ENERGY PRICE CHANGES AND THE INDUCED REVALUATION OF DURABLE CAPITAL IN U.S. MANUFACTURING DURING THE OPEC DECADE

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Energy Price Changes and the Induced Revaluation of Durable Capital in U.S. Manufacturing during the OPEC Decade

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Abstract

When energy prices increased suddenly and unexpectedly in 1973-74 and 1979-80, a portion of the long-lived capital stock in U.S. manufacturing was rendered economically less valuable. In this paper we develop an analytical framework, consistent with the theory of cost and production, that provides an appealing structural interpretation of this capital revaluation phenomenon.

In the spirit of a putty-clay model, we demonstrate that the capital revaluation elasticity is the negative of the *ex ante* substitution elasticity between energy and capital equipment. The model is implemented empirically with annual data from U.S. manufacturing, 1958-81, and vintage investment data since 1929. Maximum likelihood estimation is undertaken with nonstatic expectations of future relative price values treated as an unobservable variables problem.

Our principal empirical findings are (i) that the elasticity of capital valuation with respect to relative energy price increases -- the capital revaluation elasticity -- is between -0.234 and -0.543 in U.S. manufacturing, and (ii) that by 1981 the appropriately revalued capital stock is at least 13% less than traditional measures indicate. We also consider implications of capital revaluation for the measurement of capital-labor ratios, age-shadow price profiles, and vintage-specific Tobin's q's.

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I. INTRODUCTION

When energy prices increased suddenly and unexpectedly in 1973-74 and 1979-80, a portion of the long-lived fixed capital stock in U.S. manufacturing was rendered economically less valuable. This capital revaluation occurred for several related reasons. First, although considerable energy-capital substitution is possible *ex ante*, once in place long-lived equipment typically embodies engineering design and performance characteristics that permit very limited, if any, energy-capital substitution *ex post*. Second, the capital stock surviving to the early 1970's consisted of vintages purchased years earlier, years during which real energy prices had been low and falling, and thus this capital stock embodied energy efficiency that by post-OPEC energy price standards was economically inefficient. Third, once the 1973-74 and 1979-80 energy price increases unexpectedly occurred, it was recognized that the ability of this energy-inefficient capital stock to reduce variable input costs and to generate future net income had been seriously diminished. In particular, the present values of future services from energy inefficient capital vintages had been reduced relative to those from more efficient vintages, even though inefficient vintages were still operating effectively in an engineering sense.

It is important that changes in relative vintage values be incorporated into measures of aggregate capital stock. While traditional methods of measuring aggregate capital employ vintage specific weights, these weights typically depend only on the constant geometric decay or on the fixed vintage mortality distribution hypothesis. Neither hypothesis accommodates the effects of extraordinary and unanticipated changes in the price of a variable input such as energy.

It is our purpose in this paper to present a framework which allows one to represent analytically the capital revaluation phenomenon within the theory of cost and production, and then to quantify capital revaluation for the U.S. manufacturing sector, especially since 1973. Implications for the measurement of capital-labor ratios and vintage-specific Tobin's q will also be considered. Our principal empirical findings are that the elasticity of capital valuation with respect to relative energy price increases -- the capital revaluation elasticity -- is between -0.234 and -0.543 in U.S. manufacturing, and that by 1981 the revalued capital stock is at least 13% less than traditional measures indicate.

The outline of this paper is as follows. In Section II we present a brief historical review of energy-related events of the last decade, and also examine the longer history of relative energy prices. This historical review motivates the need for a measure of capital that includes not only its traditionally measured quantity, but also its quality, where quality is related to embodied energy efficiency, the ex ante energy-capital substitution elasticity, and relative energy prices. In Section III we provide necessary theoretical foundations for the analysis of input quantity and input quality within the framework of cost and production functions. This section draws heavily on Berndt [1983] and especially on Lau [1982], and enables us to employ the notion of energy price-dependent multiplicative factor augmentation for fixed capital.

In Section IV we develop a framework for measuring quality-adjusted capital, where the vintages of physically surviving capital are weighted by the ex ante energy-capital substitution elasticity and by the expected lifetime relative energy prices prevailing when these vintages were originally acquired. In Section V we formulate the econometric model, while in Section VI we present empirical results. In the final section of the paper, we offer a number of concluding remarks and observations.

II. A BRIEF HISTORICAL OVERVIEW

Over the 1958-72 time period, real energy prices in U.S. Manufacturing (defined as nominal energy prices divided by the manufacturing gross output price deflator) were relatively stable with a slight downward trend. Sharp changes in this trend occurred during the first OPEC epoch (1973-1978) when real energy prices suddenly rose 82%, and during the subsequent OPEC epoch (1978-1981) when they rose another 76%. These two epochs are shown in Figure 1.

The energy price shocks of OPEC-I and OPEC-II were substantial and unprecedented in the U.S., at least in this century. To see this, in Figure 2 we plot the price of energy relative to the price deflator for new equipment in U.S. manufacturing for the seventy-five year period 1906-81, normalized to unity in 1972.[1] This figure clearly indicates that although historical precedents exist for sudden increases in relative energy prices -- see the years 1916-1921 -- earlier energy price increases were considerably milder and less enduring than those of post-1973. Moreover, the long and sustained trend in falling relative energy prices from 1916 to 1970 surely contributed to expectations that future energy prices would continue to fall or at least would remain constant in real terms. As a result, entrepreneurs investing in new long-lived equipment from the 1930's to the 1960's were induced to choose engineering designs embodying relatively low energy efficiency.

Once the OPEC-I energy price shocks occurred and especially after OPEC-II, these entrepreneurs found themselves with vintages of capital equipment whose embodied energy efficiency was no longer economically optimal given the new relative energy prices. Since *ex post* possibilities for energy-capital substitution were extremely limited, and since the capital stock was relatively fixed in the short run, substantial improvements in energy efficiency could occur only as the older, energy-inefficient vintages of equipment were either substantially retrofitted or replaced with more energy-efficient designs. During this transition, however, the value of the existing capital vintages -- the ability of these vintages to reduce variable input costs and to increase net income -- was sharply reduced.

Within this context, it is of interest to examine the response of manufacturing firms to energy price increases since 1973. Over the entire 1973-81 time period, the energy input-output coefficient (E/Y) dropped only 13%, while the real price of energy (P_E) rose 220%. More interesting, however, is the fact that during OPEC-I the E/Y coefficient hardly changed at all -- it dropped but 1% (real P_E increased 82%), while during OPEC-II the E/Y coefficient decreased 12% (real P_E increased 76%). Hence gains in energy conservation and energy efficiency, while negligible during OPEC-I, accelerated substantially during OPEC-II.

A plausible hypothesis explaining this time pattern of energy conservation gains since 1973 is that such advances occurred only after substantial new investment in energy-conserving equipment took place. Support for this hypothesis is given by recent data on the investment behavior of U.S. manufacturing firms. To see this, in Figure 3 we plot the ratio of real gross investment (equipment, and equipment plus structures) to real gross output for U.S. manufacturing, 1958-81. There it is seen that while this ratio had cyclical variability over the 1958-78 time period, since 1978 it has jumped to levels much higher than that observed even during the "Golden Age" of the mid-1960's. Moreover, this sharp increase in the gross investment-gross output ratio since 1978 is not simply the result of lower output, i.e. of the denominator becoming smaller. Real annual investment in equipment averaged about $38 billion 1978-81, approximately 46% larger than the average annual equipment investment of $26 billion during 1974-77, and 100% larger than the $19 billion average during 1965-1973; for equipment plus structures, the associated constant 1972 dollar annual average values are $46 billion (1978-81), $33 billion (1974-77), and $27 billion (1965-1973).

FIGURE 1

Real Price of Energy, US Manufacturing

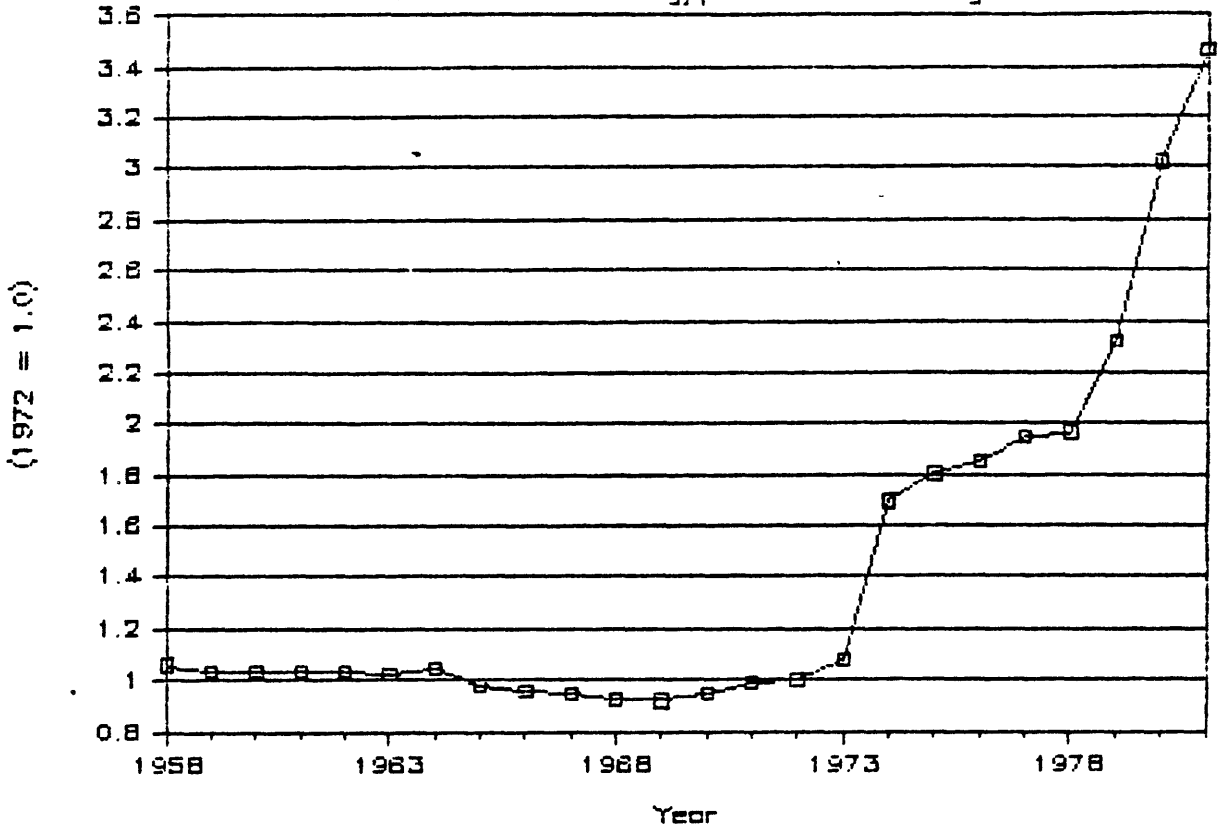


FIGURE 2

Relative Energy Prices---U.S. Mfg.

