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PRODUCTIVITY GROWTH IN THE PAPER AND PAPERBOARD INDUSTRIES : A VARIABLE COST FUNCTION APPROACH*

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Abstract

In this paper we use a simplified translog cost model to study the pattern of productivity growth in the U.S. paper and paperboard industries. For the paper industry average growth rates over the period 1958 - 1981 were estimated to be 3 - 4 %, whereas productivity in the paperboard sector increased at an average rate of only 1 %. The time path of growth was quite similar in the two industries.

In the process of calculating measures of total factor productivity, we also derive information concerning economies of scale, input price elasticities and elasticities of factor substitution.

0. Introduction

The purpose of this paper is to develop indices of productivity growth for the paper and paperboard industries in the U.S. Given the importance of productivity measures in evaluating industrial performance, it is somewhat surprising that the construction of reliable indices has not yet received the attention it deserves. Moreover, if one realizes the necessity of accurate productivity growth figures for long-term planning of capacity expansion and as an essential input in labor contract negotiations, it becomes clear that the development of better measures of technological improvements is important.

Solow (1957) defined productivity growth as the shift in the production function over time, as distinguished from movements along this function. It measures the improvements in the efficiency with which an industry transforms its production factors into output. Solow proposes a method to calculate technological progress, which has been applied to the Canadian pulp and paper industry by Manning and Thornburn (1971). Despite its clear definition, however, many studies have measured productivity as output for unit of input, see e.g., Abramovitz (1962) and Buongiorno _et al_. (1981). This type of measure, although expedient, is unacceptable as an approximation to the change in total factor productivity, because it focuses on a single factor of production (e.g., labor) and ignores the importance of factor substitution over time. If labor has been substituted for capital over time then the use of an index of labor productivity overestimates the true increase in total factor productivity.

A major methodological step forward was a paper by Jorgensen and Griliches (1967). They showed how to derive indices of technological change from the production function under the assumptions of constant returns to scale and marginal cost pricing. Although these competitive conditions may be useful approximations to the observed behavior of many industries, it is desirable to construct measures of productivity growth that do not impose these restrictions a priori. A powerful alternative that relaxes these severe assumptions was recently proposed by Caves, Christensen and Swanson (1980, 1981). The indices they develop are derived from a very general and flexible specification of the production and cost structure. No restrictions concerning the nature of scale economies, substitution elasticities, seperability etc. are imposed a priori. Moreover, their procedures allow for nonneutral technological change without complicating the analysis. A final advantage of the methodology is that indices of productivity growth can be derived under different scenarios concerning the economic behavior of the industry under investigation.

Several recent papers of the forest products industries have measured the factor bias implied by productivity growth. Greber and White (1982) e.g., apply the methodology developed by Sato (1970) and Batavia (1979) to study technical change in the U.S. lumber and wood products industry. Papers by Stier (1980, 1984) use estimates of a translog cost function to calculate the technological change bias as suggested by Binswanger (1974). Our paper differs from previous research in that we consider the construction of explicit indices of productivity growth. Although we have to impose some restrictions on the cost function estimated for the purpose of this study in order to avoid severe statistical problems, we closely follow the procedures suggested by Caves et al. (1981).

Organization of the paper is as follows. In a first section we present the theoretical derivations that lead to operational formulas for two different, but closely related, definitions of productivity growth. Evaluation of the derived measures requires the estimation of a flexible variable cost function. The specification chosen was a simplification of the more general translog model. It is discussed in Section 2. A third section contains a description of the data used. In Section 4 we present the estimation results for both the paper and paperboard industries and analyze the economic properties implied by the cost functions.[1] Calculated productivity growth rates and associated indices of technological change are given in Section 5. A final section reviews the major findings of this study.

1. Productivity measurement: methodology

In this section we show how productivity indices can be constructed for the paper and paperboard industries using estimates of cost functions for these industries. Although productivity growth rates may be derived both from the total and variable cost functions, we have chosen the latter approach in this paper for two reasons. First, it is easier to find accurate variable cost figures than reliable indicators of total costs, since the second case usually requires quite arbitrary assumptions concerning the distribution of capital costs over time. Secondly, an estimated variable cost function provides all the necessary information for the calculation of productivity measures without imposing the assumption of total cost minimization on the firms in the industries under consideration.[2]

Assume that each industry produces a single output (Q) and uses three variable inputs, labor (L), energy (E) and materials (M) in addition to a factor of production (K) which is fixed in the short run. The latter is usually described as 'capital stock' in the literature. The transformation function corresponding to the production process can be written as

$$F(Q, L, E, M, K, t) = 0 \qquad (1)$$

where t is time. This variable is included to account for technological shifts in the production function that cannot be attributed to input variations. Differentiating (1) yields

$$F_{\overline{Q}}\, d\overline{Q} + F_{\overline{L}}\, d\overline{L} + F_{\overline{E}}\, d\overline{E} + F_{\overline{M}}\, d\overline{M} + F_{\overline{K}}\, d\overline{K} + F_t\, dt = 0 \qquad (2)$$

where F_x is the partial derivative of the transformation function with respect to x and $\overline{x} = \ell n\ x$.

