where $\mu \equiv E(u) > 0$

It is assumed that u and v are independently and identically distributed and that the disturbances are also independent of x, so equation (13) satisfies all the assumptions for the traditional OLS model, except for the normality assumption of $v - u + \mu$. Also, it is assumed that ln[f(x)] is linear in the parameters, so that the OLS would yield the BLUE of the parameters, except for the constant term, denoted as α_0, for which the bias will be $-\mu$. Thus, the OLS method will give an unbiased estimator of $(\alpha_0 - \mu)$.

The estimation of the SPF by the OLS leads to consistent estimators for all the parameters, μ included, if it is assumed that v is normally and u is half-normally distributed, i.e.

$$v \sim N(0, \sigma^2_v), \qquad u \sim |N(0, \sigma^2_u)| \qquad (14)$$

In practice, both, half-normal and exponential distributions have been employed for u. However, the available evidence suggests that these two assumptions lead to similar parameters (Caves and Barton, 1990, pp. 13-14, 18).

The distribution function of the sum of the symmetric normal random variable and the truncated normal random variable was first derived by Weinstein (1964):

$$f(\varepsilon) = 2/\sigma\, f^{*}(\varepsilon/\sigma)[1 - F^{*}(\varepsilon\lambda\sigma^{-1})] \qquad -\infty \leq \varepsilon \leq +\infty \qquad (15)$$

where $\sigma^2 = \sigma^2_u + \sigma^2_v$, $\lambda = \sigma_u/\sigma_v$, $f^{*}(.)$ and $F^{*}(.)$ are the standard normal density and distribution functions respectively. This density function is asymmetric around zero, and its mean and variance are given by the following formulas:

$$E(\varepsilon) = E(-u) = -\mu = -\sigma_u\ (2/\pi)^{1/2} \tag{16}$$

$$Var(\varepsilon) = Var(u) + Var(v) = [(\pi-2)/\pi]\sigma^2_u + \sigma^2_v \tag{17}$$

Thus, a consistent estimator of μ can then be obtained if σ_u in equation (16) is replaced by its consistent estimator (see Aigner, Lovell, and Schmidt, 1977, and Schmidt and Lovell, 1979).

It can be shown that definitions of the second and third central moments of ε, denoted as $m_2(\varepsilon)$ and $m_3(\varepsilon)$, respectively, lead to the following system of equations:

$$\sigma^2_u = [(\pi/2)^{1/2}\ [\pi/(\pi-4)]\ m_3(\varepsilon)]^{2/3} \tag{18}$$

$$\sigma^2_v = m_2(\varepsilon) - [(\pi-2)/\pi\ ]\ \sigma^2_u \tag{19}$$

by $m_2(\varepsilon)$ and $m_3(\varepsilon)$ in equations (18) and (19) are replaced their sample counterparts, $\hat{m}_2(\varepsilon)$ and $\hat{m}_3(\varepsilon)$, according to the following procedure:

Estimation of equation (6) by OLS gives the residuals e_i, i=1, 2,..., N. Then the second and third central moments of the residuals, m_2 (e) and m_3 (e), are calculated using the following formulas:

$$\hat{m}_2 = (1/N) \sum_{i=1}^{N}(e_i - e)^2, \quad \hat{m}_3 = (1/N) \sum_{i=1}^{N}(e_i - e)^3 \tag{20}$$

where N is the sample size and e is the mean of the residuals e_i.

The COLS has been used as an appealing alternative to ML estimation of frontier models because of its simplicity and relative robustness. But if one is interested in properties of the moments and/or order statistics of the inefficiency distribution, or in whether the population production or cost function have reasonable densities or finite moments, as in Afriat (1972) and Richmond (1974), then one has to have a consistent estimator of COLS' asymptotic covariance matrix. Kopp and Mullahy (1993) estimated such a covariance matrix. Their work was based on their previous work in 1990. Thus, in their 1993 paper they presented a general estimation framework in which alternative distributional assumptions about the model's stochastic structure —exponential vs half-normal vs gamma etc distributions of the one-sided error term— could be tested and evaluated. Thus, a gap in existing theory was filled. Kopp and Mullahy derived their estimator as a two-step GMM [generalized method of moments (Hansen, 1982)] estimator.

In the next section, we review the most frequently used technical (in)efficiency measures.

IV. MEASURES OF TECHNICAL (IN)EFFICIENCY

The estimation of the SPF by COLS may fail to yield satisfactory estimates. Thus, type I failure occurs if the estimate of m_3 takes on a non-negative value so that σ^2_u cannot be defined. It is noted that m_3 must always be negative in the population under the assumptions (14). The smaller the σ^2_u, the greater is the probability of type I failure, because in this case the m_3 approaches to zero. But, a small value of σ^2_u implies that the gap ($\sigma_u\sqrt{2}/\sqrt{\pi}$) between the average probability function and production frontier is also small. Thus, the chances are that type I failure may occur in relatively efficient industries. The type II failure occurs if the sample m_2 is so small relative to the estimate of σ^2_u that it results in a negative value of σ^2_v. This type of failure is rare and happens for relatively inefficient industries for which the estimate of σ^2_u takes on a relatively large value.

The existing measures of technical (in)efficiency are given by the following formulas:

$$EFF = 2\exp(\sigma^2_u/2)\,[1\text{-}F(\sigma_u)] \tag{21}$$

$$ATI = [(\sigma_u\sqrt{2}/\sqrt{\pi})\,/\,[\overline{(\ln(y)}\, + (\sigma_u\sqrt{2}/\sqrt{\pi})]] \tag{22}$$

$$\lambda = \sigma_u/\sigma_v \tag{23}$$

$$S = m_3(\varepsilon)/[m_2(\varepsilon)]^{3/2} \tag{24}$$

Measure (21) was proposed by Lee and Tyler (1978), who derived this formula as the "mean technical efficiency measure", $E(e^u)$ for the Cobb-Douglas $e^u = Y/AK^{\alpha}L^{\beta}e^v$, under the assumption that u is either truncated normal or exponentially distributed. F is the cdf of the standard normal distribution, and EFF stands for efficiency. EFF is the expected value of exp(–u), or the ratio of the actual output to the SPF. If EFF=1, then the actual output is on the SPF.

