TECHNICAL PROGRESS AND STRUCTURAL EFFICIENCY OF SWEDISH DAIRY PLANTS*

Finn R Førsund and Lennart Hjalmarsson
University of Oslo IUI, Stockholm

SUMMARY

Technical change is estimated within a frontier production function allowing neutrally variable scale elasticity. To facilitate an analysis of structural change an average function is also estimated.

The results give little support for a hypothesis of neutral technical progress but rather a pattern of technical progress due to labour saving technical change increasing marginal productivity of capital relative to labour. The comparison between best-practice and average practice estimates also reveals an increased difference between best-practice and average practice techniques.

Numerical measures of the distance between best-practice and average practice are computed. Moreover, Salter's measures of bias and technical advance are also generalized and computed.

---

* Paper presented on the international colloquium on Capital in the Production Function at Paris X - Nanterre Novembre 18-20,1976.

We wish to thank H.J. Bakke and R. Teige for valuable programming and computational assistance.

Earlier versions have been presented at the Nordic Meeting of economists, Marstrand, May 1976, and at the Econometric Society European Meeting in Helsinki, August 1976.

The present version has benefitted from comments received at the Nanterre colloquium.

1. INTRODUCTION

The purpose of this paper is to put forward some results from a research project in industrial structure and structural change (in the spirit of Johansen [1972]) based on time series data from Swedish dairy plants.

To bring out the structure of the industry both average, (AP), and bets-practice, (BP), production functions are estimated. The use of combined cross-section - time-series data allows investigating technical change both for the AP and the BP functions. (In the literature (as far as we know) no explicit attempt to estimate technical change within a frontier function has been made (see e.g. Aigner & Chu [1968], Carlsson [1972], Timmer [1971]). The functional form chosen is the homothetic function, which permits the study of scale economies. (The programming estimation method of Aigner & Chu [1968] is generalized to handle this specification.)

2. ESTIMATION OF BEST PRACTICE FUNCTIONS

When estimating frontier functions three general approaches are found in the literature (see Johansen [1972] chapter 8 for a critical evaluation of some of the approaches): i) utilizing the whole sample, but restricting the observed points in the output-input space to be on or below the frontier, ii) eliminating "inefficient" observations and estimating an "average" frontier function from the subset of efficient points, iii) allowing some observations to be above the frontier either by eliminating a certain percentage of the most efficient observations (fitting a "probabilistic" frontier à la Timmer [1971]) or specify both an efficiency distribution proper and pure random variation of efficiency (see Meeusen & van den Broeck [1976]).

We will here utilize approach i) and generalize the programming method in Aigner & Chu [1968] to allow for neutrally variable returns to scale.

The best-practice production function is pre-specified to be a homothetic function of the general form

$$G(x) = g(v,t), \qquad (1)$$

where x = rate of output (single ware production), v = vector of inputs, G(x) a monotonically increasing function, and g(v,t) homogeneous of degree 1 in v.

As regards the generation of the actual data several schemes can be envisaged. One hypothesis is that the production structure is of the putty-clay type (Johansen [1972]) with simple Leontief (limitational) ex post functions. To simulate the actual performance of plants an efficiency term with respect to the utilization of the inputs distributed in the interval (0,1) can be introduced multiplicatively on the r.h.s. of Eq. (1). We will adopt this scheme and in addition assume that the plants are operated on the "efficient corners" of the isoquants. Ex post the plant managers can only choose the rate of capacity utilization. With these assumptions concern about "slack" in fulfilling marginal conditions with respect to inputs is not relevant.

As regards the estimation procedure a key question is whether a specific distribution of the efficiency terms is assumed or not. If sufficient information is available to postulate a specific distribution the natural procedure is to derive maximum likelihood estimates as pointed out in Afriat [1972]. Without a specific efficiency distribution there are several ways to formulate the estimation problem as analyzed in Afriat [1972]. In this paper we will follow this latter approach. (Specific efficiency distributions will be pursued in a forthcoming paper.)

A natural objective -- with the information available -- is that the observations should be close to the frontier in some sense. In order to keep the estimation problem as simple as possible it is here chosen to minimize the simple sum of deviations from the frontier with respect to input utilization after logarithmic transformation, subject to on or below frontier constraints.

