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Measuring productivity in an imperfect world

AKLILU A. ZEGEYE and LARRY ROSENBLUM

US Department of Labor, Bureau of Labor Statistics, Division of Productivity Research, 2 Massachusetts Ave., N.E. Room 2140 Postal Square Building, Washington DC 20212, USA

Most measures of multifactor productivity (MFP) assume constant returns to scale and perfect competition. Using a general aggregate production function together with duality theory and allowing for the possibilities of disequilibrium, markups and economies of scale, the study derives a more generalized MFP measure. The model was used to assess the economic performance in US manufacturing for the 1949 to 1988 period. The results suggest that scale and markups have substantial power in explaining MFP growth for all periods and that half of the measured MFP growth (as measured within the conventional framework) comes from biases due to scale economies, market power, and interaction effects.

I. INTRODUCTION

In attempting to account for the weak US productivity performance of the last twenty years, several researchers have suggested that market imperfections may account for a substantial portion of the measured productivity slowdown. Hall (1988) develops a model of counter-cyclical markups over marginal costs.[1] Hall further argues and presents some evidence that pro-cyclical changes in multifactor productivity may be due to the existence of a wedge between price and marginal cost. Rotemberg and Summers (1990) have further demonstrated how, with expanding output, price rigidity (counter-cyclical markups over marginal cost) and labour-hoarding, variations between price and marginal cost over the business cycle result in the observed pro-cyclical movements in multifactor productivity.

While Hall argues that returns to scale must be present when price markups occur, Basu (1995) demonstrates that returns to scale are unnecessary to explain trends in productivity growth in a counter-cyclical markup model provided that intermediate goods can also exhibit counter-cyclical markups. Building on Hall's work, Morrison (1992) develops a production framework allowing for returns to scale and markups. She derives modified growth accounting formulae which incorporate these additional market features.

Under constant returns to scale and competitive markets, Berndt and Fuss (1986) and Hulten (1986) building on the work of Jorgenson and Griliches (1967) applied the conventional production function and associated share equations for a given quasi-fixed input. In this conventional method, Berndt and Fuss and Hulten (henceforth the BFH framework) showed that this ex-post definition of capital costs implicitly accounts for the effect of changes in capacity utilization on productivity. They then derived, using a growth accounting framework, an explicit measure of the impact of capacity utilization on MFP. The BFH framework (also the Bureau of Labour Statistics (BLS) measure) allows for sub-equilibrium by using a residual measure of the cost of capital.[2] If returns to scale and markups are present, in the conventional method, these are erroneously attributed to capital income.

[1] The findings and opinions presented in this paper are strictly those of the authors and do not necessarily reflect the views of the U.S. Department of Labor. We wish to thank without implicating Charles Hulten, Michael Harper, and Edwin Dean for their many useful comments and suggestions in preparing this paper.

[2] For an extensive survey on productivity measures, see Nelson (1981), Nadiri (1970), and Denison (1979).

This paper extends the BFH framework in a manner consistent with Morrison. We develop a procedure for measuring productivity growth under conditions of sub-equilibrium, price markup, and returns to scale, a 'generalized' productivity measure. We then compare it with two other previous measures of productivity: the traditional or Solow framework measure and the conventional or BFH framework. Unlike Morrison (1992), these adjustments for sub-equilibrium, scale, and markups are consistently based on the primal output measure.[3] As part of these derivations, we will calculate capacity measures when returns to scale and markups are added to the framework.

It is important to note here that dropping the assumptions of constant returns to scale and perfect competition leads to an econometric approach rather than using non-parametric price and quantity data to measure MFP and so extending these formulas is easier in concept than in practice. To implement the above model, we estimate the restricted normalized translog cost function and the associated share equations together with an Euler equation for capital investment using data for US manufacturing from 1949 to 1988 using three-stage least squares (3SLS) estimation technique. The results of the measures of scale, markups, and capacity are then used to measure their impact on productivity growth. In the next section we derive a generalized productivity measure and compare it with the previous measures of productivity. Section III reports empirical results for US manufacturing for the 1949–1988 period and Section IV summarizes the principal findings.

II. THE MODEL

Consider a production function defined over inputs capital (K), labour (L) and the technology available at time (t):[4]

$$Q = F(K, L, t) \tag{1}$$

Taking the logarithms of both sides and differentiating with respect to (w. r. t.) time yields:

$$\frac{\dot{Q}}{Q} = \frac{\partial F}{\partial K}\frac{K}{Q}\frac{\dot{K}}{K} + \frac{\partial F}{\partial L}\frac{L}{Q}\frac{\dot{L}}{L} + \frac{\partial \ln F}{\partial t} \tag{2}$$

To see the impact of economies of scale on economic growth, let θ be the scaling effect or returns to scale measured as the sum of the elasticities of the production function w. r. t. each input i.e.:[5]

$$\theta = \frac{\partial F}{\partial K}\frac{K}{Q} + \frac{\partial F}{\partial L}\frac{L}{Q} \tag{3a}$$

in which case, the (ex-post) shadow capital elasticity is:

$$\frac{\partial F}{\partial K}\frac{K}{Q} = \theta - \frac{\partial F}{\partial L}\frac{L}{Q} \tag{3b}$$

If there are constant returns to scale, the elasticities sum to unity ($\theta = 1$). Making use of Equation 3b, the economic growth formula, Equation 2 can be written as:

$$\frac{\dot{Q}}{Q} = \left(\theta - \frac{\partial F}{\partial L}\frac{L}{Q}\right)\frac{\dot{K}}{K} + \frac{\partial F}{\partial L}\frac{L}{Q}\frac{\dot{L}}{L} + \frac{\partial \ln F}{\partial t} \tag{4}$$

With perfect competition, the shares of the inputs in revenue can be equated to the elasticity of the production function with respect to inputs. However, if there is a price markup, the input cost shares of revenue understate the elasticities because revenue includes monopoly profits and, therefore, the elasticities are *not* identical to factor shares and the cost-based MFP differs from the revenue-based Solow residual. Revenue (PQ) no longer equals the costs of production ($MC\,Q$) since price does not equal marginal cost (MC), and the latter should be used as the denominator of the cost share equations.

Expressing the price markup ω as P/MC and Z_K^* as the 'generalized' shadow price of capital when returns to scale, imperfect competition, and sub-equilibrium are present, the shares should be evaluated in terms of the marginal cost of production:

$$\frac{\partial F}{\partial K}\frac{K}{Q} = \frac{\omega(Z_K^*)K}{PQ} \quad \text{and} \quad \frac{\partial F L}{\partial L Q} = \frac{\omega P_L L}{PQ} \tag{5}$$

Equation (3a) can therefore be rewritten as:

$$\theta = \frac{\omega P_L L}{PQ} + \frac{\omega Z_K^* K}{PQ} = \frac{\omega(P_L L + Z_K^* K)}{PQ}$$

$$= \frac{P_L L + Z_K^* K}{MC(Q)} + \frac{AC^*}{MC} \tag{6}$$

Scale economies are thus measured as the ratio of the ex-post production cost to the revenues that would accrue to the firm by pricing the outputs at their MC. Equation 6 can be rearranged in terms of the 'generalized' shadow cost (S

[3] Morrison (1992) adjusts sub-equilibrium and returns to scale effect from a dual cost perspective and markups on the primal output side. Consequently, she has made use of the cost elasticity w.r.t. output as well as output demand elasticity to decompose the residual while this study has made use only of the latter. Moreover, Morrison (1992) uses a monopoly pricing formula for the markup which limits the generality of the model since one has to subscribe to a particular model of firm behaviour.

[4] Although the model used two inputs to simplify the arguments, the model could be extended to accommodate more than two inputs and this can be seen in the empirical part of the study.

