Eastern Economic Journal, Volume XIV, No. 3, July–September 1988

Aggregation of Capital and Its Substitution with Energy

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INTRODUCTION

In the post-oil embargo period, there is considerable interest in the question of whether capital and energy are substitutes or complements. A rise in the price of energy will induce capital formation if energy and capital are substitutes but will reduce capital formation if they are complements. A controversy developed over this issue when the finding by Berndt and Wood (1975) that capital and energy are complements in manufacturing was challenged by Griffin and Gregory (1976) who found capital and energy to be substitutes.

Capital was measured as an aggregate input in both studies. One may question the appropriateness of aggregating building capital with equipment capital for the manufacturing sector. It is likely that a change in the price of energy will affect building capital differently than machinery capital. Furthermore, researchers must confront, as a practical matter, the issue of aggregating building and machinery capital since the investment data are reported separately for buildings and machinery by the Bureau of Economic Analysis and by the Census of Manufacturers. These investment series are used to construct capital stock series.

The aggregation of building and machinery capital is possible only if these components of capital are weakly separable from other inputs in the production function.[1] To test the hypothesis of weak separability, we estimate for the manufacturing sector a four input production function with building capital, machinery capital, labor and energy as inputs.

The aggregation of capital has been a controversial issue in economics since the 1950s. The "Cambridge School" led by Joan Robinson (1953–54) attacked the validity of the neoclassical production function with aggregate capital as one of its arguments. Robinson questioned the neoclassical conclusion that aggregate capital-labor ratio and wage-rental ratio are always positively related. She also raised the possibility that if manufacturers are faced with a finite number of techniques with different capital-labor ratios, then the comparison of the steady-state equilibria associated with these techniques may over some range yield a negative relationship between the capital-labor ratio and the wage-rental ratio.

This reswitching problem led the researchers to question the aggregation of capital within the context of a neoclassical production function. Is it possible to aggregate heterogeneous units of capital? Is it possible to establish unambiguous linkages between input ratios and input prices? The questions as yet have not been answered with certainty; however, the concensus seems to be that with sufficient substitution among inputs, the Cambridge criticism of neoclassical theory has little empirical importance.[2] Although our focus is different from the Cambridge controversy, we also argue that the existence of an aggregate input called capital can be determined only in the context of a specific production structure.

Our empirical results do not support the aggregation of building and machinery capital into a single index of capital stock. This implies that aggregation error biases the existing estimates of the elasticity of substitution between energy and aggregate capital (σ_{KE}). Second,

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when elasticities of substitution are computed separately between buildings and energy (σ_{BE}) and machinery and energy (σ_{ME}), we find that buildings and energy are complements ($\sigma_{BE} = -3.032$) and that machinery and energy are substitutes ($\sigma_{ME} = 1.005$). When σ_{KE} is estimated using our data the value is -0.704. Thus, σ_{KE} masks important interactions between energy and the components of capital. Misrepresentation is greatest in the case of machinery since the sign of σ_{ME} differs from σ_{KE}. This has important policy implications. For example, it is frequently argued that rising energy prices reduce the rate of growth of investment in new plant and equipment. This argument is based partly on the assumption that capital and energy are complements. However, our results indicate that this assumption holds only for buildings. For machinery, a rise in the price of energy, holding output constant, will induce greater capital formation.

The data in this study are pooled cross-sectional time-series for the years 1963–66 and 1974–78.[3] The cross-sectional units are 40 states in the U.S. for which relevant manufacturing data are available.[4] Pooled cross-sectional time-series data are preferred because there is greater variation in input prices across states than is found in the U.S. as a whole over time.

Section II describes the model and the estimation procedure to test for weak separability of inputs. Section III reports empirical results. Section IV summarizes the findings of the study.

