THE ECONOMICS OF PRODUCTIVITY AND TECHNICAL CHANGE

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I. Introduction

Productivity change is both the cause and the consequence of the evolution of dynamic forces operative in an economy, like technical progress, accumulation of human and physical capital, enterprise and industrial arrangements. The problem of measuring and interpreting the behavior of such change, both at the macro and microeconomic levels, require the untangling of many complex factors, a task that has been a major challenge to economists and of extreme interest to entrepreneurs and government policy-makers during the post II World War period.[1] This can be probably attributed to the increasing evidence in which the contribution of technology to economic growth is found to be as important as --- or more important than --- the traditional inputs of labor and capital. The recent upsurge of the interest in the measurement and explanation of productivity changes is due to a productivity decline in the United States and other developed and underdeveloped economies as well. Puerto Rico has been no exception as revealed by several studies like Ruiz (1987, 1988).

Important recent advances have been very useful in dealing with the measurement of productivity growth. These include the development of new theoretical models based on duality theory; the use of flexible-form econometric specifications, such as the translog function; the developments in aggregation theory and the related theory of index numbers; and the availability of new and better data and estimation techniques.

In the following sections an overview is presented of some theoretical approaches to technical change and productivity analysis. The rest of the paper is divided into three sections. First, Section 2 presents a detailed discussion of productivity concepts and measurement. Second, technical change and the aggregate production function are discussed in

Section 3. Finally, Section 4 covers the empirical use of production functions for technical change analysis, including several new functional forms developed recently.

II. Productivity Concepts and Measurement

It has been correctly stated (Kennedy and Thirlwall, 1972, p.13), that the meaning of technical change precludes a direct measure of its rate of change. Advances in knowledge, for example, defy direct meaningful quantification. The best that can be done is to measure technical change by its effects, such as its impact on the growth of national income, or on the growth rate of factor productivity not accounted for by other inputs, with technical change left as a residual. On this basis, the most widely used indicator of technical progress is some measure of factor productivity.[2]

Productivity is generally defined in terms of the efficiency with which inputs are transformed into useful output within the production process. Thus, the earliest approach to productivity measurement was based upon ratios of a measure or index of aggregate output divided by the observed quantity of a single input, typically labour.[3] Symbollically, this index is given by:

$$P_L = \frac{Q}{L} \tag{2.1}$$

where Q and L are, respectively, the aggregate level of output and labour. The partial productivity index, based on capital, is:

$$P_k = \frac{Q}{K} \tag{2.2}$$

where K is the aggregate level of capital input. These partial indices represent, therefore, the average product of labour and capital, respectively.

A main advantage of these partial productivity indices was computational simplicity and feasibility. Nevertheless, more that twenty five years ago, professor Stigler reminded the profession that the usual measure of productivity, the average product of labor, was not an interesting economic variable.[4] In fact, this measure made it difficult to identify the causal factors accounting for observed productivity growth. For example, the substitution of capital for labour, the introduction of more efficient vintages of capital, the realisation of economies of scale, and the employment of better-trained manpower, do show up in the form of increases over time in an index of output per man-hour. In other words, changes in efficiency are mixed together with changes in the composition of inputs.

A more comprehensive index-number approach, developed in subsequent efforts to investigate the causal explanation of productivity changes, is based on total factor productivity (TFP) measures. This measure, often referred to as residual or the index of "technical progress" relates output to a weighted combination of inputs.[5] Symbolically, on the assumption of only two factors, the TFP index is given by:

$$T = \frac{Q}{\alpha\ L + \beta\ K} \tag{2.3}$$

where α and β some appropriate weights.[6] The index indicates the changes in output (Q) per unit of combined inputs foregone.

Total factor productivity measures are, undoubtedly, a clear improvement over partial or single-factor measures in that changes in the quantity and quality of all inputs can be accounted for, at least conceptually. However, because data on labor input has been collected in more countries and over longer periods of time than on other resources, indexes of labour productivity are more often computed and utilised as a measure of efficiency with little qualification. This is true in the case of the Puerto Rican economy since most productivity studies have been conducted using the partial (labour) productivity approach.

