Total factor productivity – a misleading concept *

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1. Introduction

In real business cycle models, growth accounting, as in empirical research on the link between R&D spending and economic performance, the indicator usually chosen for productivity is total factor productivity – a concept that derives from a neoclassical production function (a Cobb-Douglas in the overwhelming majority of cases). In this paper I criticise this concept as a measure of technical change and economic performance on two grounds: *i*) theoretical; *ii*) relevance to an understanding of present technological change. Criticisms of the sort can be found here and there in the literature, but the problem is that in mainstream research they are simply ignored or receive bare mention, without drawing the conclusion that this notion of productivity must be abandoned – as should also be the case for its mother concept, namely the neoclassical aggregate production function. In any case, there is a striking contrast between the few notes of criticism and the thousands of studies estimating these production functions. Hence the need to go back to the subject and reinforce the argument by showing that the alternative concept of labour productivity is the most appropriate, particularly if taken at the macroeconomic level.

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The paper is organised as follows: in Section 2 I recall the definition of the concept (this will be useful to outline the unrealistic hypotheses on which it is based – hypotheses that indeed form the foundations of the neoclassical production function); in Section 3 I go on to point out the theoretical and practical weaknesses of the notion of total factor productivity; in Section 4 I discuss the concept of labour productivity, emphasising its superiority over the rival notion; Section 5 addresses the problem of measurement.

2. Total factor productivity

The main reference is Solow (1957), who relied on this concept to measure the contribution of technical change to the growth of the US economy for the period 1909-49. Technical change – which Solow (1957, p. 312) defines as "*any kind of shift* in the [aggregate] production function"[1] – is the residual of this production function, when variations in labour and capital inputs are deducted from the growth of output per head. More precisely, Solow assumes that technical change is Hicks-neutral, i.e. shifts in the production function are pure scale changes that leave marginal rates of substitution between factors untouched at given capital/labour ratios (*ibid.*, pp. 312 and 316). In other words, technical change is a "manna from heaven" that, for any given capital/labour ratio, proportionally increases total output.

Total factor productivity (or the Solow residual) is dependent on two crucial assumptions common in the neoclassical theory:

i) the first concerns the *mathematical* properties of the production function, which is taken to be homogeneous of degree one (*ibid.*, p. 313) and convex. In turn, convexity implies:

– constant returns to scale for any given capital/labour ratio, and

[1] This author specifies that "slow-downs, speed-ups, improvements in the education of the labor force, and all sorts of things will appear as 'technical change'" (Solow 1957, p. 312). Solow's definition thus refers to *disembodied* technical change (except for the improvements in the education of the labour force).

– decreasing returns when there is a change in the proportions in which the two factors are used;

ii) the second assumption refers to the functioning of the markets: it is supposed that there is pure and perfect competition in product as well as in factor markets, each factor thus being remunerated at its marginal product. Together with the assumption of a homogeneous and linear production function – which allows for application of Euler's theorem – this hypothesis of perfect competition implies that the remuneration of factors exhausts the net product – i.e. the shares of capital and labour in the net product add up to one.[2]

In analytical terms, Solow (*ibid.*, p. 312) starts from this production function

$$Q = A(t)f(K, L) \tag{1}$$

where the multiplicative term *A(t)* represents technical change (the "manna from heaven").

Differentiating equation 1 totally with respect to time and dividing by *Q* one obtains

$$\frac{Q'}{Q} = \frac{A'}{A} + A\frac{f}{K}\frac{K'}{Q} + A\frac{f}{L}\frac{L'}{Q} \tag{2}$$

where primes (') indicate time derivatives.

Considering that from (1) $\frac{Q}{K} = A\frac{f}{K}$ and $\frac{Q}{L} = A\frac{f}{L}$, sub-

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[2] Euler's theorem states that, for any homogeneous function of degree one

$$Q = f(K, L)$$

the value of the function is

$$Q = \frac{Q}{K}K + \frac{Q}{L}L.$$

If the first formula represents a production function – where *Q*, *K* and *L* are respectively the net output, capital and labour – the second formula can be written as:

$$Q = rK + wL$$

where *r* is the rate of profit (i.e. the marginal productivity of capital) and *w* is the wage rate (the marginal productivity of labour).

stituting in 2 and manipulating there results:

$$\frac{Q'}{Q} = \frac{A'}{A} + \beta \frac{K'}{K} + \alpha \frac{L'}{L} \tag{3}$$

where β is the relative share of capital in net output $\left(\beta = \frac{Q}{K} \cdot \frac{K}{Q}\right)$ and

α is the wage share $\left(\alpha = \frac{Q}{L} \cdot \frac{L}{Q}\right)$. These input shares measure the elasticity of the production function.