II. MODEL AND THE ESTIMATION PROCEDURE

A four factor production function is assumed for the manufacturing sector. In general, it can be represented as follows:

$$y = f(B, M, L, E) \tag{1}$$

where y is real output and B, M, L and E refer respectively to buildings, machinery, labor and energy. An aggregate index of capital exists only if B and M are weakly separable from E and L. If separability is satisfied, then (1) can be rewritten as follows[5]:

$$y = f[K(B, M), L, E] \tag{2}$$

where K(·) is the aggregate function. Applying duality theory and assuming linear homogeneity yields the following cost functions associated with (1) and (2)[6]:

$$C = h(P_i) \cdot y \qquad \begin{array}{l} i = B, L, E, M \\ \text{or} \quad i = K, L, E \end{array} \tag{3}$$

where C is total cost and P_i is the price per unit of the ith input. Employing Shepard's (1970) lemma and assuming a translog functional form, the following cost share equations are derived:

$$S_i = \alpha_i + \sum_j \gamma_{ij} \ln P_j + e_i \qquad \begin{array}{l} i = B, L, E, M \\ \text{or} \quad i = K, L, E \end{array} \tag{4}$$

where S_i refers to the share of the ith factor in total cost, and e_i is the random error term associated with the ith equation. To capture non-neutral efficiency differences among states and over time, regional dummies (D_r) and time (t) are introduced as arguments in (4).[7] Therefore, (4) can be written as follows:

$$S_i = \alpha_i + \sum_j \gamma_{ij} \ln P_j + \gamma_{it} \ln t + \sum_r \gamma_{ir} D_r + e_i. \tag{5}$$

The assumption of linear homogeneity, the requirement that cost shares add to one and the conditions for cost minimization impose the following restrictions on (5):

$$\sum_i \alpha_i = 1, \quad \sum_i \gamma_{ij} = \sum_j \gamma_{ij} = 0, \quad \gamma_{ij} = \gamma_{ji} \tag{6}$$
$$\sum_i \gamma_{ir} = 0, \text{ and } \sum_i \gamma_{it} = 0.$$

In actual estimation, given the parametric restrictions in (6), one of the cost share equations can be omitted. An iterative efficient Zellner procedure (IZEF) is used for the estimation of (5). This procedure ensures that parametric estimates are invariant to the equation omitted. From the translog estimates, Allen partial elasticities of substitution (σ) are computed as follows:

$$\begin{aligned} \sigma_{ii} &= (\gamma_{ii} + S_i^2 - S_i)/S_i^2 \\ \sigma_{ij} &= (\gamma_{ij} + S_i S_j)/S_i S_j. \end{aligned} \tag{7}$$

The output constant own- and cross-price elasticities (ϵ_{ij}) are computed as:

$$\epsilon_{ij} = \sigma_{ij} \cdot S_j. \tag{8}$$

Berndt and Christensen (1973b) show that a test for weak separability can be expressed in terms of Allen elasticities of substitution. Using the values of σ computed from (7) the restrictions necessary for weak separability of building and machinery from both labor and energy are given as follows:

$$\sigma_{BE} = \sigma_{ME} \quad \text{and} \quad \sigma_{BL} = \sigma_{ML}. \tag{9}$$

For (9) to hold, given a translog functional form, the following set of conditions must be satisfied:

$$S_B\gamma_{ME} - S_M\gamma_{BE} = 0$$

and

$$S_B\gamma_{ML} - S_M\gamma_{BL} = 0 \tag{10}$$

The stipulation in (10) can be satisfied in two ways:

$$\gamma_{ME} = \gamma_{BE} = \gamma_{ML} = \gamma_{BL} = 0 \tag{11}$$

or

$$\gamma_{BL}/\gamma_{BE} = \gamma_{ML}/\gamma_{ME}. \tag{12}$$

Berndt and Christensen (1973b) refer to (11) as linear separability and to (12) as non-linear separability. The restrictions in (11) suggest that buildings share and machinery share are unaffected by the prices of energy and labor. In terms of the elasticity of substitution, this restriction implies that $\sigma_{BE} = \sigma_{ME} = \sigma_{BL} = \sigma_{ML} = 1$. Non-linear separability requires only equality between the elasticites of substitution ($\sigma_{BE} = \sigma_{ME}$ and $\sigma_{BL} = \sigma_{ML}$). If weak separability is accepted then a consistent aggregate of capital exists and the KLE specification is valid. Otherwise, BMLE is the appropriate form.

