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MEASURING TOTAL FACTOR PRODUCTIVITY, TECHNICAL CHANGE AND THE RATE OF RETURNS TO RESEARCH AND DEVELOPMENT*

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MEASURING TOTAL FACTOR PRODUCTIVITY, TECHNICAL CHANGE, AND THE RATE OF RETURNS TO RESEARCH AND DEVELOPMENT

1. Introduction

Since the observed serious declines in the rates of growth in productivity that occurred around 1973 in most OECD countries, an expansive research effort has sprung up to explain both these declines and the previous high productivity growth rates. Overviews of much of this work are provided by Maddison (1987), Link (1987), and Jorgenson (1988).

One frequently suggested reason for the declining growth rates was a fall (by some measure) in research and development expenditures. Early researchers had found a relationship between productivity growth and the investment in technology. At an aggregate level for example, Minasian (1962), Griliches (1973, 1980b), and Terleckyj (1974, 1980) found industrial research and development had significant effects on the rate of productivity growth.[1] This relationship, however, evaporated when investigators turned to it to help explain the slowdown.[2] Link (1980) and others[3] found that the aggregate data of the 1970's did not show the relationship previously demonstrated using data of the 1950's and 1960's. The connection could only be reestablished by using micro data. Mansfield (1980), and later Griliches (1984), found a strong relationship between individual firms' total factor productivity growth, and research and development expenditures. Micro data collected in the Federal Trade Commission Line of Business survey were also linked to patent activity by Scherer (1984), who found research and development an important variable in productivity growth.

More recently, Lichtenberg and Seigel (1987) have shown that before 1987, micro data studies of the link between research and development expenditures and productivity used erroneous estimates of total factor productivity growth (hereinafter termed productivity growth), arguing that some of the errors arise from incorrectly deflating inputs and outputs and from errors in the attendant aggregation. In their study, Lichtenberg and Seigel constructed a deflated measure of inputs and outputs using micro data from the Census Bureau's Longitudinal Research Data (Census Data) file to account for firm diversification. For comparison, they also calculated the conventional measure of productivity growth by assigning a single price deflator to the entire firm based on its primary product Standard Industrial Classification code. They then used the two estimates of productivity growth in the estimation of a model of research and development intensity (research and development expenditures per unit of output). Their results showed that their measure of productivity growth outperformed the conventional measure in terms of the explanatory power.

In this paper, we look at three measures of productivity growth and regress them on research and development expenditures using micro data. We employ the Tornqvist-Divisia measure and Ohta's (1974) more general measure of productivity growth. The latter imposes fewer restrictions on the firm's production technology and allows us to relax the assumptions of constant returns to scale and Hicks neutral technological change.[4] Following the work of Gollop and Roberts (1981), we use a flexible functional form. As with Lichtenberg and Seigel (1987), we use line-of-business price deflators for inputs and output developed from the Census Data. We focus on establishments in a particular industry, (the flat glass industry, Standard Industrial Classification 3211) an industry that was undergoing technological change during the period under study (see Kokkelenberg and Nguyen, 1989). Our sample consists of 15 establishments during 1972-1981. We extend the model to include two other variables that may have significant effects on productivity growth; the accumulated stock of technical knowledge resulting from previous research and development investment, and the purchase of new capital goods. Finally, we incorporate a non-linear technological index in our cost model.

2. The Model

To estimate the effect of research and development on productivity growth, previous research has often applied the following stochastic research and development intensity model[5]

$$TFPG_t = b_0 + b_1(\dot{R}_t/Q_t) + u_t, \tag{1}$$

where TFPG, $\dot{R}$ and Q respectively represent total factor productivity growth (productivity growth), the stock of research and development knowledge, and output; $\dot{R}$ denotes the time derivative of R. The b_i, i=0,1, are parameters and u is a disturbance term.

