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To Measure or Not To Measure Total Factor Productivity Growth?

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ABSTRACT *To date, the concept, measurement and interpretation of total factor productivity (TFP) growth remains highly discussed but poorly understood. This paper attempts to provide a review of these issues. First, the definition of TFP growth and the related concepts of embodied and disembodied technical change are discussed. Second, a brief overview and critique of TFP growth measuring techniques is provided. Third, the debate surrounding the accounting identity underlying the estimation of a production function for TFP growth is highlighted. Fourth, the usefulness of TFP growth is evaluated (and maintained) in the light of the criticisms hurled at this measure. Finally, some direction for future work on TFP growth is suggested.*

1. Introduction

The concept of total factor productivity (TFP) growth dates back to the works of Tinbergen (1942),[1] Abramotivz (1956), Solow (1957) and Griliches & Jorgenson (1966) among many others. The concept of TFP gained importance for sustaining output growth in the long run as input growth, which is subject to diminishing returns, is insufficient to generate more and more output growth. Thus TFP growth became synonymous with long-run growth, reflecting the potential for growth. This spurred interest in trying to obtain improved and more accurate TFP growth estimates for the economy as a whole, for the agricultural, manufacturing and services sectors, as well as for industries within a sector at various levels of disaggregation.

This paper hopes to stimulate debate on some important aspects of the TFP growth concept and its definition, measurement and interpretation. The relevance of TFP growth estimation is also questioned by reviewing some of the controversies plaguing the use of this measure.

The paper is organized as follows. First, it discusses the definition of TFP growth and its relation to the concepts of embodied and disembodied technical change. Second, it describes measurement issues for inputs and outputs, and the main TFP growth measuring methods (the frontier and non-frontier approaches). Third, it presents the debate on the notion of TFP growth based on the production function as an accounting identity. Finally, it argues that TFP is a useful concept and suggests directions for future work in the light of the criticisms directed at this measure.

Although this paper's focus is on TFP growth, that is not to say that the partial measure of labour productivity growth is unimportant. In fact, Krugman (1990) hails

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this measure as necessary when he says, "Productivity isn't everything, but in the long run it is almost everything". This is based on the notion that a country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker. Also, Chen (1979) explains that, in the long run, it is the growth of labour productivity that is more important than TFP growth, as exemplified by the comparison between Singapore and Hong Kong.

2. The Definition of TFP Growth

Since the early 1940s, the concept of TFP growth and what it measures has been hotly debated, leading to various definitions. TFP growth has often been used interchangeably with technological change/progress, technical change/progress, embodied technical change or/and disembodied technical change. Based on this, the definition of TFP is set up as follows:

$$
\begin{aligned}
\text{TFP Growth} &= \text{Output Growth} - \text{Input Growth} && (1)\\
&= \text{Technical/Technological Change} && (2)\\
&= \text{Technical/Technological Progress} && (3)\\
&= \text{Embodied Technical Change} &&\\
&\qquad + \text{Disembodied Technical Change} && (4)\\
&= \text{Changes in Technical Efficiency} &&\\
&\qquad + \text{Technological Progress.} && (5)
\end{aligned}
$$

The definition given by equation (1) is the most fundamental definition where TFP growth is measured by the standard growth accounting technique as a residual whereby it measures "everything and anything" that is not accounted for by input growth. Input growth consists of the sum of the increases in the use of all factors purchased in production. And because the determinants of TFP growth are not yet defined, this measure is often called a "measure of ignorance" (Abramovitz, 1956) since it is nothing more than a measure of what we do not know. Jorgenson & Griliches (1967) advanced the hypothesis that careful measurement of the relevant input variables would cause this residual to disappear. Nadiri (1972) explained that the growth accounting is a step towards a reconciliation of the economic balance sheet, as it provides a complete filing system in the sense that all phenomena that affect economic growth must do so through input factor qualities and relative factor intensities

The basic definition given by equation (1) has been further interpreted or refined by the other equations. While the definitions led by equations (2) and (3) for TFP growth are identical but used with different terms, equations (4) and (5) (the latter equation was popularized by Nishimizu & Page, 1982) are conceptually similar in that changes in technical efficiency in equation (5) essentially refer to embodied technical change, and disembodied technical change in equation (4) corresponds to technological progress in equation (5).