We will use two definitions of productivity growth that have recently been proposed by Caves _et_ _al_. (1981). A first growth rate (P1) measures the rate at which output can grow over time when holding the quantities of all inputs constant. Applying the definition and using (2) it follows

$$P1 = -\frac{F_t}{F_{\overline{Q}}} \qquad (3)$$

An alternative definition is to consider the common rate at which all inputs can be reduced over time with output held at a constant level. This second index, P2, is easily calculated to be

$$P2 = \frac{F_t}{F_{\overline{L}} + F_{\overline{E}} + F_{\overline{M}} + F_{\overline{K}}} \qquad (4)$$

Although both P1 and P2 correspond to valid definitions of productivity growth, the former seems to be more intuitive in the case of single output industries. It is interesting to note that the two measures will only give the same result if the industry under investigation operates under constant returns to scale. To see this, remember that the degree of returns to scale (R) has been defined in the literature as the proportional growth in output due to a proportional increase in all inputs. Holding time fixed and again using (2) we find

$$R = -\frac{F_{\overline{L}} + F_{\overline{E}} + F_{\overline{M}} + F_{\overline{K}}}{F_{\overline{Q}}} \qquad (5)$$

It is obvious that P1 = R P2 so that P1 = P2 if and only if R = 1.

If we assume that firms minimize variable costs subject to a well-behaved technology then a variable cost function exists, giving minimum variable costs required in order to produce a specified output level at observed factor prices for the variable inputs and for a given value of the fixed factor.[3]

$$C_V\ (Q,\ f_L,\ f_E,\ f_M,\ K,\ t)$$

where f_i is the factor price for input i. We now express the productivity measures P1 and P2 in terms of elasticities of the cost function. Noting that C_V is the result of minimizing variable costs subject to the transformation function (1) and using the envelope theorem, we derive after some algebra the following relations.[4]

$$\frac{\partial\ \ell n\ C_V}{\partial\ \ell n\ Q} = - \frac{F_{\bar{Q}}}{F_{\bar{L}} + F_{\bar{E}} + F_{\bar{M}}} \tag{6}$$

$$\frac{\partial\ \ell n\ C_V}{\partial\ \ell n\ K} = - \frac{F_{\bar{K}}}{F_{\bar{L}} + F_{\bar{E}} + F_{\bar{M}}} \tag{7}$$

$$\frac{\partial\ \ell n\ C_V}{\partial\ t} = - \frac{F_t}{F_{\bar{L}} + F_{\bar{E}} + F_{\bar{M}}} \tag{8}$$

By proper manipulation of relations (3), (4), (6), (7) and (8) we finally derive[5]

$$P1 = \frac{-\dfrac{\partial\ \ell n\ C_V}{\partial\ t}}{\dfrac{\partial\ \ell n\ C_V}{\partial\ \ell n\ Q}} \tag{9}$$

$$P2 = \frac{-\dfrac{\partial\ \ell n\ C_V}{\partial\ t}}{1 - \dfrac{\partial\ \ell n\ C_V}{\partial\ \ell n\ K}} \tag{10}$$

The expressions (9) and (10) can be used to calculate growth rates of productivity using estimates of a variable cost function. Also observe that analagous reasoning may be used to prove the fact that

$$R = \frac{1 - \frac{\partial \ln C_V}{\partial \ln K}}{\frac{\partial \ln C_V}{\partial \ln Q}} \tag{11}$$

2. A variable cost model for the paper and paperboard industries

In this section we discuss the properties of the variable cost function estimated for the purpose of this paper. A simplified translog model was chosen for estimation. As our data consisted of time series and many of the explanatory variables -- including output, time and factor prices -- were trended it seemed inappropriate to specify a general translog model. It is well documented in the literature that the use of time series data leads to severe multicollinearity problems. Moreover, if no additional structure is imposed on the model it may be impossible to distinguish economies of scale from technological change, see Fuss and Waverman (1978).[6] To avoid these problems as much as possible we imposed homotheticity and homogeneity on the cost function. More specifically, the following function was estimated:

$$\begin{aligned} \ln C_V = {} & \alpha_0 + \alpha_Q (\ln Q) + \beta_L(\ln f_L) + \beta_E(\ln f_E) + \beta_M(\ln f_M) + \tfrac{1}{2} \gamma_{LL} (\ln f_L)^2 \\ & + \tfrac{1}{2} \gamma_{EE} (\ln f_E)^2 + \tfrac{1}{2} \gamma_{MM} (\ln f_M)^2 + \gamma_{LE} (\ln f_L \ln f_E) \\ & + \gamma_{LM} (\ln f_L \ln f_M) + \gamma_{EM} (\ln f_E \ln f_M) + \delta_K (\ln K) \\ & + \delta_{KL} (\ln K \ln f_L) + \delta_{KE} (\ln K \ln f_E) + \delta_{KM} (\ln K \ln f_M) \\ & + \rho_t t + \rho_{tL} (t \ln f_L) + \rho_{tE} (t \ln f_E) + \rho_{tM} (t \ln f_M) + \mu \end{aligned} \tag{12}$$

where μ is a stochastic disturbance term.