A. The Measurement of Total Factor Productivity

A change in TFP, often called technical change, is usually interpreted as: (i) the rate of change of an index of output divided by an index of inputs (Jorgenson and Griliches, 1967) or (ii) a rate of shift in a production function (Tinbergen, 1942; Solow, 1957).[7] Different methods to the measurement of TFP have been developed by prominent economists such as Kendrick (1956, 1961); Solow (1957); Salter (1966); Fabricant (1959); Abramowitz (1956); Denison (1962); Griliches and Jorgenson (1969). Two major approaches, (i) index number or growth accounting and (ii) the use of econometric models have been expanded substantially to measure TFP. These approaches are outline in this section.[8] A change in TFP will be interpreted as a shift in an underlying production function, ie., definition (ii) above.

a. Index Numbers Approach

The use of index numbers to measure productivity implies that the equivalent production model must be a linear homogeneous production function subject to Hicks neutral technical change. In other words, this approach to measure productivity involves the explicit specification of a production function and the direct linkage of productivity growth to key characteristics of parameters of this function. The pioneering paper in developing this approach is that of Solow (1957), who demonstrated that the rate of productivity growth could be identified with the rate of Hicks-neutral technical change, assuming constant returns to scale and competitive markets. The production function approach introduced a new dimension to the measurement of technical change by specifying a simultaneous equation system. Actually, the important contribution of using production functions to measure technological change is that it elucidates the underlying production and equilibrium assumptions.

Since productivity measures are based on observable prices and quantities of only inputs and outputs, they are consistent with models of

production that treat technical progress using time trends only. One of the most commonly TFP is the Divisia index.

(i) The Divisia Index

This approach supposes that data are available not only at discrete points of time but at every moment of time t where t ranges over a closed interval. Solow's derivation of this index is as follows. Suppose that F(x,t) is a linearly homogeneous, concave, non-decreasing production function. Let $Q(t) \equiv F[x(t),t]$ be output at time t and let $x(t) \equiv [x_1(t), x_2(t), \ldots, x_i(t)]$ be the vector of inputs used at time t. If the production function is characterised by neutral technical change, then it can be written as $F[x(t),t] = A(t)f[x(t)]$ where A(t) is a shift factor for the production function at time t. If we differentiate the identity $Q(t) = A(t)f[x(t)]$ with respect to time, divide by Q(t), and replace the terms $A(t)\ f[x(t)]/\ x_i$ by $p_i(t)$, the nth input price at time t, we obtain the identity[9]:

$$\frac{\dot{A}(t)}{A(t)} = \frac{\dot{Q}(t)}{Q(t)} - \sum_{n=1}^{N} S_i(t)\ \frac{\dot{x}_i(t)}{x_i(t)} \tag{2.4}$$

where a dot over a variable denotes a derivative with respect to time while the ith input share is defined as $S_i(t) \equiv p_i(t)\, x_i(t)/Q(t)$. Equation (2.4) is the fundamental equation of growth accounting for continous time or Divisia index form. According to this equation (2.4), the rate of growth of TFP can be measured as the difference between the growth rate of aggregate output and a weighted sum of the growth rate of aggregate input. The weights are the respective factor shares which are equivalent to output elasticities.

If $A(t)/A(t) = 0$, then A(t) is a constant for all t and there is no exogenous shift in the production function. Alternatively, it can be stated that there is no technological progress and, therefore, no increase in TFP. In his derivation of the Divisia index, Solow supposed only one output. An extension to the multiple-output context can be found in Hulten (1973), Caves, Christensen and Swanson (1980), and Denny, Fuss and Waverman (1983).

The problem with the Divisia approach to the measurement of TFP changes is that economic data do not exist in continous-time form x(t), p(t), Q(t); rather they usually exist in discrete form x^t, p^t, Q^t Thus the continous time formula (2.4) has to be approximated using discrete time data. Actually there are many ways to approximate equation (2.4) using discrete-time data, so that the Divisia index number approach does not yield unique estimates of TFP when applied to discrete economic data.

(ii) **The Thornqvist (Translog) Index**

In empirical applications, the most commonly used discrete approximation to the continuous Divisia index form is the Thornqvist productivity index, which was introduced by Christensen and Jorgenson (1970). The derivation of this index requires to approximate the firms true cost or production function by a specific functional form. This approach would define index numbers that are consistent with the assumed functional form. Suppose for example the following translog cost function:

$$\ln C(Q^t, p^t, t) = a_o + \sum_{m=1}^{M} a_m \ln Q_m^t$$

$$+ 1/2 \sum_{m=1}^{M} \sum_{m=1}^{M} a_{mk} \ln Q_m^t \ln Q_k^t$$

$$+ \sum_{n=1}^{N} b_n \ln p_n^t$$

$$+ 1/2 \sum_{n=1}^{N} \sum_{i=1}^{N} b_{ni} \ln p_n^t \ln p_i^t$$

$$+ \sum_{m=1}^{M} \sum_{n=1}^{M} S_{mn} \ln Q_m^t \ln p_n^t$$

$$+ \sum_{m=1}^{M} a_{mt} \ln t \ln Q_m^t$$

$$+ \sum_{n=1}^{N} b_{nt} \ln t \ln p_n^t$$

$$+ a_t \ln t + a_t \tag{2.5}$$

The assumption of constant returns to scale impose the following restrictions:

$$\sum_{n=1}^{N} b_n = 1 \quad ; \quad \sum_{n=1}^{N} b_{ni} = 0 \quad ; \quad b_{it} = 0 \quad ; \quad b_{ni} = b_{in} \quad ;$$

$$a_{mk} = a_{km} \quad , \quad with\ Q^t > 0 \quad and \quad p^t > 0. \tag{2.6}$$