III. EMPIRICAL RESULTS

The system of cost-share equations (5) are estimated for the KLE and the BMLE specifications. Table 1 presents the coefficient estimates for both the specifications. The elasticities of substitution and the price elasticities of input demand are reported in Table 2.

With regard to capital-energy interactions, the estimates based on the BMLE model indicate that building and energy are highly complimentary ($\sigma_{BE} = -3.032$) while machinery and energy are substitutes ($\sigma_{ME} = 1.005$). The KLE model yields an estimate of -0.704 for σ_{KE}. Similarly the output constant energy price elasticities of building (ϵ_{BE}) and machinery (ϵ_{ME}) are -0.25 and 0.08 respectively. The energy price elasticity for aggregate capital (ϵ_{KE}) derived from the KLE model is -0.06. Since both sign and magnitude differs between building and machinery elasticities, it is impossible for the estimates of aggregate capital elasticities to represent the interactions between energy and the components of capital. This violates the basic idea of consistent aggregation as defined by Green (1964, p. 3), who states that: "Aggregation will be said to be consistent when the use of the information more detailed than that contained in aggregates would make no difference to the results of the analysis of the problem at hand."

Statistically, for consistent aggregation of building and machinery to exist, the restrictions given in equation (10) must hold. The null hypothesis for linear separability is given in (11). To test this hypothesis a likelihood ratio test is employed.[8] The computed Chi-square with four degrees of freedom is 190.4. Thus, the hypothesis of weak separability of building and machinery is decisively rejected at any reasonable alpha level. Given this evidence a consistent aggregation of prices and quantities of buildings and machinery is not possible under the assumption of linear separability.

The possibility still exists that non-linear separability may hold. The empirical validation of (12) involves non-linear parametric restrictions. To get around this problem we tested for the existence of non-linear separability at the mean values of the cost shares. The null hypothesis is that at the mean values of S_B and S_M the parametric restrictions implied by (10) are satisfied. The computed Chi-square is 64.8. Thus, non-linear separability is not satisfied at this point.

The possibility of aggregating buildings and machinery was first considered by Berndt and Christensen (1973a). Assuming a translog production function with three inputs (B, M, and L), they test the hypothesis that buildings and machinery are weakly separable from labor. They could not reject the existence of linear separability. However, they did reject the non-linear formulation of the separability hypothesis. For purposes of comparison, we also estimate the BML specification and test the Berndt and Christensen hypotheses. The computed Chi-squares are 8.4 with two degrees of freedom for the linear hypothesis and 27.6 with one degree of freedom for the non-linear hypothesis.[9] Like Berndt and Christensen, we accept the linear hypothesis (critical value is 9.21 at the .01 level) and reject the non-linear hypothesis (critical value is 6.63 at the .01 level). However, for the BMLE specification both hypotheses are rejected.

The similarity between our results and those of Berndt and Christensen is somewhat surprising given the differences in the methodology and data employed in the two studies. First, Berndt and Christensen use time-series-data for U.S. manufacturing for the period 1929–68. We use pooled cross-sectional time series for the periods 1963–66 and 1974–78. The unit of observation in our study is a state and not the nation. Second, Berndt and Christensen assume Hicks-neutral technical change, however, we allow for the possibility of biased technical progress.