In order for this cost function to correspond to a well-behaved technology it should be linear homogeneous in factor prices. This implies the following parameter restrictions:

$$\beta_L + \beta_E + \beta_M = 1$$

$$\gamma_{LL} + \gamma_{LE} + \gamma_{LM} = \gamma_{LE} + \gamma_{EE} + \gamma_{EM} = \gamma_{LM} + \gamma_{EM} + \gamma_{MM} = 0$$

$$\delta_{KL} + \delta_{KE} + \delta_{KM} = 0$$

$$\rho_{tL} + \rho_{tE} + \rho_{tM} = 0$$

Moreover, the translog function provides a second-order approximation to an arbitrary cost function so that it is necessary to specify the point of approximation. We chose the sample means of the explanatory variables as the relevant point. Therefore, all variables except C_V were divided by their mean.

An efficient estimation procedure is to estimate the cost function jointly with the factor share equations which are derived using Shepard's lemma:

$$s_L = \beta_L + \gamma_{LL} (\ln f_L) + \gamma_{LE} (\ln f_E) + \gamma_{LM} (\ln f_M) + \delta_{KL} (\ln K) + \rho_{tL} (t)$$

$$s_E = \beta_E + \gamma_{EE} (\ln f_E) + \gamma_{LE} (\ln f_L) + \gamma_{EM} (\ln f_M) + \delta_{KE} (\ln K) + \rho_{tE} (t)$$

$$s_M = \beta_M + \gamma_{MM} (\ln f_M) + \gamma_{LM} (\ln f_L) + \gamma_{EM} (\ln f_E) + \delta_{KM} (\ln K) + \rho_{tM} (t)$$

A modification of Zellner's (1962) technique for estimating seemingly unrelated regressions was used to obtain the parameters of the system of equations. To avoid the singularity of the contemperaneous variance-covariance matrix, one of the share equations is deleted prior to the second stage of Zellner's method. The estimates are asymptotically equivalent to maximum likelihood estimates and are invariant to which equation is deleted before carrying out the second stage of the procedure.[7] (See Caves et al. (1981), Berndt et al. (1974)).

The economic properties of the proposed variable cost function are easily reviewed. The Allen-Usawa partial elasticity of substitution between factors i and j is given by

$$\sigma_{ij} = \frac{\gamma_{ij}}{s_i\, s_j} + 1 \qquad i \neq j \tag{13}$$

Own price and cross-price elasticities of factor demand are, respectively

$$\varepsilon_{jj} = s_j - 1 + \frac{\gamma_{jj}}{s_j} \tag{14}$$

$$\varepsilon_{ij} = s_j + \frac{\gamma_{ij}}{s_i} \qquad i \neq j \tag{15}$$

Consequently, estimates of γ_{ij} and γ_{jj} and knowledge of the respective factor shares are sufficient to calculate substitution and price elasticities.

3. The Data

Data were collected for the paper and paperboard industries, SIC 2621 and SIC 2631, respectively. Annual data were used over the period 1958-1981. Relevant variables included output, prices of labor, energy and materials inputs, a measure for the fixed factor K, and total variable costs.

Output information was obtained from the American Paper Institute[8] and the Bureau of Labor Statistics.[9] The price of labor was derived by dividing total payroll in each industry by the total number of man-hours, both available from the U.S. Bureau of the Census.[10] An index for the price of energy was constructed as a weighed average of the prices of fuel, electricity and gasoil. Prices for these different energy sources were obtained from the Bureau of Labor Statistics.[11] The weights used correspond to the proportion of the industry's bill spent on each source. As these data are only published every four years by the U.S. Bureau of the Census[12], intermediate years were interpolated.

The price index of materials was constructed as a weighed average of the prices of wastepaper, chemicals and pulpwood. The latter was itself a weighed average of the prices of southern pine, northern softwood, and northern hardwood. The data with respect to the prices of these different types of wood are from the U.S. Department of Agriculture.[13] Price indices for wastepaper and chemicals were derived from the Bureau of Labor Statistics.[14] The proportions used to weigh the prices of wastepaper, pulpwood and chemicals were again taken from the U.S. Bureau of the Census[15] and a similar procedure to construct the final material price index was followed as in the case of the energy price.