Since lnC, defined by (2.5), is quadratic in the logarithms of output and input prices, and t, the quadractic lemma holds. If competitive profit maximizing behavior is also assumed, then the quadratic lemma yields the following identity:

(2.7)

$$1/2(\tau^1 + \tau^0) = \ln \frac{p^1 x^1}{p^0 x^0} - \left[1/2 \sum_{n=1}^{N} \left(\frac{p_n^1 x_n^1}{p^1 x^1} + \frac{p_n^0 x_n^0}{p^0 x^0} \right) \ln \frac{l}{l} \right.$$

$$- \left[1/2 \sum_{m=1}^{M} \left(\frac{p_{qm}^1 Q_m}{p_q^1 Q^1} + \frac{p_{qm}^0 Q_m}{p_q^0 Q^0} \right) \ln \frac{Q_m^1}{Q_{mo}} \right]$$

where $\tau = \ln C(Q^t, p^t, t) / t$ for $t = 0; 1$ is the period t impact effect on cost due to technological change, and $p_q = (p_{q1}, p_{q2}, \ldots, p_{qm})$ is a vector of output prices. The right hand side of (2.6) can be calculated provided that output and input data on prices and quantities for periods 0 and 1 are available.

Stated in a simpler way and using the Divisia index notation, the Thornqvist index is given by:

$$\frac{\dot{A}}{A} = \frac{\dot{Q}}{Q} - \sum_{i=1}^{N} \overline{S}_i (\dot{x}_i / x_i) \tag{2.8}$$

where:

$$\overline{S}_i = 1/2(S_{it} + S_{it-1}) \tag{2.9}$$

The $\overline{S}_i$ are the average shares over two time periods.

Based largely upon the recent work of Diewert (1976, 1978, 1980) and others in the area of "exact" or "superlative" index numbers, it has

been shown that there is a unique correspondence between the type of index used to aggregate over outputs and inputs and the structure of the underlying production technology. For example, the Laspeyres indexing procedure used in many of the earlier productivity studies, has been shown to be associated to a linear production function in which all inputs are perfect substitutes in the production process. Similarly, the Thornqvist index, a discrete approximation to the more general Divisia index, implies a homogeneous translog production function.

The index number or growth accounting approach to measure technical change suffers some important shortcomings. It has been stated, for example, that this method cannot provide more detailed information about the relationship among inputs and the relative movement of input prices, as the econometric approach, discussed in the next section. In addition, a main disadvantage of the Divisia index is that it does not lead to a definite formula for the shift in technology since there are many ways of approximating continuous time derivatives by discrete differences. The index number method has been critizised also on the grounds that it does not consider dynamic factors such as lagged adjustments of quasi-fixed inputs and the role of price expectations which may bias the measurement of productivity growth.

Several researchers have relaxed some of the basic assumptions of the index number method. For example, Denny, Fuss and Waveman (1981) in their study of Canadian telecommunications relaxed the assumptions of constant returns to scale, marginal cost pricing and perfect competition in input and output markets. Gollop and Roberts (1981) relaxed the constant returns to scale assumption also in their study of the US electric power industry. Berndt and Fuss (1982, 1986) modified an important assumption of the index number approach, namely that the rate of capital utilisation remains constant over time. In so doing they revised the method taking into consideration the possibility of lagged adjustments in the capital quasi-fixed input.[10]

b. The Econometric Approach

One of the main problems with the index numbers methods discussed above is the difficulty of disentangling technical change from the effects of economies of scale and input substitution.[11] As stated by Solow, the measures themselves are a catch-all since they combine all factors influencing output rather than labour and capital without providing a means of distinguishing the impact of the various factors. Production functions incorporate several economic effects, such as scale and substitution effects, the effects of technological change, and distributive effects. The objective of econometric modelling of producer behavior is to determine the nature of substitution among inputs, the character of differences in technology, and the role of economies of scale. It requires parametric forms to represent the patterns of production in terms of unknown parameters that specify the responses of demand and supply to changes in prices, technology, and scale.