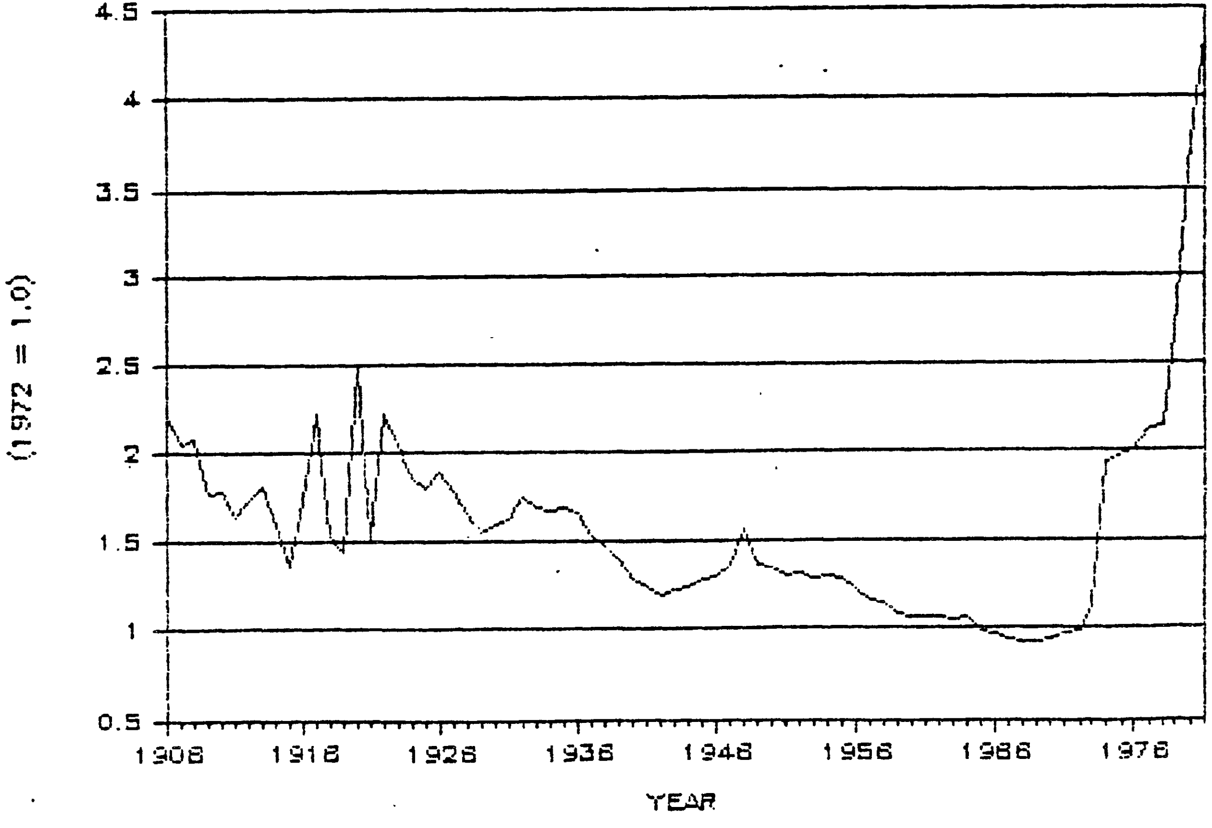
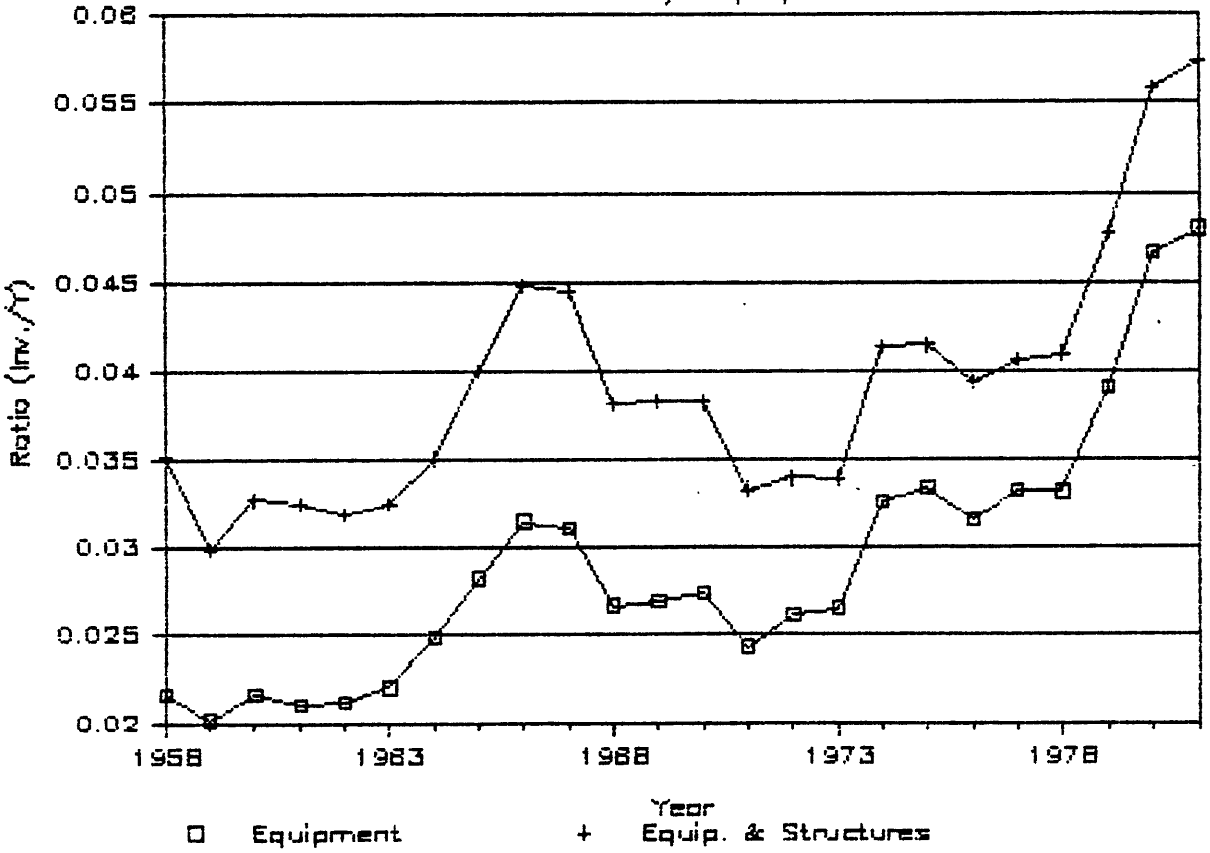


Figure 3

Ratio of Real Inv./Output, US Manuf.



The above brief review of historical data suggests to us that the behavior of manufacturing firms since 1973 can be envisaged as one of attempting to replace low quality, energy-inefficient fixed capital equipment with higher quality, more energy-efficient designs. While traditional measures of capital stock might therefore show steady and perhaps even substantial increases since 1972, measures of capital stock input adjusted for energy-related quality changes are likely to display less growth. Moreover, such quality-adjusted capital measures will reflect more accurately the (constant $) prices at which such energy-inefficient fixed capital equipment and structures could be sold.

In order to model and better understand the distinction between capital input quality and quantity, along with multiplicative factor augmentation, it is necessary first to develop an analytical framework that distinguishes quality and quantity for any input within the economic theory of cost and production. This more general discussion of input quality and quantity is the focus of Section III, while in Section IV more detailed consideration is given to specific problems in the measurement of quality-adjusted capital input.

III. QUALITY AND QUANTITY IN FACTOR DEMAND MODELS

Assume there exists a well-behaved, twice differentiable production function relating the flow of output y to the quantity flows of n strictly positive inputs, $x = [x_1, x_2, \ldots ,x_n]$, a scalar index of quality for each of the n inputs, $b = [b_1, b_2, \ldots ,b_n]$, and disembodied technical change as a function of time t,

$$y = F(x;b;t). \qquad (1)$$

Each scalar element of the vector b is specified to be a function of, for example, engineering design and performance variables, economic variables, and other relevant characteristics for each input, i.e.,

$$b_n = h_n(z_n), \tag{2}$$

where $z_n = [z_{n1}, z_{n2}, \dots, z_{nk}]$ is the vector of associated quality characteristic measures. F is assumed to be homogeneous of degree one in x and monotonically increasing in b. Note that according to (1), the relationships among y and x depend on the quality of inputs b.

The introduction of the quality vector b into the production function (1) is not new, but merits attention and interpretation.[2] Following Lau [1982] and Berndt [1983], consider the special case where the vector b is restricted to $b = [1,1, \dots, 1, b_n]$, i.e. where quality changes affect only the nth input. In the present context, interpret x_n as the capital quantity input and b_n as its quality. In such a case the production function (1) reduces to

$$y = F(x_1, x_2, \dots, x_n, b_n, t). \tag{3}$$

To provide an economic interpretation of input quality consistent with the theory of cost and production, we solve (3) to obtain an input requirement function relating the minimum quantity of x_n required given all possible quality levels b_n, evaluated at the quantity of output and the quantities of the other inputs, i.e.,

$$x_n = f(y, x_1, x_2, \dots, x_{n-1}, b_n, t). \tag{4}$$

Note that to the extent input quality is important, it manifests itself in the input quantity requirement relation (4).

The relative quality of inputs is determined as follows. Suppose two different quality levels of x_n exist, denoted b_{n0} and b_{n1}. Compare the different quantities of x_n corresponding to these two quality levels:

$$\frac{x_{n0}}{x_{n1}} = \left[\frac{f(y, x_1, x_2, \dots, x_{n-1}, b_{n0}, t)}{f(y, x_1, x_2, \dots, x_{n-1}, b_{n1}, t)}\right] \tag{5}$$

and, following Lau, call the term in square brackets the <u>quality conversion ratio</u> between two different quality levels of the n^{th} input.

Now let us obtain a measure of x_{n0} in terms of the quantity of x_{n1} having quality level b_{n1}, and call this x^*_{n0}. This can be interpreted as measuring capital quantity x_{n0} with say, energy efficiency design quality b_{n0} in terms of the capital quantity x_{n1} having a different energy efficiency design quality b_{n1}. Whatever the quantity of x_{n1} is, its equivalent quantity in terms of x_{n0} is given by rewriting (5) as

$$x^*_{n0} = \left[\frac{f(y,x_1,x_2, \dots ,x_{n-1},b_{n0},t)}{f(y,x_1,x_2, \dots ,x_{n-1},b_{n1},t)}\right] \cdot x_{n1} = B_{n0} \cdot x_{n1} \qquad (6)$$

where the quality conversion function B_{n0} now refers to y, x, and the <u>relative</u> quality levels of b_{n0} and b_{n1}. While in general the quality conversion function B_n can depend on the characteristics z_n in b_n, output and the quantities of all n inputs, it is useful to consider a special case in which B_n is a function only of x_{n-1} and z_n, where, say, x_{n-1} is energy input and z_n is a measure of the energy efficiency embodied in x_n. Note that even in this case B_n need not be constant.

For our purposes, Lau has derived three very important results, which we shall call Propositions I, II, and III, respectively. Here we merely state them a outline their significance; further discussion is found in Lau and in Berndt.