Estimating equation (1) requires a proxy for the unobserved additions to the stock of research and development knowledge and this in turn requires historical research and development expenditures data (denoted below by RI), the depreciation rate of R, and an initial stock of knowledge. Because the depreciation rate of research knowledge is not known, and historical data on research and development cover only a recent and short time span, previous work has assumed away these problems and estimated[6]

$$TFPG_t = b_0 + b_1(RI_t/Q_t) + u_t. \tag{2}$$

Equation (2) may result in biased estimation; for one thing it attributes all productivity growth to research and development expenditures. The literature suggests at least two other research related variables, the accumulated stock of technical knowledge of the industry under study (we would expect a positive sign), and new capital goods purchases. The expected sign of this latter variable is uncertain. These new capital goods can be thought of as embodying technological improvements and would thus have a positive effect on productivity.[7] However, if new capital adjustment costs exist, then we might observe a negative short-run relationship.

The extended model is now written as:

$$TFPG_t = b_0 + b_1(RI_t/Q_t) + b_2AC_t + b_3(NK_t/Q_t) + u_t, \tag{3}$$

where AC denotes the total accumulated stock of research and development of the relevant industry, while NK represents the purchases of new capital goods. Again, u is a disturbance and the b_i, i=0,1,2,3, are parameters.

We next turn to the issue of measuring total factor productivity (TFP). Conventionally, an index of TFP is defined as:

$$TFP_t = Q_t/(\sum_{i=1}^{N} x_{it}^{\beta i}), \tag{4}$$

where Q is the real output, x_i is the quantity of the ith input, and βi is a parameter to be estimated.

In practice, previous studies, generally employing aggregated data, have often used the Tornqvist-Divisia index of productivity growth,[8] and that is given as:

$$TFPG_t = \ln(Q_t/Q_{t-1}) - (0.5) \sum_{i=1}^{N} (S_{it} - S_{it-1})(\ln (x_{it}/x_{it-1})). \tag{5}$$

Here ln denotes the natural logarithm and S_i represents the total cost share of the ith input. Equation (5) is based on two assumptions: the output elasticity with respect to the ith input is equal to its actual share in total costs, and the production function is characterized by constant returns to scale. These assumptions may be valid in studies of aggregate data, but may be erroneous here.[9] Theoretically, in any given short-run period, the firm could be operating on the downward or upward sloping portion of its long-run average cost curve and hence see increasing or decreasing returns to scale. Indeed, Hall (1986a) found that 17 of 21 two-digit Standard Industrial Classification industry groups, price exceeds marginal cost.[10]

Gollop and Roberts (1981) offer a more general approach to the estimation of productivity growth without imposing these restrictions, and we employ their method. Assume that corresponding to the production function, there exists a dual cost function given as:

$$C_t = C(Q_t, P_t, \tau), \tag{6}$$

where C represents the cost of producing output Q, while P and τ respectively denote a vector of input prices and an index of the technological level. Ohta (1974) showed that total factor productivity viewed from the primal or production side equals the rate of returns to scale times the negative of $d\ln C/d\tau$, the derivative of the natural logarithm of the costs with respect to technological change. We call this the dual rate of total factor productivity, that is:[11]

$$TFPG = - [1/((\partial \ln C)/(\partial \ln Q))][\partial \ln C/\partial \tau]. \tag{7}$$

This estimate of productivity growth neither requires constant returns to scale nor Hicks neutral technical change.

A specific functional form for the cost function is required to estimate the model of equation (7). We assume the cost function is given by the transcendental logarithmic cost function (translog) for the establishments and period under study.[12] For a five input factor model, the translog cost function can be written as:

$$\begin{aligned}
\ln C = a_0 &+ \sum_{i=1}^{5} a_i \ln P_i + 0.5\sum_{i=1}^{5}\sum_{j=1}^{5} b_{ij}\ln P_i \ln P_j \\
&+ \sum_{i=1}^{5} a_{iQ}\ln P_i \ln Q + a_Q \ln Q \\
&+ \sum_{i=1}^{5} a_{i\tau}\ln P_i \tau + a_{Q\tau}\ln Q\tau \\
&+ (1/2)a_{QQ}(\ln Q)^2 + a_\tau \tau + (1/2)\ a_{\tau\tau}(\tau)^2, \\
&i,\ j = K,\ L,\ E,\ F,\ M. \qquad (8)
\end{aligned}$$