As a proxy for the fixed factor in the short-run, we preferred to use a measure of capacity rather than a direct measure of the stock of capital, which is often unreliable. Capacity figures were taken from the American Paper Institute.[16]

Total variable costs in each industry were calculated by simply adding total expenditures on labor, energy and materials in each sample year. The necessary information was found from the U.S. Bureau of the Census.[17]

4. Estimation results

Parameter estimates and their standard errors are presented in Table 1a both for the paper and paperboard industry. Table 1b summarizes the coefficients of determination and the Durbin-Watson statistics for the respective cost and factor share equations.

In the model describing the paper industry all but two coefficients are significantly different from zero at the 95% confidence level. The cost equation for the paperboard industry contains several insignificant variables. However, this will not prevent us to obtain precise estimates of the most important economic characteristics of the industry, as we will see below. Given the high explanatory power of almost all relations and the absence of significant autocorrelation problems the results may be considered quite reasonable.

The parameters of the cost functions have no clear direct interpretation as they are estimates of the gradient and Hessian of the true underlying cost functions. They can be used, however, to infer some interesting information concerning the economic properties of the industries. First consider Tables 2 and 3, which contain the price and cross-price elasticities of the demand for the factors labor, energy and materials in the paper and paperboard sectors, respectively. They were calculated using the mean factor shares over the sample period.

Although the estimated point elasticities are different, the overall results in the two industries are quite similar. All own price elasticities are significantly different from both zero and one, implying that all factor demands are inelastic. Energy demand turns out to be much more responsive to price changes than labor and material demand. This is especially the case for the paperboard industry, which is slightly more energy intensive. It is interesting to note that the labor demand elasticity is somewhat higher than the one estimated by Stier (1984), who studied the pulp and paper industry using labor, capital and wood as inputs. Buongiorno _et al_. (1983) on the other hand use a Cobb-Doublas specification to derive input price elasticities for the paper and paperboard industries. They find much higher values -- for all factors -- than those reported in this paper. It should be obvious, however, that their unduly restrictive technology is largely responsible for this result, as it forces all elasticities of substitution to equal unity.[18] Because of this constraint and the relation between price and substitution elasticities, see equations (13), (14) and (15), their finding is not surprising.

In both industries, estimated cross-price elasticities suggests substantial substitution possibilities between labor and materials and between energy and materials. Cross-effects between labor and energy are not significantly different from zero, even with a negative sign in the paperboard industry. These results are corraborated by the following substitution elasticities, calculated at the mean factor shares (standard errors in parentheses):

Paper	σ_{LE} 0.0476 (0.3240)	σ_{LM} 0.4190 (0.0767)*	σ_{EM} 0.6663 (0.2016)*
Paperboard	σ_{LE} -0.1889 (0.3059)	σ_{LM} 0.3893 (0.1016)*	σ_{EM} 1.0662 (0.2000)*

As was to be expected all substitution elasticities are significantly different from zero, except σ_{LE}. This is hardly surprising given the practical difficulties of substituting labor with energy within a specified technology.

A second piece of useful information concerns the degree of returns to scale and its short-run analogue, returns to density. A measure of the latter may be defined as one minus the variable cost elasticity with respect to output, i.e.,

$$D = 1 - \frac{\partial \ \ln C_V}{\partial \ \ln Q} \tag{16}$$

A positive value for D indicates the existence of economies of density or, in other words, variable costs increase less than proportionately with increases in output, holding the level of the fixed input constant. The following estimates were obtained:

Paper	D = 0.05086	(0.1136)
Paperboard	D = 0.331771	(0.1037)*

These numbers suggest no significant returns to density in the paper industry, whereas the paperboard sector may be characterized by mild but statistically significant returns to density. An alternative way of interpreting these results is that, for a fixed capacity level, a percentage increase in the variable inputs will only in the paperboard industry lead to a more than proportional change in output.

A measure for the more commonly used concept 'economies of scale' was given before in equation (11). This expression was evaluated for both industries at the sample means of all variables, with the following results.[19]

Paper	R = 0.645081
Paperboard	R = 0.79403

A value smaller than one indicates economies of scale. Consequently, we should conclude that both industries operate under mildly large economies of scale.[20]

Several authors have presented evidence with regard to the existence of scale economies in the forest products industries, including the paper and paperboard sectors. Increasing returns to scale have been suggested for the aggregate pulp and paper industry as early as 1950, see Entrican (1950). More recently, Buongiorno and Gilless (1980) estimated (mild) scale economies for most subsectors of this aggregate industry. Stier (1984) also estimates increasing returns, although his degree of returns to scale seems unplausibly large. According to his estimates a 10% increase in output would only result in a less than 3% increase in total costs.

