NBER WORKING PAPER SERIES

FACTOR ADJUSTMENT, QUALITY CHANGE, AND PRODUCTIVITY GROWTH FOR U.S. MANUFACTURING

Jeffrey I. Bernstein
Theofanis P. Mamuneas
Panos Pashardes

Working Paper 6877
http://www.nber.org/papers/w6877

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
January 1999

Factor Adjustment, Quality Change, and Productivity
Growth for U.S. Manufacturing
Jeffrey I. Bernstein, Theofanis P. Mamuneas,
and Panos Pashardes
NBER Working Paper No. 6877
January 1999
JEL No. D24, D47

ABSTRACT

This paper accounts for quality improvements and adjustment costs in all inputs to U.S. manufacturing production. Adjustment processes for non-capital inputs are slower than previously recognized. Annual adjustment percentages are: labor 77, capital 30, energy 20, and materials 21. Factor prices should be adjusted for quality improvements to reflect higher marginal products. The percentage increases in marginal products from quality improvements are: labor 0.25, capital 0.30, energy 2.13, and materials 0.92. Observed input growth should be adjusted for quality improvements. Unadjusted input growth causes efficiency-based productivity growth rates to exceed observed productivity growth in the slowdown period of 1974 - 1995.

Jeffrey I. Bernstein
Department of Economics
Carleton University
1125 Colonel By Drive
Ottawa, Ontario K1S 5B6
Canada
and NBER
jeff_bernstein@carleton.ca

Theofanis P. Mamuneas
Department of Economics
University of Cyprus
P.O. Bos 537
CY-1678
Nicosia, Cyprus
Theo.Mamuneas@ucy.ac.cy

Panos Pashardes
Department of Economics
University of Cyprus
P.O. Bos 537
CY-1678
Nicosia, Cyprus
Panos.Pashardes@ucy.ac.cy

1. INTRODUCTION

Factor quality advances through improvements in the design of capital and intermediate inputs, and through augmenting labor skills. However, there are costs to adjusting improved factors of production that reflect integrating equipment into production processes, training labor, and negotiating with intermediate input suppliers. Increasing factor quality raises the value of marginal products, while adjustment costs increase marginal input costs. As a consequence in the determination of factor requirements, marginal benefits, inclusive of quality improvements, must be sufficiently large to account for both factor prices and marginal adjustment costs. Thus quality improvements and adjustment costs affect the rate of factor accumulation, and thereby output, and productivity growth. This paper estimates input quality improvements, and adjustment costs, and examines the resulting implications for productivity growth in the US manufacturing sector.

The literature on input quality has developed quite independently of the adjustment cost literature, as evidenced in the recent survey by Nadiri and Prucha [1998]. In this paper, we narrow this gap. We develop a model that shows quality indexes are related to rates of factor adjustment. Coupling quality change with adjustment speeds fosters the integration of a diverse literature. This literature applies to studies on interrelated factor adjustment in the manufacturing sector (see Nadiri and Rosen [1969], Morrison and Berndt [1981], Epstein and Denny [1983], Pindyck and Rottemberg [1983], and Bernstein and Mohnen [1998]). It extends to empirical work on embodied technical change (see Jorgenson [1966], Griliches [1967], Jorgenson, Gollop and Fraumeni [1987], and Hulten [1992]).

Quality improvements and adjustment costs are usually associated with capital inputs, and occasionally with labor. Generally, intermediate inputs are assumed to have zero adjustment costs, and no quality enhanced features. However, since intermediate inputs are outputs from upstream producers, they would commonly encompass quality improvements. In this paper an empirical model of production is developed and estimated that accounts for quality improvements and adjustment costs associated with all factors of production; namely labor, capital, and intermediate inputs. There is no fixed boundary defining factors subject to adjustment costs and quality improvements on one side, and costlessly adjustable factors absent quality progression on the other.

Since quality improvements affect the future stream of marginal products, expected factor prices play important roles in determining factor requirements, and speeds of adjustment. For example, expected increases in future acquisition or hiring prices increase expected discounted marginal input costs. Higher inflation rates make it more expensive to adjust factor demands, and consequently marginal adjustment costs rise. Thus, in equilibrium, marginal product values must increase as a result of quality improvements in order to offset higher marginal adjustment costs.

Tests on the type of price expectations generating mechanisms are generally not undertaken in applications of dynamic production models. In this paper expected price generating mechanisms are specified for each factor acquisition or hiring price, and jointly estimated with the factor demand equations. Tests are conducted on the nature of price expectations, and marginal adjustment costs are calculated under different price expectation mechanisms to determine the biases in adjustment speeds associated with misspecifying expectations.

Incorrectly accounting for quality improvements and adjustment costs biases the rate of factor accumulation. These biases lead to measurement errors in the calculation of productivity growth rates.[1] In this paper we investigate the extent and source of these measurement errors by calculating productivity growth rates that encompass quality improvements and adjustment costs. One important consequence of our analysis is that the usual measures of productivity growth substantially underestimate "true" productivity growth in the slowdown period since the early 1970's. Indeed, failing to adjust for the improvements in labor, capital, and particularly intermediate inputs has led to the underestimation of productivity growth over the last two decades.

This paper is organized into four further sections. Section 2 develops the theoretical model of production with quality improvement and factor adjustment. Section 3 contains

[1] Griliches [1994], and Diewert and Fox [1997] have suggested that ignoring or incorrectly accounting for inflation rates has been an important cause of measurement error associated with productivity growth rates. Hulten [1992] has discussed output and input quantity corrections in a growth accounting framework.

the discussion on the empirical specification, including price expectation mechanisms, the regression results, hypothesis tests, and calculation of adjustment speeds, and rates of quality improvement. In section 4 productivity growth rates that capture quality improvements and adjustment costs are measured, and compared to growth rates that do not reflect these benefits and costs. The last section of the paper contains the conclusions.

2. PRODUCTION, QUALITY, AND ADJUSTMENT

This section models the determinants of factor requirements when there are adjustment processes that reflect the costs of integrating qualitatively improved factors into output production.

To begin, consider a production function

$$y_t = F(z_{1t}, ..., z_{nt}, t), \tag{1}$$

where y_t is output quantity in period t, F is the production function, z_{it} is the ith utilized input quantity in period t, and t also represents the exogenous disembodied technology indicator.

The accumulation of inputs is represented by the condition

$$v_{it} = x_{it} + (1 - \delta_i)v_{it-1}, \; i = 1, ..., n, \tag{2}$$

where v_{it} is the quantity of the ith input, and x_{it} is the addition to the quantity of the ith input in period t. Factor quantity (v_{it}) is not necessarily equal to the utilized quantity of the input (z_{it}) that enters the production function. In addition, δ_i is the ith depreciation rate, such that $0 \leq \delta_i \leq 1$. If the ith factor is not durable (in other words, it is not accumulated over more than one period), then $\delta_i = 1$, and $v_{it} = x_{it}$.

The relationship between input quantity and utilized input quantity has been specified in a number of different ways. A general relationship that encompasses the various forms is given by:

$$v_{it} - h_{it}(v_{it-1}) = m_{it}\left[z_{it} - g_{it}(v_{it-1})\right], \; i = 1, ..., n. \tag{3}$$

Equation (3) shows that factor accumulation depends on the difference between utilized and existing factor quantity. The functions denoted by h and g represent the possibility that measurement units can differ between current and past quantities. This can occur because of such elements as the loss of productive efficiency through depreciation, gains in productive efficiency through quality improvements, factor augmenting and embodied technological change.

By the specialization of the h and g functions in (3), we are able to characterize various models of factor accumulation in the literature. First, if $h_{it}(v_{it-1}) = g_{it}(v_{it-1}) = v_{it-1}$, and $m_{it} = m_i$, then we obtain the Nadiri-Rosen [1969] factor adjustment model, with:

$$z_{it} = v_{it-1} + m_i^{-1} \Delta v_{it}. \tag{3a}$$

In this case m_i represents the rate of factor adjustment for the ith factor.

Second, if $h_{it}(v_{it-1}) = g_{it}(v_{it-1}) = (1-\delta_i)v_{it-1}$, and $m_{it} = m_i$ then:

$$z_{it} = (1-\delta_i)v_{it-1} + m_i^{-1} x_{it} \tag{3b}$$

Equation (3b) relates to the Pakes-Griliches [1985] factor accumulation model. Here m_i^{-1} represents the index of productiveness or the quality index associated with additions to the ith factor. Equation (3b) is similar to (3a). The latter relates to net factor accumulation, while (3b) is defined in terms of gross additions.

Third, if $h_{it}(v_{it-1}) = (1-\delta_i)v_{it-1}$, $g_{it}(v_{it-1}) = m_{it}^{-1}(1-\delta_i)v_{it-1}$, and m_{it} is exogenous, then:

$$z_{it} = m_{it}^{-1}\left[(1-\delta_i)v_{it-1} + x_{it}\right] = m_{it}^{-1} v_{it}. \tag{3c}$$

The parameter m_{it}^{-1} is the index of ith factor quality or the index of augmenting technological efficiency in period t (see the survey by Solow [1967], and the empirical paper by Jorgenson and Griliches [1967]). There are two interpretations applicable to (3c). First, in the absence of a general disembodied technology index in the production function, (3c) depicts the special case of factor augmenting disembodied technology indicators. Second, with a general index of disembodied technology then $m_{it} = m_i$, and (3c) depicts quality indexes. Since we have included a general index of disembodied technology in the production function, the latter interpretation applies. In this case (3c) is equivalent to (3b), since normalizing the $g_{it}(v_{it-1})$ function that defines equation (3c) by the m_i parameter yields (3b).

Fourth, if $h_{it}(v_{it-1}) = (1-\delta_i)v_{it-1}$, $g_{it}(v_{it-1}) = m_{it}^{-1}(1-\delta_i)v_{it-1}$, and $m_{it}^{-1} = [x_{it}\Phi_{it} + (1-\delta_i)x_{it-1}\Phi_{it-1} + \ldots + (1-\delta_i)^t x_{i0}\Phi_{i0}]/v_{it} = \Psi_{it}$, where Φ_{it} is the index of technological efficiency for factor i in period t then:

$$z_{it} = \Psi_{it}v_{it}. \tag{3d}$$

In this model $m_{it}^{-1} = \Psi_{it}$ is an endogenous variable and it represents the average embodied technological efficiency of the ith factor in period t (see Solow [1960], and recently Hulten [1992], along with other references cited in the latter paper).[2] Equation (3d) cannot be estimated because there are as many efficiency parameters, Φ_{it}, as time periods for each factor of production. Thus for T periods and n factors, there are nT technological efficiency parameters. If the efficiency parameters are time invariant then (3d) is equivalent to (3b).