The conditions insuring that C is linearly homogenous in input prices are:

$$\sum a_i = 1, \text{ and } \sum b_{ij} = \sum a_{iQ} = \sum a_{i\tau} = 0.$$

Here, K, L, E, F, and M respectively represent the flows of service from capital, labor, electricity, fuels and intermediate materials inputs. Production technology is characterized in equation (8) by constant returns to scale if $a_Q = 1$, and $a_{QQ} = a_{i\tau} = 0$. Technical change is Hicks neutral if $a_{Q\tau} = a_{i\tau} = a_{\tau\tau} = 0$. Technical change is not present if $a_\tau = a_{i\tau} = a_{Q\tau} = a_{\tau\tau} = 0$.[13]

3. Data and Sources

Confidential data on company level research and development expenditures were taken from the National Science Foundation's Annual Research and Development in Industry Surveys conducted by the Census Bureau's Industry Division. As plant level data on research and development expenditures are not available, we used the corresponding company level data and developed a series of research and development investments at the plant level. This was done by weighting the total appropriate research and development expenses by capital and by output as a percent of the company's relevant totals.

For the total accumulated research and development, (AC) following Griliches (1980), we write:

$$AC_t = \sum_{k=1957}^{t} TRI_k, \qquad (9)$$

where TRI denotes total research and development expenditures for the Stone, Clay, Glass, and Concrete product industry (Standard Industrial Classification 32) taken from the Census Bureau's Research and Development in Industry, 1957-1981 data file. New machinery and equipment purchases, a variable in the Census data file, was used as a proxy for NK, new capital goods purchased.

Three measures of productivity growth were constructed: A Tornqvist-Divisia index computed using equation (5), denoted TFPG1, a translog cost function based form using the Ohta measure, computed using equations (7) and (8), denoted TFPG2, and a measure denoted TFPG3. This latter measure is derived in the same manner as TFPG2, but incorporates a non-linear technological proxy in the translog given by:

$$\tau = \text{arctangent } (t - z), \qquad (10)$$

where t is the time trend and z is a parameter to estimated.[14] The arctangent formulation results in an s-shaped learning curve and is detailed in the appendix.

Plant level data on costs, outputs, inputs, and prices were extracted from the Longitudinal Establishment Data file. These data are detailed in Kokkelenberg and Nguyen (1989).

4. Estimation Results

Summary statistics for the three indexes of productivity growth show substantial differences in the means as well as their ranges (see Table 1). The patterns of signs for productivity growth differ throughout the period also. Except for two years 1976 and 1977, the Tornqvist Divisia index for all 15 establishments shows positive productivity growth. In contrast when the time trend is used as a proxy for the technological level, under the Ohta method we observe negative average productivity growth or a decline in total factor productivity for all 15 establishments throughout the entire period. Finally, when using the learning curve model, the index values for all establishments are negative in the earlier years of the period, a few become positive in 1977, and are all positive by 1981. This latter pattern is consistent with what we would expect with an industry that underwent both a technological improvement and a substantial market adjustment and contraction during the sample period. The other two patterns of signs reflect an overwhelming market effect (TFPG2) or only the effect of the recession of 1974-75 (TFPG1).

The results of estimating equations (2) and (3) using the three different dependent variable are discussed next (see Table 2).[15] A review of Table 2 indicates that the full model represented by equation (3) is the best model regardless of the dependent variable. This is so because the full models yields the smallest standard errors of estimation, the highest modified Akaike information criterions,[16] the highest value of the calculated F statistics, the highest R-squared (adjusted or on the transformed model), and the highest log of the likelihood function.