Formula 3 can be written in per capita terms, by subtracting L'/L on both sides. Recalling that $a + b = 1$ (perfect competition and Euler's theorem), we obtain:

$$q^* = a + \beta (k - 1) = a + \beta k^* \tag{4}$$

where $q^* = \frac{Q'}{Q} - \frac{L'}{L}$; $a = \frac{A'}{A}$; $k = \frac{K'}{K}$; $l = \frac{L'}{L}$; $k^* = k - 1$.

Thus, the increase in per capita output is equal to the rate of increase of factor *A* (technical change) plus the rate of change of capital per capita, weighted with the share of capital in net output.

In his empirical testing, Solow (1957) found that the aggregate production function that fitted best with the data (in 1939 dollars) was a Cobb-Douglas[3]

$$Q = A L^{\alpha} K^{\beta} \tag{5}$$

[3] It should be noted that, besides the two already noted assumptions on the mathematical properties and on the market structures, the Cobb-Douglas is also based on two other stringent requirements, i.e.

a) the capital goods are malleable and adaptable at will (a 'jelly'). Thus, the aggregate capital can be treated as though it were a single commodity;

b) the value of aggregate capital can be measured independently of its return.

Following Solow, subsequent empirical research usually took the Cobb-Douglas specification to derive total factor productivity. For this reason, in the discussion below I shall refer to this type of production function.[4]

3. A misleading concept

Total factor productivity suffers from two main weaknesses. In fact, the concept is

– theoretically flawed;

– inadequate to reflect the essential characteristics of present technological change.

The first criticism is recognised in the literature, while the second has not received the emphasis it deserves.

1.a. The theoretical weakness of the notion of total factor productivity results from the fact that it derives from a neoclassical production function – an intellectual construction that has the advantage of mathematical elegance, but no relation with the real world. Here I am referring to the mathematical assumptions of convexity and linear homogeneity that are so crucial to obtaining the Solow residual – assumptions that any casual observation relegates to a purely imaginary economy.[5] Thus, if there are increasing returns to scale (the production function is not convex), input shares will not equal output elasticities and a positive Solow residual is estimated, even though there is no (disembodied) technical change (Stiroh 2001, p. 3). Now, it seems that increasing returns is precisely what characterises the present technological revolution in computer and information technologies. Take, for instance, the case of software: once created, software can be multiplied at insignificant cost, to infinity. Given the large and in-

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[4] Note, however, that the same reasoning applies *mutatis mutandis* to the CES production function, which is a generalisation of the Cobb-Douglas.

[5] I shall return on this methodological point of realism in paragraph 1.b below.

creasing fraction of software costs in the economy, this must be a major contributor to increasing returns.

The ancillary assumption of pure and perfect competition also bears no relevance to reality and, if we drop this hypothesis and adopt instead the realistic framework of oligopolistic market structures or monopolistic competition, the Solow residual loses its meaning. In fact, when non-competitive market structures prevail, the distributive share of the production function (α and β in the Cobb-Douglas) do not add up to unity and the Solow residual becomes a spurious magnitude because, along with disembodied technical change, it also captures an element reflecting market power. For this reason the observed total factor productivity usually underestimates its 'true' value.

To see this more clearly, let us take formula 4. Considering that, in the long run, the capital/labour ratio k^* increases (as the degree of mechanisation grows) and that market power entails that the share of capital in output ($b^{(nc)}$) is higher than under perfect competition, we have:

$$q^* - \beta^{(nc)} k^* < q^* - \beta k^* \qquad (6)$$

The discrepancy between changes in total factor productivity resulting from statistics and its competitive value was quantified by Hall (1988), who estimated the mark-up[6] for the US industry (for seven one-digit industry groups and 26 industries at the two-digit level) for the years 1953-84. It appeared that the bias was enormous since, for non-durable goods, the growth of disembodied technical change (the 'true' value) was almost three times higher than the observed figure. However, Hall's method was severely criticised by Felipe and McCombie (2002), who pointed out that the equation used to quantify the mark-up can be derived simply as an algebraic transformation of the accounting identity which defines the measure of output, with no behavioural implications – a criticism identical to that addressed by Shaikh to the neoclassical production function (see paragraph 1.c below). Of course, this does not mean that, empirically, the differences between observed changes in total factor productivity and the Solow residual are negligible: for instance, Bresnahan's (1989) thorough sur-