Equation set (3a) to (3d) show how factor adjustment, input quality, and technological change have been treated in the empirical literature. It is interesting to note these seemingly disparate models are contained within a unifying specification. In adapting the model for the purpose of estimation, we assume (3b), the Pakes-Griliches formulation, for inputs such as physical capital whose depreciation rates are $0 \leq \delta_i < 1$. Additionally, we use (3a), following Nadiri-Rosen, for inputs such as labor that are not accumulated beyond one period, ($\delta_i = 1$). Although (3b) could be pertinent to all inputs, it appears reasonable to view the rate of adjustment applying to factor additions even if they depreciate in a single period. If a particular input is not accumulated, gross additions to it are synonymous with levels, and so with (3b) adjustment parameters are irrelevant, and can be normalized to unity. This normalization implies that adjustment is completed in one period. However,

[2] It is possible to have indexes of disembodied and embodied technology within one model. If only the latter is considered relevant then in conjunction with (3d), the t variable in the production function is deleted.

such features as training costs could lead to adjustment rates that extend beyond one period, even for a factor of production that is not accumulated. Thus we use (3a) for these inputs.

Equation (3a) and (3b) can be written as:

$$z_{it} = (1 - \iota\delta_i)v_{it-1} + m_i^{-1}x_{it}, \tag{3e}$$

where $\iota = 1$, for $0 \leq \delta_i < 1$, and $\iota = 0$, for $\delta_i = 1$. As noted the parameter m_i^{-1} represents the quality index relating to additions of the ith factor.

Utilized input demands are governed by the minimization of the expected present value of acquisition or hiring cost. The expected present value at time t (defined as the current time period) is given by the following:

$$\sum_{s=0}^{\infty}\sum_{i=1}^{n} a(t, t+s)q^e_{it+s}x_{it+s}, \tag{4}$$

where q^e_{it+s} is the expectation in the current period t of the ith factor acquisition (or hiring) price in period $t+s$, $a(t, t+s)$ is the discount factor with $a(t,t) = 1$, and $a(t, t+1) = (1+\rho_{t+1})^{-1}$, where ρ_{t+1} is the discount rate from period t to period $t+1$.[3] The expression in (4) is minimized subject to equation sets (1), (2) and (3e).

Replacing z_{it}, and x_{it}, by substituting equation sets (2), and (3e) into (1) and (4), the Lagrangian for the problem is:

$$\begin{aligned}\mathcal{L} = \sum_{s=0}^{\infty} a(t, t+s)\Bigg\{&\sum_{i=1}^{n} q^e_{it+s}\left[v_{it+s} - (1-\delta_i)\, v_{it+s-1}\right] \\ &- \lambda_{t+s}\left[F\left(\frac{v_{1t+s} - \gamma_1\mu_1 v_{1t+s-1}}{m_1}, \ldots, \frac{v_{nt+s} - \gamma_n\mu_n v_{nt+s-1}}{m_n}, t+s\right) - y_{t+s}\right]\Bigg\}\end{aligned} \tag{5}$$

where λ_{t+s} is the Lagrangian multiplier in period $t+s$, $\mu_i = (1 - m_i)$ and $\gamma_i = (1 - \iota\delta_i)$. Based on (5) the first order conditions for the ith input quantity in period $t+s$ is:

$$\begin{aligned} a(t, t+s)q^e_{it+s} - a(t, t+s)\lambda_{t+s}\frac{\partial F}{\partial z_{it+s}}m_i^{-1} - a(t, t+s+1)q^e_{it+s+1}(1-\delta_i) \\ + a(t, t+s+1)\gamma_i\mu_i\lambda_{t+s+1}\frac{\partial F}{\partial z_{it+s+1}}m_i^{-1} = 0,\ i = 1, \ldots, n.\end{aligned} \tag{6}$$

[3] As is common in dynamic models, we are assuming that the real discount rate is constant (see Nadiri and Prucha [1998], for a survey).

Dividing (6) by $a(t, t+s)$, and defining $w^e_{it+s} = q^e_{t+s} - aq^e_{it+s+1}(1-\delta_i)$ as the period t, expected ith factor price in period $t+s$, and $a = a(t, t+s+1)/a(t, t+s)$ is the constant discount factor, equation (6) can be written as:

$$\lambda_{t+s}\frac{\partial F}{\partial z_{it+s}}m_i^{-1} = w^e_{it+s} + a\gamma_i\mu_i\lambda_{t+s+1}\frac{\partial F}{\partial z_{it+s+1}}m_i^{-1}, \; i = 1, ..., n. \tag{7}$$

Evaluating (7), for the time periods from t to $t+T$, and solving the system recursively leads to:[4]

$$\lambda_t\frac{\partial F}{\partial z_{it}}m_i^{-1} = \sum_{s=0}^{T} w^e_{it+s}(a\gamma_i\mu_i)^s + (a\gamma_i\mu_i)^{T+1}\lambda_{t+T+1}\frac{\partial F}{\partial z_{it+T+1}}m_i^{-1}, \; i = 1, .., n. \tag{8}$$

Letting $T = \infty$, and imposing the transversality condition that the shadow value of the marginal product for each factor is zero at $T = \infty$, so for $i = 1, ..., n$, $\lambda_{t+T+1}\partial F/\partial z_{it+T+1} = 0$, then we find that:

$$\lambda_t\frac{\partial F}{\partial z_{it}}m_i^{-1} = \sum_{s=0}^{\infty} w^e_{it+s}(a\gamma_i\mu_i)^s, \; i = 1, ..., n. \tag{9}$$

Equation (9) shows the shadow value of the marginal product for factor i, in the current period, equals the ith user cost, which is defined by the right side of (9). There are two ways to interpret (9). One view emphasizes the cost side and focuses on factor adjustment costs. The other view accentuates the benefits from quality improvements that are associated with factor additions. Under the adjustment cost view, equation (3e) shows that adjustment costs are incurred as inputs grow in order to increase factor utilization. These costs create a wedge between marginal product values and factor prices (given by (10)). The difference is necessary to pay for the marginal cost of factor adjustment. By rewriting (9), marginal adjustment cost is obtained from:

$$\lambda_t\frac{\partial F}{\partial z_{it}}m_i^{-1} - w_{it} = \sum_{s=1}^{\infty} w^e_{it+s}(a\gamma_i\mu_i)^s, \; i = 1, ..., n. \tag{9a}$$

[4] At this point there is no need to specify the expectations generating processes associated with the acquisition or hiring prices. Whatever the processes, they only depend on exogenous variables. One example would be autoregressive processes of any finite order.

The right side of (9a) is the marginal adjustment cost for the ith factor and it equals expected discounted future factor prices associated with the remaining adjustment of a unit of the ith input.

Under the quality improvement view, equation (3e) shows the gains arising from the utilization of improved factor additions. In this context, the right-hand side of (9a) shows the expected discounted value of the additional benefits arising from the quality improvements to the ith factor.

The user cost in this model generalizes the traditional user cost, because it is inclusive of quality indexes (or rates of adjustment). This can be seen by assuming that quality indexes are equal to one (that is $m_i = 1$) so that $\mu_i = 0$, then the right-hand side of (9) becomes

$$w_{it}^e = q_{it}^e - aq_{it+1}^e(1-\delta_i) = q_{it} - aq_{it+1}^e(1-\delta_i) = w_{it}, \tag{10}$$

which is the traditional factor price or user cost. Since w_{it+s}^e is the period t, expected ith factor price in period $t+s$, the right-hand side of (9) shows that user costs equal the discounted value of quality adjusted expected factor prices. Thus equation (9) shows how to adjust user costs for quality change. Estimating the model enables us to determine these quality parameters and calculate quality adjusted user costs.

User costs exceed current factor prices (w_{it}) by the wedge $\sum_{s=1}^{\infty} w_{it+s}^e(a\gamma_i\mu_i)^s$. Expressing user costs in this manner highlights another feature of the model. Quality change and incomplete factor adjustment imply that user costs are related to future acquisition and hiring prices, and therefore depends on price expectations. Thus future inflation rates affect current user costs. In estimating the model we incorporate and test alternative expectation generating processes. Usually in dynamic models of production one form of expectation generating process is maintained, and generally constant price expectations are assumed (see Pashardes [1986], and the survey by Nadiri and Prucha [1998]).

An alternative way to cast the problem defined by (4) is in terms of user costs. The first order conditions given by (9) reveals that the problem defined by (4) is equivalent to the following:

$$\min_{\zeta_{it}} \sum_{i=1}^{n} \omega_{it}\zeta_{it}, \tag{11}$$

subject to the production function given by $y_t = F(\zeta_{1t}/m_1, ..., \zeta_{nt}/m_n, t)$, for periods $t = 0, ..., \infty$, where $\zeta_{it} = z_{it}m_i$ is the adjusted ith factor utilization in period t, and ω_{it}, the ith user cost in period t, equals the right side of (9). The problem defined by (11) leads to the first order conditions given by (9).Thus the conditions used to determine utilized factor requirements (z_{it}), are identical to those characterizing adjusted ith factor utilization (ζ_{it}).

The optimized value of (11) defines the cost function denoted as:

$$C(\omega_{1t}, ..., \omega_{nt}, y_t, t), \tag{12}$$

and by Shephard's Lemma (see Diewert [1982]), it is possible to retrieve adjusted factor utilization such that:

$$Z_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = \frac{\partial C(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\partial \omega_{it}}, \ i = 1, ..., n. \tag{13}$$

Equation set (13) shows the determinants of utilized factor adjustment. The adjustment of ith factor utilization depends on all user costs, output quantity, and technology indicator. In addition, through the user costs, adjustment depends on expected acquisition and hiring prices, adjustment parameters.

Equation set (13) cannot be implemented because adjusted factor utilization is not observable. These variables are unobservable because adjustment parameters (m_i) are unknown, and data are usually unavailable for utilized factor quantities (z_i). However, since factor quantities (denoted as v_i) are observable, substitute (13) into (3e):

$$V_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = \frac{\partial C(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\partial \omega_{it}} + \gamma_i\mu_i v_{it-1}, \ i = 1, ..., n. \tag{14}$$

Equation set (14) shows the equilibrium conditions for factor demands defined in terms of observable factor quantities. These demands depend on the same set of variables that determine adjusted factor utilization. However, this system of equations can be estimated after specifying a cost function, and price expectation generating processes.