It should finally be stressed that the results obtained in this paper only have meaning at the industry level. Using data at the firm level, Buongiorno et al. (1981) recently indicated that scale economies exist for small to intermediate-size mills, but that no further efficiency gains were observed for very large mills. It would be quite interesting to compare our results with those obtained on the basis of cross-section data of individual mills, using econometric procedures.[21]

5. Productivity growth in the paper and paperboard industries

In this section we present the indices of productivity growth derived from the variable cost function. We evaluated expressions (9) and (10) for every year in the sample period. Although the measures P1 and P2 have to be calculated on the basis of derivatives of the cost function, they may be assumed to represent continuous approximations to discrete changes in productivity. Tables 4 and 5 contain the results for the paper and paperboard industries, respectively. The first two columns give the estimates obtained for P1 and P2. The final two columns contain productivity indices calculated from the estimated growth rates, setting the value for 1957 equal to 100.

It should be remembered that the two alternative productivity growth measures would have yielded the same results only if the industry had exhibited constant returns to scale over the sample period. As we previously indicated the existence of increasing returns to scale, the difference between P1 and P2 should come as no surprise. It must again be stressed that both are valid productivity indicators referring to slightly different definitions of the concept.

The most striking result in Tables 4 and 5 is probably the large differences in productivity growth between the paper and paperboard industries. Whereas the paper sector enjoyed average rates of technological change of 2.89% (according to P1) or 4.54% (according to P2), average growth rates for the paperboard industry amounted to only slightly more than 1% per year. This implied that the level of productivity corresponding to P1 was approximately twice as high in 1981 than in 1958 for the paper industry, while the total increase over the sample period in the paperboard industry was only 30%. Similar large differences may be observed for the indices based on P2.

The difference in productivity growth in the two sectors is remarkable and a complete analysis of why it exists is outside the scope of this paper, which mainly concentrates on the construction of indices of total factor productivity. However, a few casual observations suggests that our finding is not unreasonable. First, although over the period 1958-1981 output increased in both industries in roughly the same proportion, total variable costs rose by 12% more in the paperboard industry than in the paper sector. As the evolution of factor prices was very similar to the two industries, differences in factor prices alone cannot account for this fact. A partial explanation is the higher energy intensiveness of the paperboard industry combined with the increase of the price of energy relative to the prices of the other inputs over the sample period.[22] Second, labor productivity in the paper industry -- measured in the classical way as output per unit of labor input -- increased at a faster rate in the paper industry. Indeed, output per man-hour (production workers only) in this industry increased by almost 150% over the period 1958-1981, whereas the corresponding increase for paperboard was less than 130%. Comparisons of the change in output per employee and value added per employee showed a similar difference.

The results in Tables 4 and 5 indicate a remarkably similar time path of productivity growth in the industries under consideration. We observe a fairly steady growth, at a slightly increasing rate during the prosperous sixties and early seventies. However, both industries suffer from a slowdown of productivity increases over the period 1973-1981.

In order to understand the estimated time pattern of technological change it is useful to consider the factor bias of technical progress. The bias expresses the impact of changes in technology on factor shares. It is intended to capture the changes in factor shares that cannot be attributed to normal input substitution as a response to relative factor price variations. The bias is directly related to the coefficients of time in the factor share equations, ρ_{ti}. A formal measure was proposed by Binswanger (1974). He defines the bias, for factor i, as

$$B_i = \frac{\partial S_i}{\partial t} \frac{1}{S_i^*} = \frac{\rho_{ti}}{S_i^*}$$

where S_i^* is the share that would have been observed had relative input prices remained constant. If B_i is positive (negative) technological change is said to be factor i-using (saving).

Of course, S_i^* is unobservable. We therefore approximated the bias using the mean factor shares over the sample. The effect of the approximation is not important because S_i^* does not affect the sign neither the significance of the bias. We obtained the following results (standard errors in parentheses):

	L	E	M
Paper	-0.02 (0.007)*	0.12 (0.02)*	-0.007 (0.004)
Paperboard	-0.009 (0.008)	0.027 (0.032)	-0.003 (0.007)

According to these estimates technological progress was labor and materials saving, but energy using. Although for the paperboard industry none of the biases are statistically significant, we believe the pattern of technological change bias is a key element in explaining the observed time path of the calculated growth rates P1 and P2. Indeed, the work by Jorgenson (1984) suggests that an alternative and equivalent way of interpreting a factor-using bias is by saying that the rate of technical progress decreases with the price of that factor.[23] This interpretation applied to our results means that for the paper and paperboard industries the technological change decreases with the price of energy and increases with the prices of labor and materials. These observations largely explain our findings. During the sixties real energy prices declined and labor and material prices increased at a modest rate. Given the estimated bias of technological change, this evolution induced relatively large changes in productivity. However, the oil crisis of 1973 caused a world wide recession leading to sharp increases in labor and material prices but especially in the price of energy. The result was an increase in the real price of energy, relative to other input prices. This fact combined with the energy-using bias of technical progress explain the slowdown in productivity growth during the seventies.[24] A similar relation between the price of energy and productivity growth has been observed for many other manufacturing industries as well, see e.g., Berndt (1982).