As regards the form of the production function the following specification is employed (below called the Zellner-Revankar, Z/R, specification, cf. Zellner-Revankar [1969]):

$$x^{\alpha} e^{\beta x} = A e^{\gamma_3 t} \cdot \prod_j v_j^{a_j + \gamma_j t} \qquad (2)$$

Technical change is accounted for by specifying the possibility of changes in the constant term, A and the kernel elasticities, a_j for labour, L, and capital, K. With this specification the estimation problem turns out to be a standard linear programming problem. The objective function to be maximized becomes:

$$\sum_{t=0}^{T} \sum_{i=1}^{n} \{\beta \cdot x_i(t) + \alpha \cdot \ln x_i(t) - \ln A - \gamma_3 t$$
$$- (a_1 - \gamma_1 t) \ln L_i(t) - (a_2 + \gamma_2 t) \cdot \ln K_i(t)\} \qquad (3)$$

The signs of the trends are preselected to the most probable signs. (This is unnecessary from a LP-technical point of view.) Note that although the objective function is linear in all the unknown parameters, the specification yields satisfactory flexibility as regards technical change.

The reader should observe that this is a deterministic calculation of the frontier. Its calculated parameters cannot be given a traditional stochastic interpretation.

Concerning the constraints of the LP-model, the expression within the brackets in (3) constitutes (T+1)·n constraints securing the observed input points to be on or below the frontier:

$$\beta \cdot x_i(t) + \alpha \cdot \ln x_i(t) - \ln A - \gamma_3 t - (a_1 - \gamma_1 t) \cdot \ln L_i(t)$$
$$- (a_2 + \gamma_2 t) \cdot \ln K_i(t) \leqq 0; \quad i=1,\ldots,n;\ t=0,\ldots,T. \qquad (4)$$

In addition, we have the homogeneity constraint

$$\sum_j a_j(0) = 1. \qquad (5)$$

Since there are only two trends in the kernel function Eq. (5) implies the restriction:

$$-\gamma_1 t + \gamma_2 t = 0; \qquad t = 1, \dots, T \qquad (6)$$

In addition, we want the kernel elasticities including trends to be restricted to the interval (0,1):

$$a_1 - \gamma_1 \cdot T \geqq 0 \qquad (7)$$

$$a_2 + \gamma_2 \cdot T \leqq 1 \qquad (8)$$

Finally we have the restrictions

$$\beta, \alpha, a_1, a_2, \gamma_1, \gamma_2, \gamma_3 \geqq 0 \qquad (9)$$

(Note that ln A is not restricted to non negative values.)

3. THE ESTIMATION OF THE AVERAGE FUNCTION

With the assumptions adopted in this paper some care must be taken concerning the interpretation of an average function. It serves here only the function of giving an "average" picture of the ex post relationship between inputs and outputs across plants operating with different fixed input coefficients and capacity levels. The average function is specified to have the same functional form as the best-practice function shown in Eq. (2). (Note that the scale function is assumed to be unchanged over time.) This facilitates an analysis of structural change, but it must be noted that such an AP-specification must only be interpreted as convenient approximation to the actual relationship generated by adding new capacity according to the estimated BP-function.

As regards the estimation procedure we now start out with the assumption that deviations from the average function are simulated by introducing a random variable N(0,σ), replacing the efficiency term in the BP-function. Maximum likelihood estimates are then obtained by using the adapted non-linear Box & Cox [1964] method outlined in Førsund [1974]. The essence of the method is to estimate the parameters on the r.h.s. of Eq. (2) after logarithmic transformation by OLS for trial values of α and β until a maximum of the likelihood function in question is reached.

4. THE DATA

In the empirical part of this study we have utilized primary data for 28 individual dairy plants during the period 1964-73. We have received all data from SMR (Svenska mejeriernas riksförening), a central service organization for the dairies in Sweden.