3. MODEL SPECIFICATION AND ESTIMATION

In this section of the paper the estimation results pertaining to rates of factor adjustment and price expectations in the U.S. manufacturing sector are discussed. As noted, it is necessary to specify a cost function and expectations generating processes for the acquisition and hiring prices. The cost function, (12), is assumed to be the symmetric generalized McFadden functional form introduced by Diewert and Wales [1987]:

$$c_t = \left(\sum_{i=1}^{n} \beta_i \omega_{it} + \frac{.5 \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \omega_{it} \omega_{jt}}{\sum_{i=1}^{n} b_i \omega_{it}} + \sum_{i=1}^{n} \beta_{it} \omega_{it} t + \beta_{tt} t^2 \sum_{i=1}^{n} b_i \omega_{it} \right) y_t$$
$$+ \sum_{i=1}^{n} \alpha_i \omega_{it} + \alpha_t t \sum_{i=1}^{n} b_i \omega_{it} + \alpha_{yy} y_t^2 \sum_{i=1}^{n} b_i \omega_{it}, \tag{15}$$

where the parameters are denoted by the α's and β's. The $n \times n$ matrix formed by the β_{ij}, parameters is symmetric and negative semidefinite, so that the function is concave in factor prices (or user costs). The b_i, $i = 1, ..., n$ are nonnegative constants that are not all zero for some reference time period τ. For the reference time period, the cost function is homogenous of degree one in user costs if $\sum_{i=1}^{n} \beta_{ij} \omega_{i\tau} = 0$, and $\sum_{i=1}^{n} b_i \omega_{i\tau} \neq 0$. The expression $\sum_{i=1}^{n} b_i \omega_{it}$ is an index of input prices, and the constants b_i, $i = 1, ..., n$ are set equal to the input cost shares in the reference time period.[5] This functional form is attractive because it has the important property of flexibility even if the concavity of the cost function with respect to user costs is imposed (see Diewert and Wales [1988]).[6]

Based on the specified cost function (15), and dividing by output quantity, ith factor demand (shown by (14)) per unit of output (or the ith factor intensity) becomes,

$$\frac{V_i(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{y_t} = \beta_i + \frac{\sum_{j=1}^{n} \beta_{ij} \omega_{jt}}{\sum_{i=1}^{n} b_i \omega_{it}} - \frac{.5 b_i \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \omega_{it} \omega_{jt}}{(\sum_{i=1}^{n} b_i \omega_{it})^2}$$
$$+ \beta_{it} t + \beta_{tt} b_i t^2 + \frac{\alpha_i}{y_t} + \frac{b_i \alpha_{it} t}{y_t} + b_i \alpha_{yy} y_t + \gamma_i \mu_i \frac{v_{it-1}}{y_t}, i = 1, .., n. \tag{16}$$

[5] The reference time period is 1992, the year that the price indexes are normalized to unity.

[6] Constant returns to scale and zero technological change are not imposed on the cost function. Constant returns to scale for the adjusted inputs implies the parameter restrictions, $\alpha_i = \alpha_{yy} = \alpha_t = 0$, $i = 1, ..., n$. The parameter restrictions for no technological change are, $\beta_{it} = \beta_{tt} = \alpha_t = 0$, $i = 1, ..., n$.

The second requirement needed to estimate (14) are the expectation generating processes for the acquisition and hiring prices. It is assumed that expectations of an acquisition or hiring price follows a first order autoregressive process:[7]

$$q_{it+1} = \phi_i + \theta_i q_{it} + e_{it}, \; i = 1, ..., n, \tag{17}$$

where ϕ_i, and θ_i are parameters, e_{it} is identically and independently distributed over time, and since expectations are rational, the expected value of e_{it} is zero. Equation set (17) implies in the current period t, that the ith expected acquisition or hiring price in period $t+s$ is,

$$q^e_{it+s} = \frac{\phi_i(1-\theta_i^s)}{(1-\theta_i)} + \theta_i^s q_{it}, \; i = 1, ..., n. \tag{18}$$

Recall from (9) that the user cost for the ith factor in period t is:

$$\omega_{it} = \sum_{s=0}^{\infty} w^e_{it+s}(a\gamma_i\mu_i)^s = \sum_{s=0}^{\infty} \left[q^e_{it+s} - aq^e_{it+s+1}(1-\delta_i)\right](a\gamma_i\mu_i)^s, \; i = 1, ..., n \tag{19}$$

Substituting (18) into (19) yields:

$$\omega_{it} = \sum_{s=0}^{\infty}(a\gamma_i\mu_i)^s \left[\frac{\phi_i(1-\theta_i^s)}{(1-\theta_i)} + \theta_i^s q_{it} - ad_i\frac{\phi_i(1-\theta_i^{s+1})}{(1-\theta_i)} - ad_i\theta_i^{s+1}q_{it}\right] \tag{20}$$

for $i = 1, ..., n$, and where $d_i = (1-\delta_i)$. Collecting terms, (20) becomes

$$\begin{aligned} \omega_{it} &= q_{it}(1-ad_i\theta_i)\sum_{s=0}^{\infty}(a\gamma_i\mu_i\theta_i)^s \\ &+ \frac{\phi_i}{(1-\theta_i)}\left[(1-ad_i)\sum_{s=0}^{\infty}(a\gamma_i\mu_i)^s - (1-ad_i\theta_i)\sum_{s=0}^{\infty}(a\gamma_i\mu_i\theta_i)^s\right] \end{aligned} \tag{21}$$

and so

$$\omega_{it} = q_{it}\frac{1-ad_i\theta_i}{1-a\gamma_i\mu_i\theta_i} + \frac{\phi_i}{1-\theta_i}\left(\frac{1-ad_i}{1-a\gamma_i\mu_i} - \frac{1-ad_i\theta_i}{1-a\gamma_i\mu_i\theta_i}\right), \; i = 1, ..., n. \tag{22}$$

Equation (22) shows the user cost for the ith factor in period t. In this model the user costs are unobservable because of two parameter sets; the adjustment parameter (μ_i), and

[7]The model was also estimated under the assumption that prices followed second order autoregressive processes. However first order processes could not be rejected as the expectations generating mechanisms.

the price expectations parameters (ϕ_i, θ_i). In the special case when factors are completely adjusted, so that $\mu_i = 0$, then (22) becomes

$$\omega_{it} = q_{it}(1 - ad_i\theta_i) - ad_i\phi_i \tag{23}$$

A special case of rational, first order autoregressive price expectations is constant (or static) expectations. In this case prices are expected to remain constant over time, so that $\phi_i = 0$, $\theta_i = 1$, $i = 1, ..., n$. Thus (22) specializes to

$$\omega_{it} = q_{it}\frac{1 - ad_i}{1 - a\gamma_i\mu_i} \tag{24}$$

Moreover, a combination of constant price expectations and completely adjusted factors implies from (23) and (24), recalling with $a = (1+\rho)^{-1}$, and $d_i = (1 - \delta_i)$, that:

$$\omega_{it} = q_{it}\frac{\rho + \delta_i}{1 + \rho}, \tag{25}$$

which is the usual user cost. Equation (23), (24), and (25) show that the hypotheses of completely adjusted factors, along with constant price expectations are contained within the more general delineation of user costs in this model.[8]

Substituting (22) into (16), and along with (17) defines the system of equations that is to be estimated. We append optimizing errors $u_t = (u_{1t}, ..., u_{nt})$ to equation set (16), assuming these to be identically, independently, jointly normally distributed with zero expected value. In addition, with the errors from (17), $e_t = (e_{1t}, ..., e_{nt})$, let $E\left[(u_t, e_t)(u_s, e_s)^T\right] = \Omega$, for all s, t if $s = t$, and 0 if $s \neq t$. The matrix Ω is the positive definite covariance matrix. Equation sets (16) and (17) are jointly estimated by the Nonlinear Seemingly Unrelated Regression estimator applied to data for the U.S. manufacturing sector over the period from 1952 to 1996. There are four factors of production; labor, capital, energy, and materials (including purchased services). Thus equation set (16) and (17) consist of eight equations. There are

[8] If prices are expected to grow at a constant rate then the restrictions become $\phi_i = 0$ for $i = 1, ..., n$, and $\theta_i = \theta_j = \theta$, $i \neq j$ and $i, j = 1, ..., n$. Thus from (21) $\omega_{it} = q_{it}(1 - ad_i\theta)/(1 - a\gamma_i\mu_i\theta)$. However, by defining $(1+\rho) = (1+r)(1+\psi)$, where r is the real discount rate, and setting the discount factor to grow at the same rate as the acquisition or hiring prices then $\theta - 1 = \psi$. Substituting $\theta - 1$ for ψ into ω_{it}, shows that the user cost is independent of θ. Hence without loss of generality, θ can be set to unity.

four factor intensity equations, and four equations relating to the acquisition and hiring prices. The data used to estimate the model are discussed and presented in the Appendix.[9]

Four variants of the model are estimated: (i) factor adjustment, and *AR(1)* rational price expectations; (ii) factor adjustment and constant price expectations; (iii) fully adjusted factors and *AR(1)* rational price expectations; and (iv) fully adjusted factors and constant price expectations. The first two variants characterize dynamic models, because factors have not completely adjusted. The regression results for these two cases are presented in table 1. The last two cases assume that factors have completely adjusted. These are the static versions of the model, and their regression results are presented in table 2.

Cases (i) and (iii) are nested and variants (ii) and (iv) are nested. This feature justifies the use of Likelihood Ratio (LR) tests to determine the preferred specifications among the two groups.[10] The first and second rows of table 3 show that the static cases (iii) and (iv) are rejected. This implies that the data do not support the hypothesis that factors of production have adjusted to their long run levels.[11] In addition a Wald test *(W)* shows that constant price expectations can be rejected since the price expectation parameters ϕ_i differ from zero, and θ_i differ from one. Thus the preferred specification is the dynamic model with rational *AR(1)* price expectations.

In table 3 the results of a number of tests are provided for the dynamic production model under both types of price expectation generating processes. Since the specification with *AR(1)* price expectations is the preferred one, the discussion of the tests focuses on this model. Lagrange Multiplier *(LM)* tests are conducted for non-spherical disturbances (see Breusch and Pagan [1980], and Engle [1984]). First order, second order, and combined first

[9] Gullickson and Harper [1987] provide a detailed description of the data.

[10] The LR statistic has been small sample corrected. The calculation of the LR test statistic is from Sims [1980]. $LR = 2 \times (LLU - LLR) \times [(T-k)/T]$, where LLU is the log of the likelihood function from the unrestricted model, LLR is the log of the likelihood from the restricted model, T is the number of observations, and k is the number of parameters in the unrestricted model divided by the number of equations

[11] The dynamic versions of the model can also be seen to outperform the static versions from the standard error, R^2, and Durbin-Watson statistics, although for the latter statistic has well-known limitations when there are lagged dependent variables (see Breusch and Pagan [1980]).

and second order serial correlation are rejected and $ARCH$ is also rejected in the dynamic model.[12] In addition, table 3 shows the results of three LR tests relating to returns to scale, technological change, and concavity of the cost function with respect to the user costs. In the dynamic model, constant returns to scale, and no technological change are rejected. Lastly, concavity of the cost function, imposed using the Wiley, Schmidt and Bramble [1973] technique (suggested by Diewert and Wales [1987]) cannot be rejected.

The regression results, for the preferred specification, are given in table 1. The significance of the m parameters reported in this table suggests that none of the four factors of production has completely adjusted. Adjustment rates for $i = L$ (labor), K (capital), E (energy), M (materials) is 0.7653, 0.2527, 0.1741, and 0.1781, respectively. Thus labor adjusts faster than the other three inputs, with around three-quarters of the adjustment occurring in one year. The adjustment speeds of the other three factors are much slower than the speed for labor. Around one-quarter of the adjustment in capital takes place in a year. It is interesting to note that capital does not have the slowest adjustment speed. Both energy and materials adjust slower than capital, with around one-sixth of the adjustment for energy and materials occurring in a year. Thus we reject the usual assumption in dynamic models of production that labor, energy, and materials are variable factors of production whose adjustment is completed in one year. For the U.S. manufacturing sector, adjustment processes for non-capital inputs are slower than normally recognized.