PROPOSITION I (Lau [1982, pp. 176-177, 182]): Let the production function (3) defined in terms of x_{n1} units having quality level b_{n1},

$$y' = F(x_1,x_2, \dots ,x_{n-1},x_{n1},b_{n1},t), \qquad (7)$$

and compare the predicted output of this production function with that defined, using (6), in terms of the standardized units, i.e.,

$$y^* = F(x_1,x_2, \dots ,x_{n-1},x^*_{n0},b_{n0},t).$$

Under the above conditions, Lau shows that $y' = y^*$. This is an important result, for it not only allows one to aggregate over different types of (x_n,b_n) pairs in terms of a standardized unit, but these equivalent units can also be substituted into a production function defined in terms of the standardized unit. Note also that up to the factor of proportionality B_n (which need not be constant), the various quality-adjusted inputs are perfectly substitutable.

PROPOSITION II (Lau [1982, pp. 178, 182]): When B_n is independent of $y, x_1, \ldots, x_{n-2}$, and t, and is only a function of x_{n-1} and z_n, the production function F must have the multiplicative factor augmentation form

$$y = F(x_1, x_2, \ldots, x_{n-1}, B_n(x_{n-1}, z_n) \cdot x_n, t). \tag{8}$$

This result is useful, for it allows us to define capital in quality-adjusted units as the product of traditionally measured capital and a quality conversion (factor augmentation) index, which in turn depends on energy use and the embodied energy efficiency.

PROPOSITION III (Lau [1982, pp. 180-183]): Under the additional assumption of cost minimization, the cost function dual to (8) has the form

$$c = G(y, p_1, p_2, \ldots, p_{n-1}, p_n/B_n^*(p_{n-1}, z_n), t), \tag{9}$$

where c is unit cost. Note that while B_n depends on x_{n-1} and augments the quantity of x_n, B_n^* depends on p_{n-1} and diminishes the price p_n. For later use, define the quality-adjusted prices and quantities of x_n as

$$x_n^* = B_n \cdot x_n \tag{10}$$

and

$$p_n^* = p_n/B_n^* . \tag{11}$$

Incidentally, Lau notes that under certain more restrictive conditions, it is the case that the value of B_n equals that of B_n^*.

Before leaving this section, we wish to restate the point originally made by Lau that hedonic price equations are readily interpretable within this context. For example, if one rearranges (11) and takes logarithms, one obtains the familiar hedonic price equation having the form

$$\ln p_n = \ln p_n^* + \ln B_n^* = \ln p_n^* + \ln h_n (z_n, p_{n-1}) \qquad (12)$$

where p_n^* is a base-price per unit of standardized quality. In the context of energy-using durable goods such as automobiles, a number of authors have reported results of regression equations in which prices of used automobile models are related to engineering design and performance charcteristics, along with the price of gasoline. Such hedonic regression equations indicate quite clearly that gasoline price increases since 1973 have rendered "gas guzzler" models less valuable than they would have been had gasoline price increases not occurred, i.e. they indicate that capital quality and economic depreciation depend on energy prices and embodied energy efficiency.[3]

IV. ON THE MEASUREMENT OF CAPITAL QUALITY AND QUANTITY

Having developed a general framework for the measurement of input quality and quantity, we now turn to a consideration of more specific issues encountered in measuring capital input quality and quantity. For later reference, we define capital input in quality-adjusted units as K_t^*,

$$K_t^* = B_{K,t} \; K_t, \qquad (13)$$

where $B_{K,t}$ is the multiplicative capital factor augmentation term, and K_t is capital input based on traditional measurement procedures.

It has long been standard procedure to form an aggregate index of capital input by weighting each surviving vintage of capital by its relative marginal product or shadow value.[4] Under traditional constant geometric deterioration assumptions, it is assumed that capital vintages "evaporate" at rate δ each time period. At time t, therefore, the relative marginal products or shadow values of one unit of capital acquired at time $t-\tau-v$ compared to one unit of capital acquired at time $t-\tau$, is $(1-\delta)^v$. In such a case, relative marginal products of various vintages depend only on relative ages and the constant rate of deterioration δ. This leads to a traditional aggregate of capital over vintages defined as

$$K_t = \sum_{\tau=0}^{T} s_\tau I_{t-\tau} = \sum_{\tau=0}^{T} K_{t,t-\tau} \qquad (14)$$

where T is the physical lifetime of the asset, s_τ is the survival rate of capital of age τ, $s_\tau = (1-\delta)^\tau$, $I_{t-\tau}$ is real gross investment put in place at time $t-\tau$, and $K_{t,t-\tau}$ is the amount of such vintage $t-\tau$ investment surviving to time t. Note that according to (14), relative marginal products of capital vintages depend only on their relative ages (not on energy or any other prices), and up to this factor of proportionality the various vintages are perfectly substitutable and therefore summable.

We now consider a generalization of (14) that accommodates vintage-specific energy price-dependent quality, and that weights the various vintages of capital by their relative marginal products or shadow values, which we now specify to depend on the embodied relative energy efficiency by vintage. Specifically, define capital input in quality-adjusted units K_t^* as

$$K_t^* = \sum_{\tau=0}^{T} e_{t,t-\tau} s_\tau I_{t-\tau} = \sum_{\tau=0}^{T} e_{t,t-\tau} K_{t,t-\tau} \qquad (15)$$

where $e_{t,t-\tau}$ is some function of expected relative energy-capital prices affecting the relative energy efficiencies embodied in I_t and $I_{t-\tau}$. Note that when $e_{t,t-\tau} = \Delta 1$ for all t,τ, $K_t^* = K_t$. We now turn to a discussion of how one might measure $e_{t,t-\tau}$ in a manner consistent with relative marginal product or shadow value weighting principles.

Assume that when firms undertake investment decisions in new plant and equipment, they follow a separable, two stage decision-making process. First, firms determine the amount of funds to be devoted to the sum of the amortized capital and operating costs of new equipment; this decision is based on expected demand growth and, for example, expected wage rates. Given this decision, firms then choose the optimal split between amortized capital service costs and energy costs based on the expected relative prices of energy to equipment. Some empirical support for this assumed special relationship between energy and capital is found in Berndt-Wood [1975, 1979].

Let this *ex ante* separable sub-production function between energy and capital equipment services be constant-returns-to-scale CES with Hicks neutral disembodied technical change, and let the *ex post* substitution possibilities between energy (E) and utilized capital equipment services be zero -- in the spirit of a putty-clay specification. Using the first order conditions from cost minimization, we obtain the optimal *ex* ante energy intensity at time t, denoted by f_t, as

$$\ln f_t \equiv \ln (E/K)_t = a - \sigma \ln (P_E^*/P_K^*)_t \qquad (16)$$

where a is a constant, σ is the *ex ante* substitution elasticity between energy and capital equipment, and P_E^* and P_K^* are values of expected life cycle price functions, to be defined below. Note that this decision incorporates expected rates of utilization of this equipment.

Suppose at time $t-\tau$ enterpreneurs chose optimal $f_{t-\tau}$ ratios based on expected life cycle relative prices $(P_E^*/P_K^*)_{t-\tau}$, and that $(1-\delta)^\tau$ percent of this capital survives to time t. At time t, however, expected relative energy-capital equipment prices suddenly changed. If entrepreneurs were allowed to optimize over all their capital vintages, the new optimal energy intensity they would put in place would of course depend on $(P_E^*/P_K^*)_t$ according to (16). The relative energy intensities of these two types of capital turn out to be, for the CES function,

$$\frac{f_{t-t}}{f_t} = \left(\frac{P^*_{EK,t-t}}{P^*_{EK,t}}\right)^{-\sigma} , \tag{17}$$

where $P^*_{EK} \equiv (P^*_E/P_K)$ -- the value of the expected life cycle relative energy-capital equipment services price function. Note that if $P^*_{EK,t-\tau} < P^*_{EK,t}$ and $\sigma > 0$, then the ratio $f_{t-\tau}/f_t > 1$. Moreover, at time t total variable costs (here, energy costs) associated with $K_{t,t-\tau}$ capital equal $P_{Et} f_{t-\tau} K_{t,t-\tau}$ which will be greater than those for $K_{t,t}$ capital which equal $P_{Et} f_t K_{t,t}$. In order for the firm to be indifferent between $K_{t,t}$ and $K_{t,t-\tau}$ capital in terms of these _ex post_ variable costs and thus in terms of _ex post_ quasi-rents, it is necessary that the $K_{t,t-\tau}$ capital be re-weighted relative to the $K_{t,t}$ capital by the "shadow cost" factor $f_t/f_{t-\tau}$. Note, incidentally, that such weights could reflect less intensive utilization of the energy-inefficient vintages relative to the efficient vintages.

We therefore set $e_{t,t-\tau}$ equal to these relative "shadow values," i.e.,

$$e_{t,t-\tau} = \frac{f_t}{f_{t-\tau}} = \left(\frac{P^*_{EK,t-\tau}}{P^*_{EK,t}}\right)^{\sigma} . \tag{18}$$

We then substitute into (18) into (15) obtaining,

$$K^*_t = \sum_{\tau=0}^{T} \left(\frac{P^*_{EK,t-\tau}}{P^*_{EK,t}}\right)^{\sigma} s_\tau I_{t-\tau} = \sum_{t=0}^{T} \left(\frac{P^*_{EK,t-\tau}}{P^*_{EK,t}}\right)^{\sigma} K_{t,t-\tau} , \tag{19}$$

a measure of quality-adjusted capital that accounts for vintage-specific shadow values which in turn depend on $P^*_{EK,t-\tau}$ relative to $P^*_{EK,t}$ and the _ex ante_ substitution elasticity σ. These weights on capital vintages eliminate differences in operating costs and, therefore, leave the firm indifferent between them. Further, as will be discussed later, these $e_{t,t-\tau}$ weights may be interpreted as vintage-specific Tobin's q's and also have implications for the shape of age-shadow price profiles.

Before proceeding further, we first provide intuition regarding the interpretation of (19). Let the expected life cycle relative energy price be increasing, i.e. let $P^*_{EK,t} > P^*_{EK,t-\tau}$. If the _ex ante_ substitution elasticity σ were also zero, then optimal _ex ante_ and _ex post_ relative marginal products and hence optimal energy intensities f_t and $f_{t-\tau}$ would be equal, in spite of changes in P^*_{EK}. In such a nonsubstitution case, by (18) $e_{t,t-\tau} = 1$, and no vintage-specific capital revaluation need occur. This would correspond with the situation assumed by traditional capital aggregation procedures, in which _ex ante_ and _ex post_ substitution elasticities coincide.

Suppose instead, however, that $\sigma > 0$ and large. In such a case, provided $P^*_{EK,t} > P^*_{EK,t-\tau}$, optimal $f_{t-\tau}$ and f_t energy intensity ratios would differ significantly, and specifically, optimal $t-\tau$ vintages of capital equipment would be less energy-efficient than optimal t vintages. According to (18) and (19), in such a case $e_{t,t-\tau} < 1$, i.e. surviving capital of vintage $t-\tau$ purchased when $P^*_{EK,t-\tau}$ was smaller has a lower relative shadow value, and thus is given a smaller weight in computing the aggregate, quality-adjusted capital stock. As expected, the weight assigned earlier vintages decreases monotonically with increases in σ.