The milk production process can be divided into two stages: general milk processing, and packaging. The data refer to the first important stage in the milk production process, namely general milk processing. It includes the reception from cans or tanks of all milk, its storage and processing including pasteurizing and separation. Normally this stage defines the capacity of the plant. It is often treated as a separate unit by dairy engineers when discussing e.g. economies of scale and other aspects of costs.

Milk is regarded as a homogeneous product which is a very realistic assumption (in a very literal sense; milk is homogenized). Thus output is measured in tons of milk delivered to the plant each year. The amount of milk received is equal to the amount produced. There is no measurable waste of milk at this stage. According to SMR any difference is due to measurement errors. (Differences were of the magnitude of kilos.)

The labour input variable is defined as the hours worked by production workers including technical staff usually consisting of one engineer.

Capital data of buildings and machines are of the user-cost type, including depreciation based on current replacement cost, cost of maintenance and rate of interest. They have been centrally accounted for by SMR according to the same principles for all plants and after regularly capital inventory and revaluations of engineers from SMR. Note that this capital measure is proportional to the replacement value of capital, which can serve as a measure of the volume of capital, (see Johansen & Sørsveen [1967]). As regards the central question of capacity utilization we have investigated a measure based on the monthly maximum amount of milk received compared with the yearly average. This ratio is fairly stable for each plant over time, and the differences between plants are not very great. In consequence we have not corrected for capacity utilization. The increasing output over time for most of the plants supports the assumption.

5. THE EMPIRICAL RESULTS

The estimates of the parameters of the frontier and average production function are shown in Table 1 and the figures below. As the table reveals the trends in the marginal elasticities are important. In best-practice the trend in A is zero but becomes negative in average practice. Optimal scale obtains a considerably higher value in average practice than in best practice. The output of the largest plant has been in the interval 111 000 - 141 000 tons in the period 1964-73, except 1965 when it was 77 000, while the average output has increased from 29 000 to 39 000 tons. Taking our results at face value there are gains to be riped by increasing the average size of plants, but the gains are exaggerated by the average function.

Table 1. Estimates of the best-practice and the average practice production function. Combined time-series cross-section analysis. Estimates of the parameters of the production function

$$x^{\alpha}e^{\beta x} = Ae^{\gamma_3 t} L^{(a_1-\gamma_1 t)} \cdot K^{(a_2+\gamma_2 t)}$$

(t = 0 in 1964, t = 9 in 1973)

	Constant term ln A	Trend A $\gamma_3 \cdot 10^2$	Labour elasticity $a_1-\gamma_1 t$ 1964	Labour elasticity $a_1-\gamma_1 t$ 1973	Trend L $\gamma_1 \cdot 10^2$ $=\gamma_2 \cdot 10^2$	Capital elasticity $a_2+\gamma_2 t$ 1964	Capital elasticity $a_2+\gamma_2 t$ 1973	α	$\beta \cdot 10^5$	Optimal scale tonnes
Best practice	-8.17	0	.70	.41	3.14	.30	.59	.13	1.7	52 122
Average practice	-3.14	-6.83	.69	.37	3.62	.31	.63	.69	.40	76 610

The shape of the production functions and their development through time are shown in Fig. 1. Cutting the production functions with a vertical plane through the origin along a factor ray one obtains the classical textbook S-shaped graph of the frontier and average production function.

When assessing the somewhat surprising result above one should note the possibilities of systematic biases with the two estimation methods. Fig. 1 shows that the BP-function lies below the AP-function for small levels of output (no observations are, in fact, in this range). The BP-function is placed as close to the observations as possible, observing the on or above restrictions, including the observations of the smallest plants. The AP-function cuts through the observations of the middle range plants and lifts over the smallest while the BP-function has to be more curved in order to obey the restrictions when minimizing the sum of deviations. If engineering information could be obtained it might well turn out that it is a misspecification to allow the smallest plants to be on the frontier.