The Durbin Watson statistic is such that we fail to reject the null hypothesis of no auto correlation for the Tornqvist-Divisia measure of productivity growth regardless of the model. On the other hand, the Ohta measure (where τ=t) yields a Durbin Watson that allows us to reject the null hypothesis even after the imposition of a first order autocorrelation rho. Finally, the Ohta learning curve measure (where τ=arctan(t-z)) results in an indeterminate value of the Durbin Watson statistic in all cases except for the full model of equation (3). Here we must reject the null hypothesis although the value of 2.403 is just two percent above the upper critical bound of 2.355 (4-1.645). We also note that the two values of R squared are highest for the Ohta learning curve measure.

Turning to the individual explanatory variables, we note that only in the Ohta measure with the learning curve do we find that research and development expenditures are statistically significantly non-zero, showing a 64% return in the full equation (3) model. However, in both sets of regression with the Ohta measure as the dependent variable, we find the accumulated research and development variable to be statistically significant. Finally, we note that the coefficient on new capital goods is also statistically significant. The inclusion of the new capital goods variable passes an appropriate F test at the one percent level of significance. Notice that its sign changes from negative in the first model to positive in the last two models. We recall our earlier discussions as a possible explanation for this switching of signs for a significant estimator. In general, the results are not surprising, as the estimate of the translog cost function (reported in Kokkelenberg and Nguyen, 1989) found that the flat glass industry was characterized by an increasing returns to scale technology. Thus the constant returns to scale restriction assumed in Tornqvist-Divisia measure mismeasures the actual growth and may lead to biased estimators.

Of the four regressions using the Ohta measure with the learning curve as the dependent variable, the most complete regression (equation (3)) implies that the average private rate of returns to research and development and to new purchased capital for the 15 flat glass establishments under study were about 64% and 0.46% during the period 1972-1981. On the other hand, an increase of one million dollars in the industry's accumulated research and development results in a 1.88% increase in growth. These findings are quite reasonable in view of the process change in the flat glass industry in the late 1960s and early 1970s. Our estimate of a 64% rate of returns to research and development investment is also quite comparable to those obtained by Griliches (1980a, 1980b), Minasian (1969), and Griliches (1986).

5. Summary and Concluding Remarks

In this paper, we used micro data to estimate three alternative measures of total factor productivity growth. We found that the estimated coefficients of the models are sensitive to the measurement of total factor productivity growth. When a less constrained measure of productivity growth and a learning curve are incorporated, research and development intensity is a significant factor determining total factor productivity growth. This confirms earlier findings concerning technological influences on productivity growth. These results also confirm more recent work which shows that when using micro data and more detailed modelling, research and development continue to influence productivity. Further we found that accumulated research and development stock for the relevant industry, and new capital goods, are important additional explanatory variables. A specific technical change index capturing the learning-by-doing process was superior to the conventional time trend index.

We note that in the absence of these features a statistically significant relationship between research and development intensity and productivity growth was not found. While the results support the features used in our approach, they may only hold for this particular industry; nevertheless, the methodology and the empirical results suggest that continued research with micro-data is useful.

NOTES

1. For further examples, see Griliches (1979), Mansfield (1980), Griliches and Lichtenberg (1984), and Lichtenberg and Seigel (1987).

2. Link (1987) traces this history in some detail. Originally researchers working with data from the 1950s and 1960s found that research and development "was a significant determinant of productivity growth . . . (in various industries)." (p. 53). Researchers did not find strong evidence of this relationship when using data from the 1970s.

3. See Link (1987) for a list of more recent work in this area.

4. A generalization of the Tornqvist-Divisia Index, which permits varying returns to scale, has been developed by Caves, Christensen, and Diewert (1982). They showed that, assuming a translog form, an average of "Malmquist indexes can be computed using information on prices and quantities only, i.e., without knowledge of the translog parameters." (p. 1394). However, in the presence of increasing returns to scale, which we have in our case, the degrees of returns to scale for each firm or period are required to complete the calculations. We calculated returns to scale and found them to be increasing in all periods, though at varying degrees. This calculation, however, requires estimates of the translog parameter on output so there is no advantage in using the Caves, Christensen, and Diewert approach in our case.