From our results we can conclude that consistent aggregation of capital can be discussed

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TABLE 1
Estimated Coefficients of the Translog Cost Function

	Independent Variables													
Factor	P_B	P_M	P_E	P_L	Time	INT	MA	ENC	WNC	SA	ESC	WSC	M	P
	BMLE Specification													
Share of Buildings	0.1324	−0.0431	−0.0564	−0.330	0.0053	0.3201	0.0517	0.0392	0.0247	0.0185	−0.0184	0.0463	0.0539	0.0355
	(0.021)	(0.017)	(0.005)	(0.015)	(0.005)	(0.039)	(0.012)	(0.012)	(0.012)	(0.011)	(0.014)	(0.014)	(0.013)	(0.014)
Share of Machinery		0.0762	0.0001	−0.0333	0.0472	0.2493	−0.0064	−0.0175	−0.0403	−0.0068	−0.0206	−0.0124	−0.0070	−0.0187
		(0.018)	(0.004)	(0.011)	(0.004)	(0.025)	(0.008)	(0.009)	(0.008)	(0.008)	(0.010)	(0.009)	(0.009)	(0.010)
Share of Energy			−0.0010	0.0573	0.0211	−0.1079	−0.0058	−0.0203	−0.0157	0.0042	0.0314	0.0284	−0.0059	−0.0253
			(0.003)	(0.006)	(0.001)	(0.013)	(0.005)	(0.005)	(0.005)	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)
Share of Labor				0.0009	−0.0736	0.5385	−0.0395	−0.0014	0.0313	−0.0075	0.0076	−0.0623	−0.0410	0.0085
				(0.018)	(0.010)	(0.048)	(0.016)	(0.016)	(0.015)	(0.015)	(0.017)	(0.017)	(0.017)	(0.019)

	Independent Variables												
Factor	P_K	P_E	P_L	Time	INT	MA	ENC	WNC	SA	ESC	WSC	M	P
	KLE Specification												
Share of Capital	0.1163	−0.0577	−0.0587	0.0606	0.2881	0.0448	0.0167	−0.0203	0.0083	−0.0444	0.0277	0.0412	0.0105
	(0.018)	(0.005)	(0.019)	(0.003)	(0.013)	(0.015)	(0.015)	(0.014)	(0.014)	(0.017)	(0.016)	(0.015)	(0.017)
Share of Energy		0.0002	0.0575	0.0148	0.0610	−0.0068	−0.0193	−0.0143	0.0042	0.0329	0.0301	−0.0046	−0.0231
		(0.003)	(0.005)	(0.001)	(0.004)	(0.005)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)
Share of Labor			0.0012	−0.0750	0.6509	−0.0380	0.0026	0.0346	−0.0125	0.0115	−0.0578	−0.0366	0.0126
			(0.018)	(0.004)	(0.013)	(0.014)	(0.015)	(0.014)	(0.014)	(0.017)	(0.016)	(0.015)	(0.017)

TABLE 2
Substitution and Price Elasticities

BMLE Specifications (Elasticities of Substitution)

	B	M	L	E
B	−0.353 (0.70)	0.018 (0.40)	0.619 (0.17)	−3.032 (0.36)
M		−1.81 (0.30)	0.729 (0.09)	1.005 (0.20)
L			−0.992 (0.072)	2.412 (0.15)
E				−11.504 (0.458)

KLE Specifications (Elasticities of Substitution)

	K	L	E
K	−0.727 (0.103)	0.720 (0.09)	−0.704 (0.14)
L		−0.990 (0.072)	2.416 (0.13)
E			−11.321 (0.458)

BMLE Specifications (Own and Cross Price Elasticities)

	B	M	L	E
P_B	−0.061 (0.12)	0.003 (0.006)	0.107 (0.029)	−0.524 (0.062)
P_M	0.004 (0.098)	−0.444 (0.074)	0.179 (0.022)	0.246 (0.049)
P_L	0.310 (0.085)	0.365 (0.045)	−0.497 (0.144)	1.209 (0.075)
P_E	−0.246 (0.029)	0.081 (0.016)	0.195 (0.012)	−0.932 (0.037)

KLE Specifications (Own and Cross-Price Elasticities)

	K	L	E
P_K	−0.304 (0.043)	0.301 (0.038)	−0.294 (0.059)
P_L	0.361 (0.045)	−0.496 (0.036)	1.211 (0.065)
P_E	−0.057 (0.011)	0.196 (0.011)	−0.917 (0.037)

only with respect to a specific production function. When issues concerning energy and capital are raised, our findings show that the aggregation of building and machinery capital into a single measure of capital is inappropriate for analyzing production and cost structures.