The characteristics of technical advance can also be illustrated in the input coefficient space (cf. Salter [1960] chapter 3) by the development of the technically optimal scale curve which we will call the efficiency frontier in the case of the best practice function. See Figure 2. The efficiency frontier is the locus of all points where the elasticity of scale equals one, (see Frisch [1965] chapter 8), i.e., it is a technical relationship between inputs per unit of output for production units of optimal scale. Thus the efficiency frontier represents the optimal scale of the frontier production function. (In Johansen [1972] p.21 the efficiency frontier is referred to as the technique relation.) In the input coefficient space the frontier or ex ante production function defines the feasible set of production possibilities while the technique relation defines the efficiency frontier towards the origin of this set. (This consideration has been elaborated in detail in Førsund [1971].)

In Figure 2 the labour saving bias of technical progress is reflected in the change of the optimal scale curve and the efficiency frontier. Changes of milk reception from cans to tanks and self-cleaning separators together with one storey buildings are elements of this process of technical advance, and examples of labour saving techniques.

In average practice the trend in A gets a negative sign. In spite of this Figures 1 and 2 show that the average production function shifts upwards and that the optimal scale curve moves rapidly towards the ordinate axis and the origin, even though the optimal scale function is constant.

Note also that in spite of a higher optimal scale in the average function the efficiency frontiers are strictly closer to the origin and the axis than the corresponding optimal scale curves.

A comparison between Figures 1 and 2 illustrates two different aspects of technical progress; on the one hand the development

Figure 1. The change in the frontier and average production function through time.

Combined time-series cross-section analysis. The production function cut with a vertical plane through the origin along a ray, $(\mu L^{o}, \mu K^{o})$, L^{o} = 15 000 and K^{o} = 200 000

$$x^{\alpha}e^{\beta x} = Ae^{\gamma_3 t}(\mu L^{o})^{a_1-\gamma_1 t} \cdot (\mu K^{o})^{a_2+\gamma_2 t}$$

The factor ratio corresponds to OA in Figure 2.

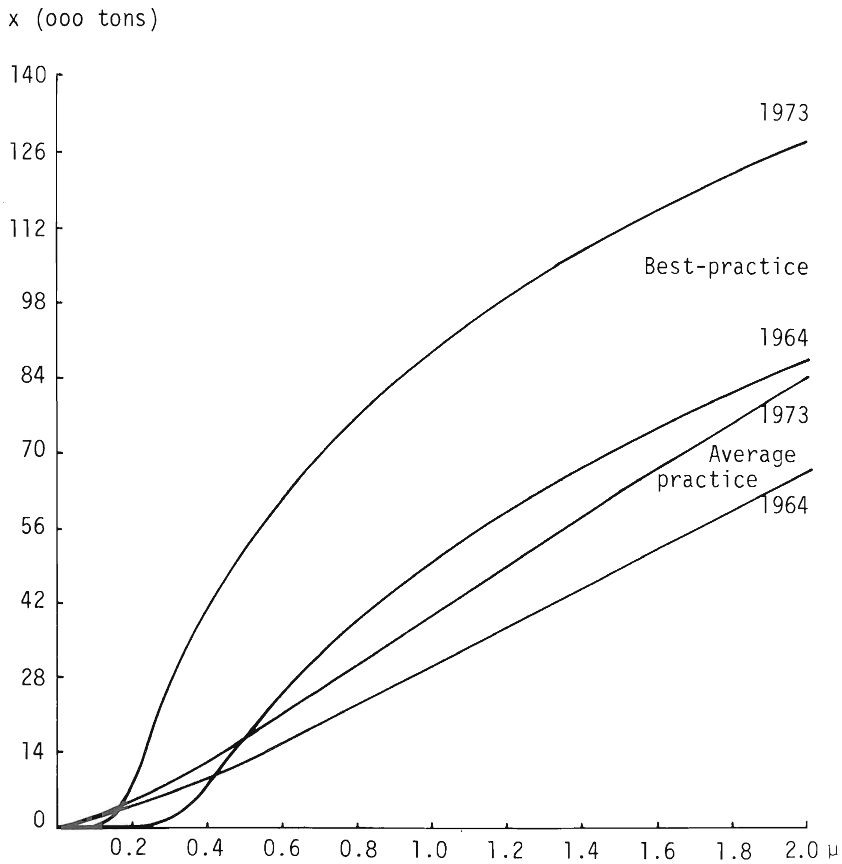


Figure 2. The changes in the efficiency frontier and the average optimal scale curve through time