[6] I.e. the ratio between prices and marginal costs.

vey of industry case-studies shows very high mark-ups (often higher than 50%) in some concentrated industries.[7]

To further consolidate the arguments above, I will now address the question of realism. As a preliminary step I shall briefly discuss the neoclassical approach to this problem (paragraph 1.b), with no pretension of being exhaustive;[8] I shall then examine the meaning of the empirical testings of the Cobb-Douglas production function in more detail (paragraph 1.c).

1.b. For many neoclassicals realism in assumptions is not necessarily an essential requisite for a good theory. For Friedman (1953, p. 15), for instance,

> "the relevant question to ask about the 'assumptions' of a theory is not whether they are descriptively 'realistic', for they never are, but whether they are sufficiently good approximations for the purpose in hand. And this question can be answered only by seeing whether the theory works, which means whether it yields sufficiently accurate predictions".

The obvious truth of this argument is that, as a necessary condition for theorising, some degree of 'unrealisticness' in the assumptions must be accepted. Of course, if the purpose of the theory is to understand real societies – and possibly modify them – not all assumptions are equally good, and this gives rise to two difficulties in relation to the subject of this article.

The first problem is general and concerns the predictive power of the theory, which is not in itself a sufficient (or even necessary) criterion for its validity. We know, in fact, that false assumptions can lead to correct predictions and, in this case, theory misses one of its

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[7] The concept of total factor productivity received another serious blow from Hartley (2000), who analysed the behaviour of the Solow residual within a real business cycle model, in which the business cycle is the result of technological change. It appeared that, within this framework, "the Solow residual does not measure changes in technology. There is not a consistent relationship between the direction and size of the Solow residual. The Solow residual often moves in the wrong direction, e.g. a negative technological shock causes a positive residual. Even when the Solow residual has the right sign, its size is not consistent with the size of the technological shock, e.g. a larger positive change in technology does not necessarily cause a larger positive Solow residual" (Hartley 2000, p. 29).

[8] For thorough discussion see Hodgson (1988, ch. 2).

most important goals, which is to explain the mechanisms conducing from assumptions to predictions.[9]

The second problem appears when assumptions are too distant from experience. In such a case, instead of being a useful device to neglect unnecessary details, assumptions lower the theory to the rank of a mere logical exercise. Discussing Friedman's paper, Musgrave (1981) argues that we should distinguish three types of assumptions: negligibility assumptions, domain assumptions and heuristic assumptions. *Negligibility assumptions* state that some known factors have a negligible effect upon the phenomenon under investigation. Thus they are not necessarily descriptively false, for they do not assert that the factors are absent but rather that they are irrelevant for the purpose in question. *Domain assumptions* specify the domain of applicability of the theory, without necessarily suggesting that the assumption is or is not realistic. *Heuristic assumptions* are means to develop a theory through successive approximations, in that simplifying assumptions are made at an early stage of the investigation, to be dropped or modified later (the 'step by step' method).

Comparing these definitions with the assumptions that underlie the notion of total factor productivity, we see that the objection of lack of realism is destructive.

Let us take the hypothesis of convexity and linear homogeneity of the Cobb-Douglas. If we ascribe them the status of negligibility assumptions, then the theory that follows becomes irrelevant. As stated above, empirical observation shows, in fact, that constant returns to scale are not the rule and that the formal features of the production function are solely for mathematical convenience, and not simply to neglect unnecessary details. Similar considerations hold for pure and perfect competition. To assess the performance of real economic systems *as if* pure and perfect competition prevailed merely leads to misleading results.

The hypotheses under discussion can legitimately be considered domain assumptions, but this leaves intact the problem of the lack of relevance of the theory. In fact, if we value testability, we have to ad-

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[9] Consider this paradoxical example leading to correct predictions:

all ravens are vegetables
all vegetables are black
→ all ravens are black.

mit that our domain assumptions are simply false, hence the theory is untestable (Musgrave 1981, pp. 381-82). Finally, the hypotheses in question are not heuristic assumptions because the theory that is deduced does not represent the first step of a more complex analysis, in which the assumptions of departure are relaxed: if this were the case, the notion of total factor productivity would simply vanish.