Measure (22), ATI or average technical inefficiency, measures the gap between the average production function and the production frontier (the numerator), normalized by the mean of the production frontier measured on the y axis (the denominator). For the calculation of ATI, the mean of $|\ln(y)|$ is used in order to correct for the error that is made for negative values of ln(y). ATI was proposed by Caves and Barton (1990). This estimator is the ratio of the intercept shift of the frontier to the average position of the production frontier. (When the half-normal distribution of σ_u is assumed, the production frontier shifts downward by $-\sigma_u\sqrt{2}/\sqrt{\pi}$.)

If type I failure occurs, EFF=1 and ATI=0. Otherwise the two measures lie in the (0,1) interval.

Measure (23) gives information about the degree of asymmetry in the distribution of $\varepsilon = v-u$. λ implies whether the gap between y and f(x) comes from u or v, since it represents a measure of technical inefficiency, σ_u, normalized by the degree of variation in the SPF, σ_v.

Measure (24) is a measure of skewness in the distribution of ε, and is closely related to λ. According to Yoo [(1992), p.128)] λ and S have a negative relationship in the interval (–0.9968, 0). As the degree of negative skew increases with the level of technical inefficiency, S is used as a measure of technical efficiency. If type I failure occurs, $\lambda=0$. In the case of type II failure, λ is undefined, while S always exists. Summarizing, EFF and S are measures of efficiency, while ATI and λ are measures of inefficiency.

The SPF has been criticized for its weakness in relation to the choice for the distribution of u and v which is usually made on an ad hoc basis. Until recently, there was a second weakness associated with the SPF: The difference between y and f(x) could not be decomposed into u and v. So, only the average technical inefficiency could be calculated until the appearance of Jondrow et al. (1982), who derived the conditional density of u given ε for both distributional cases of u, the half-normal and exponential. Later, Battese and Coelli (1988) criticized Jondrow et al. (1982) for having considered the $E(u/\varepsilon)$ instead of the correct $E[\exp(u)/\varepsilon]$ for the multiplicative production frontier model. Consequently, by correcting this mistake, Battese and Coelli (1988) derived the conditional expectation of $\exp(-u_i)$ given sample values of ε. Thus, they obtained a formula for $f[\exp(-u)/\varepsilon]$ instead of the formula for $f(u/\varepsilon)$. In their empirical application Battese and Coelli used panel data. The formula for their predictor of technical efficiency of the ith sample unit is the following:

$$TE_i = [[1\text{-}F[\sigma_* - (M^*_i/\sigma_*)]] \,/\, [1\text{-}F(-M^*_i/\sigma_*)]]\ \exp[-M^*_i + (\sigma^2_*/2)] \qquad (25)$$

where F(.) denotes the distribution function of the standard normal random variable and

$$M^*_i \equiv (-\sigma^2\, \varepsilon_i)\, (\sigma^2_u + \sigma^2_v)^{-1}, \qquad \sigma^2_* \equiv \sigma^2_u\ \sigma^2_v\ (\sigma^2_u + \sigma^2_v)^{-1}$$

Equation (25) is the minimum squared error predictor for $\exp(-u_i)$, given ε_i, and is consistent. This formula has been recently applied by Georganta (1993) who used time series data for the U.S. manufacturing sector at the four-digit SIC industry level.

Furthermore, Waldman (1984) proposed two alternative linear estimators for predicting the ith sample unit technical (in)efficiency. The first is his "linear unbiased estimator", $-\varepsilon_i$, denoted as:

$$e = -\varepsilon_i \qquad (26)$$

Measure (26) is justified by $E(-\varepsilon) = E(-v+u) = E(u)$. Waldman (1984, p. 355) explains it as "A more important reason for considering this estimator is that often the random disturbance (v) is ignored and a "full" frontier is fit to the data. In the production function case this means that no observation may lie above the frontier. One method of obtaining firm-specific measures of inefficiency is to estimate by least squares and subtract the largest (positive) residual from each residual in the sample" as in Greene (1980).

The second linear estimator that Waldman proposed is his "best linear predictor", denoted as:

$$\text{blp} = \alpha+\beta\varepsilon_i \tag{27}$$

$$\beta = -\text{Var}(u)/[\text{Var}(u)+\text{Var}(v)],\ \alpha = E(u) - \beta\, E(\varepsilon) = E(u)\ (1+\beta)$$

The theoretical superiority of the conditional expectation predictor over these two linear estimation predictors is unquestionable. However, Waldman finds very little empirical gain.

V. CONCLUDING REMARKS

Inefficiency is costly, both to the individual producer and to society at large. The cost of inefficiency is basically an empirical question and reliable answers to the question require econometric investigation both theoretical and empirical. Although earlier economic literature neglected this important aspect of economic theory and policy, the situation is rather different nowadays.

Considering the importance of efficiency investigations for practical economic policy, this paper has surveyed the more important recent econometric developments in measuring productive or technical (in)efficiency. Of course, the interpretation of efficiency measures depends on the specification of production structure, and since we have not yet developed an econometric model, which successfully incorporates both quantitative and qualitative characteristics of the production process, we have to be careful about interpreting our efficiency estimates for policy purposes. Sensitivity analysis and method comparison is necessary before policy suggestions are uttered.

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