5. For example, see Mansfield (1980), Griliches and Lichtenberg (1984), and Lichtenberg and Siegel (1987).

6. The empirical work of Griliches and Lichtenberg (1984) suggested that the depreciation rate of research and development d is approximately equal to zero. Terleckyj (1982, 1983) also obtained similar results. According to Terleckyj (1984) research and development as a source of productivity does not depreciate, and the level of productivity reached as a result of past research and development can be maintained indefinitely by replacing capital and labor of the same kind.

7. Nelson et. al., (1967), Mansfield (1968),and Terleckyj (1974) have argued that purchased new capital goods should be included in the model to capture the effect of "diffusion innovation" on productivity growth. Griliches (1979) identifies purchased capital goods (that embody quality improvement) as a type of spillover effect.

8. For example, see Griliches and Lichtenberg (1984), and Lichtenberg and Siegel (1987). This measure of productivity growth is often referred to as the primal rate of total factor productivity growth (e. g., see Ohta 1974, and Morrison and Diewert,1987). This is also referred to by Berndt and Khaled (1979) as the dual rate of total cost diminution.

9. Our previous work using plant level data for the flat glass industry indicates that the production technology of this industry was characterized by an increasing returns to scale technology. Also the assumption of neutral technical change was decisively rejected by the likelihood ratio test.

10. Thus, the firms in these industries would be experiencing non-constant returns to scale. Subsequently, Hall (1986b) found that the assumptions of constant returns to scale were in fact rejected for most of the 20 two-digit Standard Industrial Classification industry groups (SIC 20-49).

11. Gollop and Roberts (1981) write the cost function as $C = G(P, Q, \tau)$ in time t, and show the total differential as:

$$(d\ln C/dt) = (\partial \ln C/\partial \ln P)(d\ln P/dt) + (\partial \ln C/\partial \ln Q)(d\ln Q/dt) + (\partial \ln C/\partial \tau)(d\tau/dt).$$

Thus, the rate of change in costs over time is the sum of the rates of changes in prices, output levels, and technology. In their paper, they assume technical change, here denoted τ, is proxied by time, t, so the last right hand term becomes unity. If the total factor productivity growth is simply the change in output as a result of technological change, holding prices and scale constant, we have a dual form, productivity growth as a reduction in costs due to technical change, or:

$$TFPG = (-\partial \ln C/\partial \tau)_{d\ln P/dt\, =\, d\ln Q/dt\, =\, 0}.$$

Ohta (1974) writes this as:

$$TFPG = (-\partial \ln C/\partial \ln \tau)\ (\partial \ln C/\partial \ln Q)^{-1}.$$

See Berndt (1980) for further details.

12. The translog function was developed by Halter, et. al., (1957), and later employed by Christensen, Jorgenson and Lau (1971). There are other flexible functional forms such as the Extended Generalized Cobb-Douglas model and the generalized McFadden model (see Diewert and Wales, 1987). We empirically compared these forms with the translog model and found the translog model

performed equally well compared with the other two. We also found that the translog is easier to estimate (see Kokkelenberg and Nguyen, 1987).

13. Hicks neutrality requires $a_{Q\tau} = 0$ if $a_{iQ} = 0$ for any i; and also, $a_{\tau\tau} = 0$ if $a_{i\tau} = 0$ for any i, i= K,L,E,F,M.

14. The arctangent form yields a distendend s-shape curve with aysmptotes at $-\pi/2$ and $+\pi/2$. The optimal value of t was obtained by a grid search using the log of the likelihood function as the criterion.

15. The results reported here are based on weighting research and development expenses by output. These results are substantially the same as those where the weighting was by capital. Tests of Equations (1) and (3) revealed autocorrelated residuals. The estimation results reported are therefore based on the Hildreth-Lu procedure.

16. Normally, we want to minimize the Akaike's Information Criterion (AIC) [AIC =(-2/t) times(the log of the likelihood adjusted for degrees of freedom), where t is the number of observations] which is the natural log of the likelihood adjusted for degrees of freedom. SORITEC, the regression package used here, produces a modified version of the AIC wherein maximum absolute AIC is preferred.

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TABLE 1. THREE MEASURES OF TOTAL FACTOR PRODUCTIVITY GROWTH.