First, let us understand what embodied and disembodied technical change is. Embodied technical change results from the efficient use of new and better types of capital and is considered endogenous. It captures the effects of learning by doing (experience), advances in applied technology, managerial efficiency and industrial organization which transform into better methods and organization that improve the efficiency of both new and old factor inputs. With embodied technical change, more output is obtained with a given quantity of inputs or the same output can be produced with lesser inputs at the same cost, resulting in movements towards known production boundaries. Disembodied technical change, on the other hand, is not embodied in factor inputs and refers to technology as useful knowledge pertaining to the art of production, where concern is with the knowledge-creating activities of research, invention and development (Kennedy & Thirlwall, 1972), resulting in the expansion of production boundaries due to increases in knowledge.

While early works such as Tinbergen (1942) and Solow (1957) interpreted TFP growth as disembodied technical change represented as shifts in an aggregate production function, Solow (1960) developed a vintage-capital model to incorporate explicitly the changes in the age distribution of capital stocks and interpreted TFP growth as technical change embodied in new capital goods. (However, he distinguished disembodied technical change raising the productivity of both old and new investment goods without requiring gross investment, for example managerial and organizational changes.[2]) Brown (1968), on the other hand, modelled disembodied technical change as a trend term and embodied technical change with capital vintage effects, explaining that embodied technical change could be neutral or non-neutral depending on the elasticity of substitution between labour and capital.[3] Denison (1962) argued, however, that embodied technical change was so insignificant that TFP growth was best interpreted as disembodied technical change.[4] This prompted Abramovitz (1962) to call for an urgent examination of the *factual gap* between these two views. In response to this call, Jorgenson (1966) provided evidence that both embodied and disembodied technical change have precisely the same factual implications. Jorgenson (1966) also tried to convince readers that there was a one-to-one correspondence between the two types of technical change and, in view of this, he concluded that one could not distinguish a given rate of growth in embodied technical change from the corresponding rate of growth in disembodied technical change. Although there is some truth in his conclusion, it was based on the rather simplistic and easily refutable assumption that the price of investment good was an index of the quality of investment good.

Essentially, some of the confusion in the early literature on the embodied and disembodied technical change resulted from the inclusion or omission of the quality of inputs, and this is reviewed hereafter.

2.1 Quality Changes in Inputs

As a complete survey of the large literature on quality change lies outside the scope of this paper, this section only reviews some selected issues. One is the issue of eliminating aggregation errors. Jorgenson & Griliches (1967) explained the need to eliminate the errors arising from limitations on the number of separate inputs that may be distinguished empirically. The choice of commodity groups to serve as distinct "inputs" and "outputs" involves aggregation within each group by simply adding together quantities of all commodities within the group and aggregation among groups by computation of the Divisia index; but the resulting price and quantity indices are Divisia price and quantity indices of the individual commodities only if the rates of growth of either the prices or the quantities within each group are identical. Jorgenson & Griliches (1967) argued that these errors are often mislabelled as "quality change". Quality change in this sense occurs whenever the rates of growth of quantities within each separate group are not identical. For example, if high quality items grow faster than items of low quality, the rate of growth is biased downwards relative to an index treating high- and low-quality items as separate commodities. Thus, to eliminate this bias, it was argued that there was a need to construct a Divisia index of individual items within the group by using disaggregated or more detailed data, essentially capturing the changes in the composition of the use of various capital assets in aggregate capital and various types of labour in aggregate labour inputs. In this way, all factor inputs are ensured that they are of constant quality.

Labour quality, however, has been measured using the ratio of the number of workers to total hours, as was done by Jorgenson *et al.* (1987), while Gapinski & Western (1999) used average years of schooling and Jorgenson & Fraumeni (1989) went to great lengths to construct constant quality indices of labour inputs by deriving lifetime labour incomes by applying asset pricing equations (equivalent to those used for tangible assets) to wage rates.

Even though there have been many attempts to account as accurately as possible for input quality, there is still concern, as Star (1974) noted, that the numerical results of the TFP residual depend on the particular order in which data on inputs were disaggregated. He thus cautions against labelling any of these factors as the cause or explanation for TFP growth. For example, when he disaggregated labour by sex first and then education, all the improvement in the residual appeared to have been caused by the differences between the sexes, while education contributed nothing to the reduction in the residual. When the order of disaggregation was reversed, the opposite result was obtained.