1.c. We have seen that one of the main theoretical weaknesses of the concept of total factor productivity comes from its filiation from the neoclassical production function.[10] As already noted, Solow (1957) found that the Cobb-Douglas function fitted very well with data and, after him, hundreds of estimates for both time-series and cross-section data (within any one country) confirmed the strong empirical basis. Should we take this 'verdict of the facts' as proof of the soundness of neoclassicals' claim that, after all, the Cobb-Douglas is a good representation of reality?

Shaikh (1974 and 1980) provided a convincing negative answer to such a question by showing that

> "*the so-called empirical strength of aggregate production* [function] *is an illusion*, due not to some mystical laws of production, but instead, to some rather prosaic laws of algebra" (Shaikh 1980, p. 82; emphasis in the original).

In fact, at the roots of the Cobb-Douglas there is an accounting identity that relates output to the labour input and the amount of capital. Thus, so long as aggregate labour and capital shares are roughly constant, a Cobb-Douglas production function will fit the aggregate data – for any data whatsoever – regardless of the production function that actually generated the data (see also McCombie 2000-2001 for further discussion, new empirical tests and an assessment of Solow's reply to Shaikh[11]). Considering the destructive character of Shaikh's thesis, it is worth reporting his demonstration.

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[10] The aggregate production function, and the theory of capital in general, raised heated debate in the 1960s between the two Cambridges (UK and Massachusetts). The standard reference is Harcourt (1972); for an updated summary see Ahmad (1991) and Pasinetti (2000).

[11] McCombie (2000-2001) also addresses at length Solow's "second thoughts" on the question that there is no way to disentangle the results of estimating the accounting identity from the production function (Solow 1987).

The starting point is the national accounts definition of value added (Y) as the sum of wages and profits:

$$Y(t) \equiv w(t)\,L(t) + r(t)\,K(t) \tag{7}$$

where L is the number of workers, K the stock of capital (constant prices), w and r are the wage and profit rates, respectively.

Dividing by L and differentiating with respect to time, the above identity becomes:

$$y' \equiv w' + r'k + rk' \equiv w\left(\frac{w'}{w}\right) + rk\left(\frac{r'}{r}\right) + rk\left(\frac{k'}{k}\right)$$ [12]

where y and k have the already defined meaning, in per capita terms. Dividing through by y

$$\dot{y} \equiv \frac{y'}{y} \equiv \frac{w}{y}\dot{w} + \frac{rk}{y}\dot{r} + \frac{rk}{y}\dot{k}$$

where dots refer to (instantaneous) rates of change (e.g. $\dot{w} = w'/w$).

Recalling the definition of the wage share $a = (w\,L)/\,Y = w/y$ and of the profit share $b = 1 - a = (r\,K)/Y = (r\,k)/y$, the previous expression becomes

$$\dot{y} \equiv B + \beta\dot{k} \tag{8}$$

where $B = \alpha\,\dot{w} + \beta\,\dot{r}$.

Term B in identity 8 – a weighted average of the rates of change of w and r – is not correlated with the value of K[13] (nor with L), and it may be considered to be solely a function of time.

As Shaikh noted (1980, p. 83) “all relations given so far are *always* true for *any* aggregate data at all, irrespective of production or distribution conditions”.

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[12] The time index t is dropped to simplify notation.

[13] We know, indeed, that in price terms the value of aggregate capital depends on the prevailing rate of profit. However, here the capital stock is at *constant prices*, which means that its magnitude depends on the rate of profit of the base year of the price index and not on the rate of profit of any other period.

Supposing, now, constant distributive shares, identity 8 can be integrated as follows (where, for convenience, the constant of integration is written *ln C*):

$$\begin{aligned} \ln y &= \int B\,dt + \beta \ln k + \ln C \\ y &= e^{\int B dt + \ln C}\, k^{\beta} \\ y &= D\, k^{\beta} \end{aligned} \tag{9}$$

where $D = C\, e^{\int B\, dt}$.