Now following (10), define $B_{K,t}$ as the aggregate quality-adjusted, multiplicative capital revalutation factor, i.e.

$$B_{K,t} = K^*_t/K_t \tag{20}$$

and note that by (19), $B_{K,t}$ depends on σ and on the mix of surviving vintages of capital. It can easily be shown based on (19) and (20) that what we define as the capital revaluation elasticity is simply, for the CES function, the negative of the _ex ante_ substitution elasticity, i.e.

$$\frac{\partial \ln B_{K,t}}{\partial \ln P^{*}_{E,t}} = \frac{\partial \ln K^{*}_{t}}{\partial \ln P^{*}_{E,t}} = -\sigma. \qquad (21)$$

This is eminently plausible, for it suggests that the extent to which fixed capital is revalued downward in response to unexpected energy price increases depends on the extent to which newly-optimized capital equipment has an embodied energy efficiency differing from that based on older expected relative energy-capital prices.

One other fact worth noting is that in manufacturing there exist many different types of capital -- equipment, structures, land, inventories, etc. In the empirical work to follow, due to data limitations, we shall consider only two types of capital -- producers' durable equipment and nonresidential structures It is reasonable to assume that the largest proportion of energy use in U.S manufacturing is associated with the operation of motive, process heating, and electrolytic equipment, rather than with the heating and lighting of structures.

To accommodate this, we specify that expected energy prices only affect durabl equipment quality, $K^{*}_{E,t}$, and not the quality of structures. We then form an aggregate K^{*}_{t} as a Cobb-Douglas function of $K^{*}_{E,t}$ and $K_{S,t}$ (the structures capital),

$$K^{*}_{t} = K^{*\alpha}_{E,t} \cdot K^{1-\alpha}_{S,t} = B_{K,t} \cdot K^{\alpha}_{E,t} \cdot K^{1-\alpha}_{s,t} = B_{K,t} \cdot K_{t} \qquad (22)$$

Data from U.S. manufacturing suggest a reasonable value of α is 0.6. Note that when (22) is substituted into (20), the capital revaluation elasticity (21) is changed to

$$\frac{\partial \ln B_{K,t}}{\partial \ln P^{*}_{E,t}} = \frac{\partial \ln K^{*}_{t}}{\partial \ln P^{*}_{E,t}} = -\alpha\,\sigma \qquad , \qquad (21')$$

i.e. σ is weighted by the equipment share in capital in order to obtain an overall fixed capital revaluation elasticity.

Earlier we note that $P^{*}_{EK,t}$ is the value of an expected life cycle relative price function affecting the optimal energy efficiency embodied in new equipment investment. Firms choosing such optimal energy efficiency are assumed to discount expected future prices $P_{E,t+\ell}$ and $P_{K,t+\ell}$ by the real discount rate r, recognizing that equipment put in place at the beginning of the next time period physically deteriorates at the annual rate δ until it is physically scrapped in T years. We therefore define $P^*_{EK,t}$ as the life cycle discounted forecast made at time t, i.e.

$$P^*_{EK,t} = \sum_{\ell=0}^{T} \hat{P}_{EK,t+\ell+1} \left(\frac{(1-\delta)^{\ell}}{(1+r)^{\ell+1}} \right) \tag{23}$$

where $\hat{P}_{EK,t+\ell}$ is the expected future price of $\hat{P}_{E,T+\ell}$ relative to to $\hat{P}_{K,t+\ell}$. In our empirical analysis, we will consider several alternative procedures for constructing $\hat{P}_{EK,t+\ell}$ forecasts.

Before leaving this section on capital aggregation and revaluation over vintages, we note that in our framework the relative shadow values of two vintages having unequal embodied energy efficiency are specified explicitly to depend on expected relative energy-capital prices. Hence our measure of K^*_t depends on P^*_{Et}, although this dependence is additively separable in logarithms -- see (20) and (22 Traditional capital stock procedures assume separability of each capital type from all other inputs -- including energy -- and thus cannot accommodate the situation in which choice among capital vintages depends on energy prices. Our measure K^*_t is a consistent aggregate, however, provided that it is interpreted as being conditional on P^*_{Et}.[5]

Having provided an analytical framework for interpreting input quality and quantity, and having defined capital quality, we now turn to empirical implementation and quantification of the capital revaluation elasticity.

V. MODEL FORMULATION

The model we employ is based on the assumption of short-run variable cost minimization and has as exogenous variables the prices of variable inputs P_E (energy), P_M (non-energy intermediate materials), P_L (labor), the quantity of output Y, the flow of traditionally measured available capital services K (which are assumed to be proportional to the stock), the quality of these available capital services B_K, and disembodied technical change, represented by t. Cost minimization implies that the endogenous variables are factor demands E, L and M, the extent to which available capital services are utilized, total variable costs, and the shadow value or <u>ex post</u> returns to the traditionally measured capital stock, denoted R_K. We now provide further details.

Based on Lau's Proposition I, we specify a constant-returns-to-scale production function defined in standardized or quality-adjusted units, $Y = F(K^*,L,E,M,t)$ where by Lau's Proposition II $K^* = B_K \cdot K$. Dual to this production function and associated with Lau's Proposition III, let there be a short-run variable or restricted cost function $CV = g(Y,P_L,P_E,P_M,K^*,t)$, relating the minimum variable costs CV incurred in producing output Y, given input prices P_L, P_E, P_M, the state of technology t, and the short run fixed, quality-adjusted flow of available capital services, K*.

Assume that g has the translog form[6]

$$
\begin{aligned}
\ln CV = {} & \alpha_0 + \alpha_Y \ln Y + \sum_i \alpha_i \ln P_i + \beta_K \ln K^* + \alpha_t t + 1/2\,\alpha_{tt} t^2 + 1/2\,\gamma_{YY}(\ln Y)^2 \\
& + 1/2 \sum_i \sum_j \gamma_{ij} \ln P_i \ln P_j + 1/2\,\delta_{KK}(\ln K^*)^2 + \sum_i \rho_{Yi} \ln Y \ln P_i \\
& + \rho_{YK} \ln Y \ln K^* + \sum_i \rho_{Ki} \ln K^* \ln P_i + \rho_{TY} t \ln Y + \rho_{TK} t \ln K^* \\
& + \sum_i \rho_{Ti} t \ln P_i\,, \qquad i = L, E, M
\end{aligned}
\tag{24}
$$

where $\gamma_{ij} = \gamma_{ji}$. Constant returns to scale on the dual production function $Y = F(K^*,L,E,M,t)$ imposes the following restrictions on (23):

$$
\begin{aligned}
& \alpha_Y + \beta_K = 1 \qquad && \rho_{Yi} + \rho_{Ki} = 0, \qquad && i = L, E, M \\
& \gamma_{YY} + \rho_{YK} = 0 && \rho_{YK} + \delta_{KK} = 0, && \rho_{TY} + \rho_{TK} = 0 \;.
\end{aligned}
\tag{25}
$$

When (22) is substituted into (24), the condition that variable costs be homogeneous of degree one in prices given output and capital quantity implies the restrictions:

$$(26)\qquad \sum_i \alpha_i - \alpha\,\sigma\,\beta_K = 1 \qquad \sum_j \gamma_{ij} - \alpha\,\sigma\,\rho_{Ki} = 0\ , \qquad i = L, E, M$$

$$\sum_i \rho_{Ti} - \alpha\,\sigma\,\rho_{TK} = 0 \qquad \sum_i \rho_{Ki} - \alpha\,\sigma\,\gamma_{YY} = 0\ .$$

We now logarithmically differentiate the variable cost function (24) with respect to K, and interpret the resulting shadow value of capital relationship as the percentage reduction in variable costs realized by increasing K, holding output quantity, capital quality, and input prices fixed. This yields

$$(27)\qquad \frac{\partial \ln CV}{\partial \ln K} \equiv SH_K = \frac{-R_K K}{CV} = \beta_K + \rho_{KL}\ln(P_L/P_M) + \rho_{KE}\ln(P_E/P_M)$$
$$+ \gamma_{YY}[\ln(K/Y) + \ln(B_K/P_M)] + \rho_{KT}\cdot t\ ,$$

where R_K is a capital shadow price incorporating the *ex post* (one period) return to traditionally measured capital. Note that according to (27), this *ex post* return to capital is endogenous, and depends on input prices, output demand, the quantity of capital K, its quality coefficient B_K, and disembodied technical change, represented by t. Hence a particularly attractive feature of (27) is that the shadow value of capital depends on the energy price-dependent quality of capital, as well as on cyclical output demand Y.[7]

Use of Lau's [1978] variant of Shephard's Lemma yields the variable input cost share equations:

$$(28)\quad \frac{\partial \ln CV}{\partial \ln P_L} = S_L = \frac{P_L L}{CV} = \alpha_L + \gamma_{LL}\ln(P_L/P_M) + \gamma_{LE}\ln(P_E/P_M) + \rho_{KL}[\ln(K/Y) + \ln(B_K/P_M] + \rho_{T}$$

$$(29)\quad \frac{\partial \ln CV}{\partial \ln P_M} = S_M = \frac{P_M M}{CV} = \alpha_M + \gamma_{LM}\ln(P_L/P_M) + \gamma_{EM}\ln(P_E/P_M) + \rho_{KM}[\ln(K/Y) + \ln(B_K/P_M)] + \rho_{T}$$

$$(30)\quad \frac{\partial \ln CV}{\partial \ln P_E} = S_E = \frac{P_E E}{CV} = \alpha_E + \gamma_{LE}\ln(P_L/P_M) + \gamma_{EE}\ln(P_E/P_M) + \rho_{KE}[\ln(K/Y) + \ln(B_K/P_M)]$$
$$+ \rho_{TE}\cdot t - \alpha\,\sigma\,SH_K\ .$$

A number of comments are worth noting here. First, when the restrictions (25) and (26) are imposed, the variable input shares sum to unity; this implies that only two of the three variable input share equations are linearly independent. Second, these variable input demand equations depend not only on the quantity of available capital services K but also on their quality, B_K. To see this, substitute back from (28) to (20), and obtain for the labor variable input share (28),

$$(28') \qquad S_L = \alpha_L + \gamma_{LL} \ln(P_L/P_M) + \gamma_{LE} \ln(P_E/P_M) + \rho_{KL} \ln(K^*/Y) + \rho_{TL} \cdot t ,$$

which makes clear the quantity-quality interaction in this factor demand model. Third, since K/Y (and K*/Y) are exogenous in (28)-(30), these variable input equations generate endogenous utilization of available capital services K; while energy and utilized capital services are non-substitutable ex post, the extent to which available capital services are utilized is endogenous and depends on Y, K, K*, P_L, P_E, P_M, and t.

Fourth, energy price changes have direct (via P_E in (28)-(30)) and indirect (via K*, which in turn depends on P_E) effects on variable input and shadow value relationships, where the direct effect is the traditional short-run substitution and utilization effect induced by energy price changes, and the indirect effect stems from the induced reduction in the quality of available capital services generated by the energy price increases. Further, if $\sigma = 0$, then by (19) and (20) $B_K = 1$ and the translog specification reverts to the traditional form where quality issues are not relevant. Hence $\sigma = 0$ is a testable special case of (27)-(30).