Nevertheless, Star (1974) asserted that the great advantage of using disaggregated data is that quality changes in inputs are transformed into quantity changes in inputs and these are attributed to input growth, not TFP growth. But quality changes affect embodied technical change in the long run. For instance, the age and educational level of workers can be expected to affect their efficiency and their willingness to work with more advanced technology or capital. With capital, the use of more computers and less of other office equipment would clearly change the dynamics of productivity in the workplace. Thus, when quality changes in inputs are translated to quantity changes in output, they constitute embodied technical change and are attributed to TFP growth. This means that the gains from quality changes in inputs are somewhat suppressed in the contribution of inputs in the short run but they are measured when they emerge in the output growth component in the long run. Hence, with significant changes in the composition of inputs, one must be careful to interpret the often understated potential for growth given by the estimated TFP growth measure. Alternatively, in the short run, measures of input quality changes can be indicative of potential embodied technical change in the long run.

This formed the basis for one of the many disagreements in the classic debate on productivity between Jorgenson & Griliches (1967, 1972a, b) and Denison (1972a, b). Jorgenson & Griliches (1972a, b) pointed out that quality changes estimated from differences in marginal product or related to different vintages should be counted as inputs. This essentially means that all embodied technical change is to be transferred to inputs and thus the residual TFP measures only disembodied technical change. Denison (1972a) claimed that the contribution of such "unmeasured quality changes" to growth is embodied technical change as the development of better capital goods leads to advances in knowledge. So, should the quality of factors be necessarily adjusted for? Kennedy & Thirlwall (1972) argued that this depends on the purpose of the study. If the purpose is simply to measure the increase in the productivity of factors over time, it makes no sense to adjust factors for quality changes. However, if interest is in advances in knowledge or to understand the conditions for growth, the effects of factor quality changes need to be isolated.

Chen (1997) suggested that if labour and capital are correctly measured, encompassing quality changes, then the residual TFP is confined to disembodied technical change. Chen's (1997) interpretation of TFP stems from technical change being defined as a function of time and, being a trend parameter, it is thus exogenous. Where the quality of physical capital is unchanged, the growth of labour productivity becomes the real measure of technological advance. This is because the use of more physical capital (of the same quality) will increase output, and if the number of workers employed does not increase it contributes to labour productivity.

Recent studies have renewed the interest in quantifying and reassessing embodied technical change. This is led by Gordon (1990), who derived new price indices for capital to show the understated effect of capital, and Hulten's (1992) findings indicate that 20% or more of TFP growth could be attributed to embodied technological change.[5] While models of disembodied technical change are based on the concept of capital vintages, Hulten (1992) revitalizes Denison's (1972b) view on capital that successive vintages of investment also embody differences in technical design. For instance, a computer of vintage 1990 will tend to be more efficient at producing output, *ceteris paribus*, than a machine of vintage 1980, even if there is no physical change in capacity. Thus, "better" is equivalent to "more" investment and this can be measured by technical-efficiency units, as discussed by Fisher (1965).

To date, improvements in capital goods have been discussed as constituting embodied technical change, while improvements in labour specific to the firm or industry have remained neglected. Why are training costs or on-the-job training expenditure not explicitly considered as embodied technical change? Is it due to the lack of data? Partly so, and partly because it is likely that, since such labour skills are meant to affect organizational and industrial organization, they defy direct quantification. Thus, Hulten's (1992) study has understated embodied technical change, as only attempts to measure capital-embodied technical change have been considered.

In a similar vein, the concept of disembodied technical change has not escaped criticism. Creamer (1972) argued that this form of technical change in the form of knowledge-creating innovations is in fact embodied in the minds of individuals engaged in management. Thus, a comprehensive measure of labour input would embody these so-called disembodied innovations. Robinson (1970) also doubted the reality of the disembodied concept, with a parenthetical remark, "the value of equipment-absorbing disembodied progress (if there is such a thing) …".