The econometric approach to the measurement of technical change is based on these arguments. Formally speaking, the approach can be stated as follows. If data on output produced during period t, Q^t, and inputs used during period t, $x^t \equiv (x^t_1, x^t_2, \dots x^t_i)$, are available, then it is necessary only to assume a convenient functional form for the production function f and estimate the parameters that characterize f using the regression equation:

$$Q^t = f(\boldsymbol{x}^t, t) + error. \tag{2.10}$$

A convenient measure of technical change during period t is given by ln $f(x^t, t)/ t$, the percentage change in output due to an increment of time. It is useful to assume a functional form for f that can provide a second order approximation to an arbitrary twice-continuously-differentiable production function.[12] An example of such functional form is the translogarithmic (translog for short) (Christensen, Jorgenson and Lau, 1973).

Assuming that the producer faces the positive vector of input prices $p^t = (p^t_1, p^t_2, \dots, p^t_i) > O_N$ during period t

and behaves competitively with respect to inputs, then the producer's cost function C is defined as the solution to the following constrained cost minimization problem:

$$C(Q^t, \boldsymbol{p}^t, t) \equiv \min \{ \boldsymbol{p}^t \boldsymbol{x}^t : f(x, t) \geq Q^t, x : \tag{2.11}$$

Note that $p^t.x^t \equiv \sum_{i=1}^{N} p^t_i x^t_i$ denotes the product between the vectors p^t and x^t.

The cost function C is completely determined by f. Moreover, under certain regularity conditions, C completely determines f, and we also have the following useful result, known as Shephard's Lemma (Shephard, 1953, 1970):

$$x^t = \nabla_p C(Q^t, p_t, t) \tag{2.12}$$

where:

$$\nabla_p C(Q^t, p_t, t) \equiv [\partial C/\partial p_1, \partial C/\partial p_2, \dots, \partial C/\partial p_n] \tag{2.13}$$

is a vector of partial derivatives of C with respect to the components of the input price vector p evaluated at (Q^t, p^t, t). In other words, the producer's system of input demand equations can be obtained by differentiating the cost function with respect to input prices.

If a specific functional form for the cost function is assumed and we differentiate with respect to input prices, then upon adding errors to equations (2.12), the parameters of the cost function can be estimated statistically. It is useful to use a functional form for the cost function that can provide a second - order approximation to an arbitrary cost function. Binswanger (1974a) was the first to implement this approach using a translog cost function. The advantage of this second approach to measure technical progress over the first approach suggested above, i.e., using (2.10), is that the system of equations (2.12) has many more degrees of freedom in a statistical sense than the single equation (2.10). The disadvantage of this second approach is that it requires the assumption of competitive behavior in the inputs market on the part of the producer.

Given our discussion of the most important methods to measure TFP, the next section presents a discussion of the nature of technical change and the aggregate production function.

III. Technical Change and the Aggregate Production Function

A. Introduction

Producers theory is concerned with the behavior of firms in hiring and combining productive inputs to supply commodities at appropriate prices. Two important issues are involved in this process: one is the technological constraints which limit the range of feasible production process, while the other is the institutional context, such as the characteristics of the market where commodities and inputs are purchased and sold. Production technology describes the technological constraints which limits the range of productive processes for an individual firm. A production technology consists of certain alternative methods of transforming materials and services to produce goods and services.

Characteristically, the growth of output is attributed to the growth of the labour force, the growth of the capital stock, and the improvement in production efficiency, i.e., productivity. As discussed already, productivity measures can be divorced from economic theory, and used as a descriptive measure of changes in the ratio of output per unit of an aggregate particular input, as in the case of the partial productivity indices. In this case no importance is given to the underlying economic structure, and process that led to the changes in productivity.

Nevertheless, there is a rough concensus among academic economists that productivity measures should be linked to the economic theory of production. In fact, all the TFP measures discussed above, in spite of the methodological differences, are linked firmly to an underlying aggregate production function.[13] Specifically, productivity improvements in terms of the TFP are translated into shifts in the underlying production function.[14] Therefore, the concept of an aggregate production function defines the very basis of derivation of the indices used to measure technical change.

B. Nature and Types of Technical Change

It was stated in a previous section that technical change will be considered in this study as a measure of shift in the production function due to the adoption of new techniques that might arise from a combination of invention, innovation, and research and development.[15] Nothing has been said, nevertheless, about the nature of this shift.