We now address several econometric issues. First, we append an additive disturbance term to (27) and to two of the three linearly independent equations in (28)-(30), and assume in addition that the resulting disturbance vector is independently and identically multivariate normally distributed with mean vector zero and constant nonsingular covariance matrix. Second, note that since the endogenous "shadow share" SH_K also appears as a regressor in the S_E equation (29), the implied log-likelihood function has a Jacobian term. It can easily be shown, however, that the Jacobian term involves a triangular matrix whose determinant is unity, implying that estimation by the iterated "seemingly unrelated" Zellner estimation method is numerically equivalent to estimation by full information maximum likelihood.[8] This triangularity occurs even though disturbances across equations may be contemporaneously correlated, since the S_E share depends on endogenous SH_K, but SH_K is not a function of endogenous S_L, S_E or S_M.

Third, note that identification of σ is not possible if only two of the three linearly independent variable input cost share equations (28)-(30) are estimated; identification is attainable, however, if one also estimates the shadow share relationship (27) and/or the variable cost function (24).

Fourth, according to (23), (20) and (19), the variable B_K is a distributed lag of length T of previous discounted expected life cycle relative energy-equipment prices and real investment in equipment. Explicit substitution for B_K in (27)-(30) would therefore involve very long and nonlinear estimation formulae, whose numerical convergence may be difficult to obtain. We have therefore embarked on the strategy of assuming a value for σ, generating the implied B_K using (19) and historical data on I_t and $P^*_{EK,t}$, and then estimating (28)-(30) by maximum likelihood, conditional on this σ. A grid of different σ values is employed, and that value of σ which generates the largest sample log-likelihood is then chosen as the maximum likelihood estimate.

The final econometric issue concerns nonstatic expectations. Specifically, since the capital quality factor augmentation index $B_{K,t}$ (20) depends on expected life cycle rather than current relative energy-capital equipment prices -- see (19) -- it is possible that traditional estimation procedures employing only current-valued variables could suffer from an errors-in-variables problem and could therefore yield inconsistent estimates of the parameters.

In order to deal with the issue of nonstatic expectations, we pursue and compare several approaches. First, if one believes entrepreneurs assumed future values of $\hat{P}_{EK}$ would grow at a constant rate g, i.e. if

$$\hat{P}_{EK,t+\ell} = (1+g)^{\ell} P_{EK,t} \quad , \tag{31}$$

then $P^*_{EK,t}$ in (23) is the sum of a finite geometric series,

$$P^*_{EK,t} = \Gamma \; P_{EK,t} \tag{32}$$

where $\Gamma = (1-\lambda^T)/(1-\lambda)$ and $\lambda = (1-\delta)(1+g)/(1+r)$. In such a case, substitution into (16) results in a composite intercept term $a^* = a + \ln \Gamma$, but leaves (17) unaffected. Hence, use of $P_{EK,t}$ as a regressor in (17) instead of $P^*_{EK,t}$ is appropriate if throughout the historical sample investors assumed P_{EK} would grow at a constant rate g. While such a hypothesis is unlikely to be reasonable (see Figures 1 and 2), we employ it as a basis for comparison with other assumptions.

A more plausible hypothesis is that entrepreneurs constructed time-varying forecasts based on historical data, and updated these forecasts given new information. We therefore employ time series techniques and obtain forecasts of $P_{EK,t+}$ using Box-Jenkins procedures, and then construct $P^*_{EK,t}$ by discounting these forecasts according to (23). Such time-series forecasts are preferable to those based on constant growth rate assumptions as in (31), but it is still possible that these forecasted $P^*_{EK,t}$ contain measurement errors correlated with the equation disturbances.

Our third econometric procedure deals with measurement errors and unobservable variables more directly, and relates to a tradition of employing instrumental variables, established by Miller-Modigliani [1966], McCallum [1976], Lahiri [1976] and Startz [1983]. Specifically, given time series forecasts of $P^*_{EK,t}$, the resulting $B_{K,t}$ (see (19) and (20)) is treated as measuring "true" capital quality with error. In turn, $B_{K,t}$ is then related via a regression equation to a number of exogenous variables correlated with $B_{K,t}$ but independent of the measurement error, and the fitted value of this equation is then used as an instrument to attain consistent (but not necessarily efficient) estimates of the parameters. Incidentally, if one chooses these exogenous variables judiciously so that they can be interpreted as comprising the information set available to firms which form the basis of their expectations at time t, then as has been noted by Pindyck-Rotemberg [1983], the residual measurement error is by instrumental variable estimation orthogonal to the regressors -- the information set available to firms. Since the expectation of this error term is zero, under the assumption of conditional homoskedasticity the resulting estimates are consistent with the error-orthogonality property of the rational expectations hypothesis (REH), even though the REH is not explicitly incorporated into the model.[9]

A final alternative procedure for estimation of this nonstatic expectations or errors in variables model involves the method of maximum likelihood, and is due to Goldberger [1972], Griliches [1974], Hausman [1977] and Lahiri-Schmidt [1978]. Let us rewrite the shadow value relationship (27) as

(33) $y_1 = x\beta_1 + z^*\gamma_1 + \varepsilon_1$,

and the labor and energy cost share equations (27) and (29) as

(34) $y_2 = x\beta_2 + z^*\gamma_2 + \varepsilon_2$, and

(35) $y_3 = x\beta_3 + z^*\gamma_3 + y_1\delta_3 + \varepsilon_3$

where y_1, y_2 and y_3 are SH_K, S_L, and S_E, respectively, x is a vector of exogenous variables measured without error (in this case, it includes $\ln(P_E/P_M)$, $\ln(P_L/P_M)$, $\ln(K/Y)$ and t), and β_1, β_2 and β_3 are the associated parameter vectors. The variable z* is the "true" capital quality variable in (27), (28) and (30), equal to $\ln(B_K/P_M)$, but it is measured by z with random error, i.e.

(36) $z = z^* + \varepsilon_4$.

Finally, a number of other (latent) variables w are specified to affect the capital quality variable.

$$(37) \qquad z^* = w\alpha_5 + \varepsilon_5 \quad ,$$

where w is a vector of selected exogenous variables measured without error, and β_5 and α_5 are associated parameter vectors to be estimated.

The ε_i are random disturbance terms, each with a zero expectation. These ε_i are assumed to have constant variances and covariances, denoted σ_{ij}, $i,j=1,\ldots 5$ Since ε_4 is a random measurement error, it is assumed that $\sigma_{14}=\sigma_{24}=\sigma_{34}=\sigma_{45}=0$.

When (36) is inserted into (33)-(35) and (37) is substituted into (36), the resulting composite disturbance vectors u_i in terms of the original ε_i turn out to be $u_i = \varepsilon_i - \gamma_i\varepsilon_4$, $i = 1, 2$, $u_3 = -(\gamma_3 + \delta_3\gamma_1)\varepsilon_4 + \delta_3\varepsilon_1 + \varepsilon_3$, and $u_4 = \varepsilon_4 + \varepsilon_5$. Denote the resulting symmetric covariance matrix of the u_i as Ω, whose upper triangle can be shown to be equal to

$$(38) \qquad \Omega = \begin{bmatrix} \sigma_{11}+\gamma_1^2\sigma_{44} & \sigma_{12}+\gamma_1\gamma_2\sigma_{44} & \sigma_{13}+\delta_3\sigma_{11}+\gamma_1\gamma_6\sigma_{44} & -\gamma_1\sigma_{44}+\sigma_{15} \\ & \sigma_{22}+\gamma_2^2\sigma_{44} & \sigma_{23}+\delta_3\sigma_{12}+\gamma_2\gamma_6\sigma_{44} & -\gamma_2\sigma_{44}+\sigma_{25} \\ & & \sigma_{33}+\delta_3^2\sigma_{11}+2\delta_3\sigma_{13}+\gamma_6^2\sigma_{44} & -\gamma_6\sigma_{44}+\sigma_{35}+\delta_3\sigma_{15} \\ & & & \sigma_{44}+\sigma_{55} \end{bmatrix}$$

where $\gamma_6 = \gamma_3 + \delta_3\gamma_1$. This 4 x 4 covariance matrix has ten free elements, but given any γ_i and δ_3 estimates there are eleven non-zero σ_{ij} to be estimated. To attain identification, one of σ_{15}, σ_{25} and σ_{35} can be set to zero; note that if all three of these σ_{ij} are set to zero, overidentification occurs and Ω must be restricted.[10]

We proceed by setting $\sigma_{15} = 0$, but allow σ_{25} and σ_{35} to be non-zero. Now assume that the disturbance vector u is independently and identically multivariate normally distributed with mean vector zero and constant nonsingular covariance matrix Ω. The concentrated log-likelihood can be shown to be

$$(39) \qquad \ln L = \text{constant} - N/2 \ln |\Omega| + N \ln |J| ,$$

where N is the number of observations in each equation and where the Jacobian transformation term is $\{ \partial u_i / \partial y_j \}$, i=1,2,3,4 and $y_j = y_1, y_2, y_3$, and z,

$$(40) \qquad |J| = \begin{vmatrix} 1 & 0 & 0 & -\gamma_1 \\ 0 & 1 & 0 & -\gamma_2 \\ -\delta_3 & 0 & 1 & -\gamma_3 \\ 0 & 0 & 0 & 1 \end{vmatrix} .$$

Note that even though J is non-triangular, it can easily be triangularized, and thus its determinant is unity. Therefore ln |J| drops out of the log-likelihood function (39), which implies that the iterated Zellner estimator provides parameter estimates numerically equivalent to the full information maximum likelihood estimator of this model with measurement errors.

In the empirical implementation reported below, we estimate the shadow, labor and energy share equations (27), (28) and (30) by maximum likelihood assuming time invariant constant growth rate expectations -- see (31) -- and no measurement error. We denote this estimation procedure as Method I, and note also that myopic expectations are a special case of this when g = 0.

Our second estimation procedure involves nonstatic expectations more directly, and computes forecasted $\hat{P}_{EK,t+\ell}$ based on time series analysis. Specifically, using Box-Jenkins techniques, the 1931-81 series was represented by an AR(1) process, first differenced in logarithms, with the estimated autocorrelation coefficient being 0.451, and having a standard error of 0.131. This specification yielded low and statistically insignificant residual autocorrelations, as judged by the Box-Pierce Q-statistic. For each time period beginning with T years prior to 1958, the $\hat{P}_{EK,t+\ell}$ series were forecasted and then discounted using (23), with r = .10. The resulting $P^*_{EK,t}$ were then used in estimation by the maximum likelihood method, under the assumption of no measurement error or, of having a stochastic error uncorrelated with the equation disturbances. This estimation procedure is denoted Method II.