Equation 9 is mathematically identical to a Cobb-Douglas production function with a shift parameter *D*. In fact, recalling the definitions of *y* and *k* ($y = Y/L$; $k = K/L$) and substituting we have

$$Y = D\, L^{(1-\beta)} K^{\beta} \qquad \text{(5 bis)}$$

However, equation 5 bis "is not a *production* function at all, but merely an algebraic relationship which always holds for *any* output-input data" (Shaikh 1980, p. 83). Thus no wonder if, in econometric studies that *assume* constant distributive shares adding up to one, the fit with statistical data is very good ("too good to be true", comments McCombie 2000-2001, p. 269). Shaikh substantiated his thesis by constructing a hypothetical data set perfectly consistent with a Cobb-Douglas function[14] with the property that if output per worker is plotted against capital per worker, one can clearly discern the word HUMBUG in the scattergram (Shaikh 1980, p. 86).

Subsequently, empirical testing performed by several scholars (surveyed by Sylos Labini 1995, pp. 487-88 and 490) confirmed that the apparent empirical success of the Cobb-Douglas stems from the constancy of the distributive shares α and β, whose sum is assumed to be close to unity. However, such an assumption is far from reflecting reality. In fact, when $\alpha + \beta = 1$ is not taken as an *assumption*, in the overwhelming majority of econometric estimates the sum of these two exponents of the Cobb-Douglas is decidedly far from unity; worse,

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[14] I.e. the function had 'constant returns to scale', 'neutral technical change', and satisfies 'marginal productivity rules'.

> "even if one imposes the said constraint, the results are often ridiculous, as in the case when one exponent turns out to be greater than unity, so that the other exponent is negative" (Sylos Labini 1995, p. 488).

2. The second type of criticism of the notion of total factor productivity derives from the fact that it does not reflect the essential characteristic of present technical change. Indeed, even supposing that all the heroic assumptions on which this measure of productivity depends are not fictions, the concept encompasses exclusively *disembodied* technical change, i.e. organisational innovations, learning by doing/using, spillovers and so on.

These kinds of innovations, and possible external effects, certainly are relevant in the present period of structural change, but they are only a small part of the story. The most salient feature of such a change is that technical progress is first and foremost *embodied* in capital goods, and it is precisely because the workforce operates with improved machines that the enterprise benefits from an impressive increase in the productivity of *labour*. If, for instance, a research worker can now invert a $n \times n$ matrix – not only numerically but also analytically – in a few seconds, it is because he/she has a PC of appropriate capacity and speed in which mathematical software is incorporated. The fact that technical change is embodied in capital goods (plant and machinery as well as software)[15] is so evident that it would be tedious to insist with other examples from industry, services and administrations. Of course, to be successful, computer-based innovations must be complemented by organisational changes, but this is ancillary with respect to the initial step.

It is interesting to note that, in his seminal 1957 article, Solow wrote: "Obviously much, perhaps nearly all, innovation must be embodied in new plant and equipment to be realised at all" (p. 316). Curiously enough, in spite of this clear recognition, in this paper he considered technical change only as a disembodied phenomenon and, following his example, a legion of scholars continued to rely on total factor productivity for growth accounting exercises as well as for measuring the economic effects of R&D.

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[15] In fact, in national accounting, computer software is part of intangible assets that, with tangible assets, form gross investment (gross fixed capital formation). See EUROSTAT (1996, paras 3.102 and 3.110 b).

Of course, this does not mean that the neoclassicals have completely neglected embodied technical change. Indeed, the vast literature on 'vintage models', in which each layer of capital stock incorporates the latest technique, proves the opposite to be the case. Moreover, Solow (1960) himself dealt analytically with this case of technical change and examined the conditions for obtaining a Cobb-Douglas production function with capital of different vintages, hence of different efficiency. However, his endeavour to bring this realistic case of capital accumulation within the neoclassical framework did not induce him to change his way of appraising technical change as a "peculiarly disembodied" phenomenon (Solow 1960, p. 90).

4. A more appropriate measure

The alternative way of measuring economic performance is the productivity of labour. This concept has the advantages that productivity of labour:

– to be defined, does not need to refer to a particular kind of production function. Thus it is not dependent on the unrealistic assumptions on which total factor productivity is based. Furthermore, to quantify labour productivity one has not to rely on the distributive shares in output, which are strongly influenced by market power;

– encompasses all kinds of technical advances, since both embodied and disembodied technical changes have a direct effect on output and/or on the quantity of labour.