[5] While the debate as to the existence or the importance of returns to scale is far from settled, it is worthwhile exploring how a production function characterized by returns to scale would differ from one which assumes constant returns to scale. Regardless, the non-constant returns to scale (compared to constant returns to scale) is a less restrictive model of production. See, for example, Stigler (1961) and Berndt and Khaled (1979).

which is a measure of the cost that would have occurred if all factors were paid the value of their marginal products ($S^* = (\theta/\omega)PQ = P_L L + Z_K^* K$), or in terms of the 'generalized' average shadow cost ($AC^* = (\theta/\omega)P$) as well as 'generalized' shadow price of capital

$$(Z_K^* = ((\theta PQ/\omega S) - P_L L)/K)$$

Substituting the elasticities (Equation 5), the growth Equation 4 yields:

$$\frac{\dot{Q}}{Q} = \left(\theta - \frac{\omega P_L L}{PQ}\right)\frac{\dot{K}}{K} + \frac{\omega P_L L}{PQ}\frac{\dot{L}}{L} + \left(\frac{\dot{A}^*}{A^*}\right)^G \tag{7}$$

where

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \frac{\partial \ln F}{\partial t}$$

is the 'generalized' MFP measure in the sense that it is no longer based on the assumption of perfect competition and constant returns to scale (i.e. $\omega \neq 1$ and $\theta \neq 1$). Expressing Equation 7 in terms of the generalized MFP:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \frac{\dot{Q}}{Q} - \left(\theta - \frac{\omega P_L L}{PQ}\right)\frac{\dot{K}}{K} - \frac{\omega P_L L}{PQ}\frac{\dot{L}}{L} \tag{8}$$

shows how economies of scale and markup pricing alter the usual primal measurement of productivity growth.

To explore how imperfect competition and returns to scale affect the MFP measure, this generalized productivity measure framework is compared with an MFP measure $(\dot{A}^*)/(A^*)$ expressed as follows:

$$\left(\frac{\dot{A}^*}{A^*}\right) = \frac{\dot{Q}}{Q} - \frac{P_L L}{PQ}\frac{\dot{L}}{L} - \frac{Z_K K}{PQ}\frac{\dot{K}}{K} \qquad (P_K \neq Z_K) \tag{9}$$

where Z_K is the shadow price of capital and is the residual portion of total revenue not accruing to labour per unit of capital ($Z_K = (PQ - P_L L)/K$). This quasi-rent measure is widely used in productivity analysis.[6] We can see that with no markups and constant returns to scale (i.e. $\omega = 1$ and $\theta = 1$), $Z_K^* = Z_K$. However, if markups and returns to scale are present, they are included in total costs and therefore in Z_K.

To compare these two measures of MFP, solve for $(\dot{Q}/Q)$ in Equation 9 and substitute it into Equation 8 from which, with some substitution and rearrangement of terms, we get the following:[7]

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \left(\frac{\dot{A}^*}{A^*}\right) + (\omega - 1)\frac{P_L L}{PQ}\left(\frac{\dot{K}}{K} - \frac{\dot{L}}{L}\right) + (1 - \theta)\frac{\dot{K}}{K} \tag{10}$$

Hulten (1986) derived a measure of the contribution of capacity utilization to productivity change under the assumptions of constant returns to scale and perfect competition (i.e., $\theta = 1$ and $\omega = 1$). He defined this contribution as the difference between an MFP measure which assumes long-run equilibrium, the traditional Solow framework $((\dot{A}^F)/(A^F))$, and an MFP which allows for varying capacity utilization only, ~~or the 'naive' MFP measure~~ $((\dot{A}^*)/(A^*))$:

$$\left(\frac{\dot{A}^*}{A^*}\right) = \frac{\dot{A}^F}{A^F} + \left(\frac{PQ}{S} - 1\right)\left(\frac{\dot{Q}}{Q} - \frac{\dot{A}^*}{A^*} - \frac{\dot{K}}{K}\right) \qquad (P_K \neq Z_K = Z_K^*) \tag{11a}$$

where the last term of Equation 11a is the effect of capacity on productivity. Under these assumptions, the generalized MFP measure equals the BFH framework measure, i.e. $(\dot{A}^*/A^*)^G = ((\dot{A}^*)/(A^*)$.

It can be seen that capacity utilization affects productivity when ex-post costs differ from revenue. However, once constant returns to scale and perfect competition are dropped, the BFH or the BLS capacity effect also has to be adjusted to account for these two effects (see Appendix B for derivation):

$$\left(\frac{\dot{A}^*}{A^*}\right) = \frac{\dot{A}^F}{A^F} + \left(\frac{\theta PQ}{\omega S} - 1\right)\left(\frac{\dot{Q}}{Q} - \frac{\dot{A}^*}{A^*} - \frac{\dot{K}}{K}\right) \qquad (P_K \neq Z_K \neq Z_K^*) \tag{11b}$$

where the second term on the right-hand side of the equation is termed here, for the sake of convenience, 'generalized' capacity. Again productivity is affected by capacity when ex-post costs differ from revenue, but now costs should not include monopoly profits or returns to scale. The generalized shadow price of capital, Z_K^*, excludes these other sources of revenue and so the difference between Z_K^* and the ex-ante price of capital, P_K, is the source of the 'generalized' capacity effect.

In Hulten's framework, capacity exerts an effect on productivity measures when production is not operating on the minimum of its long-run average cost curve. Once price markups and returns to scale are introduced, that point may change and Equation 11b reflects how those forces affect the capacity measures, and consequently MFP. In this case, the generalized productivity measure of Equation 10 can be decomposed into four different effects: the traditional (Solow) framework productivity measure and the contributions of generalized capacity utilization, markups, and returns to scale:

[6] The rate of return we get with the residual is an average value whereas the rate of return we get when all the assumptions are relaxed is a marginal rate of return. See Domowitz *et al.* (1988) for details.

[7] In order to save space and keep the flow of the discussion smooth, the derivative of Equation 10 and other equations have been relegated to Appendixes A and B.

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \frac{\dot{A}^F}{A^F} + \left(\frac{\theta PQ}{\omega S} - 1\right)\left(\frac{\dot{Q}}{Q} - \frac{\dot{A}^*}{A^*} - \frac{\dot{K}}{K}\right) + (\omega - 1)\frac{P_L L}{PQ}\left(\frac{\dot{K}}{K} - \frac{\dot{L}}{L}\right) + (1 - \theta)\frac{\dot{K}}{K} \quad (P_K \neq Z_K \neq Z_K^*) \quad (12)$$

The impact of returns to scale and price markup on the capacity effects can be measured as the difference between Equations 11b and 11a.

The generalized capacity can be viewed as the combined effect of the standard (Hulten's) capacity and the interaction effect. We would expect the generalized capacity effect to be smaller (larger) in absolute value than the standard (Hulten's) capacity if $\theta < \omega$ ($\theta > \omega$).

The generalized productivity measure $(\dot{A}^*/A^*)^G$ of Equation 10 can then be decomposed into four separate components: the conventional (BFH or BLS) framework productivity measure $(\dot{A}^*/A^*)^{\#}$, and the effects of the contribution of the interaction effect, markups, and returns to scale to productivity growth and is written as:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \left(\frac{\dot{A}^*}{A^*}\right)^{\#} - \left(\frac{\theta PQ}{\omega S} - \frac{PQ}{S}\right)\left(\frac{\dot{Q}}{Q} - \frac{\dot{A}^*}{A^*} - \frac{\dot{K}}{K}\right) + (\omega - 1)\frac{P_L L}{PQ}\left(\frac{\dot{K}}{K} - \frac{\dot{L}}{L}\right) + (1 - \theta)\frac{\dot{K}}{K} \quad (P_K \neq Z_K \neq Z_K^*) \quad (13)$$

Equations 12 and 14 allow one to see how the measured concepts $[\dot{A}^F/A^F$ and $\dot{A}^*/A^*]$ differ from the generalized MFP $(\dot{A}^*/A^*)^G$.

A basic issue of productivity analysis is the allocation of output growth to the growth rates of the inputs and the efficiency of production. By analysing a one output–two inputs production function, this study has developed a generalized framework of measuring MFP. Table 1 summarizes how sub-equilibrium, scale and price markups affect the measures of input elasticities and in turn the measures of productivity growth.

In essence, the measurement of productivity rests, in large part, on the definition of the price of capital. When production exhibits constant returns to scale and product markets are both competitive and in long-run equilibrium, an ex-ante concept of the price of capital, P_K, is appropriate. In this case, the output elasticities could be equated to the factor shares and all measures of MFP yield identical estimates (see Table 1 column 3). Dropping the assumption of long-run equilibrium but maintaining the two other assumptions, Jorgenson and Griliches (1967) and later BFH developed an ex-post or shadow price for capital, Z_K, which differs from P_K.