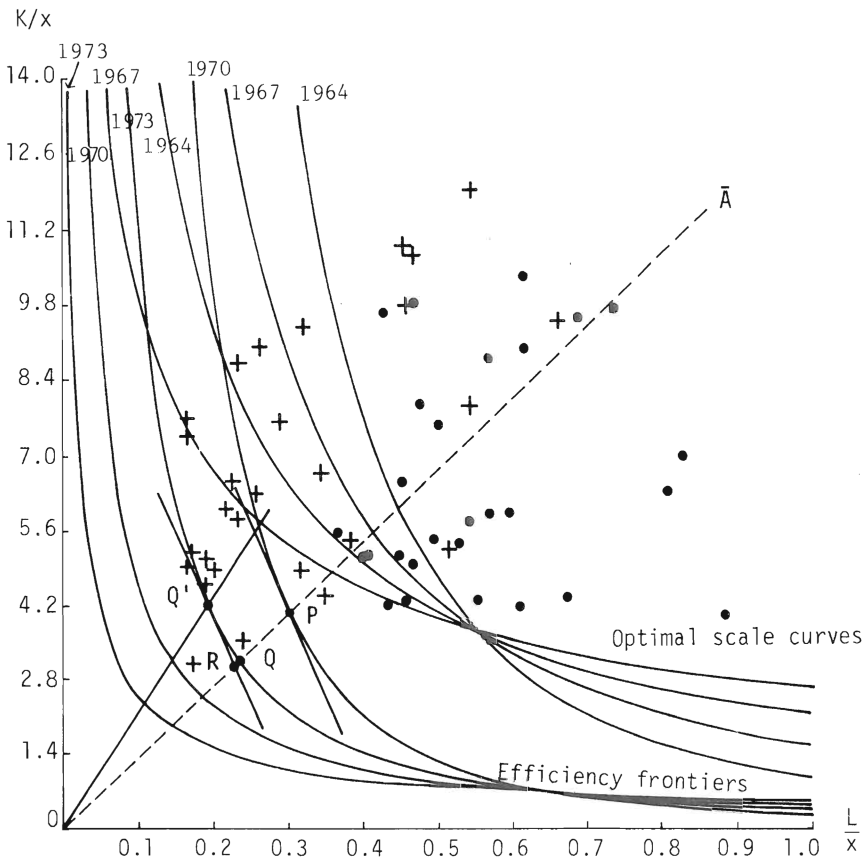
Combined time-series cross-section analysis. Estimates of the production function

$$x^{\alpha} e^{\beta x} = Ae^{\gamma_3 t} L^{(a_1-\gamma_1 t)} \cdot K^{(a_2+\gamma_2 t)}$$

with the efficiency frontier and optimal scale curve

$$\left(\frac{L}{x}\right)^{a_1-\gamma_1 t} \left(\frac{K}{x}\right)^{a_2+\gamma_2 t} \cdot Ae^{\gamma_3 t} \cdot \left(\frac{e\beta}{1-\alpha}\right)^{\alpha-1} = 1$$

The observed input coefficients for the years 1964 (dots) and 1973 (crosses) are plotted.



of the efficiency frontier and the optimal scale curve, on the other hand the development of the production function surface for a given factor ratio. While the most scale efficient plants are close to the efficiency frontiers, the best-practice production function reveals the most technically efficient plants which comprise both small and large plants, i.e., also scale inefficient plants. (These efficiency aspects will be treated in a separate paper. Se also Førsund and Hjalmarsson [1974].)

Measured along rays through the origin the distance between the efficiency frontier and the optimal scale curve has increased for all relevant factor ratios. Figure 1 also indicates that the distance between best-practice and average practice has increased during the period.

A numerical measure of the distance between best-practice and average practice can be obtained in several ways. (Førsund and Hjalmarsson [1974].) One measure utilized here is obtained by comparing the observed average output with the output obtained on the frontier function for the observed average amount of inputs. This measure can be regarded as a measure of structural efficiency and is denoted by S* and calculated according to the formula

$S^* = \frac{\bar{x}^o}{\bar{x}^*}$, where $\bar{x}^o$ is observed average production and $\bar{x}^*$ is obtained as the solution of $x^{\alpha}e^{\beta x} = A \cdot \prod_j \left(\frac{1}{n}\, \Sigma v_{ij}^o\right)^{a_j}$.