Lucas (1988) offered a theoretical distinction between embodied and disembodied technical change by distinguishing between the internal and external effects of human capital accumulation. Learning-by-doing or on-the-job-training have internal effects since they affect an individual's own productivity and are hence internalized. Schooling is more general and creates external effects, contributing to the productivity of all factors of production, and its benefits are externalized. Although Lucas recognizes the difficulty in distinguishing and measuring these internal and external benefits, he concedes that if it were easy to perform such a classification of internal and external effects, then productivity effects would incorporate both internal human capital effects and exogenous technical effects.

The term "learning-by-doing" (Arrow, 1962) is another source of confusion, although many studies use it to mean embodied technical change. Learning-by-doing or the acquisition of knowledge is the product of experience, and experience is a function of time. If that is so, it can be considered exogenous and hence taken to be disembodied technical change. For instance, Arrow (1962) reported that the Horndal iron works in Sweden had no new investment (and therefore no embodied technical change) for 15 years, yet productivity (output per man hour) rose by close to 2% per annum. This improvement in performance was imputed to learning from experience.

3. Measurement Issues

Kaldor (1957) and later Scott (1989) argued that it was pointless and artificial to try and distinguish between shifts in the production function and movements along it because in the real world, we do not observe the production function but only actual combinations of factors and output in a dynamic process. Nelson (1981) and Shaw (1992) have raised similar concerns on the decomposition concept (of segregating output growth into input growth and TFP growth) given that the inputs as well as the other efficiency measures comprising TFP growth are complementary and interdependent.

3.1 Causality Between Embodied and Disembodied Technical Change

Embodied technical change such as the construction of new and better capital requires advances in technical knowledge (disembodied technical change) that can be transmitted through improvements in capital goods (embodied technical change) or via research and development or experience (both of which are disembodied). There is a very high possibility of bi-directional causality between the two types of technical change which, empirically speaking, defies accurate measurement. It is analogous to the problem of which comes first, the chicken or the egg.

While the above discussion suggests that the relationship between the two types of technical change is positive, this is not necessarily the case (if we assume that the two types of technical change can be measured). This is shown by the empirical evidence provided by Nishimizu & Page (1982) and Mahadevan & Kalirajan (2000). There may well be a high rate of adoption of new technology (disembodied technical change) without technological mastery (embodied technical change) or vice versa.

3.2 Causality Between Technical Change and Factor Input Growth

As established earlier, quality changes and hence factor input growth lead to embodied technical change in the long run. While Rodrik (1997) argues that labour-saving technical change and capital accumulation are not independent, especially in the East Asian economies, Fry (1990) asserts that high rates of return to capital stock due to TFP growth certainly encourage capital accumulation. But capital-embodied technical change would also require skilled labour to manage the advanced capital or machinery. This is the situation of capital-deepening and labour-deepening occurring simultaneously.

By way of the bi-directional causality between the two types of technical change established above, a three-way causality can be said to exist between factor input growth, embodied and disembodied technical change.

3.3 Input and Output Measurement

The problem of TFP growth measurement is also confounded with problems of measuring input and output.

First is the emergence of new outputs over time and the problem of product mix. Very few firms produce one homogenous product. Firms often change their product mix over time and differences in output characteristics affect the number and type of inputs required. The use of price indices to deflate non-perfectly representative mix of actual outputs is clearly inaccurate. Any index of real output also has to account for quality. Market prices in the base period are often taken to reflect relative values that capture quality differences, but when quality changes are not associated with increases in production costs (and hence market prices) productivity is underestimated.

The measurement of service outcomes is especially intractable and is exacerbated by the development of information technology and the growth in producer services.[6] As with government services, the problem of valuation has led to a largely underestimated measure of output in these areas by the common use of the cost of inputs that go into the production of such services. The uniqueness of services also makes aggregation of output more difficult. As discussed earlier, the problem of considering quality changes is more pronounced in service output. For example, how does one take into account faster transport, a more effective communication system and increased array of financial services?

With labour input, the common way is to use the number of hours worked or the number of workers employed. Often, the former is preferred to the latter as it accounts more accurately for part- and full-time employees in terms of actual hours worked. However, even total number of hours worked is not a satisfactory measure if a mix of skilled and unskilled workers is employed. Hours of work by highly skilled workers generally contribute more to production than hours by unskilled workers. To incorporate quality of labour input, in addition to skill level, the composition and demographic characteristics are also considered by constructing employment matrices cross-classified by sex, education, employment status and, in some cases, regional status of workers.