Under this BFH framework the shadow value of capital, $Z_K K$, is appropriate for estimating output elasticities (see Table 1 column 4). By dropping the assumptions of constant returns to scale and perfect competition, a still different ex-post or 'generalized' shadow price of capital emerges, Z_K^*, in which case the 'generalized' shadow value of capital, $Z_K^* K$, is the appropriate measure for estimating output elasticities and requires a generalized productivity measure based on the complete specification of Equations 12 and 14 (Table 1 columns 5 and 6). In the next section we discuss functional forms as well as data sources to illustrate the above model empirically.

III. EMPIRICAL ANALYSIS

Data and methodology

The generalized MFP, unlike those MFP measures developed by BLS multifactor programme, cannot be directly obtained from data on costs and quantities of inputs and outputs. Estimates of returns to scale and price markups or equivalently, ex-post generalized shadow cost of capital and marginal cost are obtained through estimation of a cost function subject to several constraints. Thus duality theory has been applied to incorporate structural determinants of productivity into the production structure to calculate the shape and shift (i.e. productivity growth) of the production function indirectly from the cost function. Although a production function was used to develop the model, a cost function is used for measurement because the model uses deviations among price and average cost as well as derivatives of the cost function (marginal cost and average 'shadow' cost) to show the impact of the assumptions on productivity within a growth accounting framework.

We take the aggregate production function that relates the flow of gross output (Q) to five inputs ($KLEMB$): a quasi-fixed capital input (K), and variable inputs, labour (L), energy (E), non-energy materials (M), and purchased business services (B); $Q = Q(L, E, M, B, K, \Delta K, t)$. Corresponding to such a production function there exists a dual cost function, S, including the adjustment cost for net investment which is conditioned on a set of variable input prices P_L, P_E, P_M, and P_B, a quasi-fixed capital input and the change in the capital input as well as a desired or exogenously determined level of output and has a general form: $S = S(Q, P_L, P_E, P_M, P_B, K, \Delta K, t)$.

The methodology used to implement the above model is the transcendental logarithmic cost (TLC) function developed by Christensen *et al.* (1973) with some modification.[8] A well-behaved cost (a factor demand) function must be homogeneous of degree one (zero) in prices. The prices of the inputs are normalized by the price of business services P_B. Symmetry ($\beta_{ij} = \beta_{ji}$) and Hick's neutrality are imposed. The general form is:

Table 1. *Three ways of measuring MFP using the 'residual' method*

	Theoretical values	Traditional measure of MFP (Solow framework)	Conventional measure of MFP (Berndt-Fuss-Hulten (BFH) framework)	The generalized framework	Comments on generalized framework
Marginal products of capital and labour, respectively	$\frac{\partial Q}{\partial K}=\frac{P_K}{MC}$ and $\frac{\partial Q}{\partial L}=\frac{P_L}{MC}$	$\frac{\partial Q}{\partial K}=\frac{P_K}{P}$ and $\frac{\partial Q}{\partial L}=\frac{P_L}{P}$	$\frac{\partial Q}{\partial K}=\frac{Z_K}{P}$ and $\frac{\partial Q}{\partial L}=\frac{P_L}{P}$	$\frac{\partial Q}{\partial K}=\frac{Z_K^*}{MC}$ and $\frac{\partial Q}{\partial L}=\frac{P_L}{MC}$	$\frac{\partial Q}{\partial K}=\frac{\omega Z_K^*}{P}$ and $\frac{\partial Q}{\partial L}=\frac{\omega P_L}{P}$
Elasticity of output w.r.t. capital	$\frac{\partial Q}{\partial K}\frac{K}{Q}=\frac{P_K}{MC}\frac{K}{Q}$	$\frac{\partial Q}{\partial K}\frac{K}{Q}=\frac{P_K}{P}\frac{K}{Q}$	$\frac{\partial Q}{\partial K}\frac{K}{Q}=\frac{Z_K}{P}\frac{K}{Q}$	$\frac{\partial Q}{\partial K}\frac{K}{Q}=\frac{Z_K^*}{MC}\frac{K}{Q}$	$\frac{\partial Q}{\partial K}\frac{K}{Q}=\frac{\omega Z_K^*}{P}\frac{K}{Q}$
and					
Elasticity of output w.r.t. labour	$\frac{\partial Q}{\partial L}\frac{L}{Q}=\frac{P_L}{MC}\frac{L}{Q}$	$\frac{\partial Q}{\partial L}\frac{L}{Q}=\frac{P_L}{P}\frac{L}{Q}$	$\frac{\partial Q}{\partial L}\frac{L}{Q}=\frac{P_L}{P}\frac{L}{Q}$	$\frac{\partial Q}{\partial L}\frac{L}{Q}=\frac{P_L}{MC}\frac{L}{Q}$	$\frac{\partial Q}{\partial L}\frac{L}{Q}=\frac{\omega P_K}{P}\frac{L}{Q}$
Returns to scale (θ)	$\frac{\partial Q}{\partial K}\frac{K}{Q}+\frac{\partial Q}{\partial L}\frac{L}{Q}$ $\theta=\frac{P_K}{MC}\frac{K}{Q}+\frac{P_L}{MC}\frac{L}{Q}$	$\frac{\partial Q}{\partial K}\frac{K}{Q}+\frac{\partial Q}{\partial L}\frac{L}{Q}$ $1=\frac{P_K}{P}\frac{K}{Q}+\frac{P_L}{MC}\frac{L}{Q}$	$\frac{\partial Q}{\partial K}\frac{K}{Q}+\frac{\partial Q}{\partial L}\frac{L}{Q}$ $1=\frac{Z_K}{P}\frac{K}{Q}+\frac{P_L}{P}\frac{L}{Q}$	$\theta=\frac{Z_K^*}{MC}\frac{K}{Q}+\frac{P_L}{MC}\frac{L}{Q}$ $\theta=\frac{\omega Z_K^*}{P}\frac{K}{Q}+\frac{\omega P_L}{P}\frac{L}{Q}$	
Multi-factor productivity, $\frac{\partial Q/\partial t}{Q}$	$\frac{\dot{Q}}{Q}-\left(\frac{\partial Q}{\partial K}\frac{L}{Q}\right)\frac{\dot{K}}{K}-\left(\frac{\partial Q}{\partial L}\frac{L}{Q}\right)\frac{\dot{L}}{L}$	$\frac{\dot{Q}}{Q}-\left(\frac{P_K}{P}\frac{K}{Q}\right)\frac{\dot{K}}{K}-\left(\frac{P_L}{P}\frac{L}{Q}\right)\frac{\dot{L}}{L}$ $=\left(\frac{\dot{A}^F}{A^F}\right)$	$\frac{\dot{Q}}{Q}-\left(\frac{Z_K}{P}\frac{K}{Q}\right)\frac{\dot{K}}{K}-\left(\frac{P_L}{PQ}\right)\frac{\dot{L}}{L}$ $=\left(\frac{\dot{A}^*}{A^*}\right)$	$\frac{\dot{Q}}{Q}-\left(\frac{Z_K^*}{MC}\frac{\dot{K}}{Q}\right)\frac{\dot{K}}{K}-\left(\frac{P_L L}{MCQ}\right)\frac{\dot{L}}{L}$ $=\left(\frac{\dot{A}^*}{A^*}\right)^G$	$\left(\frac{\dot{A}^*}{A^*}\right)+\left(\frac{\theta}{\omega}-\frac{\omega}{S}\right)\frac{PQ}{S}\left(\frac{\dot{Q}}{Q}-\frac{\dot{A}^*}{A^*}-\frac{\dot{K}}{K}\right)$ $+(\omega-1)\frac{P_L}{P}\frac{L}{Q}\left(\frac{\dot{K}}{K}-\frac{\dot{L}}{L}\right)+(1-\theta)\frac{\dot{K}}{K}$

A simplified verison of the production function with one output–two inputs (capital (K) and labour (L)) and technology available at time (t) is used here: $Q=Q(K,L,t)$.