In the same way the distance between the average plant and the average function, $\bar{S}$, can be obtained.

A measure, S, which measures the distance between the frontier and average function can now be obtained by dividing S* with $\bar{S}$.

The numerical values of all three measures are presented in Table 2.

Table 2. The numerical values of S, S*, $\bar{S}$

Year	S	S*	$\bar{S}$
1964	0.60	0.61	1.01
1965	0.55	0.59	1.08
1966	0.53	0.54	1.01
1967	0.50	0.51	1.01
1968	0.54	0.51	0.95
1969	0.49	0.49	1.01
1970	0.47	0.46	0.97
1971	0.46	0.47	1.03
1972	0.42	0.47	1.12
1973	0.43	0.45	1.04

A clearly decreasing trend in the values of structural efficiency can be observed. One positive reason for this is a rapid technological progress which has increased the dispersion of the structure and the distance between the best practice and average practice techniques. All plants in the sample have survived the entire period. During the same time a lot of dairies have been closed down in Sweden. Thus the development of structural efficiency for all plants might have been another than for the set utilized here.

In order to improve the understanding of the technical change as measured in Figures 1 and 2 we will follow Salter's [1960] suggestions. He introduces three measures describing technical advance:

i) Rate of technical advance measured by the relative change in total unit cost for constant input prices;

ii) Labour- or capital saving bias measured by relative change in the optimal (cost minimizing) factor proportion for constant input prices;

iii) Relative change in the elasticity of substitution.

It might be of interest to note that the two first measures have direct connections with the overall- technical-, and price efficiency measures introduced by Farrell [1957].

When working with non-homogeneous production functions it is natural to replace the unit isoquants in Farrell's and Salter's analysis with the efficiency frontiers or scale curves shown in Figure 2. (See Førsund [1974], Førsund and Hjalmarsson [1974] for interpretations of the Farrell measures in a setting of inhomogeneous functions.) Let P in Figure 2 be the point of reference on the efficiency frontier for the base period. Q' is the point on the efficiency frontier for a later period where the marginal rate of substitution is the same. A measure analogous to the Salter measure i) above, assuming cost minimization, is then the relative change in unit cost from P to Q', i.e., the unit cost reduction possible when choosing techniques from two different ex ante functions for constant factor prices and realizing optimal scale. (In our case the optimal scale output is constant for the BP- and AP-functions.) This change is equal to OR/OP in Figure 2 which is also the Farrell overall efficiency measure for a production unit with observed input coefficients given by P relative to the next periods efficiency frontier.

The Farrell overall measure, and correspondingly the Salter technical advance measure, can be split multiplicatively into technical efficiency, OQ/OP, and price efficiency, OR/OQ. In our context this splitting shows the relative reduction in unit cost due to the movement along a factor ray and the movement along the next period efficiency frontier generated by biased technical change.

The efficiency frontiers or scale curves used here are given by

$$\xi_{2,t} = A^{-1/a_{2,t}} \, e^{-\gamma_3 t/a_{2,t}} \left(\frac{e \cdot \beta}{1-\alpha}\right)^{(1-\alpha)/a_{2,t}} \cdot \xi_{1,t}^{\;-a_{1,t}/a_{2,t}} \tag{10}$$

where $\xi_1 = L/x$ and $\xi_2 = K/x$. The marginal rate of substitution MRS, for this function is equal to the MRS for the production function and equal to

$$\frac{-d\xi_{2,t}}{d\xi_{1,t}} = \frac{a_{1,t}}{a_{2,t}} \cdot \frac{\xi_{2,t}}{\xi_{1,t}} \tag{11}$$