Recall that an alternative interpretation of the m parameters relates to their inverses. The parameter m_i^{-1} defines the index of quality associated with additions to the ith factor. If the quality of factor additions in period t equals factor quality in period $t-1$ then the quality index would be equal to one. Thus between periods t and $t-1$ the rate of quality change for the ith factor equals $m_i^{-1} - 1$. Our estimates show that for the four factors of production their rates of quality change are 0.31 percent for labor, 3.0 percent for capital, 4.7 percent for energy, and 4.6 percent for materials. Rates of quality change generally have

[12] Tests conducted for the static versions of the model showed that serial correlation could not be rejected. From the LM test viewpoint, the existence of serial correlation implies omitted variables. Thus the absence of serial correlation in the dynamic specifications is a further argument against the static formulations.

not been estimated for non-capital inputs. However, for capital, Hulten [1992] applying growth accounting methods, and using the quality adjusted capital prices developed by Gordon [1990], found that the annual average rate of embodied efficiency over the period 1949-1983 was 3.0 percent. Our estimates are remarkably consistent with Hulten's findings, and provide additional evidence to support the Gordon quality adjustment of capital prices. The results in this paper also suggest that the other input prices warrant adjustment for quality improvements.

It is also possible to calculate annual factor adjustment. From equations (13), and (14),

$$\frac{Z_i(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\gamma_i v_{it-1}} = \eta_{it} + m_i, \; i = 1, ..., n, \tag{26}$$

where $\eta_{it} = [V_{it}(\omega_{1t}, ..., \omega_{nt}, y_t, t) - \gamma_i v_{it-1}] / \gamma_i v_{it}$, $i = 1, ..., n$, is the net of depreciation growth rate for the ith factor in period t. The growth rates are obtained from (16). Equation (26) defines the proportion of adjusted factor utilization to existing input quantity for each factor. Notice that growth rates are evaluated at their optimized values. Since the optimized values depend on user costs, which in turn depend on adjustment and expectation parameters, it is interesting to see how these two parameter sets affect the ratio of adjusted factor utilization to factor quantity. Thus we calculate the ratios for the dynamic models with rational *AR(1)* and constant price expectations.

Rates of factor adjustment defined by (26) are presented in table 4. The proportion of adjusted factor utilization to factor quantity is relatively constant over the sample period. This result occurs irrespective of the price expectation processes. With respect to the dynamic model with *AR(1)* expectations, the average annual rate of factor adjustment is 77 percent for labor, 30 percent for capital, 20 percent for energy, and 21 percent for materials. The results for the average annual rate of factor adjustment when price expectations are constant show that the rate for labor is invariant to price expectation generating processes. However, this is not the case for the other three inputs. If price expectations are assumed to be constant then the average annual rate of capital adjustment is 37 percent lower than the rate in the preferred specification. The opposite conclusion is found for energy and materials. For these two factors, average annual rates of adjustment are respectively 25 percent and 57 percent higher when price expectations are constant compared to the model, when prices expectations are *AR(1)*. Therefore, misspecifying rates of price inflation results in a downward bias in the rate of adjustment for capital, and upward bias in the rates for energy, and materials.

User costs depend on quality adjustment and price expectations parameters. As a consequence, they are unobservable variables, but their values can be calculated once the parameter estimates are substituted into the user cost formulas. Equation (22) shows how user costs are to be adjusted for quality improvements with *AR(1)* price expectations. These user costs represent the (shadow) values of the marginal products for the factors of production (see equation (9)). The calculated user costs are presented in the columns of table 5, labeled *dynamic*. These columns represent the annual value in 1992 dollars of the marginal products. From table 5 the average annual 1992 dollar value of the marginal products are: labor \$0.75, capital \$1.06, energy \$1.89, and materials \$1.36. Since all marginal products are valued at the same shadow price, table 5 shows that on average, in quality adjusted terms energy and materials are relatively more productive at the margin than capital and labor.

The user costs labeled *dynamic* in table 5 represent the values of the marginal products inclusive of quality improvements. By comparing these marginal products to the marginal products that do not encompass quality changes, it is possible to determine relative quality gains associated with each factor of production. If there were no quality improvements, marginal product values would equal user costs defined for $m_i = 1$ under *AR(1)* price expectations. These user costs are given by (23), and are shown in table 5 under the columns labeled *static*. Table 5 shows that percentage differences between classes of user cost are quite large for each of the factors of production. In the absence of quality improvements these percentage differences in user costs would be zero. On average, and over the entire sample period, the percentage difference between dynamic and static user costs is 0.25 for labor, 0.30 for capital, 2.13 for energy, and 0.92 for materials. These percentage differences represent the elasticity of quality. They show the percentage difference in marginal products inclusive and exclusive of quality. We find substantial annual percentage increases in marginal products arising from quality improvements associated with each factor. Moreover, coupled with the previous result on relative marginal products, the most productive inputs also experience the highest quality elasticities. Hulten [1992] refers to these percentage changes as elasticities of embodiment. He found that on average over the period 1949-1983 the elasticity of embodiment for capital was 0.23 percent. This elasticity is consistent with our estimate for capital. Our findings suggest that the elasticity for labor is similar to capital, while embodiment or quality elasticities for intermediate inputs are substantially above those estimated for labor and capital.

4. PRODUCTIVITY GROWTH AND DECOMPOSITION

In this section of the paper productivity growth rates for the U.S. manufacturing sector are measured and decomposed in the context of the dynamic factor demand model described in section 2, using the results obtained from the empirical analysis in section 3 of the paper. Productivity growth represents a performance indicator of a production process and is calculated as differences between output and input growth rates. However, observed rates of productivity growth do not necessarily reflect the efficient set of factor requirements used in the production process. When inputs have not completely adjusted, and encompass quality improvements observed factor quantities do not necessarily represent cost minimizing input requirements, and observed factor prices may not reflect user costs of production. Thus measured productivity growth rates can differ from efficiency-based measures of productivity that capture adjustment costs and quality improvements, and thereby reflect "true" productivity gains (or losses) that have been achieved (or incurred).

In order to derive efficiency-based productivity growth and its components consider a general cost function given by (11), $C(\omega_{1t,}..., \omega_{nt,} y_t, t)$. Since the empirical specification of the cost function (15) is second order, and the second order parameters do not change over time then the difference in cost between periods s and t is (see Diewert [1981], Denny and

Fuss [1983], and Berndt and Fuss [1986], Bernstein and Mohnen [1998])

$$c_t - c_s = .5\sum_{i=1}^{n}\left(\frac{\partial c_t}{\partial \omega_{it}} + \frac{\partial c_s}{\partial \omega_{is}}\right)(\omega_{it} - \omega_{is}) + .5\left(\frac{\partial c_t}{\partial y_t} + \frac{\partial c_s}{\partial y_s}\right)(y_t - y_s) + .5\left(\frac{\partial c_t}{\partial t} + \frac{\partial c_s}{\partial s}\right)(t - s). \tag{27}$$

Using (13), $Z_i(\omega_{1t},...,\omega_{nt}, y_t, t) = \partial c_t/\partial \omega_{it} = \zeta_{it}^*$, $i = 1, ..., n$, where ζ_{it}^* is the optimized value of ζ_{it}. Collecting terms in the first line of (27) and defining $\zeta_{im}^* = .5(\zeta_{it}^* + \zeta_{is}^*)$, then (27) becomes

$$.5\left[\sum_{i=1}^{n}\frac{\omega_{it}\zeta_{it}^*(\zeta_{it}^* - \zeta_{is}^*)\zeta_{im}^*}{\zeta_{im}^*\zeta_{it}^*} + \sum_{i=1}^{n}\frac{\omega_{is}\zeta_{is}^*(\zeta_{it}^* - \zeta_{is}^*)\zeta_{im}^*}{\zeta_{im}^*\zeta_{is}^*}\right] = .5\left(\frac{\partial c_t}{\partial y_t} + \frac{\partial c_s}{\partial y_s}\right)(y_t - y_s) + .5\left(\frac{\partial c_t}{\partial t} + \frac{\partial c_s}{\partial s}\right)(t - s). \tag{28}$$

Next multiplying (28) by -1, adding $(c/y)_m(y_t - y_s) = .5\left[c_t/y_t + c_s/y_s\right](y_t - y_s)$, and collecting terms yields

$$\left(\frac{c}{y}\right)_m y_m\frac{(y_t - y_s)}{y_m} - .5\left[\sum_{i=1}^{n}\frac{s_{it}(\zeta_{it}^* - \zeta_{is}^*)\zeta_{im}^* c_t}{\zeta_{im}^*\zeta_{it}^*} + \sum_{i=1}^{n}\frac{s_{is}(\zeta_{it}^* - \zeta_{is}^*)\zeta_{im}^* c_s}{\zeta_{im}^*\zeta_{is}^*}\right] = .5\left[(1 - \rho_{yt}^{-1})\left(\frac{c}{y}\right)_t + (1 - \rho_{ys}^{-1})\left(\frac{c}{y}\right)_s\right](y_t - y_s) + .5\left(\xi_{\nu t}c_t + \xi_{\nu s}c_s\right)(t - s), \tag{29}$$

where $s_{it} = \omega_{it}\zeta_{it}^*/c_t$ is the cost share for ith factor utilization, $\rho_{yt} = \left[(\partial c_t/\partial y_t)(y_t/c_t)\right]^{-1}$ is the degree of returns to scale, and $\xi_{\nu t} = (\partial c_t/\partial t)/c_t$ is the input-based rate of technological change in period t. The expression,

$$(\dot{\zeta}/\zeta)^* = .5\sum_{i=1}^{n} s_{it}\left[(\zeta_{it}^* - \zeta_{is}^*)/\zeta_{im}^*\right](\zeta_{im}^*/y_m)(y/\zeta_i^*)_t(c/y)_t(y/c)_m + .5\sum_{i=1}^{n} s_{is}\left[(\zeta_{it}^* - \zeta_{is}^*)/\zeta_{im}^*\right](\zeta_{im}^*/y_m)(y/\zeta_i^*)_s(c/y)_s(y/c)_m$$

is the growth rate of utilized factors, and output growth is $\dot{Y}/Y = (y_t - y_s)/y_m$, then an efficiency-based measure of total factor productivity *(TFP)* growth between periods s, and t can be defined as,[13]

$$TFPG^e(s,t) = \dot{Y}/Y - (\dot{\zeta}/\zeta)^* \tag{30}$$

[13]Total factor productivity growth is also referred to as multifactor productivity growth.