$$\begin{aligned}\ln S = {} & \beta_0 + \beta_Q \ln Q + \beta_L \ln(P_L/P_B) + \beta_M \ln(P_M/P_B) \\ & + \beta_E \ln(P_E/P_B) + \beta_K \ln K \\ & + 1/2\beta_{QQ}(\ln Q)^2 + 1/2\beta_{LL}(\ln(P_L/P_B)^2 \\ & + \beta_{LM} \ln(P_L/P_B)\ln(P_M/P_B) \\ & + \beta_{LE} \ln(P_L/P_B)\ln(P_E/P_B) + \beta_{EM}\ln(P_E/P_B) \\ & \times (\ln(P_M/P_B)) + 1/2\beta_{EE}(\ln(P_E/P_B))^2 \\ & + 1/2\beta_{MM}(\ln(P_M/P_B))^2 + 1/2\beta_{KK}(\ln K)^2 \\ & + \beta_{QE}\ln Q \ln(P_E/P_B) + \beta_{QL}\ln Q\ln(P_L/P_B) \\ & + \beta_{QM}\ln Q\ln(P_M/P_B) + \beta_{KL}\ln K\ln(P_L/P_B) \\ & + \beta_{KE}\ln K\ln(P_E/P_B) + \beta_{KM}\ln K\ln(P_M/P_B) \\ & + \beta_{QK}\ln K\ln Q + \beta_t t + 1/2\beta_{\Delta K\Delta K}(\Delta K)^2 \qquad (14)\end{aligned}$$

Costless adjustment of capital is inconsistent with a short run fixed capital stock. Fixity of capital arises from additional costs required to alter the stocks of capital. Consequently, changes in net capital stocks, ΔK, are a partial adjustment to an optimal (long-run profit maximizing) capital stock, K^*, given a current set of prices and output. The change in capital, $\Delta K = K - K_{-1}$, is the discrete analogue to the continuous change ($\mathrm{d}K/\mathrm{d}t$) and imposes additional costs due to the cost of changes in the fixed input with the existing variable inputs. The translog form which has a logarithmic transformation of K and ΔK has been adjusted accordingly:

$$(K - K_{-1})/K_{-1} = \Delta K/K_{-1} \approx \ln K/K_{-1} \qquad (15a)$$

in which case,

$$\Delta K = (K_{-1}(\ln(K^*/K_{-1})))^{\delta} \qquad (15b)$$

where the 'speed of adjustment', δ, of actual capital stock to the optimal stock is:

$$\delta = 1/2(r - (r^2 + 4\beta_{KK}/\beta_{\Delta K\Delta K})^{1/2}) \qquad (15c)$$

where r is the ex-ante rate of return to capital and β_{KK} and $\beta_{\Delta K\Delta K}$ are the coefficients of the second partial derivatives of the translog function w. r. t. K and ΔK, respectively. The internal cost of adjustment is incorporated to the cost function under the condition that the marginal cost of adjustment must be zero when no change in the net stock occurs. This constrains all the parameters relating to the speed of adjustment except for $\beta_{\Delta K\Delta K}$ to be zero.[9]

Using Shepherd's Lemma (1957), the corresponding restricted factor demand equations calculated from the share equations are:

$$\begin{aligned}L = {} & (S/P_L)(\beta_L + \beta_{LL}\ln(P_L/P_B) + \beta_{LM}\ln(P_M/P_B) \\ & + \beta_{LE}\ln(P_E/P_B) + \beta_{QL}\ln Q + \beta_{KL}\ln K) \\ E = {} & (S/P_E)(\beta_E + \beta_{EE}\ln(P_E/P_B) + \beta_{LE}\ln(P_L/P_B) \\ & + \beta_{EM}\ln(P_M/P_B) + \beta_{QE}\ln Q + \beta_{KE}\ln K) \\ M = {} & (S/P_M)(\beta_M + \beta_{MM}\ln(P_M/P_B) + \beta_{LM}\ln(P_L/P_B) \\ & + \beta_{EM}\ln(P_E/P_B) + \beta_{QM}\ln Q + \beta_{KM}\ln K) \qquad (16)\end{aligned}$$

The necessary Euler condition for a minimum can be written as follows:

$$S_K - rS_{\Delta K} - P_K/P_B - (-S_{\Delta K\Delta K}) - (-S_{K\Delta K}) = 0 \quad (17a)$$

In terms of the optimal path with the quasi-fixed capital input (P_K is the ex-ante cost of capital and is normalized by P_B) we have:

$$\frac{P_K}{P_B} = S_K - rS_{\Delta K} - (-S_{\Delta K\Delta K}) - (-S_{K\Delta K}) \qquad (17b)$$

where S_K is the partial derivative of the cost function w. r. t. capital (K):

$$\begin{aligned}S_K = \frac{\partial S}{\partial K} = {} & (S/K)(\beta_K + \beta_{KK}\ln K + \beta_{KL}\ln(P_L/P_B) \\ & + \beta_{KE}\ln(P_E/P_B) + \beta_{KM}\ln(P_M/P_B) \\ & + \beta_{QK}\ln Q) \qquad (18a)\end{aligned}$$

$S_{\Delta K}$ is the partial derivative of the cost function w. r. t. (ΔK):

$$S_{\Delta K} = \frac{\partial S}{\partial \Delta K} = (\beta_{\Delta K\Delta K}\ln(\Delta K))(S/\Delta K) \qquad (18b)$$

$S_{\Delta K\Delta K}$ is the second partial derivative of the cost function w. r. t. ΔK:

$$\begin{aligned}S_{\Delta K\Delta K} = {} & \frac{\partial^2(S_{\Delta K})}{(\partial\Delta K)^2} \\ = {} & (S/\Delta K)(\beta_{\Delta K\Delta K} + (\beta_{\Delta K\Delta K}\ln(\Delta K)/\Delta K) \\ & \times (\beta_{\Delta K\Delta K}\ln(\Delta K) - 1)) \qquad (18c)\end{aligned}$$

$S_{K\Delta K}$ is the second partial derivative of the cost function

[8] This TLC function is modified to accommodate for the quasi-fixity of some of the inputs by Brown and Christensen (1981) in Chapter 10 of *Modelling and Measuring Natural Resources Substitution*, by E. R. Berndt and B. C. Field.
[9] The internal cost of adjustment is derived by minimizing the present value of the future stream of costs w.r.t. the production function. For a detailed analysis and construction of a dynamic internal cost of adjustment, see Berndt *et al.* (1980) and Morrison (1986).

w.r.t. K and ΔK:

$$S_{K\Delta K} = \frac{\partial^2}{\partial \Delta K\, \partial K}$$
$$= (S/K)(\beta_{\Delta K \Delta K} \ln(\Delta K)/\Delta K)(S_K) \quad (18d)$$

The estimating form of the Euler equation is found by substituting these values (Equations 18a–18d) into Equations 17b:

$$\frac{P_K}{P_B} = S\{[\beta_K + \beta_{KK} \ln K + \beta_{KL} \ln(P_L/P_B)$$
$$+ \beta_{KE} \ln(P_E/P_B) + \beta_{KM} \ln(P_M/P_B)$$
$$+ (\beta_{\Delta K \Delta K} \ln(\Delta K)/\Delta K)](1/K)$$
$$+ [(\beta_{\Delta K \Delta K} \ln \Delta K(1-r)$$
$$+ (\beta_{\Delta K \Delta K} + (\beta_{\Delta K \Delta K} \ln(\Delta K)/\Delta K)$$
$$\times (\beta_{\Delta K \Delta K} \ln(\Delta K) - 1)](1/\Delta K)\} \quad (19)$$

We estimate the restricted normalized translog cost function (Equation 14) and the associated derived factor demand equations (Equation 16) together with the Euler equation for capital (Equation 19). The model is estimated using data for US manufacturing from 1949 to 1988 using three-stage least squares (3SLS).

Data on the price and quantity of output, quasi-fixed capital, labour, energy, non-energy intermediate materials and purchased business services are obtained from the Bureau of Labor Statistics 2-digit manufacturing multifactor measures.[10] Price and quantity measures for capital investment in US manufacturing are used to construct ex-ante rather than ex-post measures of capital services so that quasi-rents can be measured directly rather than implicitly included in the measures of capital income. To implement this approach an ex-ante rental price of capital is calculated using Moody's Baa bond rates and assuming no ex-ante capital gains, instead of the BLS approach, which uses ex-post rates of return and ex-post capital gains. The resultant ex-ante rental prices are used to compute share weights which are in turn used to Tornqvist aggregate capital into a measure of the ex-ante capital services.