6. Summary and Conclusions

In this study we applied the methodology recently proposed by Caves <u>et al</u>. (1981) to develop measures of total factor productivity in the paper and paperboard industries. The procedure involved the estimation of flexible variable cost functions to describe the cost and production structure in the industries under investigation. The results were then used to calculate two closely related indices of productivity growth.

A simplified translog model was used to estimate the cost structure in the two industries. Our most important findings are easily summarized. According to our estimates, both industries operate under mild economies of scale. This result is consistent with previous studies. All variable inputs considered in this paper were estimated to be price inelastic. Energy demand was found to be much less inelastic than the demand for labor and materials, however. Cross-price elasticities and elasticities of substitution between input suggested the existence of substantial substitution possibilities between energy and materials, and between labor and materials. Our results indicate no significant trade-offs between labor and energy.

Calculated productivity indices suggest that the time path of technological improvements was quite similar in the two industries. Productivity grew at a slightly increasing rate during the sixties and the early seventies under the influence of general economic prosperity. However, the recession caused by the oil crisis slowed down the process of further technological changes. This is clearly reflected in our estimated indices which show a sharp decline in productivity growth since 1973.

Average rates of growth were estimated to be much higher in the paper sector than in the paperboard industry. Depending upon the definition used average growth rates of 2.89% and 4.54% per year were estimated for the paper industry, whereas in the case of paperboard both definitions yielded annual growth rates of only slightly more than 1%. Although a complete analysis of the observed difference was outside the scope of this paper, a partial explanation was offered in terms of differences in the growth of labor productivity.

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Footnotes

1 In this paper we treat the two industries as totally separated. Although it is likely that several firms classified under the paper industry also produce a small amount of paperboard and vice versa, data limitations preclude a more general analysis in which this joint production aspect is taken into account. This would require information with respect to the production of paper and paperboard on the firm level. The possibility of some joint production should be kept in mind, although it cannot be dealt with using aggregate data.

2 It should be noted that the productivity growth rates derived from a variable cost function will in general be different from those based on a total cost function, since different assumptions underlie the analysis. The same results will only be obtained if indeed the assumption of total cost minimization holds.

3 See e.g., McFadden (1978).

4 See Appendix for the derivations.

5 The expression for P1 is easily found by comparing (3), (6) and (8). To arrive at (10) start from (4)

$$P2 = \frac{F_t}{F_{\bar{L}} + F_{\bar{E}} + F_M + F_{\bar{K}}} = -\frac{\partial \ell n\, C_V}{\partial t}\left(\frac{F_{\bar{L}} + F_{\bar{E}} + F_{\bar{M}}}{F_{\bar{L}} + F_{\bar{E}} + F_{\bar{M}} + F_{\bar{K}}}\right) \qquad \text{using (8)}$$

$$= -\frac{\partial \ell n\, C_V}{\partial t}\left(\frac{1}{1 - \frac{\partial \ell n\, C_V}{\partial \ell n\, K}}\right) \qquad \text{using (7)}$$

6 This is probably what happened when we did estimate a general translog specification. Although the results with respect to price and substitution elasticities were very similar to those based on the simplified model, the cost elasticity with respect to output and the economies of scale parameter R were themselves very trended over time. As convincingly argued by Fuss and Waverman (1978, p. 36-37) this is highly suspicious and it may be an indication of the problems previously mentioned. In practice we would expect variations in scale economies over time to be limited, especially in a relatively short time period.

7 It should be stressed that the estimation procedure is only efficient and invariant with respect to which equation is deleted if the assumption of zero autocorrelation holds. On the basis of the Durbin-Watson statistics and the first-order autocorrelation coefficients in the different equations we did not consider it necessary to correct for autocorrelation along the lines suggested by Berndt and Savin (1975).

8 American Paper Institute, Wood, Pulp and Fiber Statistics, New York, 1958-1976.

[9] U.S. Bureau of Labor Statistics, Survey of Current Business, Washington, D.C., 1977-1981.

[10] U.S. Bureau of the Census, Annual Survey of Manufacturers, Washington, D.C., 1958-1981.

[11] U.S. Bureau of Labor Statistics, Producer Prices and Price Indices, Washington, D.C., 1958-1981.

[12] U.S. Bureau of the Census, Census of Manufacturers, Washington, D.C., various issues.

[13] U.S. Department of Agriculture, U.S. Timber Producton, Trade, Consumption and Price Statistics, 1958-1981.

[14] U.S. Bureau of Labor Statistics, Producer Prices and Price Indices, 1958-1981.

[15] U.S. Bureau of the Census, Census of Manufacturers, Washington, D.C.