Assuming that the aggregate production function exists and is specified accurately, and that inputs are properly measured, factor productivity is determined by two major factors: the technological characteristics of the production process and the movement of the relative factor prices. The often mentioned technological characteristics are[16]:

(i) the efficiency of production, i.e., reducing the unit cost of all factors of production equally by applying better techniques;

(ii) the bias in technical change, i.e., the nature of the new technique is such that it leads to a greater saving in one input than in the other;

(iii) the elasticity of substitution, which measures the ease of substituting factors of production in the course of the production process;

(iv) the scale of operation of the production process, i.e., economies (diseconomies) that arise due to changes in the scale of operation of the economy; and

(v) the homotheticity of the production function, i.e., whether returns to scale are evenly distributed among all factors of production.

Technological change can be defined, then, in terms of changes in the above characteristics. When new techniques are adopted, they either have a neutral effect on the production process, or change the input-output relationships. Neutrality of technical change can be measured by its effects on certain economic variables such as capital-output, labour-output, and capital-labour ratios, which normally remain invariant under technological change. By defining the relationship between these variables and their relative prices different types of technical progress can be defined.[17]

Several definitions of technical change has been proposed, such as: (i) product-augmenting, (ii) labour or capital-augmenting, (iii) input-decreasing and output augmenting, among others (Beckmann, Sato and Schupack, 1972). However, the most familiar definitions are those of Hicks (1932), Harrod (1948) and Solow (1962). According to the Hicksian definition, changes in relative shares of the inputs are used as a measure of technical bias. Harrod's definition measures the bias along a constant capital-output ratio, and thus allows for long-run adjustments of factor availability. Nevertheless, this definition imposes the restriction of a constant rate of return on capital. Solow's definition measures the bias along a constant labour-output ratio.[18] Symbollically:

S_1 S_2 --- T	X_1/X_2 constant	> - 0 , <	Hicks	labour-saving neutral capital-saving
S_1 S_2 --- T	X_1/Q constant	> - 0 , <	Harrod	labour-saving neutral capital-saving
S_1 S_2 --- T	X_2/Q constant	> - 0 , <	Solow	labour-saving neutral capital-saving

where Q is output, x_1 and x_2 are capital and labour, S_1 and S_2 are the capital and labour shares, respectively, and T is time.

Hicks (1963) introduced the bias of technical change as a measure of the impact of change in technology on patterns of demand for inputs. The bias of technical changes is the response of the share of an input in the value of output to a change in the level of technology. If the bias is positive, changes in technology increase demand for the input and are said to use the input. If the bias is negative, changes in technology decrease demand for the input and are said to save input. If technical change neither uses or saves an input (bias equals zero), the change is neutral. Hicks neutrality, which requires the constancy of relative shares along a path where the capital-labour ratio is constant, is geared to analysing a short-run situation when capital and labour availabilities are fixed.

The types of technical change of Hicks, Harrod and Solow are equivalent to an increase in inputs. The only difference is that in fact the quantity of the input does not increase, its effectiveness does. Hence, Solow-neutral and Harrod-neutral technical change are also known as capital and labour augmenting technical change since they add to the effectiveness of those respective inputs. They are also called biased technical change since the augmentation of capital is not the same as labour, as it is in the Hicksian case where they are augmented at the same rate.

a. Embodied and Disembodied Technical Change

Technical progress can be also classified in the manner in which it affects the efficiency of factor inputs. In this sense, technical change can be embodied or disembodied. It is called embodied if effects are reflected in an increase in efficiency of all existing labour or capital stock despite their age. Stated alternatively, technical change is disembodied if, independent of any changes in factor inputs, the isoquant contours of the production function shift inward towards the origin over time. In other words, the minimum output that can be produced from a fixed factor supply, increase as a result of technical advances that follow from sources other that changes in input combination. Managerial and/or organisational changes are often cited as examples of disembodied technical progress.

Formally speaking, a neoclassical production function having n inputs, and disembodied technical change can be written as:

(2.14)

$$Q = f(x_1, x_2, \ldots, x_n; t)$$

where t denotes time. It is assumed that f is a well-behaved production function with continuous first and second partial derivatives with respect to all its arguments. Since technical change is assumed, then f/ t > O. It is also assumed that f has the usual neoclassical properties for any given $t = \bar{t}$.

One important form of disembodied technological progress is the factor-augmenting hypothesis in which the general neoclassical production function (with two inputs: capital and labour) can be written as:

$$Q = f(K, L, t) = G[a(t)K, b(t)L] \tag{2.15}$$

where a and b are functions of time alone and G is homogeneous to degree one. The factors a(t)K and b(t)L are often called as "effective" capital and "effective" labour, respectively. Defining the ratio:

$$Z = \frac{a(t)K}{b(t)L} \tag{2.16}$$

(2.15) can be written as follows:

$$\frac{Q}{b(t)L} = G\left[\frac{a(t)K}{b(t)L}, 1\right] = G[Z, 1] = G(Z) \tag{2.17}$$

Technological change is said to be purely labour augmenting if a(t) = 0 and b(t)L > 0. It is purely capital augmenting if b(t)L = 0 and a(t)K > 0. (The dots represent time derivatives).