Empirical results

The 3SLS parameter estimates of the model are presented in Table 2. In general, the parameter estimates satisfy the model's theoretical restrictions in terms of correct economic signs, reasonable magnitudes, and statistical significance. The results were robust to changes such as the period of estimation. The magnitudes of the estimated elasticities are plausible and support the use of the model and data.[11]

Table 2. *Results of the coefficients estimates in 3SLS*

Parameters	Estimates	(standard error)	Parameters	Estimates	(standard error)
β_O	0.05	(0.07)	β_{BL}	0.07	(0.02)
β_Q	0.95	(1.22)	β_{KL}	0.02	(0.02)
β_T	0.001	(0.03)	β_{KE}	0.03	(0.01)
β_L	0.31	(0.001)	β_{KM}	−0.05	(0.01)
β_E	0.02	(0.001)	β_{KB}	0.01	(0.02)
β_M	0.62	(0.001)	β_{EM}	0.01	(0.004)
β_B	0.06	(0.001)	β_{EB}	0.02	(0.004)
β_K	−0.16	(1.07)	β_{EQ}	−0.001	(0.42)
β_{LL}	0.05	(0.02)	β_{MQ}	0.09	(0.13)
β_{EE}	0.01	(0.001)	β_{BQ}	−0.03	(0.01)
β_{MM}	0.15	(0.01)	β_{LQ}	−0.07	(0.01)
β_{BB}	0.01	(0.01)	β_{KQ}	−0.66	(6.96)
β_{KK}	0.69	(5.82)	β_M	−0.08	(0.01)
β_{QQ}	−0.42	(8.75)	$\beta_{\Delta K\Delta K}$	0.002	(0.003)
β_{ML}	−0.08	(0.01)	β_{EL}	−0.04	(0.01)

Based on the parameter estimates, values for marginal cost (MC) and the 'generalized' price of the quasi-fixed capital input, Z^*_K, are derived and then used to calculate generalized AC^*; MC and AC^* together with data for price (P) and ex-ante average total cost (AC) are constructed to measure scale economies, markups and capacity utilization. Table 3 shows Z^*_K together with the other capital prices, several price measures, and the implied measures of capacity, scale, and markups for representative years (1956, 1966, 1976 and 1986). See also Tables C1 and C2 in Appendix C.

From Table 3 we see that an ex-ante price of capital, P_K, is less than both of the ex-post shadow prices, Z_K and Z^*_K, except for the years 1956 and 1966 where $Z^*_K < P_K$. Over the entire period the price markup (P/MC) and the standard long-run scale (AC/MC) measures show a consistent decline (markup falls from 1.35 in 1956 to 1.05 in 1986, while the standard scale fell from 1.25% in 1956 to 1.04% in 1986). The generalized scale (AC^*/MC) measure is greater than unity (a value of 1.2) indicating increasing returns to scale. This is large but plausible when we consider that we are working with an aggregated data set where returns to scale could be due not only to factors of internal firm scale economies but also to other factors of external economies such as R & D and knowledge spillover.

[10] See Gullickson (1992) for details. The two-digit data are aggregated into manufacturing composites by Tornqvist indexing.
[11] The estimates of elasticities (own-price elasticities, cross-price elasticities, capital stock elasticities, output demand elasticities), price and cost measures, implied measures of capacity, scale, and markups for all years 1950–1988 are available upon request and are contained in Zegeye (1993).

Table 3. *Price and cost measures and implied measures of capacity, scale, and markups in US manufacturing: 1956, 1966, 1976, 1986*
Output Price, P, *1982 = 1.00*

Measure	1956	1966	1976	1986
Capital measures				
Ex-ante capital price (P_K)	0.19	0.27	0.46	0.92
Shadow capital price (Z_K)	0.45	0.59	0.78	1.01
'Generalized' shadow Capital price (Z_K^*)	0.09	0.15	1.16	2.38
Price measures				
Output price (P)	0.33	0.36	0.63	1.00
Average total cost (AC)	0.30	0.33	0.59	0.99
Average 'Generalized' shadow cost (AC^*)	0.29	0.32	0.67	1.16
Marginal cost (MC)	0.24	0.27	0.55	0.95
Cost measures (in billions of $)				
Variable cost ($P_L L + P_E E + P_M M + P_B B$)	291.2	463.5	1028.9	1972.5
Total cost ($P_K K + VC$)	309.3	498.7	1121.6	2225.9
'Generalized' shadow cost ($Z_K^* K + VC$)	299.3	483.4	1260.8	2626.4
Revenue (PQ)	333.6	540.5	1185.7	2251.6
Measures of capacity scale, and markups				
Generalized capacity ($AC^*/AC = \psi$)	0.97	0.97	1.12	1.18
Markups ($P/MC = \omega$)	1.35	1.34	1.14	1.05
Generalized scale ($AC^*/MC = \theta$)	1.21	1.19	1.21	1.23
Standard capacity ($P/AC = \phi = (\theta/\omega)\psi$)	1.08	1.08	1.06	1.01
Standard scale (long-run, $\lambda = \theta/\psi$)	1.25	1.23	1.08	1.04
Ratio of scale to markups (θ/ω)	0.90	0.89	1.07	1.17

Once the markup and scale effects have been incorporated into the model, the capacity effect also has to be adjusted to account for these two effects. The 'generalized' capacity ratio (AC^*/AC) is capacity measured with all the effects of imperfect competition and scale economies. These values have increased over time (i.e. a larger deviation between the short-run and long-run average costs and thus a less 'flat' SRAC).

The standard capacity measure (measure of profitability) P/AC is close to unity. This implies a normal economic profit is common for most years despite significant scale and markups and this is consistent with Hall's (1988) contention that US manufacturing exhibits monopolistically competitive behavior. This measure (P/AC) could be thought of as the full adjustment effect since it could be expressed as the product of price markups, the inverse of full scale, and the generalized capacity measures: $P/AC = [(P/MC)(MC/AC^*)(AC^*/AC)]$. This again indicates that markups (P/MC) are offset by scale and capacity effects. The breakdown of the standard capacity into the full adjustment effect helps us understand the deviations between costs and revenues. Table 3 shows that total costs multiplied by this full adjustment effect give us revenues.

Decomposition of multifactor productivity

The primary purpose of this study is to decompose the sources of conventional MFP growth into a scale effect, a markup effect, a capacity utilization effect (generalized as well as the standard capacity) and generalized MFP in the hope of isolating a better measure of technical progress. The decomposition of MFP is done using Equations 12 and 14 from the theoretical part of the paper. The results are presented in Table 4.

In the second column of Table 4, the traditional MFP growth measure (Solow framework) is presented where MFP is measured under the assumptions of constant returns to scale (CRTS), perfect competition (PC), and full capacity utilization (FCU). The third column shows the impact on productivity of correcting for the standard capacity effect measured under CRTS and PC assumptions. The conventionally measured MFP (BFH framework) index that recognizes this quasi-fixity of capital is presented in column 4 of Table 4. By using an ex-post returns to capital, the standard capacity effect is removed from the traditional MFP measure and the resulting BFH framework incorporates (non-parametrically) the short-run effect of cyclical fluctuations. This column coincides with

Table 4. *Decomposition of multifactor productivity growth in US manufacturing: 1949-1988 (percentage change)*