The measurement of capital services is less straightforward than labour services. Recall that the production function $Q = \mathrm{F}\ (K, L)$ is conventionally interpreted as a relationship between the flow of output and the flow of inputs' services. As no data on the flow of capital services are available, the easiest option has been to assume that capital flows are proportional to net capital stock after depreciation. But even the depreciation rate is often specific to asset types rather than industries and they do not change over time. However, the mix of assets in a given industry may well change significantly through time.

In reality, as capital input is not used with a constant intensity over time, it should be adjusted for capital utilization since the use of capital is subject to cyclical factors such as in a recession or boom. If excess capacity is understated, then the residual TFP growth will be understated. In a way, utilization rates are seen as a means of converting capital stocks to flows, but these rates are hard to come by. Some, however, claim that in the long run, cyclical fluctuations in the flow of services average out and one can take the ratio of the capital service flow to the capital stock to be constant, which allows the use of the perpetual inventory equation to measure capital services.

3.4 Approaches to TFP Growth Measurement

This section reviews the main TFP growth measurement techniques, the frontier and non-frontier approaches (Figure 1). Most studies have used the non-frontier approach for calculating TFP growth. The frontier approach was initiated by Farrell (1957), but it was not until the late 1970s that the approach was formalized and used for empirical investigation.

The crucial distinction between the frontier and non-frontier approaches lies in the definition of "frontier". A frontier refers to a bounding function or, more appropriately, a set of best obtainable positions. Thus, a production frontier traces the set of maximum outputs obtainable from a given set of inputs and technology, and a cost frontier traces the minimum achievable cost given input prices and output. The

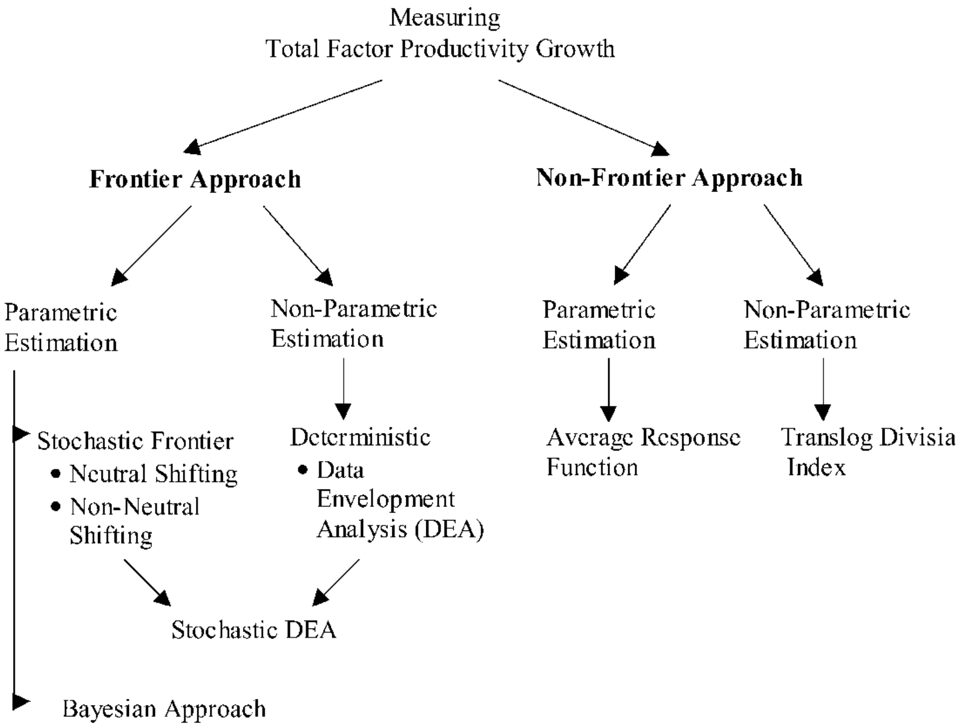

Figure 1. Total factor productivity estimation methods.

production frontier is an unobservable function that is said to represent the "best practice" function as it is a function bounding or enveloping the sample data. This is different from the average function, which is often estimated by the ordinary least square regression as a line of best fit through the sample data.