[16] American Paper Institute, Statistics of Paper, 1958-1981.

[17] U.S. Bureau of the Census, Annual Survey of Manufacturers, 1958-1981.

[18] Elasticities of substitution in this study are estimated to be much lower in most cases, see below.

[19] We also evaluated (11) in each year of the sample. Although R was found to vary somewhat over time, this variation was relatively small and, more importantly, no monotonic trend was observed. This suggests that our simplified model is more reliable than the more general translog function, at least for our sample.

[20] Note that an intimate relation between economies of scale and density can be established. Using (11) and (16) we derive

$$R = \left(1 - \frac{\partial \ln C_V}{\partial \ln K}\right)/(1 - D).$$

[21] Buongiorno <u>et al</u>. (1981) use simple measures of profitability and productivity for mills of different sizes.

[22] The factor share for energy over the sample period was over 12% in the paperboard industry, compared to 9% in the paper sector.

[23] Using a general equilibrium framework, Jorgenson (1984, p. 28) points out the dual role of the bias of productivity growth. It expresses the effect of technological change on the share of a factor and, alternatively the negative effect of the price of the factor on technological change.

[24] Note that the energy-using bias is by far larger than the input-saving biases for labor and materials. This suggests that the downward effect of energy prices on productivity more than offset upward pressures due to increasing prices for labor and materials.

<u>Appendix</u>: Derivation of Equation (6), (7) and (8)

The cost function C_V (Q, f_L, f_E, f_M, K, t) may be obtained by solving the problem

$$\text{Minimize} \quad f_L L + f_E E + f_M M$$
$$\text{subject to} \quad F(Q, L, E, M, K, t) = 0$$

where Q, K and t are to be treated as constants. The first-order conditions imply $f_L = \lambda F_L$, $f_E = \lambda F_E$, $f_M = \lambda F_M$, where as before F_i indicates the partial derivative of the transformation function with respect to factor i and λ is the Lagrange multiplier corresponding to the constraint. If we denote the optimal values to previous minimization problem by starred variables then we have

$$C_V = f_L L^* + f_E E^* + f_M M^* = \lambda(F_L L + F_E E + F_M M) = \lambda(F_{\overline{L}} + F_{\overline{E}} + F_{\overline{M}})$$

The envelope theorem implies on the other hand the following relations:

$$\frac{\partial C_V}{\partial Q} = -\lambda F_Q$$
$$\frac{\partial C_V}{\partial K} = -\lambda F_K$$
$$\frac{\partial C_V}{\partial t} = -\lambda F_t$$

Combining these and previous results we easily derive

$$\frac{\partial C_V}{\partial Q}\frac{Q}{C_V} = \frac{-F_{\overline{Q}}}{F_{\overline{L}} + F_{\overline{E}} + F_{\overline{M}}}, \quad \frac{\partial C_V}{\partial K}\frac{K}{C_V} = \frac{-F_{\overline{K}}}{F_{\overline{L}} + F_{\overline{E}} + F_{\overline{M}}}, \quad \frac{\partial C_V}{\partial t}\frac{1}{C_V} = \frac{-F_t}{F_{\overline{L}} + F_{\overline{E}} + F_{\overline{M}}}$$

which are equations (6), (7) and (8) in the text.

Table 1a. Estimation results variable cost model.

	Paper Industry		Paperboard Industry	
Parameter	Estimate	Standard Error	Estimate	Standard Error
α_0	8.5794	(0.0049)*	7.9571	(0.0067)*
α_Q	0.9491	(0.1136)*	0.6682	(0.1037)*
β_L	0.2734	(0.0021)*	0.2454	(0.0020)*
β_E	0.0906	(0.0021)*	0.1268	(0.0044)*
β_M	0.6360	(0.0026)*	0.6278	(0.0045)*
γ_{LL}	0.1252	(0.0119)*	0.1317	(0.0139)*
γ_{EE}	0.0441	(0.0107)*	0.0309	(0.0138)*
γ_{MM}	0.1205	(0.0202)*	0.0907	(0.0123)*
γ_{LE}	-0.0244	(0.0083)*	-0.0360	(0.0093)*
γ_{LM}	-0.1008	(0.0133)*	-0.0957	(0.0159)*
γ_{EM}	-0.0197	(0.0119)	0.0051	(0.0153)
δ_K	0.3763	(0.1727)*	0.4685	(0.2008)*
δ_{KL}	0.0047	(0.0579)	-0.0879	(0.0530)
δ_{KE}	-0.2129	(0.0559)*	-0.0004	(0.1162)
δ_{KM}	0.2082	(0.0684)*	0.0883	(0.1180)
ρ_t	-0.0269	(0.0039)*	-0.0072	(0.0023)*
ρ_{tL}	-0.0055	(0.0019)*	-0.0022	(0.0018)
ρ_{tE}	0.0102	(0.0019)*	0.0033	(0.0040)
ρ_{tM}	-0.0047	(0.0023)*	-0.0011	(0.0041)

Note: * indicates regression coefficients significant at the 95% confidence level.