Statistic	Tornqvist Index TFPG1	τ=t TFPG2	τ=Arctan (t-z) TFPG3
Mean	.139	-.831	-.163
Standard Deviation	.128	.411	.284
Minimum	-.147	-2.388	-.710
Maximum	.609	-.267	.745

Observation Number	Year	-------------------Pattern of Signs------------------- Neg.	Pos.	Neg.	Pos.	Neg.	Pos.
2	1973	-0-	15	15	-0-	15	-0-
3	1974	-0-	15	15	-0-	15	-0-
4	1975	-0-	15	15	-0-	15	-0-
5	1976	4	11	15	-0-	15	-0-
6	1977	10	5	15	-0-	12	3
7	1978	-0-	15	15	-0-	8	7
8	1979	-0-	15	15	-0-	6	9
9	1980	-0-	15	15	-0-	2	13
10	1981	-0-	15	15	-0-	0	15

TABLE 2A. ESTIMATION RESULTS. TORNQVIST-DIVISIA INDEX MEASURE OF PRODUCTIVITY GROWTH AND RESEARCH AND DEVELOPMENT (STANDARD ERRORS IN PARENTHESES).

Dependent Variable	Intercept	RI/Q	AC	NK/Q	Rho	SE	$\bar{R}^2$	$\tilde{R}^2$	DW	AIC	F	LNL
TFPG1	-.077 (.016)	-1.472 (.873)			-.15 (.345)	.1881	.028	.529	1.92	28.22	4.479	30.22
TFPG1	-.781 (.532)		.045 (.034)		-.10 (.469)	.1890	.019	.525	1.98	27.63	3.277	29.63
TFPG1	-.703 (.519)	-1.424 (.873)	.040 (.034)		-.15 (.345)	.1877	.032	.535	1.92	27.45	2.976	30.45
TFPG1	-.432 (.352)	-.713 (.575)	.024 (.023)	-.060 (.006)	-.40 (.131)	.1450	.432	.725	2.02	57.47	30.054	61.47

Variables are defined in text. Estimation based on the Hildreth-Lu technique. SE denotes standard error of regression, DW denotes Durbin Watson statistic, AIC denotes a modified Akaike information criterion, and LNL dentoes the log of the likelihood function. N=120, and $\tilde{R}^2$ is based on the transformed model. The adjusted R^2 is denoted $\bar{R}^2$. The critical value of the Durbin Watson at 5% significance, k'=1: L=1.680, U=1.767; k'=2: L=1.663, U=1.733; ln'=3:L=1.645, U=1.751.

TABLE 2B. ESTIMATION RESULTS. OHTA MEASURE (s = t) OF PRODUCTIVITY GROWTH AND RESEARCH AND DEVELOPMENT (STANDARD ERRORS IN PARENTHESES).

Dependent Variable	Intercept	RI/Q	AC	NK/Q	Rho	SE	$\bar{R}^2$	$\tilde{R}^2$	DW	AIC	F	LNL
TFPG2	.042 (.011)	.027 (.062)			.95 (.019)	.0059	.993	-.768	1.54	443.73	16850	445.73
TFPG2	.397 (.139)		.003 (.001)		.95 (.019)	.0056	.994	-.615	1.49	449.17	18462	451.17
TFPG2	.396 (.014)	.033 (.059)	.003 (.001)		.95 (.019)	.0057	.994	-.611	1.50	447.82	9177	450.82
TFPG2	.392 (.014)	.020 (.058)	.003 (.001)	.001 (.0004)	.95 (.019)	.0055	.994	-.521	1.61	449.74	6426	453.74

See Table 2a for footnotes.

TABLE 2C. ESTIMATION RESULTS. OHTA MEASURE (s = ARCTAN (t - z) OF PRODUCTIVITY GROWTH AND RESEARCH AND DEVELOPMENT (STANDARD ERRORS IN PARENTHESES).