Labour productivity can be split into two components, one referring to the degree of mechanisation (the capital/labour ratio), the other to the inverse of the capital intensity of production (the 'productivity of capital')

$$\frac{Y}{L} \equiv \frac{K}{L}\,\frac{Y}{K} \qquad (10)$$

where Y is value added at constant prices; K is the stock of capital at constant prices;[16] L is the number of workers, expressed as *full-time equivalents.*[17] Labour is assumed homogeneous, the transformation of complex labour into simple labour being obtained on the basis of some convenient aggregation procedure (for instance in the way suggested by Roncaglia 1973).

In terms of (instantaneous) rates of change, identity 10 is

$$\dot{\Pi} \equiv \dot{k}_l + \dot{y}_k \qquad (11)$$

where P is productivity of labour; k_l is the capital/labour ratio; y_k is the productivity of capital.

Embodied technical change is statistically reflected in the capital/labour ratio $\dot{k}_l$, while the term $\dot{y}_k$, *considered together* with $\dot{k}_l$, is usually a proxy of disembodied technical change. Consider, in fact, the following four cases:

Case 1:	$\dot{\Pi} > 0$;	$\dot{k}_l = 0$;	$\dot{y}_k > 0$
Case 2:	$\dot{\Pi} = 0$;	$\dot{k}_l > 0$;	$\dot{y}_k < 0$
Case 3:	$\dot{\Pi} > 0$;	$\dot{k}_l > 0$;	$\dot{y}_k = 0$
Case 4:	$\dot{\Pi} > 0$;	$\dot{k}_l > 0$;	$\dot{y}_k > 0$

The first is a case of pure disembodied technical change, since the increase in productivity is obtained on the basis of the same quantity and quality of capital[18] and labour (K and L remain constant). Hence, the origin of the positive result in question should be traced in organisational improvements and/or other forms of disembodied technical change.

The second case depicts the 'productivity paradox':[19] in spite of the fact that a new – more productive – technology is adopted (the de-

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[16] It is perhaps worth clarifying that, so long as one does not set out to explain the distributive shares, no logical problem arises in measuring aggregate capital in constant prices.

[17] This point is particularly relevant when part-time work is important and changes over time.

[18] As pointed out in Section 5 below, national accounts rules require qualitative improvements in commodities to be registered as increases in their *quantity*.

[19] "You can see the computer age everywhere but in the productivity statistics" (R. Solow, *New York Times Book Review*, 12 July 1987). The explanation of this para-

gree of mechanisation increases), productivity remains stationary because the introduction of new plant and equipment was not accompanied by appropriate organisational change. Statistically this is reflected in a decline in the 'productivity of capital'. This example emphasises the distinction between the *choice* of technique and the *change* of technique: *ex ante* (when choosing the technique) it was profitable to adopt the new technology but *ex post* (when the change materialised) this choice revealed a failure.

The third case is self-explanatory: the growth of labour productivity results from embodied technical change, coupled with an appropriate adaptation in the organisational structure of the firms, whose effects appear in the same percentage increase for *Y* and *K*.

The fourth case is not clear-cut because we cannot establish whether the increase in the productivity of capital is entirely due to disembodied technical change or, also, to the fact that the new technique was so productive as to entail an increase in the output/capital ratio.

Turning to the 'stylised facts', empirical observation shows that, in the long term, the capital-labour ratio follows a strong growing trend, while the trend in capital/output ratio is roughly stationary (see, for instance, Reati 1990). This confirms that, in the long run, the main contribution to productivity growth comes from embodied technical change and that the productivity of capital is essentially an indicator of disembodied technical change.

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dox raised lively debate, which is summarised in OECD (1991). Two explanations seem particularly relevant. There is, in the first place, a serious mismeasurement of productivity, which has increased over time. The second, and most important explanation, is a mismatch between old institutions and new technological opportunities. In fact, the efficient implementation of information and communication technologies requires a profound organisational change in the innovating enterprise, which is not readily performed: mastering a radically new technology is a long process. Complementary technologies are needed, workers must be trained and this is sometimes required for customers and suppliers: "The presence of a powerful computer does not suffice to improve productivity" (OECD 1996, vol. 2, p. 47).