As our third estimation procedure, we allow for disturbance-correlated measurement error in $P^*_{EK,t}$, and estimate the three-equation system (27), (28), and (30) by the three-stage least squares (3SLS) instrumental variable estimator, using as instruments a constant, t, and current, once- and twice-lagged values of the exogenous variables $\ln(K/Y)$ and $\ln(P_L/P_M)$. Note that $\ln(P_E/P_M)$ is not used as an instrument, for P_E enters into the calculation of $P^*_{EK,t}$. This 3SLS procedure is denoted Method III, and provides consistent (but not necessarily efficient) estimates of the parameters in the presence of measurement error.

Finally, we estimate the four equation system consisting of (27), (28), and (30), along with the measurement error equation

$$(41) \qquad \begin{aligned} \ln(B_K/P_M)_t = {} & a_0 + a_1 \ln(K/Y)_t + a_2 \ln(K/Y)_{t-1} + a_3 \ln(K/Y)_{t-2} \\ & + a_4 \ln(P_L/P_M)_t + a_5 \ln(P_L/P_M)_{t-1} + a_6 \ln(P_L/P_M)_{t-2} \\ & + a_7 \cdot t + u_{4,t} \end{aligned}$$

by the method of FIML, as outlined above, using the time series forecasts to construct $P^*_{EK,t+\ell}$. This procedure is denoted by Method IV and, under the assumptions made above, provides consistent and asymptotically efficient estimates of the parameters in the context of simultaneity and measurement error.

VI. DATA AND EMPIRICAL RESULTS

A. Data

We now turn to a discussion of data, parameter estimates, and implied estimates of the revalued capital stock. Although data on all variables are available for the 1950-81 time period, certain data series from 1950-57 have been constructed using proportionality and interpolation techniques, and thus are of lower quality than those beginning in 1958. Since direct annual survey observations based on the Census and the Annual Survey of Manufacturers (ASM) began only in 1958, we concentrate on the 1958-81 time period.

The data series on L and P_L are taken from Berndt-Morrison [1979], updated to 1981. Labor quantity measures incorporate changes over time in hours at work per week for production and nonproduction workers, as well as educational attainment; the corresponding wage rate includes costs to employers of supplementary benefits.

Data series for Y, P_E, E, P_M and M for 1931-81 are taken from Berndt-Wood [1975, 1979] updated through 1981 using data from the Census and ASM, and the Bureau of Economic Analysis (BEA). Updates for Y are taken from BEA worksheets underlying the computation of manufacturing value added, and were provided us by Vesta Jones. Updates to P_E and E are based on the ASM Fuel and Electric Power reports for fuel and power consumption, and the 1972 and 1977 Census of Manufacturing for "feedstock" consumption. Finally, the P_M and M updates are based on the gross intermediate materials (materials, services and energy) data from the BEA worksheets minus the energy components.

The data series on K was constructed as a Divisia quantity index of producers' durable equipment (EQUIP) and non-residential structures (STRUC). In turn, the EQUIP and STRUC series were computed using the perpetual inventory method and investment data since 1929, provided by Mr. Jerry Silverstein of the U.S. Department of Commerce, Bureau of Economic Analysis.

As in Berndt-Wood [1975, 1979], the assumed rates of geometric physical deterioration are .135 for EQUIP and .071 for STRUC. For equipment, this rate of deterioration implies that 95% of any initial investment is deteriorated in 21 years; we therefore set the physical lifetime for T in (19) equal to 21.

The rental prices for EQUIP and STRUC used in the Divisia aggregation procedure are of the Hall-Jorgenson form, with effective tax rates incorporated; this tax data was provided us by Dale Jorgenson, Barbara Fraumeni, Daniel Holland, and Stewart C. Myers. Since K is exogenous in the short-run, the measure of K must reflect available rather than the endogenous actual utilized services (recall that the former are assumed to be proportional to available stocks). Thus the interest rate used is the *ex ante* Moody Baa corporate bond yield, rather than an *ex post* return to capital. By contrast, the rate of return used in R_K, the endogenous shadow value of capital relationship, incorporates *ex post* returns to capital in the manufacturing sector; this data was kindly provided by Daniel Holland and Stewart C. Myers, and incorporates updates of series presented in their 1980 paper.

In order to calculate the series underlying K* since 1958, it is necessary to obtain data on P_{EK} for T years prior to 1958, which in this case is since 1937. Berndt-Wood [1984] discuss procedures for computing a Divisia index of various energy types from 1906-1950; many of their data sources have also been discussed by Schurr-Netschert [1960]. The variable $P_{EK} = P_E/PEQUIP$ is constructed as the ratio of the aggregate energy price to the rental price of equipment, both normalized to unity in 1972, where the rental price again incorporates tax variables and the exogenous Moody Baa corporate bond yield.

B. Empirical Results

Estimation of the quality-quantity model proceeded in a grid search manner, initially with σ ranging from 0.0 to 1.50 in steps of 0.05. Once the range of the largest maximized sample log-likelihood was obtained, we re-estimated with σ varying within this range in steps of 0.005. For 3SLS, the same grid procedure was employed, and E'HH'E was minimized. Computations were carried out using the Time Series Processer, Version 4.0D, on the Harvard University Science Center Vax 780.

Since the estimation was carried out conditional on a value of σ, the standard error estimates and corresponding asymptotic t-ratios in Table 2 must be interpreted as conditional. To obtain an asymptotic t-ratio for σ, we estimated the model with $\sigma=0$, used the likelihood ratio test procedure to obtain a chi-square test statistic with one degree of freedom, and then obtained the asymptotic t-ratio as the square root of this chi-square variable.[11]

In Table 1 we report alternative estimates of the *ex ante* energy-capital equipment substitution σ, as well as of the implied capital revaluation elasticity, $-\alpha\sigma$. As noted earlier, α -- the share of equipment in total equipment-structures capital -- has been set at 0.6. When estimation is undertaken assuming constant growth expectations and no measurement error in (23) and (31), the Method I ML estimate obtained for σ is 0.935, with an asymptotic t-ratio of 3.72; the implied capital revaluation elasticity is -0.561. If, however, future $\hat{P}_{EK}$ are constructed based on estimated time series parameters, and if these forecasts are then assumed either to have no measurement error or to have an error uncorrelated with the equation disturbances, the Method II M_L estimate of σ drops to 0.650, with an asymptotic t-ratio of 4.73; the implied capital revaluation elasticity falls to -0.390.

Neither Method I nor Method II estimates account for possible measurement error that could be correlated with the equation disturbances. When 3SLS (Method III) and FIML (Method IV) estimation procedures are employed that accommodate such measurement errors, the range of σ estimates increases, from 0.905 (t = 3.41) for Method III to 0.390 (t = 3.82) for Method IV; the

Table 1
Alternative Estimates of the Ex Ante Energy-Capital Equipment Substitution Elasticity, and the Capital Revaluation Elasticity, U.S. Manufacturing
(Asymptotic t-ratio in parentheses)

	Elasticity	
	σ	$-\alpha\sigma$
Method 1 (Constant growth expectations, no measurement error, maximum likelihood)	0.935 (3.72)	-0.561
Method II (Nonstatic expectations, no measurement error, maximum likelihood)	0.650 (4.73)	-0.390
Method III (Nonstatic expectations, measurement error, 3SLS)	0.905 (3.41)	-0.543
Method IV (Nonstatic expectations, measurement error, maximum likelihood)	0.390 (3.82)	-0.234

corresponding capital revaluation elasticities are -0.543 and -0.234, respectively. Note that the Method III and IV estimates bracket that of Method II, and that by coincidence the Method II estimate is approximately the mean of the Method III and IV estimates. We therefore view our Method IV estimate of σ (0.390) as a conservative one, that based on Method III (0.905) as an upper bound, and the Method II estimate as our preferred mid-range estimate.

In Table 2 we present parameter estimates and associated statistics for Models I through IV. As is seen there, the parameter estimates do not change dramatically when the estimation procedure is altered. However, note that Method III estimates of ρ_{TL}, γ_{LM}, and γ_{MM} differ in sign from those of the other methods, as does the Method IV estimate of γ_{LE}.

At the bottom of Table 2 we report goodness-of-fit statistics. In each of the estimated equations (and in the implicitly estimated S_M equation), the fit is good, and surprisingly good for the energy share equation. For the Method III estimates, the value of the J statistic (E'HH'E) is 11.966, which implies that the test for overidentifying restrictions cannot be rejected; the .05 chi-square critical value with eleven degrees of freedom is 19.675.

In terms of autocorrelation, to the extent that the Durbin-Watson statistic is appropriate for equations in this model, autocorrelation does not appear to be significant, although the Method III statistics for the S_L and S_M equations are marginal. A more appropriate procedure, proposed by Breusch and Godfrey [1981], is to employ the vector of lagged residuals in the augmented equation system and to test for first order vector autocorrelation using the Lagrange Multiplier test. For the three equation system estimated by Methods I, II and III, the test statistics for the null hypothesis that the full autocovariance matrix is zero are 9.362, 9.988, and 9.547, respectively; the .05 chi-square critical value with nine degrees of freedom is 16.919.[12] For the four equation system estimated by Method IV, the corresponding test

Table 2

Parameter Estimates of Translog Variable Cost Function Model
U.S. Manufacturing, 1958-81
(Asymptotic t-ratios in Parentheses)

Parameter	Method I	Method II	Method III	Method IV*
σ	0.935	.650	.905	.390
	(3.72)	(4.73)	(3.41)	(3.82)
β_K	-.103	-.106	-.100	-.106
	(12.53)	(14.57)	(12.61)	(11.32)
α_L	.408	.408	.371	.433
	(34.91)	(31.64)	(18.58)	(30.76)
α_E	.008	.024	.004	.048
	(1.15)	(3.78)	(0.65)	(7.36)
α_M	.526	.527	.571	.494
	(36.78)	(32.83)	(23.86)	(27.95)
ρ_{KL}	.028	.023	.050	.036
	(3.98)	(3.47)	(2.42)	(4.99)
ρ_{KE}	.004	.006	.008	.011
	(1.54)	(2.35)	(2.34)	(3.96)
ρ_{KM}	-.043	-.037	-.072	-.052
	(5.29)	(4.68)	(2.87)	(6.13)
γ_{YY}	-.020	-.021	-.025	-0.25
	(5.09)	(6.38)	(4.19)	(5.50)
ρ_{TK}	-.001	-.001	-.002	-.001
	(4.43)	(5.29)	(2.80)	(6.25)
ρ_{TL}	-.001	-.002	.0037	-.001
	(1.86)	(3.05)	(1.20)	(2.42)
ρ_{TE}	.0003	.0003	.001	.0002
	(2.35)	(2.55)	(2.73)	(2.20)
ρ_{TM}	.0003	.001	-.005	.0007
	(0.38)	(1.58)	(1.55)	(1.17)
γ_{LL}	.136	.153	-.047	.148
	(5.79)	(6.93)	(0.45)	(7.17)
γ_{LE}	-.004	-.004	-.032	.001
	(0.85)	(0.85)	(2.43)	(0.27)
γ_{LM}	-.116	.139	.106	-.141
	(4.16)	(5.34)	(0.85)	(5.80)

Table 2

(continued)

Parameter	Method I	Method II	Method III	Method IV*
γ_{LM}	-.116 (4.16)	-.139 (5.34)	.106 (0.85)	-.141 (5.80)
γ_{EE}	.072 (24.66)	.071 (27.79)	.069 (23.21)	.073 (31.12)
γ_{EM}	-.066 (10.46)	-.065 (9.95)	-.032 (2.01)	-.072 (11.40)
γ_{MM}	.170 (5.18)	.196 (6.36)	-.098 (0.66)	.203 (7.04)
ln L or E'HH'E	352.501	356.759	11.966	408.013
Breusch-Godfrey LM or Wald test	9.362	9.988	9.547	25.516
R^2 $-SH_K$	0.883	0.914	0.896	0.891
S_L	0.974	0.968	0.945	0.969
S_E	0.995	0.996	0.996	0.997
S_M	0.784	0.765	0.659	0.799
$\ln(B_K/P_M)$	--	--	--	0.994
DW $-SH_K$	1.528	1.571	1.584	1.531
S_L	1.655	1.583	0.989	1.610
S_E	2.108	2.136	1.926	2.318
S_K	1.713	1.587	1.072	1.602
$\ln(B_K/P_M)$	--	--	--	1.402

*The estimates and asymptotic t-statistics for the a_0 - a_7 parameters are, respectively, -.284(0.89), -.530(4.55), .103(0.75), -.366(3.04), 2.622(10.34), -.365(1.04), .327(1.47), and -.080(45.30) statistic is 25.516, while the .05 chi-square critical value with 16 degrees of freedom is 26.296. Together, these results imply that disturbances in the various models are free of first order correlation, although the Method IV estimates are only marginally so. Incidentally, as noted by Breusch-Godfrey, these test statistics correspond to either a test of first order vector autoregressive or first order vector moving average errors.