Salter's measure of bias is, in general:

$$D_{21} = \frac{\xi_{2,t+1}/\xi_{1,t+1}}{\xi_{2,t}/\xi_{1,t}} \tag{12}$$

when keeping factor prices constant, or equivalently, keeping the MRS constant. We then get:

$$\frac{a_{1,t}}{a_{2,t}} \, \frac{\xi_{2,t}}{\xi_{1,t}} = \frac{a_{1,t+1}}{a_{2,t+1}} \, \frac{\xi_{2,t+1}}{\xi_{1,t+1}} \text{ , i.e.}$$

$$\frac{\xi_{2,t+1}/\xi_{1,t+1}}{\xi_{2,t}/\xi_{1,t}} = \frac{a_{1,t}/a_{2,t}}{a_{1,t+1}/a_{2,t+1}} \, . \tag{13}$$

Since the elasticity of substitution is constant and equal to 1 the relative change in the factor ratio (the MRS being constant) is equal to the relative change in the MRS for a constant factor ratio, $b = \xi_2/\xi_1$:

$$\frac{MRS_t}{MRS_{t+1}} = \frac{a_{1,t}}{a_{2,t}} \cdot b \Bigg/ \frac{a_{1,t+1}}{a_{2,t+1}} \cdot b = \frac{a_{1,t}/a_{2,t}}{a_{1,t+1}/a_{2,t+1}} \, . \tag{14}$$

Note that the bias measure is here independent of the price- or factor ratio chosen.

The Salter technical advance measure, choosing the Laspeyre version for convenience, becomes:

$$T = \left(\xi_{1,t+1} + \xi_{2,t+1}\left(\frac{\partial x/\partial K_t}{\partial x/\partial L_t}\right)\right) \Big/ \left(\xi_{1,t}+\xi_{2,t}\left(\frac{\partial x/\partial K_t}{\partial x/\partial L_t}\right)\right) = \frac{\xi_{1,t+1}}{\xi_{1,t}} \cdot \frac{a_{1,t}}{a_{1,t+1}} \quad (15)$$

utilizing that $MRS_t = MRS_{t+1}$ and that the kernel function is homogeneous of degree 1. We find it more convenient here to start out from a given factor ratio, $b = \xi_2/\xi_1$, rather than a price ratio. (This is, of course, equivalent.) From (10) we then have

$$\xi_{1,t} = b^{-a_{2,t}} A^{-1} e^{-\gamma_3 t} \left(\frac{e\beta}{1-\alpha}\right)^{1-\alpha} \quad (16)$$

where b is the chosen factor ratio. Remembering (13) yields

$$\xi_{1,t+1} = (D_{21} \cdot b)^{-a_{2,t+1}} A^{-1} e^{-\gamma_3 (t+1)} \left(\frac{e\beta}{1-\alpha}\right)^{1-\alpha} \quad (17)$$

Inserting (16) and (17) in (15) introducing $a_{1,t} = a_1-\gamma_1 t$, $a_{2,t} = a_2+\gamma_2 t$ yields

$$T = e^{-\gamma_3} b^{-\gamma_2} D_{21}^{-a_2-\gamma_2(t+1)} \cdot \frac{a_1-\gamma_1 t}{a_1-\gamma_1(t+1)} \, . \quad (18)$$

The relative unit cost reduction due to a movement along a factor ray (Farrell technical efficiency) is

$$(\xi_{1,t+1}/\xi_{1,t})_{b=\text{const.}} = e^{-\gamma_3} b^{-\gamma_2} \quad (19)$$

The price- or allocative efficiency measure must then be

$$D_{21}^{-a_2-\gamma_2(t+1)} \cdot \frac{a_1-\gamma_1 t}{a_1-\gamma_1(t+1)} \, . \quad (20)$$

We see the close connection between the relative unit cost reduction due to the bias and the Salter bias measure with our functional specification. The "pure movement" measure, OQ/OP, is here independent of time, but depends on the chosen factor ratio (relative factor prices) and the trend parameters, while the bias gain measure, OR/OQ, is independent of the factor ratio (relative factor prices), but depends on time and the bias trend parameter.

The various measures corresponding to the estimates reported in Table 1 are set out below.