The frontier and non-frontier categorization is of methodological importance since the frontier approach identifies the role of technical efficiency in overall firm performance, while the non-frontier approach assumes that firms are technically efficient. Technical efficiency is represented by a movement towards the frontier and refers to the efficient use of inputs and technology due to the accumulation of knowledge in the learning-by-doing process, diffusion of new technology, improved managerial practice, etc. The frontier TFP growth measure consists of outward shifts of the production function resulting from technological progress, as well as technical efficiency related to movements towards the production frontier. An algebraic decomposition of the production frontier measure of TFP growth into technological progress and technical efficiency gains has been illustrated by Mahadevan & Kalirajan (1999). Bauer (1990) provided the decomposition of the cost TFP growth measure into technological progress, technical efficiency, allocative efficiency and the nature of returns to scale.[7] The non-frontier approach only considers technological progress as a measure of TFP growth.

Kalirajan & Shand (1994) related the absence of technical inefficiency in the non-frontier approach to an implicit assumption of long-run equilibrium behaviour. Following Schultz (1975), they argued that the short-run disequilibrium is a more usual condition, and understanding how firms or industries proceed to equilibrium over time depends both on their efficiency in responding to any given disequilibrium and on the costs and returns of the sequence of adjustments available to them.

Another difference between the frontier and non-frontier approaches is that the former is best suited to describe industry or firm behaviour. This is due to the benchmarking characteristic of the frontier approach, whereby a firm's actual performance is compared with its own maximum potential performance or as defined by the best-practice efficient firm in the sample. Benchmarking has little place in the non-frontier approach, which was first used to obtain estimates of aggregate TFP growth measure for the entire economy and then was progressively used for various sectors or industry-level analysis when disaggregated data became more widely available. The parametric non-frontier approach is typically statistical and is characterized as a central tendency approach; thus, it evaluates firms relative to an average producer.

One feature shared by the frontier and non-frontier approaches is that they can both be estimated using parametric or non-parametric methods. The parametric technique is an econometric estimation of a specific model and since it is based on the statistical properties of the error terms, it allows for statistical testing and hence validation of the chosen model. The choice of the functional form is crucial to model the data as different model specification can give rise to different results. However, an often ignored problem in the parametric estimation of the production function is that of simultaneity bias. This arises because the right-side variables containing the inputs are chosen in some optimal way by producers themselves and thus are not exogenous. While the problem is often reduced by adopting Zellner *et al.*'s (1966) argument that producers maximize expected profit or assume profit maximization *ex ante* or *ex post* to get around the endogeneity problem econometrically, some studies have used instrumental variables estimation, but this has met with mixed success as obtaining appropriate instruments is not easy.

The non-parametric technique of the frontier approach, given by data envelopment analysis (DEA), does not impose any functional form on the model but has the drawback that it cannot be validated by direct statistical tests. Nevertheless, recent work on DEA has opened up ways of exploring the statistical properties of its non-parametric estimators for sensitivity analysis, using sampling techniques such as jackknifing and bootstrapping, the application of semi-parametric methods and the use of chance-constrained programming techniques. These theoretical developments have drawn the parametric and non-parametric techniques of the frontier approach closer and models such as the stochastic DEA have allowed the marriage of the strengths of these techniques; but it is lamentable that such models have yet to catch on in empirical applications of productivity growth as they are mostly used in operations research. One reason for this is the lack of computational and programming skills on the part of the applied economists and until this technique becomes more accessible for use, it will remain underutilized in productivity growth analysis.

The Bayesian approach to stochastic frontier modelling is another relatively recent development that provides robustness to model and parameter uncertainty. In particular, focus on the distribution of individual efficiency or function of efficiencies allows standard deviations, and hence statistical differences, between the performance of the units in question to be compared. Although this is a significant advantage, the Bayesian approach can be computationally burdensome and one needs to be well versed with other techniques, such as Monte Carlo integration, to analyse some complex problems.

The literature to date is inconclusive on the best method to estimate TFP growth. Typically, no measure of TFP is necessarily the best for all purposes. As the empirical results are model dependent, there is always a model selection problem, but simulation studies using Monte Carlo experiments, which may help improve our understanding of the properties of the different models and facilitate model choice, have yet to be satisfactorily undertaken. Until then, depending on the case under consideration, a choice has to be made by weighing the advantages and disadvantages of the methods.