Dependent Variable	Intercept	RI/Q	AC	NK/Q	Rho	SE	$\bar{R}^2$	$\tilde{R}^2$	DW	AIC	F	LNL
TFPG3	.415 (.043)	.570 (.243)			.95 (.019)	.023	.919	.074	1.82	279.62	1348	281.62
TFPG3	.231 (.052)		.016 (.003)		.95 (.019)	.021	.933	.240	2.28	291.44	1667	293.44
TFPG3	-.088 (.044)	.703 (.209)	.018 (.003)		.90 (.028)	.020	.939	.306	2.28	295.36	910	298.36
TFPG3	-.101 (.042)	.641 (.202)	.019 (.003)	.005 (.001)	.90 (.028)	.019	.943	.364	2.40	299.16	661	303.16

See Table 2a for footnotes.

Appendix

Consider the production function for a plant with a single input X, and a single output Q, operating in period t as:

$$Q = F^1 (X), \tag{1}$$

or the maximum under the technology F^1. This plant is operating at the frontier of technical efficiency as Farrell[1957] has observed. In Figure 1, this situation is represented by point A on the curve F^1. Note that this is a static model.

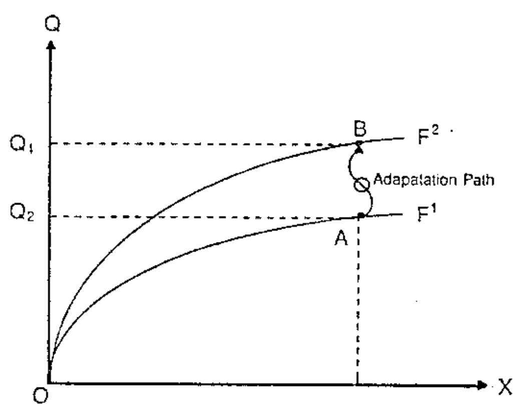

Fig. 1. Technical change, the production function, and the adaptation path.

Now, with the installation of the new technology, the production frontier shifts (assuming technical progress) to F^2 [R.M. Solow, 1957]. We assume that after the firm makes the necessary changes in its machinery and equipment capital to allow it to achieve F^2, it must then learn how to efficiently use the technology.[1]. The graphical depiction is the movement from point A to point B on F^2; this is labeled an adaptation path.[2]

The problem of modeling this change has been addressed in earlier studies by making the model dynamic through the inclusion of a time variable to account for the change in the level of technology.[3] Yet the time variable is probably an unsuitable proxy for technical change; for one thing, it assumes that technical knowledge grows linearly. This time proxy also ignores the literature on learning.[4] It also is serving as a proxy for both kinds of technical change, adoption and adaptation. Without further technical apparatus, the inclusion of time as a proxy for technology may also implicitly presume that firms are always at their long-run cost minimization point; that is, always on the frontier. Arrow [1962] condemned trend projections (the use of time to model technical change) as "a confession of ignorance and what is worse from a practical viewpoint . . . not [a] policy variables[s]."[5]

Appendix Notes

1. Theoretically, the stock of capital associated with the new technology may also differ from that of the old technology in another important aspect, that of raw materials and work-in-process inventories. In this study, we lack the appropriate data to determine the exact differences in the raw and intermediate materials inputs under the old and the new technologies. A perusal of the technical literature suggests that there are not substantive differences in the raw materials required in either process [c.f. the Encyclopedia of Chemical Technology, 1977]. Therefore we adopt the usual practice of using the stock of capital and the output of the final product to proxy for this omission.

2. The adaptation cost is not to be confused with the Eisner and Strotz [1963] concept of adjustment cost. The latter is a cost which accompanies the installation of the new quasi-fixed inputs.

3. See Binswanger, H.P., "The Measurement of Technical Change Biases with Many Factors of Production." The American Economic Review 1974. 7:964-76 and Helliwell, J.F. Aggregate Investment. 1976 Penguin: Middlesex, England.

4. See Ross, David, R. "Learning to Dominate," Journal of Industrial Economics, 1986 34:337-353.

5. Arrow, K. J., "The Economic Implication of Learning by Doing." Review of Economic Studies 1962, 29:156.