Burmeister and Dobell (1969) have derived three theorems to characterise neutrality of technical change as follows:

(i) Technical change is Hicks neutral if, and only if, there exist functions a(t) and b(t) such that f may be represented in the factor-augmenting form with a(t) ≡ b(t).

(ii) Technical change is Harrod neutral if, and only if, f may be represented in the factor-augmenting form with b(t) ≡ 1.

(iii) Technical change is Solow neutral if, and only if, f may be represented in the factor-augmenting form with a(t) ≡ 1.

Embodied technical change refers to technological advances that involve changes in factor proportions. In Solow's (1959) words:

> Improvements in technology affect output only to the extent that they are carried into practice either by net capital formation or by the replacement of old-fashioned equipment by the last models, with a consequent shift in the distribution of equipment by date of birth.

When technical change is embodied in factor inputs, biases of technical change do not depend on changes in relative shares. The bias in technical change will depend upon the elasticity of substitution, and the differential rates of growth of input embodiment. Embodiment means that, because of technological advance, the new inputs are more efficient than the old ones.

Suppose a two-factor (capital and labour) production function like (2.15), where a(t) and b(t) are, as before, the coefficients of factor augmentation. Since the direction of technical change depends upon the ratio a(t)K/b(t)L, it is Hicks-neutral if this ratio is constant, Harrod-neutral (labour-augmenting) if a(t) is constant, and Solow-neutral (capital-augmenting) if b(t) is constant. In this case, the bias is defined as follows:

$$B = [\, \dot{b}(t)/b(t) - \dot{a}(t)/a(t)\,]\ (1 - 1/\sigma) \qquad (2.18)$$

where σ is the elasticity of substitution.

It is important to emphasize that the embodiment effect should be distinguished from the augmentation effect and quality correction of inputs. In Nadiri's (1982, p.444) words:

> The augmentation effect means that the productivity increase of an input due to technical advances is expressed as equivalent to a specific increase in its quantity. Embodiment of technical change in capital, for example, could perfectly well produce purely labour-augmenting (but nonetheless capital-embodied) technical change. Nor should all quality improvement in an input be considered equivalent to the embodiment effect. The latter refers only to quality improvement associated with vintage of capital or cohort of labour. For example, productivity increases due to sex and race characteristics (at a point in time) are not part of the embodiment effect, while improvements due to age and education are part of it.

IV. Empirical Use of Production Functions for Technical Change Analysis

A. The Traditional Approach

For empirical analysis of technical change it is necessary to specify the form of the production function more precisely. The idea is to link changes in the "abstract technology" embedded in the production function to key characteristics or parameters of this function. The magnitude and stability of the measures obtained, depend upon how accurately the production function is specified and estimated. In principle, if all the inputs are properly measured and the function correctly specified, then the technical (or TFP) change measures should be zero or approximately zero.

The traditional approach to economic modelling of producer behavior begins with the assumption that the production function is additive and homogeneous. Under these restrictions demand and supply functions can be derived explicity from the production function and the necessary conditions for producer's equilibrium. However, this approach has the disadvantage of imposing restrictions on patterns of producer behavior- thereby frustrating the objective of determining these patterns empirically.

The best known members of conventional production functions used in econometric estimations are the following:

(i) The fixed proportions (Leontief) production function:

$$Q = \min\ (x_1/\alpha,\ x_2/\beta) \quad with\ \ \sigma = 0;\ \ \alpha,\ \beta > 0 \qquad (2.19)$$

(ii) The Cobb-Douglas production function:

$$Q = A\ x_1^{\alpha}\ x_2^{\beta} \quad with\ \ \sigma = 1\ \ and\ \ \mu = \alpha + \beta > / < 1 \qquad (2.20)$$

(iii) The CES production function:

$$Q = A[\ \delta\ x_1^{-\rho} + (1-\delta)\ x_2^{-\rho}]^{-\mu/\rho} \quad with\ \ \sigma = \frac{1}{1+\rho} \qquad (2.21)$$

where x_1 and x_2 are the inputs, α and ß are constant elasticities of the inputs, A is the efficiency parameter, $\delta (0 < \delta < 1)$ is the input intensity, $\infty \geq \ \geq -1$ is the substitution parameter and μ is the return to scale parameter.