4. The Accounting Identity and the Notion of TFP Growth

Many have argued that the theoretical problems underlying the notion of TFP growth are so significant that the whole concept is seriously flawed. One view is that aggregate production functions do not exist in the first place; they are derived from an income accounting identity (Shaikh, 1980) and thus the estimation of TFP growth does not make sense. Extending this argument and using the Equifinality theorem, Felipe & McCombie (2003) disputed the estimation of the aggregate production function on two grounds. First, they showed that the (putative) production function precludes any testing and is far from estimating TFP growth as it yields only a weighted average of the growth rates of wage and profit rates. The accounting identity in growth rates (assuming factor shares are constant) is given by:

$$Y_t = (1-a)w_t + ar_t + (1-a)L_t + aK_t = \phi_t + (1-a)\ L_t + a\ K_t, \tag{6}$$

where Y_t is real value added; w_t is the real wage rate; r_t is the real average profit rate; $\phi_t = (1-a)\ w_t + ar_t$; $(1-a) = (w_t\ L_t)/Y_t$ is labour's share; and $a = (r_t\ K_t)/Y_t$ is capital's share.

Felipe & McCombie (2003) showed that the above expression can be mathematically formulated to resemble any production function and, as such, the "estimated" production function, being an identity, does not provide any information on TFP growth. In addition, they also proved that if factor shares are constant and wage and profit rates grow at constant rates, the Cobb–Douglas production function will always give a good fit.

Jorgenson (1966) explained that the accounting identity is important in defining an appropriate method of measuring TFP and it provides a useful check on the consistency of any proposed definitions of total output and total input. The fundamental identity for each accounting period is that the value of output is equal to the value of input:

$$q_i Y_i = p_j X_j, \tag{7}$$

where q_i is the price of the ith output; Y_i is the quantity of the ith output; p_j is the price of the jth input; and X_j is the quantity of the jth input.

Denison (1972b) claimed that no such accounting identity exists except in one special case, that of a current-dollar series (not in constant prices) for gross or net national product valued at factor cost. The identity is said to hold in this series because the value placed upon each unit of output is, by definition, the amounts earned by the factors providing it. But most productivity studies use GDP valued at (constant) market prices and, according to the above argument, this is not based on the identity. This questions Felipe & McCombie's (2003) assertion that TFP measurements are not valid as they are derived from "identities". Ironically, Denison (1972b) had not only accused Jorgenson & Griliches (1967) of making their estimates satisfy the accounting identity, but he also concluded that productivity change is precisely a measure of the degree to which the identity does not hold! Griliches & Mairesse (1997) further argued that in most cases, the production function is estimated as a tool for answering questions that are too interesting to give up even though the framework used may be problematic.

Felipe & McCombie (2003) maintained that one cannot estimate the aggregate production function from the theoretical notion of firm-level production functions by merely summing up the latter as this requires heroic assumptions which do not hold. Nataf (1948) has also pointed out that aggregation over sectors was possible if, and only if, micro production functions were additively separable in their inputs. For instance, the equilibrium conditions underlying the micro variables may not hold at the macro level, and/or the separability conditions of inputs in an aggregate production function related to their marginal rate of substitution among the various inputs may not be satisfied. Star (1974) explained that in order to add together different units of items in the heterogeneous component of inputs, each item must be a perfect substitute for any other unit, that is, the marginal rate of substitution is constant and the unit measurement is chosen so that the marginal products of every unit are equal.

Nevertheless, Felipe & McCombie (2003) are willing to accept the notion of a production function if the output and input variables are measured in physical quantities. But this does not necessarily give a better measure of TFP growth as the problems of capacity utilization, accounting for changing physical characteristics of mix of output, and the elusive measure of capital stock do not vanish. Some studies advocate a different type of analysis, that of a microeconomic nature where productivity growth, organization and management, and government policies are explicitly studied. Perhaps more should be drawn from other lines of research such as the views of the evolutionary theory that recognizes technical progress as an uncertain and costly business.