We now turn to a discussion of the implications of the above estimates for the measurement of revalued capital. In Table 3 we present traditional measures of capital (K), annually 1958-81, as well as estimates of the multiplicative capital augmentation coefficient B_K, where $K^*_t = B_{K,t} \cdot K_t$. Estimates of $B_{K,t}$ are presented for Methods II, III and IV; Method I estimates are not reported since they would be very close to that of Method III. Recall that if no revaluation occurred, all $B_{K,t}$ would equal unity.

Due primarily to falling expected relative energy prices from 1958-70, until 1970 B_K was slightly larger than unity (except for 1964), and was especially large in 1968-69 (from 1.049 to 1.121), when actual $P_{EK,t}$ attained its historical minimum value. The $B_{K,t}$ values for 1971-73 were slightly less than unity (real energy prices began to rise in 1970 -- see Figure 1), but fell sharply in 1974 as OPEC-I occurred; the conservative estimate (Method IV) is that a 15% downward revaluation resulted, the upper bound estimate (Method III) is 33%, and the mid-range Method II estimate is 25%. As growth in real energy prices stabilized from 1975 to 1978, however, $B_{K,t}$ rose to .875 (Method III), .902 (Method II), or .935 (Method IV). When OPEC-II occurred in 1979-80, $B_{K,t}$ values again fell, although the drop was not as sharp as earlier since substantial new energy-efficient investment had already taken place (see Figure 3). By 1981, a conservative estimate is that capital plant and equipment had been revalued downward by 13%, the upper bound estimate is 26%, and the mid-range estimate is 20%.

Table 3

Traditional and Quality-Adjusted Measures of Fixed Capital in U.S. Manufacturing, 1958-81
Calculations Based on Methods II, III, and IV Estimates

	K	B_K(II)	B_K(III)	B_K(IV)
1958	134.475	1.043	1.061	1.025
1959	134.855	1.084	1.121	1.049
1960	134.659	1.056	1.080	1.032
1961	136.106	1.048	1.069	1.028
1962	137.053	1.014	1.022	1.008
1963	139.003	1.021	1.031	1.012
1964	142.068	0.980	0.974	0.988
1965	147.489	1.035	1.050	1.021
1966	156.910	1.053	1.075	1.031
1967	169.493	1.051	1.073	1.030
1968	181.069	1.085	1.121	1.050
1969	187.976	1.084	1.121	1.049
1970	195.189	1.062	1.089	1.036
1971	200.106	0.998	0.998	0.998
1972	201.621	0.994	0.993	0.996
1973	205.710	0.952	0.934	0.970
1974	211.375	0.713	0.625	0.816
1975	221.207	0.795	0.735	0.868
1976	227.478	0.874	0.840	0.918
1977	233.621	0.842	0.796	0.898
1978	242.304	0.902	0.875	0.935
1979	251.924	0.825	0.772	0.888
1980	267.061	0.772	0.704	0.852
1981	284.757	0.801	0.743	0.870

Table 4

Traditional and Quality-Adjusted Measures of Capital-Labor Ratios in U.S. Manufacturing, 1958-81 Calculations Based on Methods II, III, and IV Estimates

	K*/L(I)	K*/L(II)	K*/L(III)	K*/L(IV)
1958	.221	.230	.234	.226
1959	.208	.226	.233	.218
1960	.206	.217	.222	.212
1961	.211	.221	.226	.217
1962	.201	.204	.206	.203
1963	.203	.207	.209	.205
1964	.202	.198	.196	.199
1965	.199	.206	.209	.204
1966	.198	.208	.213	.204
1967	.211	.222	.226	.217
1968	.222	.241	.249	.233
1969	.227	.246	.254	.238
1970	.248	.263	.270	.257
1971	.262	.261	.261	.261
1972	.252	.251	.250	.251
1973	.241	.230	.225	.234
1974	.252	.179	.157	.205
1975	.288	.229	.212	.250
1976	.283	.247	.237	.259
1977	.279	.235	.222	.251
1978	.277	.250	.243	.260
1979	.282	.233	.218	.250
1980	.311	.240	.219	.264
1981	.333	.266	.247	.289

It is worth noting that while this amount of capital revaluation may appear to be very large, our measure of K refers only to equipment and structures, and does not include land, working capital and inventories; roughly, together these latter assets tend to be equal in value to the sum of equipment and structures. Hence, assuming that energy price-induced revaluation does not occur for land, working capital, and inventories, the capital revaluation for total capital might be only half as large as that implied in Table 3.[13]

Another way in which one can assess the damages wrought by OPEC-I and OPEC-II is to examine traditional and revalued capital-labor ratios; these series are presented in Table 4. As is seen there, althought the traditional K/L ratios rose 23% between 1972 and 1980, revalued K*/L ratios fell 12% (Method III), fell 4% (Method II), or increased only 5% (Method IV). Since conservative (Method IV) estimates of $B_{K,t}$ in 1971 and 1980 are virtually identical while mid-range Method II estimates are equal in 1970 and 1981, one view of the damages sustained by the U.S. manufacturing sector is that effective or quality-adjusted capital-labor ratios by 1980 were set back about a decade. Whether this stagnation or drop in K*/L ratios helps explain the slow growth in real wages over the last decade remains, however, an issue for further research.

VII. CONCLUDING REMARKS AND OBSERVATIONS

In this paper we have pursued three goals, namely, (i) to develop an analytical framework consistent with the theory of cost and production that provides an intuitively appealing interpretation of the capital revaluation phenomenon, (ii) to implement the model empirically and obtain plausible estimates of the important elasticities, and (iii) to outline some of the implications of the capital revaluation phenomenon. While much more work remains to be done, we believe that in this paper we have made substantial progress in attaining all three goals.

In the spirit of a putty-clay model with fixed energy-capital service coefficients ex post, we have demonstrated that the revaluation elasticity is the negative of the ex ante substitution elasticity between energy and capital equipment. The time path of depreciation of durable capital thus depends on the age of the capital, the current expected energy-capital price relative to that prevailing when the surviving vintages were originally acquired, and the ex ante substitution elasticity between energy and capital equipment. Hence this model allows for variable depreciation in a manner advocated by Feldstein-Rothschild [1974].

A useful way of summarizing our empirical results involves graphing age-shadow profiles for surviving vintages of capital, evaluated in different relative energy price eras. Recall that in our model, economic depreciation and physical deterioration will coincide only if $P^*_{Ek,t}$ remains constant over time, in which case vintage-specific shadow prices will decline with age at a constant rate δ. Such a geometric age-price profile is shown in Figure 4 by the smooth profile and square boxes. If, however, expected relative energy prices suddenly increase (decrease) at time t after an extended period of stability, then shadow values for vintages acquired earlier will fall (rise) to a lower (higher) level than would be the case with constant geometric depreciation.

With this in mind, in Figure 4 we plot three alternative age-shadow price profiles for producers' durable equipment, that occuring in 1969 when real energy prices were still falling (the profile with plus signs), in 1975 when the effects of OPEC-I were becoming clearer (the profile with triangles), and in 1981 after both OPEC-I and OPEC-II had occurred (the profile with diamonds). In all cases, the relative value of a new asset has been normalized to unity.