Building capital and machinery capital also may contain aggregation bias. It is unlikely that our capital categories of "buildings" and "machinery" are elementary inputs which are defined by Green (1964) as input categories where individual units of the input are perfect substitutes.[10] If different units of "machinery" and "buildings" are not perfect substitutes then the maintained hypothesis that different units of "machinery" and "buildings" are weakly separable from other inputs will not hold. In this case, a finer level of disaggregation than the one attempted in our study is needed. To the best of our knowledge, more disaggregated information by asset type is unavailable for manufacturers at the state level. Thus, we are forced to assume that "buildings" and "machinery" are consistent aggregates. By treating "buildings" and "machinery" as separate arguments in the production function we can avoid at least some potential aggregation errors which could lead to inappropriate and/or incorrect policy conclusions.

Since a consistent aggregate of capital does not exist for the BMLE specification, the policy formulator can be mislead if only ϵ_{KE} is used as a guide for policy. For instance, on the basis of aggregate capital and energy complementarity one might conclude that rising energy prices will reduce the rate of capital formation. Our results indicate that this conclusion is valid only for buildings. Furthermore, the magnitude of change in the capital formation of buildings would be underestimated given the relative size of ϵ_{BE} and ϵ_{KE}. Another example is an economic policy designed to lower long-term interest rates for the purpose of stimulating investment in new plant and equipment. Based on our results, a reduction in the price of buildings will, ceteris paribus, increase energy demand whereas lowering the price of machinery will bring about lower energy utilization. However, looking only at ϵ_{EK} one would draw the conclusion that policies geared toward lowering interest rates will come into conflict with the goal of energy conservation.

Our estimate of σ_{KE} sheds new light on the capital-energy controversy. The issue is whether capital and energy are complements or substitutes. Berndt and Wood (1975) find them to be complements whereas Griffin and Gregory (1976) find a positive value for σ_{KE}. Attempts at reconciliation of the conflicting results focus on two differences between the studies. One involves the nature of the data. Griffin and Gregory (1976, 1981a) stress that cross-section time series data tend to yield a positive estimate of σ_{KE}. On the other hand, they argue that time-series data tend to capture short-run influences and therefore often yield a negative elasticity of substitution. The second issue concerns the treatment of material inputs in the production process. Berndt and Woods (1981a, 1981b) show that a net estimate of σ_{KE} is obtained when material inputs are included in the production function while a gross estimate is obtained when material inputs are assumed to be separable from other inputs. It is possible, as they note, for capital and energy to be gross substitutes but net complements. However, Griffin (1981a, 1981b) notes that for the Berndt and Wood reconciliation to hold the elasticity of substitution between material and non-material inputs (σ_{VM}) would have to be 3.7 which is an unrealistically high value. Griffin (1981b, p. 1101) estimates $\sigma_{VM} = 0.60$ with a standard deviation of 0.06.

The approach in this study is similar to that of Griffin's and Gregory's. Both studies use cross-sectional time series data and assume separability of material inputs from other inputs in the production structure. Yet, unlike Griffin and Gregory, we find K-E complementarity. This implies that factors other than the nature of the data and the treatment of material inputs play a role in determining the sign of σ_{KE}. Our findings suggest that the composition of capital and the strength of the interaction between energy and the components of capital also are important considerations. Although we can only speculate, the international panel data used by Griffin and Gregory are likely to have a higher percentage of machinery than the national time-series observations in Berndt's and Wood's study. Given our results, this would tend to lead to a positive value of σ_{KE} in Griffin's and Gregory's study.