Table 3. Characterization of technical change by the movements of the efficiency frontiers and optimal scale curves,[a] Salter measures and Farrell-inspired splitting-up
Factor ratio b = 13.33 corresponding to OA in Figure 2

Type of measure	AP		BP	
	1964-65	1972-73	1964-65	1972-73
Technical advance:				
Overall relative change in unit cost on optimal scale	.9719	.9722	.9198	.9200
Proportionate unit cost change	.9749	.9749	.9219	.9219
Bias unit cost change	.9970	.9972	.9977	.9980
Labour saving bias:				
Relative change in capital-labour ratio	1.1786	1.1658	1.1565	1.1365

[a] Note that since we operate with constant scale functions the measures in Table 3 are independent of the output level chosen.

The splitting-up of the total reduction in unit cost reveals that although the yearly optimal increase of the capital-labour ratio is about 17 % for the AP- and 15 % for the BP-function this change yields minimal cost reductions, .3 to .2 %. It is the displacement of the frontier towards the origin as measured along a factor ray (Farrell technical efficiency of the past technology relative to the present) that results in significant reductions in unit costs; about 3 % for the AP- and 8 % for the BP-function. The AP-function has a somewhat stronger labour saving bias and a markedly slower displacement of the optimal scale curve towards the origin than the BP-function.

One possible economic explanation of this sustained difference is that the total capacity of the sector has been increasing, at a yearly average of 3.34 % only, implying an investment growth rate too small to update average sector performance in pace with best-practice performance.

Another explanation might be that technical progress is overestimated by the frontier function during the last years of the period because we have assumed constant trends during the whole period. (The development of the marginal elasticities must be broken sooner or later as the values are restricted to the interval (0,1). During the whole period five plants is on the frontier, two year 0, one year 1, one year 4 and one year 8. Thus in the last year no plant is on the frontier and the slacks show that the distance to the nearest plant is relatively large. On the other hand the next last year one plant is on the frontier.

REFERENCES

Afriat. S.N. ,1972, "Efficiency Estimation of Production Functions". International Economic Review, 13(3), October, pp.568-598.

Aigner, O.J. and Chu, S.F., 1968, "On Estimating the Industry Production Function". American Economic Review, 58(4), pp. 226-239.

Box, G.E.P. and Cox, D.R., 1964, "An Analysis of Transformation". Journal of the Royal Statistical Society, (Series B), 26(2), 211-245.

Carlsson, B., 1972, "The Measurement of Efficiency in Production: An Application to Swedish Manufacturing Industries 1968". Swedish Journal of Economics, 74(4), pp.468-485.

Farrell, M.J., 1957, "The Measurement of Productive Efficiency". Journal of the Royal Statistical Society, Series A (General), Part III, 120, pp.253-290.

Frisch, R., 1965, Theory of Production. D. Reidl Publishing Co. Dordrecht-Holland.

Førsund, F.R., 1971, "A note on the technically optimal scale in inhomogeneous production functions". Swedish Journal of Economics, 73(2), pp.225-240.

Førsund, F.R., 1974, "Studies in neoclassical theory of production". Memorandum from the Institute of Economics, University of Oslo, February 4.

Førsund, F.R., 1975, "The Homothetic Production Function". Swedish Journal of Economics, 77(2), pp.234-244.

Førsund, F.R. and Hjalmarsson, L., 1974, "On the Measurement of Productive Efficiency". Swedish Journal of Economics, 76(2), pp.141-154.

Johansen, L. and Sørsveen, Å., 1967, "Notes on the measurement of real capital in relation to economic planning models". The Review of Income and Wealth, 13(2), June, pp.175-197.

Johansen, L., 1972, Production Functions, North,Holland, Amsterdam.

Meeusen, W. and van den Broeck, J., 1976, Efficiency estimation from Cobb-Douglas production functions with composed error. Paper presented at the European Meeting of the Econometric Society, Helsinki.

Salter, W.E.G., 1960, Productivity and Technical Change. University Press, Cambridge.

Timmer, C.P., 1971, "Using a Probabilistic Frontier Production Function to Measure Technical Efficiency". Journal of Political Economy, 79(4), pp.776-794.

Zellner, A. and Revankar, N.S., 1969, "Generalized Production Functions". Review of Economic Studies, 36(2), April pp.241-250.