Year	Traditional MFP[a]	Standard capacity effect	BLS MFP[b]	Interaction effect	Scale effect	Markup effect	Generalized MFP[c]
1950	4.89	0.45	5.33	0.03	−0.57	−2.27	2.52
1951	0.12	−0.04	0.08	−0.00	1.28	−0.14	−1.34
1952	1.67	−0.09	1.58	−0.01	−0.91	0.39	1.06
1953	1.34	0.39	1.73	0.04	−0.59	−1.89	−0.71
1954	0.45	−0.56	−0.11	−0.02	−0.26	2.76	2.38
1955	2.42	0.41	2.83	0.03	−0.76	−2.28	−0.18
1956	−1.22	−0.15	−1.37	−0.01	−0.92	0.95	−1.36
1957	0.97	−0.30	0.67	0.01	−0.75	1.26	1.17
1958	−0.56	−0.46	−1.02	0.00	−0.44	2.42	0.97
1959	4.50	0.43	4.92	0.04	−0.44	−2.35	2.36
1960	−0.36	−0.04	−0.40	−0.00	−0.23	0.19	−0.72
1961	1.84	−0.14	1.71	−0.00	0.33	0.47	1.84
1962	2.22	0.15	2.37	0.01	−0.63	−1.07	0.69
1963	3.29	−0.06	3.23	−0.00	−0.60	−0.14	2.49
1964	3.35	−0.06	3.30	−0.00	−0.71	−0.30	2.28
1965	2.78	0.04	2.82	0.00	−1.01	−0.58	1.23
1966	−0.78	−0.07	0.70	−0.00	−1.43	0.17	−0.56
1967	−0.93	−0.32	−1.10	0.00	−1.54	1.54	−1.11
1968	1.04	−0.07	0.86	0.00	−1.16	0.18	−0.11
1969	−1.44	−0.12	0.92	0.00	−1.04	0.62	0.50
1970	−1.35	−0.14	−1.59	−0.00	−0.96	1.85	−0.70
1971	2.99	−0.12	2.87	−0.00	−0.63	0.48	2.72
1972	3.96	0.14	4.10	−0.00	−0.64	−0.85	2.61
1973	3.46	0.04	3.50	−0.00	−0.80	−0.27	2.43
1974	−2.81	−0.23	−3.04	−0.01	−0.99	0.90	−3.13
1975	−2.46	−0.53	−2.99	−0.10	−1.04	1.42	−2.71
1976	3.05	0.16	3.21	−0.02	−0.73	−0.46	2.05
1977	1.37	0.14	1.51	−0.02	−0.82	−0.43	0.29
1978	0.35	0.04	0.39	−0.01	−0.82	−0.10	−0.52
1979	0.37	−0.22	0.15	−0.05	−1.00	0.35	−0.55
1980	−0.67	−0.14	−0.81	−0.20	−0.94	0.54	−1.40
1981	0.90	−0.03	0.87	−0.13	−0.84	−0.14	0.03
1982	0.28	0.18	0.46	−0.33	−0.61	−0.25	−0.23
1983	1.73	−0.01	1.72	0.07	−0.14	−0.08	1.57
1984	1.82	−0.06	1.77	0.10	−0.62	−0.23	2.94
1985	1.68	0.07	1.75	−0.11	−0.64	0.13	1.12
1986	2.31	−0.02	2.29	−0.06	−0.41	0.05	1.86
1987	3.30	0.10	3.40	0.07	−0.31	−0.23	2.94
1988	3.34	−0.01	3.33	−0.00	−0.45	−0.08	2.80

Assumptions: CRTS – constant returns to scale, PC – perfect competition, FCU – full capacity utilization.
Note: To get the generalized capacity, combine the standard capacity and interaction effects.
[a] Traditional MFP assumes constant returns to scale, perfect competition and full capacity utilization.
[b] BLS MFP assumes constant returns to scale and perfect competition. BLS MFP = traditional MFP + standard capacity effect.
[c] Generalized MFP uses none of the above assumptions. Generalized MFP = BLS MFP + interaction effect + scale effect + markup effect.

the concept of BLS multifactor productivity for the total manufacturing sector.

The next three columns of Table 4 show the decomposition of MFP growth into the contributions made by the interaction, scale, and markups effects (columns 5, 6, and 7 respectively). The last column of Table 4 reports the fully adjusted MFP growth (or generalized framework) measure since it excludes the effects of these adjustments. Hence, the generalized framework is a residual measure of technical progress after adjustment for the full set of structural and behavioural factors considered above.

A comparison of these different MFP growth measures (columns 2, 4, and 8 of Table 4) reveal that the corrections for the different biases resulting from scale, markups, and standard capacity are quantitatively important while the interaction effect is minimal. The interaction effect on

Table 5. *The productivity slowdown in US manufacturing (1949–1988): average annual growth rates*

(*a*) Using growth accounting framework
(percentage change)

Selected periods	('49–'73)	('73–'79)	('79–'88)	('73–'88)	('49–'88)
Solow MFP $(\dot{A}/A)^F$	1.45	−0.04	1.63	0.96	1.26
plus: std capacity effect	−0.05	−0.11	−0.01	−0.04	−0.04
equals: BLS(B–F–H) MFP $(\dot{A}^*/A^*)^H$	1.40	−0.15	1.62	0.92	1.21
plus: interaction effect	−0.00	−0.02	−0.07	−0.05	−0.02
plus: markup effect	0.14	0.28	0.06	0.15	0.14
plus: scale effect	−0.79	−0.90	−0.55	−0.69	−0.75
equals: generalized framework $(\dot{A}^*/A^*)^G$ (technical change)	0.77	−0.78	1.07	0.33	0.60

Note: The numbers may not sum to exact figures because of rounding.

(*b*) Using regression

1949–1988
Generalized MFP growth rate = −0.24 + 0.67 BLS MFP growth rate Adj. $R^2 = 0.69$ $F(1, 37) = 85.70$
(Technical change) (9.19)
(*t*-value)

1949-1973
Generalized MFP growth rate = 0.27 + 0.52 BLS MFP growth rate Adj. $R^2 = 0.50$ $F(1, 22) = 23.99$
(Technical change) (4.90)
(*t*-value)

1973-1988
Generalized MFP growth rate = −0.50 + 0.89 BLS MFP growth rate Adj. $R^2 = 0.96$ $F(1, 14) = 429.34$
(Technical change) (20.72)
(*t*-value)

MFP was found to be so small that using the Hulten's capacity effect is empirically equivalent to the generalized capacity in measuring MFP (i.e. using Equation 10 instead of Equation 12). However, even though markup ratios and full-scale measures display large and similar values, we see in Table 4 that scale has a stronger impact on MFP growth than markups. Table 4 shows that for the 1950–1988 period, 13 observations reported nearly no markup effects (values below 1/4 of a percentage point) on MFP growth while only two for scale effects were so small.

Although the year-to-year measures of MFP growth yield some indication of economic performance, trends can be seen clearly in Table 5. In Table 5 part (a), adding technical change (generalized framework) to the effects of interaction, markups and scale yields the BLS MFP growth rates (BFH framework). By next adding the standard capacity to the BLS MFP measure, the traditional (Solow framework) MFP is obtained. In Table 5 part (b), the results displayed indicate how much of the variation in technical change is explained by the BLS MFP (BFH framework) and how much of the variation is explained by measurement biases due to the restrictive assumptions made (for the different time periods).

In general, the generalized MFP measure grows much slower than the conventional (BFH framework) or traditional (Solow framework) measures. Over the entire 1949–1988 period, the traditional (Solow framework) measured MFP for US manufacturing grew 1.26% per year. Making adjustments for sub-equilibrium, the BLS (BFH framework) measure grew nearly as fast, at 1.21% per year. After adjusting for the full set of structural and behavioural factors, generalized framework (technical change) registers a much lower growth rate of 0.60% per year. Despite the fact that scale and markups are vsimilar in magnitude (see Table 4), scale has by far the largest impact on MFP (see Table 5). Table 5 Part A shows that scale has a larger absolute impact than markups for all periods.

All three MFP measures conform to the stylized facts of dramatically slower growth in the 1970s followed by a rebound to rapid growth in the 1980s. The traditional MFP measure (Solow framework) reported a rebound of 1.67% per year (from a −0.04% growth rate per year in the 1973–1979 period to a growth rate of 1.63% in the 1979–1988 period). The conventional MFP measure (BFH framework) reported a 1.77% rebound in growth rate per year (from a −0.15% growth rate in the 1970s to a 1.62% growth rate in the 1980s); while the generalized framework measure registered a 1.85% growth rate per year (from −0.78% in the 1973–1979 period to 1.07% for the 1979–1988 period).

Unlike Morrison, including returns to scale and markup do not substantially alter the interpretation of the productivity slowdown and subsequent rebound. Technical change continues to account for nearly all of the change in productivity and changes in structure are only net small contributors to the slowdown.