Apart from the nature of the capital-energy substitutability, the empirical results also reveal some other important characteristics of the underlying production structure. We find that the degree of substitution between labor and aggregate capital ($\sigma_{KL} = 0.72$) is very similar to the degree of substitution between labor and the individual components of aggregate capital ($\sigma_{BL} = 0.619$ and $\sigma_{ML} = 0.729$). With regard to labor-energy interactions, the elasticity of substitution (σ_{LE}) and the output constant energy price elasticity of demand for labor (ϵ_{LE}) are approximately the same for both the BMLE and the KLE specifications ($\sigma_{LE} = 2.4$ and $\epsilon_{LE} = 0.2$). The positive value of ϵ_{LE} implies that the rising real price of energy during the 1970s, through the substitution effect, had a favorable impact on the labor utilization in the manufacturing sector. The total effect of an increase in the energy price on manufacturing employment could still be negative due to the output effect. However, given the share of energy in total cost, the own price elasticity of demand for manufacturing output (η_D) would have to be extremely elastic for the negative output effect of a rise in energy price on demand for labor to dominate the positive substitution effect.[11] Our results also indicate that labor utilization is adversely affected by the negative own price effect of the rise in real price of labor and the nature of technical progress which is primarily labor saving.

Given the nature of the data, differences in regional cost structures can also be explored.[12] The introduction of regional dummary variables (New England is the omitted region) into the cost-share equations permits an estimate of non-neutral technical change across regions. Three regional patterns are worth noting. First, energy cost share in the South (SA, ESC, and WSC) is higher than it is in other regions. This result suggests that energy used per unit of output, other things remaining the same, is highest in the South since the coefficients on the regional dummy variables are based on the assumption that input prices and technical progress over time are held constant. Second, there is no strong evidence that labor per unit of output is higher in the South than it is in the traditional manufacturing regions of Middle Atlantic and East North Central. In fact, the West South Central shows a pattern of lower labor intensity when compared to MA and ENC. Third, the coefficients on machinery capital are negative for all regions; however, the coefficients on building capital are positive with the exception of East South Central. The regional dummy coefficients for the KLE specification are positive for six of the eight regions. This is another piece of evidence suggesting that the aggregation of capital yields a result which is not consistent with the patterns demonstrated by machinery capital and building capital separately.

The estimated coefficients of time in Table 1 provide some interesting insights regarding the nature of technical progress in U.S. manufacturing. The extent of biased technical change (BTC) for any input is defined as the change, over time, in the cost share of the input, holding factor prices and non-neutral regional efficiency differentials constant.[13] The following table indicates BTC for each input during the sample period, i.e., 1963–78.[14]

	B	M	L	E
BTC	0.0144	0.1278	−0.199	0.0571

The most striking result from the table is that technical progress is strongly labor saving and machinery augmenting. This suggests that holding relative input prices constant, manufacturers would substitute machinery for labor over time. The other two inputs have considerably lower values for BTC. Although the bias for buildings is in the same direction as machinery, the magnitudes are quite different which provides another rationale for using the BMLE specification. This may also partly explain the observed trend that share of machinery in total capital stock has been increasing. Finally, energy conservation observed in recent years is primarily accounted for by the rise in the price of energy and not by biased technical progress. In fact, biased technical change indicates that technology is energy augmenting rather than energy saving.