The traditional approach originated since the early 1930s following the publication of "A Theory of Production" by Charles Cobb and Paul Douglas (1928). Their production function became the subject of intense criticism beginning from 1947 when Leontief established that the validity of such function rests on stringent separability restrictions. In addition, this function imposes a-priori that the Allen partial elasticities of substitution between each pairs of inputs must be identically one. In spite of its restrictiveness, however, the Cobb-Douglas production function framework has proved extremely useful in a variety of applications.

The constant elasticity of substitution (CES) production function introduced by Arrow, Chenery, Minhas and Solow (1961) adds flexibility to the traditional approach by treating the elasticity of substitution as an unknown parameter, where $\sigma = 1/1 +$, and includes the Leontief and Cobb-Douglas production functions as special cases. But, in spite of its greater flexibility over the Cobb-Douglas function, the CES production function retains the assumptions of additivity and homogeneity and imposes the restriction of constant elasticity of substitution.

An additional limitation of the CES production function is that it is confined to only two inputs. Attempts to include more than two inputs have led researchers in the beginning to formulate multifactor analogs of the conventional two factor functional forms. Such formulations gave rise to a variety of problems. In particular, McFadden (1963) and Uzama (1962) have shown that when more than two inputs are included in the CES function, strict assumptions about partial elasticities of substitution σ_{ij} are required for estimation purposes. That is, all the pairs of partial elasticities of the different classes of inputs must either have the same constant value or should be unity for all subsets of the inputs. Berndt and Christensen (1973a) have shown that this is tantamount to specify a-priori certain input strong separability restrictions.[19] Such functional forms, therefore, place unacceptable a-priori restrictions on their parameters as maintained hypotheses.[20]

Attempts to remove the restrictive assumption of a constant elasticity of substitution within the two-inputs boundaries, lead to the development of the variable elasticity of substitution production function (VES) proposed by Lu and Fletcher (1968), and Sato and Hoffman (1968), which includes the Leontief, Cobb - Douglas, and CES production functions as special cases.[21] This function admits an arbitrary set of partial elasticities of substitution between pairs of inputs. But even though the VES function

is more flexible than the other traditional forms, it is confined to the case of two inputs.

B. Development of General Functional Forms

A major advance in the economic theory of production which has proved useful in the analysis of technical change, input substitution, economies of scale, and other characteristics of technology, has been the dual formulation of production theory.[22] Recognition of the limitations of conventional functional forms to estimate technical change and other parameters that characterise the structure of production, and the development of duality theory, has motivated substantial research towards conceiving new functional forms which do not impose arbitrary restrictions on technology, like separability, constant elasticity of substitution, neutral technical change and constant returns to scale.

In recent years there has been great interest in the development and estimation of these so-called "flexible" functional forms to represent production technology. These developments define a major breakthrough in the theory of production and represents the current edge of the econometrical frontier. The "flexible" functional forms have been used primarily as vehicles for testing hypotheses on functional separability, substitution possibilities, demand elasticities, and, more frequently, scale economies. Proponents of these forms point to their ability to model a wide variety of production structures, since they leave separability, substitution, the nature of technical change and scale behavior as hypotheses to be tested rather than maintained.

A number of highly general flexible functional forms have been proposed recently. Among these are the Generalized Leontief (GL), Generalized Cobb-Douglas (GCD), Translog (TLOG), Generalized Square-Root Quadratic (GSRQ), and Generalized Box-Cox (GBC). The GL, GCD, and GSRQ forms were introduced by Diewert (1971, 1973 and 1974, respectively). The TLOG was initiated by Christensen, Jorgenson and Lau (1973), and the GBC by Khaled (1978).

Two specific forms of duality based production functions are the GL and the TLOG. The GL is a quadratic form in an arbitrary number of inputs. It reduces to the Leontief production function as a special case.

The trascendental logarithmic production function (translog for short), has both linear and quadratic terms with an arbitrary number of inputs. It reduces to a CES and multi-input Cobb-Douglas forms under certain restrictions. A formal discussion of them will be the subject of a forthcoming paper.

Notes

1. See Nadiri (1970, p. 1137).

2. The limitations of productivity measurement in relation to technical change are succintly discussed by Brown (1966) and Nelson (1973).

3. Early discussions of technological progress attempted to evaluate the effect of mechanisation on the level of employment and consequently, on labour's participation in the income generated by an economic system. It was natural that discussions focused on classifying types of technological change according to their effect on income shares accrucing to specific factors.

4. Cited by May and Denny (1979, p. 759).

5. See Jorgenson and Griliches (1967).

6. The weights could be the prices of the services of the corresponding factor or the income shares of the factors of production.