Dividing (29) by $(c/y)_m y_m$, and using (30) then

$$TFPG^e(s,t) = .5\left[(1-\rho_{yt}^{-1})\left(\frac{c}{y}\right)_t + (1-\rho_{ys}^{-1})\left(\frac{c}{y}\right)_s\right]\frac{\dot{Y}/Y}{(c/y)_m}$$
$$+ .5\left[\xi_{\nu t}\left(\frac{c}{y}\right)_t y_t + \xi_{\nu s}\left(\frac{c}{y}\right)_s y_s\right]\frac{(t-s)}{(c/y)_m y_m}. \qquad (31)$$

Equation (31) is an efficiency-based measure of *TFP* growth because it encompasses cost-minimizing behavior. This efficiency-based formula consists of two elements, returns to scale and rates of technological change.

An alternative efficiency-based measure defines *TFP* growth to reflect technological change. A rationale for this measure, implied by the work of Domar [1963], Jorgenson [1966], Griliches [1967], and recently by Hulten [1992], centers on output adjustment arising from quality improvements. In this view there are quality improvements associated with inputs, and output, and not just the former. Output quality changes are reflected in any deviations from constant returns to scale. For example, increasing returns to scale is seen to be synonymous to output quality improvements. In this "better is equivalent to more" framework, under increasing returns to scale more output can be produced from a given quantity of inputs compared to the case of constant returns to scale. From the usual definition of returns to scale, $\rho_{yt} y_t = \sum_{i=1}^{n}(\partial F/\partial z_{it})z_{it}$, the degree of returns to scale, ρ_{yt}, can be interpreted to be a quality index, where $\rho_{yt} y_t$ measures output in quality adjusted units. Thus an alternative measure of efficiency-based TFP growth can be defined such that deviations from constant returns to scale are assigned to quality adjustments in output. This measure can be obtained from (31), and reflects the rate of technological change,

$$TFPG^c(s,t) = .5\left[\xi_{\nu t}\left(\frac{c}{y}\right)_t y_t + \xi_{\nu s}\left(\frac{c}{y}\right)_s y_s\right]\frac{(t-s)}{(c/y)_m y_m}, \qquad (32)$$

where from (30),

$$TFPG^c(s,t) = \dot{O}/O - (\dot{\zeta}/\zeta)^* \qquad (33)$$

and $\dot{O}/O = \dot{Y}/Y - .5\left[(1-\rho_{yt}^{-1})\left(\frac{c}{y}\right)_t + (1-\rho_{ys}^{-1})\left(\frac{c}{y}\right)_s\right]\left[(\dot{Y}/Y)/(c/y)_m\right]$.[14] Notice that

[14] Efficiency-based productivity growth defined by (32) can be directly determined from (28). In addition, from (32) we can derive (31). Thus one efficiency-based measure does not logically precede the other.

when there are constant returns to scale, $\dot{O}/O = \dot{Y}/Y$, so both efficiency-based measures are equal.

Observed rates of productivity growth are derived from equation (31) by subtracting,

$$\begin{aligned}\dot{V}/V = .5\sum_{i=1}^{n}\varphi_{it}\left[(v_{it}-v_{is})/v_{im}\right](v_{im}/y_m)(y_t/v_{it})(\varsigma/y)_t(y/\varsigma)_m \\ +.5\sum_{i=1}^{n}\varphi_{is}\left[(v_{it}-v_{is})/v_{im}\right](v_{im}/y_m)(y_s/v_{is})(\varsigma/y)_s(y/\varsigma)_m,\end{aligned}$$

which is the observed growth rate of inputs, and adding $(\dot{\zeta}/\zeta)^*$ to the equation. The term $\varphi_{it} = w_{it}v_{it}/\varsigma_t$ is the ith factor cost share, $\varsigma_t = \sum_{i=1}^{n} w_{it}v_{it}$ is factor cost, w_{it} is the ith observed factor price (defined by (25)), in period t. Observed *TFP* growth rate between any two periods is output growth net of input growth or

$$TFPG^o(s,t) = \dot{Y}/Y - \dot{V}/V. \tag{34}$$

Thus with (34), (31) becomes

$$\begin{aligned}TFPG^o(s,t) = .5\left[(1-\rho_{yt}^{-1})\left(\frac{c}{y}\right)_t + (1-\rho_{ys}^{-1})\left(\frac{c}{y}\right)_s\right]\frac{\dot{Y}/Y}{(c/y)_m} \\ +.5\left[\xi_{vt}\left(\frac{c}{y}\right)_t y_t + \xi_{vs}\left(\frac{c}{y}\right)_s y_s\right]\frac{(t-s)}{(c/y)_m y_m} \\ -\left[\left(\frac{\dot{V}}{V}\right) - \left(\frac{\dot{\zeta}}{\zeta}\right)^*\right].\end{aligned} \tag{35}$$

Equation (35) shows that observed *TFP* growth consists of three elements; a term reflecting returns to scale, because observed output quantities are used, a technological change term and a factor adjustment term. The latter element forms part of the productivity decomposition for two reasons. First, observed factors are not necessarily cost minimizing utilized inputs. Second, the weights used to construct the input growth rates $(\dot{V}/V)$ are based on observed factor prices, while the weights used to construct utilized factor growth rates $(\dot{\zeta}/\zeta)^*$ are formed by user costs which embody adjustment costs and inflation rates.

The formula for the observed *TFP* growth rates denoted by (34) represents one of numerous ways to calculate productivity growth rates using observed prices and quantities.

Observed TFP growth from equation (34) is attractive because as (35) shows it can be linked to one of the efficiency-based productivity growth rates (denoted by (31) and (32)) via the McFadden-Diewert-Wales cost function.

A second measure of observed productivity growth based on a Fisher index is also calculated. Diewert [1992] shows Fisher indexes satisfy an important set of properties that govern index numbers. The Fisher productivity index is the geometric mean of Laspeyres and Paasche output quantity indexes divided by the geometric mean of Laspeyres and Paasche input quantity indexes. To obtain the decomposition of Fisher productivity growth rates ($TFPG^f(s,t)$), in (35), add $TFPG^f(s,t)$ and subtract $TFPG^o(s,t)$, thus

$$\begin{aligned} TFPG^f(s,t) = {} & .5\left[(1-\rho_{yt}^{-1})\left(\frac{c}{y}\right)_t + (1-\rho_{ys}^{-1})\left(\frac{c}{y}\right)_s\right]\frac{\dot{Y}/Y}{(c/y)_m} \\ & + .5\left[\xi_{\nu t}\left(\frac{c}{y}\right)_t y_t + \xi_{\nu s}\left(\frac{c}{y}\right)_s y_s\right]\frac{(t-s)}{(c/y)_m y_m} \\ & - \left[\left(\frac{\dot{V}}{V}\right) - \left(\frac{\dot{\varsigma}}{\varsigma}\right)^*\right] + R(s,t), \end{aligned} \tag{36}$$

where $R(s,t) = TFPG^f(s,t) - TFPG^o(s,t)$ is the residual between the two types of observed productivity growth rates. Thus Fisher *TFP* growth rates consist of efficiency-based growth rates (inclusive of a scale term), the factor adjustment term, and a residual.

In order to determine the magnitude and source of differences between efficiency-based and observed productivity growth rates, we first consider whether efficiency-based productivity growth rates differ from zero. Tests were conducted on the degree of returns to scale, and the rates of technological change. Recall from table 3 that the hypotheses of constant returns to scale, and no technological change were rejected. Thus with technological change, we can reject the hypothesis of no efficiency-based productivity growth defined as $TFPG^c$ (in equation (32)). In addition, with increasing returns to scale and nonnegative output growth rates, efficiency-based productivity growth defined as $TFPG^e$ from (31) is also nonzero.

Table 6 shows the degree of returns to scale, and rates of technological change, obtained from the dynamic model with rational *AR(1)* price expectations. From this table, on average over the estimation period, the degree of returns to scale for U.S. manufacturing is

1.44, and the average annual rate of technological change is approximately 1 percent. Thus if efficiency-based TFP growth is $TFPG^c$, which reflects the rate of technological change, then the average annual rate is about 1 percent over this period.

The effect of quality adjustment on output growth can also be determined using the results in table 6. The difference in the estimate of returns to scale (1.44), from constant returns to scale shows that quality-adjusted output growth adds about 0.44 percentage points to output growth. Our findings are consistent with Hulten [1992]. In a growth accounting framework, using Gordon [1990] quality adjusted prices, he finds that quality-adjustment increases output growth by around 0.40 percentage points over the 1949-1983 period and this figure does not vary over the sample.

The complete set of productivity growth rates and their decomposition are presented in table 7. The Fisher productivity growth rates ($TFPG^f$based on (36)) are presented in the Fisher TFPG column and the other observed productivity growth rates ($TFPG^o$from (35)) are found by subtracting the residual from the Fisher rate. From table 7, both variants of observed productivity growth rates are very similar throughout the period from 1953 to 1995. In absolute value the residual never exceeds 0.05 percent. In the years prior to 1973 (the year when observed productivity growth started to decline, see Griliches [1994] and the references therein) the average annual rate of the residual is -0.003 percent. This rate is, in absolute value, 0.2 percent of the average annual Fisher productivity growth rate of 1.44 percent. In the slowdown era the residual annually accounts for 0.6 percent on average of the 0.80 percent Fisher productivity growth rate. Therefore the two sets of observed productivity growth rates are virtually identical.

Efficiency-based productivity growth rates, defined by $TFPG^e$, (denoted by (31)) are derived from table 7 by adding the columns labeled returns to scale effect, and technological change effect. In the period from 1953 to 1973, average annual $TFPG^e$ is 1.425 percent. Thus in the pre-slowdown era, this measure of efficiency-based productivity growth is very similar to Fisher productivity growth.

In the slowdown period, Fisher and $TFPG^e$ efficiency-based productivity growth rates diverge. From 1974 to 1995 the average annual efficiency-based productivity growth rate is

1.998 percent. This represents about 1.2 percentage points more than the Fisher productivity growth rate or more than a 150 percent increase over the Fisher measure.

Accounting for the difference between efficiency-based and Fisher productivity growth rates is the factor adjustment term. Table 8 shows that from 1974 to 1995, observed input growth rates are too high because they are not adjusted for the quality improvements associated with labor, capital and especially materials. Unadjusted input growth cause observed and efficiency-based productivity growth rates to diverge. In addition, over the entire period of 1953-1995 the average annual efficiency-based productivity growth rate is 1.718 percent. This rate is 55 percent greater than the observed measure of 1.110 percent.

As we discussed, $TFPG^{\varepsilon}$ is an efficiency-based measure of productivity growth when factors of production are adjusted for technical changes. $TFPG^{c}$ defines the efficiency-based measure that adjusts inputs and output. It is found in the column labeled technological change effect in table 7. For the two main sub-periods, 1953-1973, and 1974-1995, $TFPG^{c}$ differs from the observed Fisher productivity growth rates. In the pre-slowdown period average annual Fisher productivity growth is 50 percent greater than the average annual $TFPG^{c}$. This difference arises because annual output quality adjustment of 0.466 percent are assigned to observed productivity growth and not to output growth. In the slowdown period, $TFPG^{c}$ exceeded observed productivity growth by 27 percent. In this period, as noted from table 8, the difference in productivity growth rates arises because observed input growth rates are too high. Observed input growth is not adjusted for input quality changes, and particularly the improvements associated with materials.