This empirical exercise indicates that by using the procedures developed in this study and isolating the different impacts of scale, markups, and capacity from technical change (or generalized framework), measurement biases could not only explain the causes of the post-1973 productivity slowdown but also indicate that simpler productivity measures are not as weak as perceived by past studies.

IV. SUMMARY AND CONCLUSION

To provide a wider insight into determinants of productivity, a more general productivity measurement framework is introduced here. It extends the formulae of the Berndt–Fuss–Hulten (BFH) framework to allow for the possibility of returns to scale and markups. Productivity measures which allow only for varying capacity utilization and returns to scale (for example, non-constant capital utilization studies by Berndt-Fuss, 1986 and Hulten, 1986 and non-constant returns to scale by Hall, 1988) have been shown to be special cases of this more generalized productivity measurement framework.

The model was used to assess the economic performance of US manufacturing between 1949 and 1988. The methodology employed a variable restricted and normalized translog cost function, variable input demand equations for labour, energy and non-energy materials, and a Euler equation for the quasi-fixed capital input which reflects adjustment cost for capital. This model was estimated using 3SLS estimation techniques. Most of the parameter estimates were plausible in terms of their economic signs, magnitudes and statistical significance.

The resultant measures of scale, markups and capacity were used to develop productivity measures and then compared to the BLS (BFH framework) measures. The results suggest that scale and markups have substantial power in explaining MFP growth for all periods. The study found that half of the measured MFP growth (as measured within the BFH framework) comes from biases due to scale economies and market power. Generalizing the residual framework does not appear to alter the interpretation of a productivity slowdown or subsequent rebound.

This paper has not addressed the determination of the sources of returns to scale and markups over the forty-year period of the study. While markups are determined by the behaviour of manufacturing firms, returns to scale are largely technologically driven. The possibility of increasing foreign competition simultaneously reducing domestic markups and returns to scale in manufacturing and replacing them by some important source of growth such as technical change is a question for further research.

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APPENDIX A

To explore how imperfect competition and returns to scale could affect the MFP measure, this general productivity measure, $(\dot{A}^*)^G/(A^*)$:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \frac{\dot{Q}}{Q} - \left(\theta - \frac{\omega P_L L}{PQ}\right)\frac{\dot{K}}{K} - \frac{\omega P_L L}{PQ}\frac{\dot{L}}{L} \qquad \text{(A1)}$$

is compared with the Berndt–Fuss and Hulten (BFH framework) productivity measure denoted here as $(\dot{A}^*)/(A^*)$. According to Hulten (1986), $(\dot{A})/(A^*)$ is measured under sub-equilibrium conditions $(Z_K^* = Z_K \neq P_K)$ and is defined as:

$$\left(\frac{\dot{A}^*}{A^*}\right) = \frac{\dot{Q}}{Q} - \frac{P_L L}{PQ}\frac{\dot{L}}{L} - \frac{Z_K K}{PQ}\frac{\dot{K}}{K} \qquad \text{(A2)}$$

The quasi-rent, Z_K, is calculated as $Z_K = (PQ - P_L L)/K$ and is a widely used procedure in productivity analysis. To compare these two measures of MFP, solve for $\dot{Q}/Q$ in Equation A2 and substitute that value of $\dot{Q}/Q$ into equation A1 to get:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \left(\frac{\dot{A}^*}{A^*}\right) + \frac{P_L L}{PQ}\frac{\dot{L}}{L} + \frac{Z_K K}{PQ}\frac{\dot{K}}{K} - \left(\theta - \frac{\omega P_L L}{PQ}\right)\frac{\dot{K}}{K} - \frac{\omega P_L L}{PQ}\frac{\dot{L}}{L} \qquad \text{(A3)}$$

Rearranging similar terms:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \left(\frac{\dot{A}^*}{A^*}\right) + \left(\frac{P_L L}{PQ} - \frac{\omega P_L L}{PQ}\right)\frac{\dot{L}}{L} + \left(\frac{Z_K K}{PQ} - \left(\frac{\theta PQ}{PQ} - \frac{\omega P_L L}{PQ}\right)\right)\frac{\dot{K}}{K} \qquad \text{(A4)}$$

Manipulating and making use of the following equation:

$$\theta = \frac{\omega P_L L}{PQ} + \frac{\omega Z_K^* K}{PQ} \qquad \text{(A5)}$$

Equation A4 can be written as:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \left(\frac{\dot{A}^*}{A^*}\right) + \left(\frac{P_L L}{PQ} - \frac{\omega P_L L}{PQ}\right)\frac{\dot{L}}{L} + \frac{[Z_K - \omega Z_K^*]}{PQ}\frac{\dot{K}}{K} \qquad \text{(A6)}$$

Simplifying Equation A6 we obtain the following:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \left(\frac{\dot{A}^*}{A^*}\right) + (1-\omega)\frac{P_L L}{PQ}\frac{\dot{L}}{L} + \frac{Z_K K - \omega Z_K^* K}{PQ}\frac{\dot{K}}{K} \qquad \text{(A7)}$$

Now, the last term in the numerator of Equation A7 could be simplified as follows:

$$\begin{aligned} Z_K K - \omega(Z_K^*)K &= (PQ - P_L L) - (\theta PQ - \omega P_L L) \\ &= (1-\theta)PQ - (1-\omega)P_L L \end{aligned} \qquad \text{(A8)}$$

Substituting Equation A8 in Equation A7 and simplifying terms yield what we see in Equation 10:

$$\left(\frac{\dot{A}^*}{A^*}\right)^G = \left(\frac{\dot{A}^*}{A^*}\right) + (\omega - 1)\frac{P_L L}{PQ}\left(\frac{\dot{K}}{K} - \frac{\dot{L}}{L}\right) + (1-\theta)\frac{\dot{K}}{K} \qquad \text{(A9)}$$

APPENDIX B

The purpose of this appendix is to derive the 'generalized' capacity effect which is similar to Hulten's (1986) effect of capacity utilization. Begin by defining MFP change, $(\dot{A}^F)/(A^F)$, as the growth rate of output less weighted growth rates in inputs. The weights are ex-ante cost shares and are based on ex-ante user cost of capital, P_K:

$$\frac{\dot{A}^F}{A^F} = \frac{\dot{Q}}{Q} - \frac{P_L L}{S}\frac{\dot{L}}{L} - \frac{P_K K}{S}\frac{\dot{K}}{K} \tag{B1}$$

Equation B1 is derived under cost minimization conditions. The restrictive cost function is:

$$S = S(P_L, K, Y = \theta Q, A(t))$$
$$= S(P_L, K, Y = \theta Q, A(t)) + P_K K$$
$$S = P_L L + P_K K \tag{B2}$$

where Y is the output of a production that exhibits returns to scale, i.e. $Y = \theta Q$. Differentiating equation (B2) w. r. t. time yields:

$$\frac{\partial S}{\partial t} = \frac{\partial S}{\partial P_L}\frac{\mathrm{d}P_L}{\mathrm{d}t} + \frac{\partial S}{\partial K}\frac{\mathrm{d}K}{\mathrm{d}t} + \frac{\partial S}{\partial Y}\frac{\partial Y}{\partial Q}\frac{\mathrm{d}Q}{\mathrm{d}t} - \frac{\partial S/\partial t}{S} + \frac{\partial S}{\partial P_K}\frac{\mathrm{d}P_K}{\mathrm{d}t} \tag{B3}$$

Using Shephard's lemma the above derivatives are as follows:

$$\frac{\partial S}{\partial Y}\frac{\partial Y}{\partial Q} = MC\frac{\partial Y}{\partial Q} = \frac{\theta P}{\omega} \qquad \frac{\partial S}{\partial K} = \left(P_L\frac{\partial L}{\partial K} + P_K\right)$$

where

$$\frac{\partial L}{\partial K} = MRS_{KL} = \frac{-Z_K^*}{P_L}$$

therefore,

$$\frac{\partial S}{\partial K} = P_K - Z_K^*$$

and

$$\frac{\partial S}{\partial P_L} = L \qquad \frac{\partial S}{\partial P_K} = K \tag{B4}$$