7. Tinbergen (1942) was the first to estimate explicitly technical change as a separate item in the aggregate production function, using an exponential time trend. Valvanis (1955), however, was the first to actually use the productivity term in the Cobb-Douglas function to estimate technological progress for the American economy over the period 1869-1948 (Kennedy and Thirlwall (1972, p. 17)).

8. This section and the next are based on Diewert (1981). No discussion is provided in present work in relation to the various approaches for productivity measurement using input-output techniques.

9. As correctly stated by Diewert (1981, p. 20): "This replacement is valid if the producer is paying inputs the value of their marginal products, i.e. it is valid if the producer is behaving competitively with respect to inputs."

10. In recent empirical research, other authors have dealt with dynamic issues, such as lagged adjustments of quasi-fixed inputs in the short run, by adopting an econometric approach-to be discussed shortly-and estimating translog variable cost functions. In this respect, see, for example, Brown and Christensen (1981), and Tansini and Zeján (1990).

11. The literature contains several interesting papers-for example, Diamond, McFadden, and Rodríguez (1978); Sato (1970); and Sato and Calem (1981) - on the question of whether the simultaneous effects of economies of scale and non-neutral change can be disentangled empirically.

12. Such functional forms are called "flexible". (Diewert, 1974, and Lau, 1974).

13. In other words, the productivity indices are deduced either from an explicitly defined production function or from a distribution theory where there is an implicit production function (Nadiri, 1970). In addition, Diewert (1974, 1976, 1978) demonstrated that there is a unique correspondence between the type of index used to aggregate outputs and inputs, and the assumptions concerning the structure of the underlying technology.

14. Factor accumulation, like increases in the capital stock, on the other hand is associated with a movement along the production function provided that the production function exhibits constant returns to scale.

15. The spread of new technology depends on the rate of adoüption and diffusion. For further details, see Kennedy and Thirlwall (1972), and Stoneman (1983).

16. See Nadiri (1970, p. 1140). The first four are what Brown (1966, p. 12) called the characteristics of an "abstract technology". The "abstract technology" concept is used by Brown to express the technology embedded in a production function. It is interesting to point out that Brown (p.13) used the concepts of returns to scale and scale economies interchangeably as if they were similar concepts. Hanoch (1975) demonstrated that these

are equivalent technological characteristics only for homothetic production functions.

17. Following Brown's (1966) terminology, in terms of the "abstract technology", variations in the efficiency of technology and economies of scale produce neutral technical changes. Non-neutral technical changes are produced by variations in the capital intensity and ease of substitution of capital for labour.

18. Ussually, classification of technological progress attempts to measure its impact on some predetermined variable, i.e., the capital-output ratio, the marginal rate of technical substitution, factor shares, average rate of productivity, etc. However, these variables are not dependent on technology alone; they also depend on proportional factor supplies. Thus, it is necessary to isolate the technological effect by specifying a particular path along which the pure effect of technological change is measured.

19. Separability between inputs is discussed in detail in Berndt and Christensen (1973).

20. Other limitations of the CES production function are discussed in Brown (1966, pp.59 - 61).

21. A recent interesting use of the VES production function has been in the study of the impact of biotechnology in agriculture (Diwan and Kallianpur, 1985).

22. A formal statement of duality theory is presented in Diewert (1971).

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PRIVATIZACION DE EMPRESAS PUBLICAS: APUNTES TEORICOS PERTINENTES AL CASO DE PUERTO RICO (*)

Dr. Edwin Irizarry Mora

Introducción

Nicolás Van de Walle define privatización como "una transferencia de control sobre propiedad o equidad, del sector público al privado, con particular referencia a la venta de activos." (Van de Walle, **World Development**, mayo de 1989.) Es obvio que de Walle se refiere en su artículo únicamente a la medida extrema de privatización, que es la que usualmente se tiene como marco de referencia para el análisis conceptual y para la discusión del tema.

Este artículo intenta examinar las tendencias actuales y prospectivas del proceso conocido usualmente como privatización, con énfasis en el contexto global y sus influencias sobre el nacional. Me propongo vincular --aunque muy brevemente-- los acontecimientos recientes en el sector público de Puerto Rico con los escenarios de otros países, de manera que podamos corroborar hasta qué punto la privatización es un fenómeno de carácter local, o si en realidad se trata de un nuevo ciclo del capitalismo, o si, por otra parte se trata simplemente de una moda que, como tantas otras, pasará con el paso del tiempo... o tal vez con la caída de regímenes privatizadores (v.g. el gobierno de Thatcher en Inglaterra).

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