FIGURE 4 Equipment Age-Price Profiles

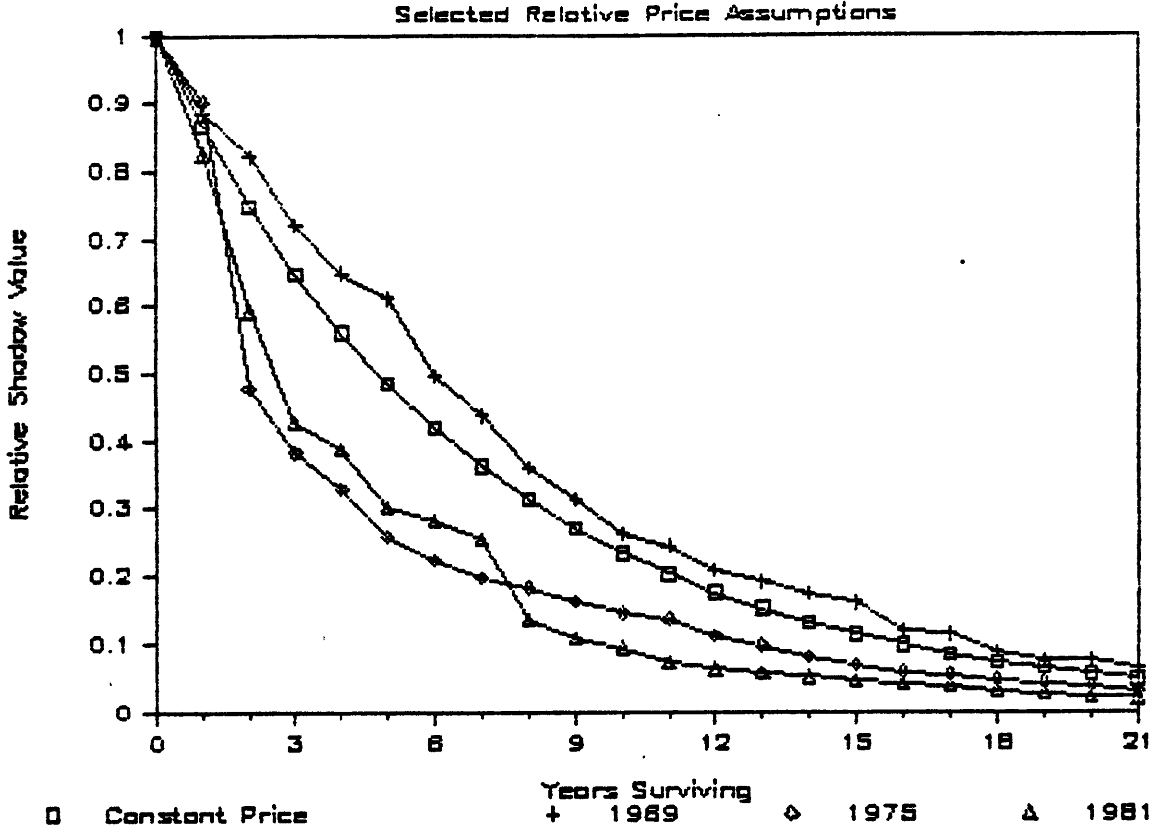
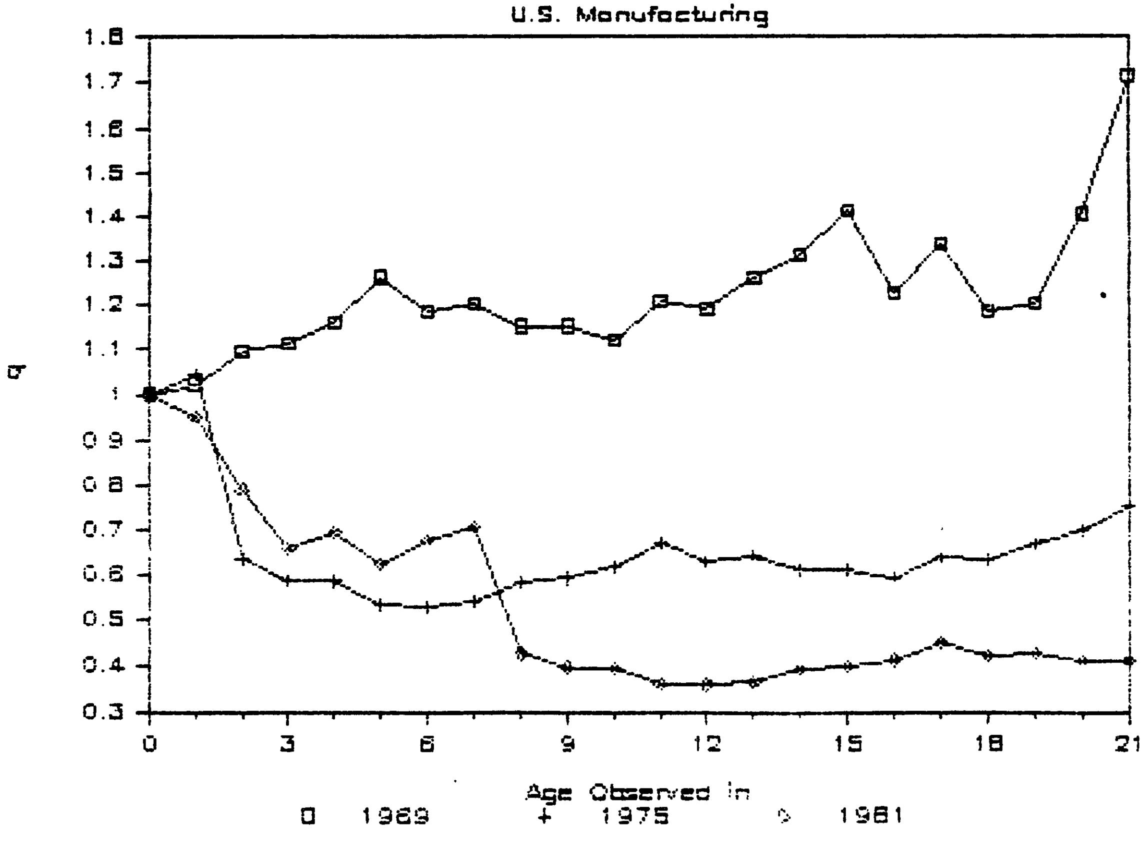


FIGURE 5 Vintage-Specific q's for Equipment



Notice first that with 1969 relative energy prices, the entire age-price profile is above that for constant geometric decay, and thus the rate of economic depreciation is generally smaller than δ. For example, a five-year old asset in 1969 has a shadow value of about 20% greater than that implied by constant geometric depreciation. By contrast, the 1975 and 1981 age-shadow price profiles both lie entirely underneath that for constant depreciation. Two-year old equipment in 1975 has about a 35% lower shadow value than two-year old equipment with constant depreciation, and a 45% lower shadow value than two-year old equipment observed in 1969 when relative energy prices were still falling. Note also that the 1975 age-price profile is initially below that for 1981, but these profiles cross between ages seven and eight, after which the 1981 profile is lower. This crossover occurs, since eight year and older assets observed in 1981 were acquired before OPEC-I in 1973, and thus experienced greater depreciation. Finally, note that even when equipment is ten years old, substantial differences in age-price profiles persist -- as seen in Figure 4, the relative shadow values range from about 0.11 (1975 prices) to 0.26 (1969 prices). These empirical results demonstrate quite clearly the important impact of unexpected changes in relative energy prices on the economic depreciation of durable equipment in the manufacturing sector.

Because of this energy price-induced economic depreciation, we find that by 1981 the appropriately revalued capital stock (equipment plus structures) is between 13% and 26% less than that indicated by traditional measures; our mid-range Method II estimate of this downward revaluation is 20%. We believe these results are plausible, and also help to explain: (i) why Tobin's q measures for U.S. manufacturing suddenly fell from about 1.0 to 0.6 in 1974, (ii) why these q measures have remained within the 0.5 to 0.7 range since 1973, and (iii) why investment has been substantial in the last decade even while q values were below unity.

More specifically, following David Wildasin [1984], one can envisage the overall (average) q as a weighted average of vintage-specific q's. In fact, if one assigns the value of unity to the q on current investment, one can interpret our $e_{t,t-\tau}$ vintage-specific aggregation weights in (18) and (19) as vintage-specific q's, for they represent the ratio of the shadow value of $K_{t,t-\tau}$ capital to its depreciated "book value." On a second-hand market, for example, at time t firms would only be willing to pay $e_{t,t-\tau}$ for a dollar of $K_{t,t-\tau}$ capital, since that is its shadow value relative to a dollar of $K_{t,t}$ capital.

To highlight this q interpretation of our $e_{t,t-\tau}$ weights, in Figure 5 we graph vintage-specific q's for equipment, evaluated in 1969 when relative energy prices were still falling, in 1975 after OPEC-I, and in 1981 after both OPEC-I and OPEC-II, all based on our mid-range Method II estimates. Notice that in 1969, all the vintage-specific q's are greater than unity, due to unexpected falling energy prices of the 1969 era. By contrast, the vintage-specific q's are all less than one for vintages observed in 1975 or 1981, since by post-OPEC standards these vintages are energy-inefficient. As an extreme example, in 1981 a twelve-year old asset (acquired in 1969 when relative energy prices were at their historical minimum value) had a q of only about 0.4. Thus the entries in Figure 5 illustrate the revaluation of durable capital equipment wrought by OPEC-I and II.

Finally, our empirical results also have implications for the measurement of capacity utilization and multifactor productivity growth. Recent apparent low rates of estimated capacity utilization in certain U.S. manufacturing industries might be biased downward, since a portion of the underlying capital stock has been subject to extraordinary economic depreciation. Moreover, to the extent capital services have been incorrectly measured, especially since OPEC-I and OPEC-II, our results tend to support the Martin Baily [1981a,b] hypothesis that the correct measurement of capital services since 1973 could provide an important ingredient in unraveling the post-1973 productivity growth slowdown.[14] Future empirical research on interactions among capacity utilization, multifactor productivity growth, and capital revaluation therefore appears particularly promising, as does research on capital revaluation at a more disaggregated level of detail.

Our analytical framework might be extended in a number of ways. For example, in our model T, the physical lifetime of assets, is fixed; in a more general model T might be specified to depend on accumulated utilization. It should be noted, however, that it is not necessarily the case that T will fall as unexpected energy price increases occur; for example, old "gas guzzlers" may be utilized less on an annual basis, and thus their lifetimes may actually increase. Further, the effect of changes in vintage-specific lifetimes on aggregate capital measures may not be very significant empirically, since $(1-\delta)^T$ is already rather small for $T > 15$.

In terms of other analytical extensions, although we have posited a homogeneously separable ex ante sub-production function between energy and utilized capital services, we have not investigated what conditions might be necessary to impose envelope consistency of this ex ante function with the ex post short-run translog variable cost function.[15] In general, this dynamic optimization problem of irreversibility is difficult to model, especially in an empirically amenable manner; see, for example, Ben Bernanke [1983]. However, a tractable and interesting extension would involve analysis of what type of investment function is consistent with our quality-quantity model with multiplicative factor augmentation of capital.

Footnotes

[1] For discussion of these and other related energy data, see Berndt-Wood [1984].

[2] See Muellbauer [1975] for quality specifications in the context of utility functions; also see Hall [1968], Diamond, McFadden and Rodriguez [1978], Mohr [1980], Norsworthy-Zabala [1983], and especially Lau [1982].

[3] See, for example, the studies by Daly-Mayor [1983], Kahn [1982], and Ohta-Griliches [1983].

[4] For further discussion, see Diamond [1965].

[5] For further discussion on capital aggregation issues, see Robert M. Solow [1956] and F. M. Fisher [1965], on weakly recursive separability see Charles Blackorby et al. [1975], and on conditional aggregate indexes see Robert Pollak [1975].

[6] Brown-Christensen [1981] provide a discussion of the translog restricted cost function.

[7] We are indebted to Melvyn Fuss, who first pointed out to us the possibility of employing this shadow value relationship as an equation to be estimated.

[8] Note, however, that while one-step Zellner estimation provides inconsistent estimates of the parameters, iterated Zellner estimation is numerically equivalent to full information maximum likelihood. See Lahiri-Schmidt [1978] and Hausman [1984] for further discussion.

[9] Pindyck-Rotemberg note that this procedure is due to a suggestion in Hansen-Singleton [1982].

[10] Note that there are, however, sign restrictions on the elements of Ω in (38) when it is just identified; see Goldberger for further discussion.

[11] When 3SLS estimation was employed, the asymptotic t-ratio was computed as the square root of the difference in the E'HH'E or J statistic, with $\sigma = 0$ and with σ at its minimized E'HH'E value.

Footnotes (cont.)

[12] For 3SLS estimation, the Wald rather than LM test statistic is appropriate and was therefore computed; see Breusch-Godfrey, Appendix A, for further discussion.

[13] However, to the extent that unintended inventory accumulation consists of durable, energy-intensive products, inventories might also be subject to energy price induced capital revaluation.

[14] Further elaboration of the reduced capital services hypothesis is provided by Gordon [1981] and Solow [1981]. For an alternative discussion of this slowdown, see Jorgenson-Fraumeni [1981]; an historical overview is also provided by Hamilton [1983].

[15] For a discussion of such issues, see Fuss-McFadden [1978] and Fuss [1978]. Also, note that in our framework depreciation and physical lifetimes of capital are exogenous; see Epstein-Denny [1980] for a model with endogenous depreciation.

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