Table 1b. Summary statistics variable cost model.

	R^2		D.W.	
	paper	paperboard	paper	paperboard
Cost function	0.9940	0.9902	1.8854	2.1358
Share equation labor	0.9768	0.9754	1.1995	1.8662
Share equation energy	0.9772	0.9430	1.9405	2.003
Share equation materials	0.7458	0.7659	1.9798	1.4889

Note: D.W. is the Durbin-Watson statistic.

Table 2. Price and cross-price elasticities of factor demand (calculated at the mean factor shares) in the paper industry.

ε_{LL} -0.2693* (0.0434)	ε_{EL} 0.0131 (0.0889)	ε_{ML} 0.1150* (0.0210)
ε_{LE} 0.0044 (0.0303)	ε_{EE} -0.4343* (0.1146)	ε_{ME} 0.0622* (0.0188)
ε_{LM} 0.2645* (0.0485)	ε_{EM} 0.4212* (0.1275)	ε_{MM} -0.1772* (0.0319)

Notes: Asymptotic standard errors were calculated using the formulas $S.E.(\varepsilon_{ij}) = S.E.((\gamma_{ij})/S_i)$, where S_i is the observed, nonstochastic factor share for input i.

* indicates estimate is significantly different from zero at the 95% confidence level.

Table 3. Price and cross-price elasticities of factor demand in the paperboard industry (calculated at the mean factor shares).

ε_{LL}	-0.2222 (0.0557)*	ε_{EL}	-0.0470 (0.0762)	ε_{ML}	0.0969 (0.0253)*
ε_{LE}	-0.0229 (0.0372)	ε_{EE}	-0.6242 (0.1134)*	ε_{ME}	0.1295 (0.0243)*
ε_{LM}	0.2451 (0.0639)*	ε_{EM}	0.6742 (0.1259)*	ε_{MM}	-0.2264 (0.0392)*

Notes: See Table 2.

Table 4. Calculated productivity growth rates and productivity indices paper industry.

	Annual Growth Rate P1 (%)	Annual Growth Rate P2 (%)	Index Based on P1	Index Based on P2
1957			100	100
1958	2.87	4.62	102.87	104.62
1959	2.89	4.69	105.84	109.53
1960	2.91	4.71	108.92	114.69
1961	2.90	4.64	112.08	120.01
1962	2.93	4.68	115.37	125.62
1963	2.96	4.71	118.78	131.54
1964	3.03	4.93	122.38	138.02
1965	3.03	4.94	126.09	144.84
1966	3.05	4.94	129.93	152.00
1967	3.06	4.94	133.91	159.51
1968	3.11	5.06	138.07	167.58
1969	3.14	5.13	142.41	176.18
1970	3.19	5.25	146.95	185.42
1971	3.17	5.16	151.61	194.99
1972	3.20	5.22	156.46	205.17
1973	3.13	5.07	161.36	215.57
1974	2.87	4.49	165.99	225.25
1975	2.85	4.51	170.72	235.41
1976	2.77	4.20	175.45	245.30
1977	2.70	3.94	180.19	254.96
1978	2.67	3.80	184.99	264.85
1979	2.54	3.51	189.70	273.94
1980	2.29	2.99	194.04	282.13
1981	2.17	2.74	198.25	289.86

Table 5. Calculated productivity growth rates and productivity indices paperboard industry.

	Annual Growth Rate P1 (%)	Annual Growth Rate P2 (%)	Index Based on P1	Index Based on P2
1957			100	100
1958	1.08	1.45	101.08	101.45
1959	1.09	1.43	102.18	102.90
1960	1.10	1.43	103.31	104.37
1961	1.10	1.43	104.44	105.86
1962	1.12	1.46	105.61	107.41
1963	1.13	1.45	106.81	108.97
1964	1.17	1.50	108.05	110.60
1965	1.17	1.50	109.31	112.26
1966	1.18	1.50	110.60	113.95
1967	1.18	1.49	111.91	115.64
1968	1.21	1.52	113.26	117.40
1969	1.23	1.54	114.66	119.21
1970	1.24	1.54	116.08	121.04
1971	1.24	1.51	117.52	122.87
1972	1.26	1.54	119.00	124.76
1973	1.23	1.54	120.46	126.69
1974	1.08	1.38	121.76	128.43
1975	1.04	1.31	123.03	130.12
1976	1.02	1.26	124.08	131.76
1977	0.99	1.22	125.51	133.36
1978	0.99	1.27	126.76	134.98
1979	0.94	1.14	127.95	136.52
1980	0.82	0.99	129.00	137.87
1981	0.77	0.93	129.99	139.45