Our results show that within each of the two periods, output quality adjustments differ from input quality adjustments, although on average, from 1953 to 1995, output and input quality adjustments approximately offset each other. Moreover, both efficiency-based measures of productivity growth show that observed input growth should be adjusted for quality improvements. Unadjusted input growth causes efficiency-based productivity growth rates to exceed observed productivity growth in the slowdown period of 1974-1995.

5. CONCLUSION

This paper extended previous empirical dynamic production models to account for adjustment costs, and quality improvements associated with all factors of production. A number of new results pertaining to speeds of adjustment, rates of quality change, and productivity growth rates emerged from the analysis.

First, with respect adjustment speeds, none of the factors of production completely adjusted within one year. Average annual rates of factor adjustment were 77 percent for labor, 30 percent for capital, 20 percent for energy, and 21 percent for materials. In addition, the failure to account for inflation associated with acquisition and hiring prices leads to a downward bias in the rate of adjustment for capital by 37 percent and upward biases in the adjustment speeds for energy, and materials by 25 and 57 percent respectively.

Second, our estimates show that the rates of quality change are 0.31 percent for labor, 3.0 percent for capital, 4.7 percent for energy, and 4.6 percent for materials. Quality improvements affect marginal products. The percentage differences between marginal products inclusive and exclusive of quality improvements define the elasticities of quality. The quality elasticities are 0.25 percent for labor, 0.30 for capital, 2.13 for energy, and 0.92 for materials. Our findings provide additional evidence supporting the Gordon-Hulten analysis of quality adjusted capital prices. Moreover, our findings suggest that it is important to adjust non-capital factor prices for quality improvements too.

Third, efficiency-based productivity growth rates that adjust inputs for quality improvements are similar to observed annual productivity growth of 1.44 percent in the pre-slowdown period of 1953-1973. In the slowdown period, these productivity growth rates diverge. From 1974 to 1995 the average annual efficiency-based productivity growth rate is 1.998 percent or more than a 150 percent increase over the observed measure. The divergence arises because observed input growth rates, especially materials, are not adjusted for quality improvements. Consequently observed input growth rates are too high.

Efficiency-based productivity growth that adjusts inputs and output diverge from observed productivity growth rates within both of the sub-periods 1953-1973, and 1974-1995.

Our results show that, within the pre-slowdown and slowdown periods, output quality adjustments differ from input quality adjustments. Output quality improvements dominate in the first sub-period and changes in input quality dominate in the slowdown period. However, we find that over the entire period quality adjustments on output and input approximately offset each other.

In general, efficiency-based productivity growth rates exceed observed productivity growth in the slowdown period of 1974-1995. The divergence is mainly attributable to observed input growth rates that are not adjusted for quality improvements, and thereby are too high.

APPENDIX: DATA DESCRIPTION

Data from 1952 to 1996 on the quantities and price indices for output, and inputs related to labor, capital, energy, and materials (inclusive of purchased services) have been obtained from the Bureau of Labor Statistics (*BLS*). The data relate to the US manufacturing sector as a whole. The mean, standard deviation, minimum and maximum values of the variables are presented in table A1. All price indices have been normalized to one in 1992 and all quantities are measured in billions of 1992 dollars.

The quantity of output is measured as the value of gross output divided by the output price index. The value of gross output corresponds to shipments plus the change of inventories. The output price deflator index is implicitly defined by a Törnqvist aggregation of two-digit gross outputs. The labor input is measured in man-hours, estimated by the *BLS Current Establishment Survey*. It corresponds to the sum of hours of all persons engaged in production in the sector. The price deflator of labor is measured implicitly by dividing the labor compensation by labor man-hours. Labor input quantity is measured as the cost of labor divided by the labor price. The quantity of energy is measured as the cost of energy divided by the energy price index. The quantity of materials is measured as the total cost of materials (inclusive of purchased services) divided by the price index of materials. The price index of materials is a Törnqvist index of the price indices of materials and purchased services. Capital input is defined as the flow of services of equipment, structures, inventories and land. The stocks of depreciable assets, equipment and structures, is constructed using the perpetual inventory method. The quantity of capital is measured as the value of capital services divided by the capital price index (see Gullickson and Harper [1987] for a detailed description of the data).

Note that output and material inputs are adjusted for intersectoral transactions, i.e., transactions between establishments in the sector are removed from both gross output and material inputs. In addition, the value of production is adjusted to exclude the indirect business taxes and government subsidies that are not related to capital. The *BLS* data that are used in this paper are not adjusted so that the cost of production equals the value of output, since this adjustment implies constant returns to scale. Lastly, the real discount rate is set to 4 percent.

Table A1. MANUFACTURING-SECTOR DATA

Descriptive Statistics (1952-1996)

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Output	1300.92	486.00	628.52	2298.98
Labor	747.61	45.40	641.86	818.74
Capital	177.91	82.37	69.92	324.14
Materials	501.28	200.12	239.41	866.78
Energy	42.25	12.22	18.65	64.33
Output Price	0.5839	0.2980	0.2660	1.0430
Labor Price	0.4583	0.3364	0.1000	1.1210
Capital Price	0.6572	0.2792	0.3610	1.3660
Material Price	0.5944	0.3289	0.2568	1.1360
Energy Price	0.5473	0.4120	0.1610	1.2240

References

Bernstein, J.I. and P. Mohnen (1998) "International R&D Spillovers Between U.S. and Japanese R&D Intensive Sectors", *Journal of International Economics*, 44, 315-338.

Berndt, E. R. and M. A. Fuss (1986) "Productivity Measurement with Adjustments for Variations in Capacity Utilization and Other Forms of Temporary Equilibrium," *Journal of Econometrics*, 33, 7-29.

Breusch, T. S., and A. R. Pagan (1980) "The Lagrange Multiplier Test and its Application to Model Specification in Econometrics", *Review of Economic Studies*, 47, 239-254.

Denny, M. and M. Fuss (1983) "The Use of Discrete Variables in Superlative Index Number Comparisons", *International Economic Review*, 24, 419-421.

Diewert, W. E., (1992) "Fisher Ideal Output, Input, and Productivity Indexes Revisited", *Journal of Productivity Analysis*, 3, 211-248.

Diewert, W. E. (1982) "Duality Approaches to Microeconomic Theory", in K. Arrow and M. Intrilligator, eds., *Handbook of Mathematical Economics, Vol.2*, Elsevier Science Publishers, Amsterdam, The Netherlands.

Diewert, W.E. (1981) "The Economic Theory of Index Numbers: A Survey", in A. Deaton, ed., *Essays in the Theory and Measurement of Consumer Behaviour in Honour of Sir Richard Stone*, Cambridge University Press, London, U. K.

Diewert, W. E. and K. Fox, (1997) "Can Measurement Error Explain the Productivity Paradox", forthcoming *Canadian Journal of Economics.*

Diewert, W. E. and T. J. Wales (1988) " A Normalized Quadratic Semiflexible Functional Form", *Journal of Econometrics*, 37, 327-342.

Diewert, W. E. and T. J. Wales (1987) " Flexible Functional Forms and Global Curvature Conditions," *Econometrica*, 55, 43-68.

Domar, Evsey D. (1963) "Total Factor Productivity and the Quality of Capital," *Journal of Political Economy*, 71, 586-588

Engle, R. F. (1984) "Wald, Likelihood Ratio, and Lagrange Multiplier Tests in Econometrics", in Z. Griliches and M. Intriligator, eds., *Handbook of Econometrics. Vol 2*, Elsevier Science Publishers, Amsterdam, The Netherlands.

Epstein, L. and M. Denny (1983), "The Multivariate Flexible Accelerator Model: Its Empirical Restriction and Application to U.S. Manufacturing", *Econometrica*, 51, 647-674.

Gullickson, W. and M. J. Harper (1987) " Multifactor Productivity in US Manufacturing, 1949- 83," *Monthly Labor Review*, 110, 18-28.

Griliches, Zvi (1994) "Productivity, R&D, and the Data Constraint", *American Economic Review*, 84, 1-23.

Griliches, Zvi (1967) "Production Functions in Manufacturing: Some Preliminary Results," in M. Brown ed., *The Theory and Empirical Analysis of Production*, NBER, Columbia University Press, New York, USA.

Gordon, Robert J. (1990) *The Measurement of Durable Goods Prices*, NBER, University of Chicago Press, Chicago, USA.

Hulten, Charles R. (1992) "Growth Accounting When Technical Change is Embodied in Capital," *American Economic Review*, 82, 964-980.

Jorgenson, Dale W. (1966) "The Embodiment Hypothesis," *Journal of Political Economy*, 74, 1- 17.

Jorgenson, Dale W., and Zvi Griliches (1967) "The Explanation of Productivity Change," *Review of Economic Studies*, 34, 349-383.

Jorgenson Dale W., Frank Gollup, and Barbara Fraumeni (1987) *Productivity and US Economic Growth*, Harvard University Press, Cambridge ,USA.

Morrison, C. J. and E. R. Berndt (1981), " Short-Run Labor Productivity in a Dynamic Model," *Journal of Econometrics*, 16, 339-365.

Nadiri, M. I., and I. R. Prucha (1998) "Dynamic Factor Demand Models and Productivity Analysis", Paper Prepared for CRIW Conference, Washington, D.C.

Nadiri, M. I. and S. Rosen (1969) "Interrelated Factor Demand Functions," *American Economic Review*, 54, 457-471.

Pakes, A. and Z. Griliches (1985) "Estimating Distributed Lags in Short Panels With an Application to the Specification of Depreciation Patterns and Capital Stock Constructs," *Review of Economic Studies*, 51, 243-262.

Pashardes, P. (1986), " Myopic and Forward Looking Behavior in a Dynamic Demand System," *International Economic Review*, 27, 387-397.

Pindyck, R. S. and J. J. Rotemberg (1983), "Dynamic Factor Demand and the Effects of Energy Price Shocks," *American Economic Review*, 73, 1066-1079.

Solow, R.M. (1967) "Some Recent Developments in the Theory of Production," in M. Brown ed., *The Theory and Empirical Analysis of Production*, NBER, Columbia University Press, New York, USA.

Solow, R.M. (1960) "Investment and Technical Progress," in K. Arrow, S. Karlin, and P. Suppes eds., *Mathematical Methods in the Social Sciences*, 1959, Stanford University Press, Stanford, USA.

Sims, A. (1980) "Macroeconomics and Reality," *Econometrica*, 3, 1-48.

Wiley, D. E., W. H. Schmidt, and W. J. Bramble (1973), " Studies of a Class of Covariance Structure Models," *Journal of American Statistical Association*, 68, 317-323.