5. A warning on statistical measurement

In the above pages I have, I believe, demonstrated that, when seeking to assess the effects of technical change, productivity of labour is clearly better than its rival notion of total factor productivity. However, both indicators suffer from the same weakness on statistical measurement. I am referring here to the fact that official statistics do not provide a faithful picture of a phenomenon that strongly characterises the present technological revolution in computer and information technologies, i.e. the appearance of new products and quality improvements of already existing commodities.

At the level of principles the situation is perfectly clear. The European manual for national accounts states:

> "The change in quality due, for example, to the modification of the physical characteristics of a product must be considered to be a change in volume and not in price" (EUROSTAT 1996, para. 10.18).

Thus, when a new computer with double memory for the same price replaces an old one, the volume of investment grows by 100%. When a new capital good has at the same time better quality and a higher price, it is necessary to make a price/quality adjustment in order to separate the quality improvement (to be registered as increase in volume) from the price increase. Statisticians have developed a number of criteria and techniques to make such an adjustment, which is also called the 'hedonic prices' deflators.

However, in practice this price/quality adjustment is a difficult task that, in any case, implies substantial margins of appreciation. So far the adjustment for quality changes has been very poorly applied in most European countries, with the result that, when we observe an increase in investment at constant prices, we do not know if this really corresponds to a greater quantity of machines, to improved performance of the same number of machines or to their unit price increase.[20] The situation is nevertheless improving and, in the not too distant future, we will certainly have more accurate statistics. In the

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[20] At present only France and Sweden employ 'hedonic prices' deflators for investment in computer and information technologies.

meantime, it remains true that, computing productivity (be it total factor productivity or labour productivity) according to available data, we include all measurement errors.[21] In the US the situation is more satisfactory, since the 'hedonic prices' adjustment has been applied for quite a long time, in such a way that measures of productivity are more reliable (or less unreliable) than the European ones.[22]

6. Conclusions

In this paper I have shown that total factor productivity (the 'Solow residual') is not the appropriate measure of technical change, particularly if one considers the present technological revolution, in which technical change is embodied in computers and other capital goods relating to information technologies.

a) At the theoretical level, the main weakness of the concept of total factor productivity lies in its derivation from a neoclassical production function – a device that makes nice mathematics but has no connection with reality. I am referring here to the *mathematical* assumptions of convexity and linear homogeneity – which allow for application of Euler's theorem and justify the hypothesis of constant returns to scale – and to the additional assumption of pure and perfect competition in both product and factors markets.

If, for the sake of realism, one drops these heroic assumptions, total factor productivity becomes a spurious magnitude that is more a measure of noise than a quantification of real-world phenomena. In fact, if we admit increasing returns to scale – something that seems to characterise the innovations in computer and information technologies – we then go on to estimate a positive Solow residual even though there is no (disembodied) technical change. Moreover, if we adopt the

[21] In some cases scholars rectify European data for price/quality adjustment applying US 'hedonic prices'. Such a procedure is perhaps better than nothing, but leaves great uncertainty about the reliability of the corrected figures.

[22] See however Nordhaus (1997) for a pessimistic view on the practical capability of current techniques to capture the impact on prices of new technologies adequately, especially radical innovations. On this question of measurement see also the first three essays (by J. Haltiwanger and R.S. Jarmin, B.R. Moulton, P.A. David) in Brynjolfsson and Kahin (2000, pp. 13-95).

realistic framework of non-competitive market structures, observed total factor productivity is seriously biased because it includes an element related to market power. Empirically, this component is far from being negligible.

b) The second type of insufficiency derives from the fact that total factor productivity encompasses exclusively disembodied technical change, i.e. organisational innovations, learning by doing/using, spillover effects and such like. Now, the essential characteristic of present technological change is that it is first and foremost embodied in capital goods. And it is precisely because the labour force enjoys the use of new machines that enterprises benefit from an impressive increase in productivity of *labour*. Obviously, there is no doubt that disembodied technical change is important, but it is certainly not the main part of the story.

The alternative concept of productivity of labour escapes the above criticisms. In the first place, to define labour productivity we do not need a particular type of production function and, secondly, such a measure of productivity encompasses all kinds of technical change – embodied and disembodied. The relative influence of these two types of technical change can be measured separately by splitting the formula of productivity of labour into its components – the degree of mechanisation (the capital/labour ratio), and the 'productivity of capital'. It appears that the productivity of capital is usually an indicator of disembodied technical change.

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