SUMMARY AND CONCLUSIONS

In recent years a controversy has developed over the question of whether capital and energy are substitutes or complements. In the existing literature, the interaction between aggregate capital (K) and energy (E) has been extensively analyzed. In these research efforts the implicit assumption has been that a consistent aggregate index of capital exists. The investment data are reported separately by buildings (B) and machinery (M) by the *Bureau of Economic Analysis* and by the *Census of Manufacturers*. In order to build a meaningful aggregate capital index from the B and M series, we have to empirically validate the hypothesis that B and M are weakly separable from L and E. We test this hypothesis by estimating an empirical model, which is derived by using duality theory and a translog functional form. Our results convincingly reject the notion that B and M can be consistently aggregated into a single index called capital. We find that B and E are complements whereas M and E are substitutes. Estimation of the empirical model with aggregate capital (K) instead of B and M yields the result that K and E are complements. These findings have important implications for the policy formulation. The sign and magnitude of the elasticity of substitution between E and K (σ_{KE}) cannot be given a meaningful interpretation since it is not representative of the interactions between E and the individual components of capital, namely B and M. The misguided focus on σ_{KE} may lead to the conclusion that a rise in the price of energy would lower the demand for capital. This is true only for building capital and not for machinery capital. Similarly the impact of changes in the price of capital on energy conservation will have to be analyzed separately for the individual components of capital. The empirical results also provide some interesting insights with regard to the impact of rising energy prices on manufacturing employment, regional differences in the cost structures and the nature of the technical progress.

FOOTNOTES

1. Field and Grebenstein (1980) and Kopp and Smith (1981) have considered the decomposition of capital into physical and working capital. They find evidence that working capital and energy are substitutes and physical capital and energy are complements. Griffin (1981a) has raised serious theoretical and empirical objections to this disaggregation of capital. Theoretically, only physical capital should enter into a production function. Empirically, it is very difficult to determine working capital when using aggregate industrial data.
2. After the original Robinson criticism (1953–54), numerous articles followed including Samuelson (1962, 1966) and Solow (1955–56). For a summary of the various issues of the Cambridge controversy see Ferguson (1969), Layard and Walters (1978) and Brown (1980).
3. Data are described in Appendix A.
4. States included in the estimation are listed in Appendix B.
5. For a good discussion of functional separability and aggregation see Green (1964), Berndt and Christensen (1973a), Berndt and Christensen (1973b) and Blackorby, Primont and Russel (1978).
6. For details see Diewert (1974).
7. This type of non-neutral efficiency differences have been specified by Binswanger (1974). Regions are defined in Appendix B.
8. The test statistic is based on the log of the likelihood ratio (λ) formed by the maximum values of the likelihood functions with the implied parametric restrictions of the null hypothesis and the maximum value of the likelihood function in the unrestricted case. The value -2λ is distributed Chi-square with degrees of freedom given by the number of restrictions implied by the null hypothesis. See Theil (1971, pp. 396–397).
9. The non-linear hypothesis is tested at the mean of the cost-shares.
10. The energy price elasticity of demand for labor (ϵ^*_{LE}) is: $\epsilon^*_{LE} = \epsilon_{LE} + S_E\eta_D$ where ϵ_{LE} is the output constant energy price elasticity of labor demand, S_E is the share of energy in total cost and η_D is the

own price elasticity of demand for the manufacturing output. In this study we find ϵ_{LE} to be approximately 0.2 and S_E to be around 0.09. Therefore, for ϵ^*_{LE} to be negative η_D would have to be rather high.

11. Green (1969) points out that no two input units are exactly alike, "for example, they cannot occupy the same space at the same time." (p. 9) Furthermore, he states that, "there is a degree of disaggregation at which it is legitimate to assume the perfect substitutability of elements treated as units of a given commodity or input."
12. The regional patterns of input elasticities for the KLE specification are analyzed by the authors in an earlier article (Garofalo and Malhotra, 1984). We have also computed the input demand elasticities for the BMLE specification for each of the census regions. This information is available from the authors on request.
13. The procedure followed here is outlined in Binswanger (1974). The magnitude of the biased technical change for input is computed as: $BTC_i = \gamma_{it} d \ln t$. Thus, the direction of the bias will depend upon the sign of γ_{it}.
14. BTC is being measured as the change in the input share attributable only to technical change, i.e., dS_i holding input prices and non-neutral regional differences constant. Since $\Sigma_i S_i = 1$; therefore, $\Sigma_i dS_i = 0$.