Table 1. Regression Results for Dynamic Models

	AR(1) Expectations		*Constant Expectations*	
Parameter	**Estimate**	**Std. Error**	**Estimate**	**Std. Error**
β_{LL}	-1.19E-03	3.26E-03	-9.00E-02	8.84E-02
β_{LK}	3.21E-03	4.68E-03	1.98E-02	7.76E-03
β_{LE}	-1.09E-03	1.48E-03	-7.43E-03	4.50E-03
β_{KK}	-8.69E-03	2.69E-03	-4.59E-03	2.22E-03
β_{KE}	2.94E-03	4.36E-04	1.96E-03	5.73E-04
β_{EE}	-9.97E-04	2.46E-04	-1.03E-03	7.12E-04
β_L	5.15E-01	6.12E-02	4.27E-01	7.30E-02
β_K	7.63E-02	1.35E-02	5.81E-02	1.49E-02
β_E	1.58E-02	3.33E-03	1.51E-02	4.25E-03
β_M	1.93E-01	4.14E-02	1.62E-01	4.33E-02
α_{YY}	3.35E-06	5.41E-05	4.19E-05	5.12E-05
β_{LT}	-1.16E-02	2.18E-03	-9.71E-03	2.12E-03
β_{KT}	-2.08E-03	8.91E-04	-2.03E-03	7.75E-04
β_{ET}	-4.42E-04	1.55E-04	-3.95E-04	1.52E-04
β_{MT}	-6.03E-03	2.40E-03	-4.67E-03	2.18E-03
β_{TT}	2.85E-04	9.35E-05	2.13E-04	9.11E-05
α_L	209.2640	51.8621	216.3980	49.5495
α_K	-24.3085	6.7099	-21.4445	6.8208
α_E	-7.1938	1.5456	-7.5765	1.8020
α_M	-77.6223	28.6871	-36.8544	29.8211
α_T	7.0293	2.8746	6.7980	2.5834
m_L	0.7653	0.0853	0.7596	0.0788
m_K	0.2527	0.0661	0.1531	0.0699
m_E	0.1741	0.0290	0.2193	0.0419
m_M	0.1781	0.0812	0.3011	0.0875

Table 1 (Cont'd). REGRESSION RESULTS FOR DYNAMIC MODELS

	AR(1) Expectations		*Constant Expectations*	
Parameter	**Estimate**	**Std. Error**	**Estimate**	**Std. Error**
ϕ_L	3.03E-03	2.20E-03		
ϕ_K	4.17E-02	1.07E-02		
ϕ_E	6.86E-03	5.03E-03		
ϕ_M	2.00E-02	6.03E-03		
θ_L	0.9675	0.0401		
θ_K	0.2243	0.1207		
θ_E	0.8655	0.0591		
θ_M	0.5941	0.0846		

Equation	**Std. Error**	R^2	D-W	**Std. Error**	R^2	D-W
Labor	1.87E-02	0.994	1.33	1.71E-02	0.995	1.33
Capital	1.40E-03	0.993	1.67	1.40E-03	0.993	1.56
Energy	8.35E-04	0.969	2.23	7.90E-04	0.970	2.25
Materials	1.30E-02	0.676	2.29	6.00E-03	0.695	1.52
Labor Price	9.24E-03	0.999	2.22			
Capital Price	5.89E-02	0.959	1.81			
Energy Price	2.88E-02	0.995	1.75			
Material Price	3.06E-02	0.992	1.57			
Log of L. F.		1184.3			753.7	

Table 2. REGRESSION RESULTS FOR STATIC MODELS

	AR(1) Expectations		*Constant Expectations*	
Parameter	**Estimate**	**Std. Error**	**Estimate**	**Std. Error**
β_{LL}	-4.03E-03	3.67E-03	-4.36E-02	2.31E-02
β_{LK}	5.06E-03	2.68E-03	3.22E-02	9.93E-03
β_{LE}	-6.81E-03	3.09E-03	6.94E-03	7.11E-03
β_{KK}	-1.22E-02	2.34E-03	-2.56E-02	4.19E-03
β_{KE}	8.56E-03	1.12E-03	1.59E-04	2.51E-03
β_{EE}	-1.15E-02	1.56E-03	-1.65E-02	2.11E-03
β_L	7.00E-01	6.74E-02	7.19E-01	7.18E-02
β_K	1.66E-01	2.03E-02	1.89E-01	2.25E-02
β_E	6.41E-02	8.92E-03	7.40E-02	8.97E-03
β_M	4.06E-01	6.05E-02	4.45E-01	6.54E-02
α_{YY}	-5.37E-04	6.18E-05	-5.78E-04	6.78E-05
β_{LT}	4.70E-03	2.49E-03	5.41E-03	2.79E-03
β_{KT}	6.04E-03	9.55E-04	5.81E-03	1.04E-03
β_{ET}	-2.52E-04	1.28E-04	4.50E-04	2.31E-04
β_{MT}	6.42E-04	2.21E-04	1.68E-02	2.85E-03
β_{TT}	1.66E-02	2.62E-03	-2.36E-04	1.43E-04
α_L	350.3750	37.9693	312.9440	38.1813
α_K	8.1372	10.3877	11.8784	11.4914
α_E	-21.2864	5.1529	-18.2829	4.8284
α_M	85.7046	32.7846	64.8499	35.4496
α_T	-23.3179	3.4138	-24.1021	3.7237
m_L				
m_K				
m_E				
m_M				

Table 2 (Cont'd). REGRESSION RESULTS FOR STATIC MODELS

	AR(1) Expectations			*Constant Expectations*		
Parameter	**Estimate**	**Std. Error**		**Estimate**	**Std. Error**	
ϕ_L	3.41E-03	2.21E-03				
ϕ_K	4.23E-02	1.08E-02				
ϕ_E	8.48E-03	5.11E-03				
ϕ_M	2.38E-02	6.21E-03				
θ_L	0.9595	0.0403				
θ_K	0.2041	0.1207				
θ_E	0.8315	0.0627				
θ_M	0.5150	0.0885				
Equation	**Std. Error**	R^2	D-W	**Std. Error**	R^2	D-W
Labor	2.04E-02	0.992	0.86	1.86E-02	0.994	0.80
Capital	3.91E-03	0.943	0.81	3.50E-03	0.954	0.76
Energy	3.25E-03	0.544	0.55	2.70E-03	0.669	0.35
Materials	1.41E-02	0.544	0.53	1.38E-02	0.561	0.55
Labor Price	9.23E-03	0.999	2.21			
Capital Price	5.90E-02	0.959	1.77			
Energy Price	2.89E-02	0.995	1.70			
Material Price	3.12E-02	0.992	1.41			
Log of L. F.		1095.01			669.8	

Table 3. Hypothesis Testing for the Dynamic Models

	Model with $AR(1)$ Expectations	$\chi^2_{0.05}$ **Value**	**Model with Constant Expectations**	$\chi^2_{0.05}$ **Value**
Static Model with $AR(1)$ Expectations	$LR(8) = 161.68$	15.507		
Static Model with Constant Expectations			$LR(4) = 143.97$	9.488
Dynamic Model with Constant Expectations	$W(8) = 62.53$	15.507		
1st and 2nd Order Serial Correlation	$LM(128) = 88.71$	155.405	$LM(32) = 33.10$	46.194
1st Order Serial Correlation	$LM(64) = 74.08$	83.675	$LM(16) = 24.92$	26.296
2nd Order Serial Correlation	$LM(64) = 48.46$	83.675	$LM(16) = 13.37$	26.296
Heteroskedasticity ($ARCH$)	$LM(16) = 15.65$	26.296	$LM(8) = 5.97$	15.507
Constant Returns to Scale	$LR(6) = 20.29$	12.592	$LR(6) = 32.83$	12.592
No Technological Change	$LR(6) = 34.09$	12.592	$LR(6) = 24.11$	12.592
Concavity	$LR(6) = 3.60$	12.592	$LR(6) = 0.48$	12.592

Table 4. Ratio of Adjusted Factor Utilization to Lagged Factor Quantity

	AR(1) Expectations				Constant Expectations			
Year	**Labor** (L)	**Capital** (K)	**Energy** (E)	**Mater.** (M)	**Labor** (L)	**Capital** (K)	**Energy** (E)	**Mater.** (M)
1952	0.7378	0.2605	0.2536	0.1886	0.7261	0.1661	0.2870	0.3180
1953	0.7652	0.2993	0.2862	0.2112	0.7525	0.1984	0.3239	0.3342
1954	0.6992	0.2560	0.2312	0.1618	0.6870	0.1642	0.2602	0.2765
1955	0.8058	0.3100	0.2703	0.2133	0.8010	0.1953	0.3389	0.3399
1956	0.7599	0.3010	0.2354	0.1948	0.7519	0.1929	0.2867	0.3113
1957	0.7407	0.2881	0.2084	0.1897	0.7319	0.1843	0.2529	0.3065
1958	0.7164	0.2480	0.1696	0.1628	0.7042	0.1575	0.1979	0.2814
1959	0.8194	0.2858	0.1959	0.1996	0.8150	0.1753	0.2554	0.3279
1960	0.7778	0.2930	0.1838	0.1990	0.7701	0.1830	0.2327	0.3263
1961	0.7709	0.2876	0.1763	0.1939	0.7640	0.1778	0.2265	0.3202
1962	0.8072	0.3110	0.1935	0.2112	0.8057	0.1890	0.2628	0.3392
1963	0.7850	0.3211	0.1928	0.2247	0.7878	0.1923	0.2726	0.3558
1964	0.8038	0.3387	0.1990	0.2359	0.8101	0.2021	0.2884	0.3668
1965	0.8110	0.3581	0.2000	0.2484	0.8255	0.2096	0.3051	0.3799
1966	0.7867	0.3677	0.2054	0.2600	0.8013	0.2181	0.3129	0.3923
1967	0.7407	0.3531	0.1958	0.2476	0.7480	0.2156	0.2857	0.3729
1968	0.7587	0.3448	0.1898	0.2414	0.7672	0.2108	0.2794	0.3627
1969	0.7513	0.3338	0.1808	0.2430	0.7539	0.2090	0.2566	0.3660
1970	0.7209	0.3079	0.1633	0.2324	0.7118	0.2002	0.2127	0.3547
1971	0.7684	0.3023	0.1668	0.2306	0.7641	0.1916	0.2263	0.3530
1972	0.8201	0.3177	0.1763	0.2422	0.8223	0.1988	0.2491	0.3691
1973	0.8066	0.3352	0.1844	0.2487	0.8094	0.2130	0.2601	0.3790
1974	0.7583	0.3180	0.1721	0.2288	0.7461	0.2130	0.2177	0.3523
1975	0.7467	0.2842	0.1511	0.1908	0.7343	0.1854	0.1885	0.2972