5. TFP—A Truly Fruitful Possibility or Totally False Proposition?

While Felipe (1999) claims that by definition we cannot explain what we do not know—the residual—Hulten (2001) feels that the static residual measure only correctly measures the shift in the production possibilities, it does not capture the induced effects of technology on growth. Griliches (1988) summed up the sentiments of the many critics of TFP growth measures by stating that, "despite all this work, there is still no general agreement on what the computed productivity measures actually measure, how they are to be interpreted and what are the major sources of their fluctuations and growth". Of late, attempts to explain or solve the productivity puzzle have been directed at understanding the effect of computers and information technology on the economy. This leads one to wonder if TFP growth explanations are getting murky because of the strong temptation to link the explanations to factors that are themselves conceptually rather blurred and hence difficult to measure. Perhaps this is due to a rush to develop exciting new fields of research and "doing more" in this sense may leave us wiser but with much of the original productivity puzzle still intact.

The general contention, however, is that past productivity work is not completely futile as we now know more about the nature of productivity and output growth than we did a decade ago. The use of TFP is appealing in that evaluating TFP growth often has policy formulation as the ultimate objective. This also means that the study of TFP growth trends rather than the *magnitudes* of TFP growth estimates are of greater interest and may be more reliable. Thus, there is little need to be overly concerned with obtaining the so-called accurate or "real" TFP growth rate as there will always be the possible emergence of empirical regularities or irregularities as more work is done with different methods on the same data. In any case, such quantitative empirical investigation needs to be complemented with extensive and more comprehensive qualitative discussion provided by surveys and interviews at the disaggregated or firm level. There is clearly a need to work at the micro level to understand more fully the dynamics of productivity growth at the macro level.

Moreover, as TFP growth measures a range of things, it is best to decompose TFP growth to allow an understanding of the sources of productivity growth for policy purposes. This can be done by first considering and modelling appropriately any interactions or causality effects between the components underlying decomposed TFP growth. Alternatively, if one takes the view that econometrics is only a tool in applied work and thus should not dominate the economics underlying the existing type of decompositional framework, the trends of the sources of productivity growth can pave the way for the valuable exercise of empirically investigating the significance of various factors. Studies have often regressed a host of factors on TFP growth to draw policy implications, but this is misguided as the components of TFP growth are conceptually different and may move in opposite directions, thereby calling for different policies.

Another issue ignored in the process of obtaining the "right" TFP growth estimate is the question of how TFP growth can be maximized. In other words, is there an optimal mix of the components of TFP growth, such as technological progress and technical efficiency? This then leads to the next question of how sustainable would such an optimal TFP growth rate be? Should we settle for less than maximum but sustained TFP growth or work towards reaching the optimal, but not necessarily sustainable, productivity growth? To answer these questions, the trade-off between the components of TFP growth must be investigated and incorporated in modelling efforts.

While TFP will always be controversial, most economists agree on the importance of productivity growth for an economy. This will ensure strong interest in the measurement and explanation of productivity and efficiency changes. In addition, the development of new and better theoretical models, the availability of new and better data and estimation techniques, and the advent of large-scale computers and better econometric software will continue to sustain work on the TFP growth measure. These have also made possible the testing of refined hypotheses that have widened the scope and scale of applications in the framework of productivity analysis. Even with the best estimation techniques, to obtain reliable estimates of productivity change, data that are much more accurate and detailed than those presently available are required. But it is easy to make a long list of desired data and measurement improvements instead of acknowledging and appreciating the gains from past research that also often provide more direction to future research. At the same time, it is important to bear in mind the criticisms underlying the TFP growth measure.

Notes

1. Tinbergen's paper was first written in German and was not published in English until 1959.
2. Solow (1960) went further to show that, in the long run, the embodied and disembodied models yield the same rate of TFP growth when the elasticity of substitution between labour and capital is unity; but when the elasticity of substitution differs, differential rates of growth may result.
3. It was explained that if the elasticity is less than unity, a rise in the stock of capital (for any given capital–labour ratio) lowers the income share of capital, and embodied technical change is capital-saving.
4. This view was supported by Wickens (1970), You (1976), Gregory & James (1973) and Baily & Gordon (1988).
5. More recently, Sakellaris & Wilson (2002) found that embodied technical change accounted for about two-thirds of total technical change between 1972 and 1996 in their sample of US manufacturing plants and asserted that the role of investment is even larger than previously estimated.

6. For a more through discussion, see Baily & Gordon (1988) and Griliches (1992).
7. One limitation of this type of framework is that modelling efforts to capture the interaction between the various components is yet to be undertaken.

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