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APPENDIX A

Data Description

Data are cross-sectional time series. Time periods are the years from 1963 to 1966 and from 1974 to 1978. Cross-sectional units are states. The dollar value of capital stock in each state is estimated by the perpetual inventory method. We follow the procedure outlined by Faucett (1977). Capital stock in any period is the sum of past investments after adjustments have been made for discards and depreciation. Investment series are constructed for buildings and structures (IB) from 1919–1978 and for machinery and equipment (IM) from 1915–1978. Data on IB and IM from 1951 to 1978 are published either in the *Census of Manufacturers* or *The Annual Survey of Manufacturers*. Prior to 1951 IB and IM in each state had to be estimated. IB are based on the value of contracts for construction in each state. We assume that the elasticity of IB with respect to the value of contracts has remained constant from 1919–1950. The elasticity is estimated for each state using data from 1951 to 1978. IM are estimated by decomposing investment into a replacement portion and a net investment portion. Net investment is a function of the growth of capital stock in machinery at the national level and the growth of value added at the national and state level. Replacement depends on the estimated amount of capital stock in the state and the rate of depreciation. Although estimated investment figures enter into the computation of capital stock, given the rates of depreciation and discards they have low weights particularly in the estimation of machinery capital. For buildings the estimated figures comprise a somewhat larger fraction of the capital stock estimates.

The measure of the price of capital in this study follows the approach of Jorgenson (Hall and Jorgenson, 1967 and Christensen and Jorgenson, 1969, 1970). This approach assumes that the value of an asset is equal to the discounted value of its service flow. The formula to compute the price of capital is taken from Fraumeni and Jorgenson (1980, p. 95). It assumes that price of capital is a function of federal and state corporate tax rates, present value of depreciation deductions on one dollar of investment, price deflator for either B or M, rate of return, rates of depreciation, and property tax rates. Aggregate price of capital is constructed by a divisia index. Details on the construction of the price of capital and capital stock are available from the authors.

Labor is the number of man-hours worked by production workers. Wage rate is total wages of production workers divided by total man-hours worked. Total expenditure on energy is the value of fuels and electric energy purchased by the manufacturers. Price per unit is total expenditure divided by the number of btu's used by manufacturers. For the period 1963–1966, the quantity of btu's per state had to be estimated. Since the only available data by both year and state are KWH's of electricity purchased by manufacturers, it was necessary to assume that the U.S. manufacturing ratio of KWH's of electricity to btu's of total energy purchased could be applied to each state. In this period data on KWH's are reported for only 40 states. Hence, the cross-sectional units had to be limited to the 40 states which are listed in Appendix B. *The Annual Survey of Manufacturers* did not report any energy data from 1967–1973. These years are excluded from the analysis. To obtain real input prices, all input prices are divided by the producer's price index for finished products (base year is 1972).

APPENDIX B

Regional Definitions

New England (NE)
- Maine
- Massachusetts
- Rhode Island
- Connecticut

Middle Atlantic (MA)
- New York
- New Jersey
- Pennsylvania

East North Central (ENC)
- Ohio
- Indiana
- Illinois
- Michigan
- Wisconsin

West North Central (WNC)
- Minnesota
- Iowa
- Missouri
- Nebraska
- Kansas

South Atlantic (SA)
- Maryland
- Virginia
- West Virginia
- North Carolina
- South Carolina
- Georgia
- Florida

East South Central (ESC)
- Kentucky
- Tennessee
- Alabama

West South Central (WSC)
- Arkansas
- Louisiana
- Oklahoma
- Texas

Mountain (M)
- Montana
- Idaho
- Colorado
- New Mexico
- Arizona
- Utah

Pacific (P)
- Washington
- Oregon
- California