Table 4 (Cont.'d). RATIO OF ADJUSTED FACTOR UTILIZATION

Year	AR(1) Expectations				Constant Expectations			
	Labor (L)	Capital (K)	Energy (E)	Mater. (M)	Labor (L)	Capital (K)	Energy (E)	Mater. (M)
1976	0.8366	0.2924	0.1775	0.2110	0.8269	0.1907	0.2276	0.3284
1977	0.8244	0.3038	0.1833	0.2113	0.8184	0.1987	0.2393	0.3301
1978	0.7977	0.3050	0.1908	0.2007	0.7912	0.2024	0.2463	0.3156
1979	0.7641	0.2956	0.1880	0.1941	0.7501	0.2020	0.2283	0.3079
1980	0.7271	0.2737	0.1692	0.1856	0.7023	0.1928	0.1842	0.2966
1981	0.7552	0.2650	0.1751	0.1926	0.7312	0.1843	0.1914	0.3087
1982	0.7330	0.2479	0.1670	0.1908	0.6992	0.1778	0.1626	0.3079
1983	0.8076	0.2523	0.1923	0.2043	0.7762	0.1774	0.1967	0.3301
1984	0.8203	0.2715	0.2069	0.2086	0.8042	0.1836	0.2384	0.3383
1985	0.7716	0.2720	0.1983	0.2002	0.7501	0.1889	0.2181	0.3275
1986	0.7706	0.2675	0.2088	0.1965	0.7500	0.1851	0.2328	0.3229
1987	0.7796	0.2707	0.2120	0.1952	0.7733	0.1784	0.2598	0.3205
1988	0.7744	0.2762	0.2064	0.2043	0.7829	0.1751	0.2738	0.3364
1989	0.7324	0.2750	0.1979	0.1999	0.7426	0.1720	0.2636	0.3288
1990	0.7132	0.2708	0.1960	0.1949	0.7198	0.1701	0.2537	0.3202
1991	0.7070	0.2614	0.1874	0.1895	0.7033	0.1672	0.2265	0.3102
1992	0.7346	0.2678	0.1940	0.1969	0.7297	0.1742	0.2313	0.3249
1993	0.7475	0.2771	0.1966	0.1901	0.7479	0.1786	0.2393	0.3145
1994	0.7397	0.2875	0.1957	0.1945	0.7629	0.1763	0.2653	0.3224
1995	0.7195	0.2956	0.1956	0.1973	0.7565	0.1773	0.2788	0.3283
Mean	0.7662	0.2944	0.1959	0.2082	0.7616	0.1886	0.2486	0.3319
Std. Dev	0.0360	0.0300	0.0264	0.0228	0.0387	0.0152	0.0379	0.0262
Min.	0.6992	0.2479	0.1511	0.1618	0.6870	0.1575	0.1626	0.2765
Max.	0.8366	0.3677	0.2862	0.2600	0.8269	0.2181	0.3389	0.3923

Table 5. USER COSTS

Year	Labor		Capital		Energy		Materials	
	Static	*Dynamic*	*Static*	*Dynamic*	*Static*	*Dynamic*	*Static*	*Dynamic*
1952	0.1026	0.1309	0.4504	0.6136	0.1735	0.5524	0.3126	0.6123
1953	0.1146	0.1455	0.4805	0.6501	0.1880	0.5922	0.3450	0.6732
1954	0.1286	0.1626	0.5096	0.6853	0.2063	0.6430	0.3764	0.7322
1955	0.1446	0.1819	0.5372	0.7190	0.2275	0.7023	0.4063	0.7888
1956	0.1623	0.2032	0.5635	0.7509	0.2508	0.7683	0.4350	0.8429
1957	0.1815	0.2263	0.5885	0.7813	0.2756	0.8394	0.4622	0.8946
1958	0.2020	0.2511	0.6122	0.8102	0.3014	0.9141	0.4881	0.9438
1959	0.2238	0.2773	0.6348	0.8376	0.3276	0.9914	0.5127	0.9906
1960	0.2465	0.3048	0.6562	0.8637	0.3541	1.0702	0.5362	1.0352
1961	0.2702	0.3335	0.6766	0.8885	0.3805	1.1497	0.5584	1.0775
1962	0.2946	0.3632	0.6959	0.9120	0.4066	1.2294	0.5795	1.1177
1963	0.3197	0.3938	0.7143	0.9343	0.4323	1.3085	0.5996	1.1559
1964	0.3453	0.4251	0.7317	0.9556	0.4574	1.3867	0.6187	1.1923
1965	0.3714	0.4571	0.7483	0.9757	0.4819	1.4637	0.6368	1.2268
1966	0.3978	0.4897	0.7641	0.9949	0.5056	1.5391	0.6540	1.2595
1967	0.4244	0.5226	0.7790	1.0131	0.5286	1.6126	0.6704	1.2907
1968	0.4513	0.5560	0.7932	1.0304	0.5508	1.6842	0.6859	1.3203
1969	0.4783	0.5896	0.8067	1.0468	0.5721	1.7537	0.7007	1.3484
1970	0.5053	0.6234	0.8196	1.0624	0.5926	1.8210	0.7147	1.3751
1971	0.5324	0.6573	0.8317	1.0772	0.6123	1.8860	0.7280	1.4005
1972	0.5594	0.6913	0.8433	1.0913	0.6312	1.9488	0.7407	1.4246
1973	0.5862	0.7253	0.8543	1.1047	0.6493	2.0092	0.7527	1.4475
1974	0.6129	0.7593	0.8648	1.1174	0.6666	2.0673	0.7641	1.4692
1975	0.6394	0.7931	0.8747	1.1295	0.6831	2.1231	0.7750	1.4899

Table 5 (Cont'd). USER COSTS

Year	Labor		Capital		Energy		Materials	
	Static	*Dynamic*	*Static*	*Dynamic*	*Static*	*Dynamic*	*Static*	*Dynamic*
1976	0.6657	0.8268	0.8841	1.1409	0.6988	2.1767	0.7853	1.5095
1977	0.6917	0.8603	0.8931	1.1518	0.7139	2.2281	0.7951	1.5282
1978	0.7175	0.8935	0.9016	1.1622	0.7282	2.2773	0.8044	1.5459
1979	0.7429	0.9265	0.9097	1.1720	0.7419	2.3244	0.8132	1.5627
1980	0.7679	0.9592	0.9174	1.1813	0.7549	2.3694	0.8216	1.5787
1981	0.7926	0.9916	0.9247	1.1902	0.7673	2.4124	0.8296	1.5939
1982	0.8170	1.0236	0.9316	1.1987	0.7791	2.4536	0.8372	1.6083
1983	0.8409	1.0552	0.9382	1.2067	0.7904	2.4928	0.8444	1.6220
1984	0.8644	1.0864	0.9444	1.2143	0.8011	2.5303	0.8512	1.6350
1985	0.8875	1.1173	0.9504	1.2215	0.8112	2.5660	0.8577	1.6474
1986	0.9101	1.1476	0.9560	1.2284	0.8209	2.6001	0.8639	1.6592
1987	0.9324	1.1776	0.9614	1.2349	0.8301	2.6325	0.8697	1.6703
1988	0.9541	1.2070	0.9665	1.2411	0.8389	2.6635	0.8753	1.6809
1989	0.9755	1.2360	0.9713	1.2470	0.8472	2.6930	0.8806	1.6910
1990	0.9963	1.2646	0.9759	1.2526	0.8551	2.7211	0.8856	1.7006
1991	1.0168	1.2926	0.9803	1.2579	0.8626	2.7478	0.8904	1.7097
1992	1.0367	1.3201	0.9844	1.2629	0.8698	2.7733	0.8950	1.7183
1993	1.0562	1.3472	0.9884	1.2677	0.8766	2.7975	0.8993	1.7265
1994	1.0753	1.3737	0.9921	1.2723	0.8831	2.8205	0.9034	1.7343
1995	1.0939	1.3998	0.9957	1.2766	0.8892	2.8425	0.9072	1.7417
Mean	0.5939	0.7448	0.8136	1.0551	0.6049	1.8904	0.7083	1.3630
Std. Dev.	0.3115	0.3972	0.1563	0.1901	0.2240	0.7237	0.1707	0.3247
Min	0.1026	0.1309	0.4504	0.6136	0.1735	0.5524	0.3126	0.6123
Max	1.0939	1.3998	0.9957	1.2766	0.8892	2.8425	0.9072	1.7417

Table 6. RETURNS TO SCALE AND RATES OF TECHNOLOGICAL CHANGE

Period	Returns to Scale	Rates of Technological Change
1953-1995	1.437	0.0098
1953-1973	1.137	0.0097
1974-1995	1.724	0.0100
1953-1958	0.905	0.0087
1959-1963	1.099	0.0080
1964-1968	1.233	0.0108
1969-1973	1.359	0.0113
1974-1978	1.485	0.0112
1979-1983	1.645	0.0103
1984-1988	1.746	0.0102
1989-1993	1.917	0.0089
1994-1995	1.977	0.0085

Table 7. RATES AND DECOMPOSITION OF TFP GROWTH

Average Annual Rates (percent)

Period	Fisher TFPG	Returns to Scale Effect	Technological Change Effect	Factor Adjustment Effect	Residual
1953-1995	1.110	0.734	0.984	-0.610	0.001
1953-1973	1.440	0.466	0.959	0.017	-0.003
1974-1995	0.795	0.990	1.008	-1.208	0.005
1953-1958	0.331	-0.324	0.894	-0.198	-0.041
1959-1963	2.378	0.305	0.780	1.279	0.014
1964-1968	1.518	1.056	1.050	-0.596	0.008
1969-1973	1.754	0.987	1.126	-0.374	0.016
1974-1978	-0.315	0.883	1.126	-2.355	0.029
1979-1983	0.517	-0.070	1.051	-0.432	-0.031
1984-1988	1.880	1.942	1.015	-1.093	0.016
1989-1993	0.049	0.640	0.904	-1.482	-0.013
1994-1995	3.417	2.404	0.843	0.119	0.051

Table 8. DECOMPOSITION OF FACTOR ADJUSTMENT EFFECT

Average Annual Rates (percent)

Period	Total	Labor	Capital	Energy	Materials
1953-1995	-0.610	-0.007	-0.235	0.014	-0.381
1953-1973	0.017	0.294	-0.246	0.007	-0.038
1974-1995	-1.208	-0.294	-0.225	0.021	-0.709
1953-1958	-0.198	0.439	-0.221	-0.070	-0.346
1959-1963	1.279	0.225	0.170	0.064	0.819
1964-1968	-0.596	0.006	-0.593	0.021	-0.030
1969-1973	-0.374	0.479	-0.344	0.026	-0.534
1974-1978	-2.355	-0.023	-0.443	0.046	-1.934
1979-1983	-0.432	-0.220	-0.399	0.072	0.115
1984-1988	-1.093	-0.399	-0.050	-0.001	-0.643
1989-1993	-1.482	-0.423	-0.137	-0.011	-0.911
1994-1995	0.119	-0.574	0.093	-0.038	0.638