Substituting these values into Equation B3, we have the following:

$$\frac{\partial S}{\partial t} = L\frac{\mathrm{d}P_L}{\mathrm{d}t} + (P_K - Z_K^*)\frac{\mathrm{d}K}{\mathrm{d}t} + \frac{\theta PQ}{\omega}\frac{\mathrm{d}Q}{\mathrm{d}t} - \frac{\partial S/\partial t}{S} + K\frac{\mathrm{d}P_K}{\mathrm{d}t} \tag{B5}$$

Total logarithmic differentiation of Equation B5 yields:

$$\frac{\dot{S}}{S} = \frac{P_L L}{S}\frac{\dot{P}_L}{P_L} + \frac{P_K K}{S}\frac{\dot{P}_K}{P_K} - \frac{Z_K^* K}{S}\frac{\dot{K}}{K} + \frac{\theta PQ}{\omega S}\frac{\dot{Q}}{Q} + \frac{P_K K}{S}\frac{\dot{K}}{K} - \frac{\partial S/\partial t}{S} \tag{B6}$$

The last term in Equation B6 could be expanded as follows:

$$\frac{\partial S/\partial t}{S} = \frac{\partial S}{\partial Y}\frac{\partial Y}{\partial Q}\frac{\partial Q}{\partial t}\frac{1}{S} = \frac{\theta PQ}{\omega S}\frac{\partial Q}{\partial t}\Big/Q = \frac{\theta PQ}{\omega S}\left(\frac{\dot{A}^*}{A^*}\right) \tag{B7}$$

Under constant returns to scale and perfect competition, Equation B7 would reduce to:

$$\frac{\partial S}{\partial t}\Big/S = \frac{\partial S}{\partial Q}\frac{\partial Q}{\partial t}\frac{1}{S} = \frac{PQ}{S}\frac{\partial Q}{\partial t}\Big/Q = \frac{PQ}{S}\left(\frac{\dot{A}^*}{A^*}\right) \tag{B8}$$

Substituting Equation B7 into Equation B6, adding and subtracting $\dot{Q}/Q$ and rearranging terms, we could define the growth rate of real short-run average cost (SRAC) as follows:

$$\left(\frac{\dot{S}}{S} - \frac{\dot{Q}}{Q} - \frac{P_L L}{S}\frac{\dot{P}_L}{P_L} - \frac{P_K K}{S}\frac{\dot{P}_K}{P_K}\right) = \left(\frac{P_K - Z_k^*}{S}\right)K\frac{\dot{K}}{K} + \left(\frac{\theta PQ}{\omega S} - 1\right)\frac{\dot{Q}}{Q} - \frac{\theta PQ}{\omega S}\left(\frac{\dot{A}^*}{A^*}\right) \tag{B9}$$

Total logarithmic differentiation of $S = P_L L + P_K K$ in Equation B2 yields:

$$\frac{\dot{S}}{S} = \frac{P_L L}{S}\frac{\dot{P}_L}{P_L} + \frac{P_K K}{S}\frac{\dot{P}_K}{P_K} + \frac{P_L L}{S}\frac{\dot{L}}{L} + \frac{P_K K}{S}\frac{\dot{K}}{K} \tag{B10}$$

Adding and subtracting $\dot{Q}/Q$ and rearranging terms we see that the growth rate of real short-run average cost is given by Equation B1 since:

$$\frac{\dot{S}}{S} - \frac{\dot{Q}}{Q} - \frac{P_L L}{S}\frac{\dot{P}_L}{P_L} - \frac{P_K K}{S}\frac{\dot{P}_K}{P_K} = -\left(\frac{\dot{Q}}{Q} - \frac{P_L L}{S}\frac{\dot{L}}{L} - \frac{P_K K}{S}\frac{\dot{K}}{K}\right) \tag{B11}$$

The right-hand side of Equation B11 is $(\dot{A}^F)/(A^F)$ and thus:

$$\frac{\dot{S}}{S} - \frac{\dot{Q}}{Q} - \frac{P_L L}{S}\frac{\dot{P}_L}{P_L} - \frac{P_K K}{S}\frac{\dot{P}_K}{P_K} = -\left(\frac{\dot{A}^F}{A^F}\right) \tag{B12}$$

Therefore, Equation B9 could be written as:

$$-\left(\frac{\dot{A}^F}{A^F}\right) = \left(\frac{P_K - Z_K^*}{S}\right)\frac{K\dot{K}}{K} + \left(\frac{\theta PQ}{\omega S} - 1\right)\frac{\dot{Q}}{Q} - \frac{\theta PQ}{\omega S}\left(\frac{\dot{A}^*}{A^*}\right) \tag{B13}$$

Adding and subtracting $(\dot{A}^*)/(A^*)$ and rearranging terms yields:

$$\left(\frac{\dot{A}^*}{A^*}\right) = \left(\frac{\dot{A}^F}{A^F}\right) + \left(\frac{\theta PQ}{\omega S} - 1\right)\left(\frac{\dot{Q}}{Q} - \frac{\dot{A}^*}{A^*} - \frac{\dot{K}}{K}\right) \qquad (P_K \neq Z_K \neq Z_K^*) \tag{B14}$$

(which is Equation 11b in the body of the paper).

APPENDIX C

Table C1. *Price and capital measures*

	Price of capital						
Year	'Generalized' shadow price (Z_K^*)	Shadow price (Z_K)	Observed (P_K)	Marginal cost (MC)	'Generalized' shadow cost (AC^*)	Average total cost (AC)	Average price of output (P)
1950	0.02	0.40	0.14	0.19	0.24	0.27	0.28
1951	0.03	0.39	0.15	0.23	0.27	0.30	0.31
1952	0.06	0.40	0.16	0.22	0.27	0.30	0.30
1953	0.04	0.43	0.19	0.23	0.27	0.30	0.30
1954	0.03	0.40	0.20	0.23	0.28	0.30	0.31
1955	0.11	0.45	0.19	0.23	0.28	0.30	0.31
1956	0.03	0.45	0.19	0.24	0.30	0.32	0.32
1957	0.09	0.44	0.22	0.25	0.31	0.33	0.34
1958	0.15	0.41	0.23	0.26	0.32	0.33	0.34
1959	0.25	0.50	0.26	0.26	0.31	0.33	0.34
1960	0.19	0.48	0.27	0.26	0.32	0.33	0.34
1961	0.19	0.48	0.27	0.26	0.32	0.33	0.34
1962	0.21	0.51	0.27	0.26	0.32	0.33	0.34
1963	0.17	0.55	0.27	0.25	0.31	0.33	0.34
1964	0.16	0.55	0.26	0.26	0.31	0.33	0.34
1965	0.15	0.59	0.25	0.26	0.31	0.34	0.35
1966	0.13	0.59	0.27	0.27	0.32	0.34	0.36
1967	0.15	0.56	0.29	0.28	0.34	0.35	0.36
1968	0.25	0.57	0.33	0.29	0.35	0.36	0.37
1969	0.33	0.56	0.37	0.31	0.37	0.38	0.40
1970	0.40	0.56	0.37	0.33	0.37	0.38	0.40
1971	0.52	0.53	0.40	0.34	0.42	0.39	0.41
1972	0.58	0.60	0.37	0.35	0.42	0.41	0.42
1973	0.58	0.68	0.36	0.38	0.45	0.43	0.45
1974	0.62	0.72	0.36	0.46	0.55	0.51	0.54
1975	0.85	0.67	0.42	0.53	0.65	0.58	0.60
1976	1.08	0.78	0.46	0.55	0.67	0.60	0.63
1977	1.16	0.86	0.50	0.59	0.71	0.64	0.66
1978	1.23	0.90	0.52	0.64	0.76	0.68	0.71
1979	1.36	0.92	0.51	0.73	0.87	0.76	0.79
1980	1.62	0.84	0.72	0.85	1.03	0.86	0.89
1981	1.99	0.87	0.83	0.93	1.13	0.94	0.97
1982	2.25	0.85	1.00	0.96	1.19	0.97	1.00
1983	2.43	0.92	0.96	0.97	1.19	0.97	1.01
1984	2.43	1.01	1.14	0.98	1.20	0.99	1.03
1985	2.44	0.98	1.12	0.98	1.20	0.99	1.02
1986	2.38	1.01	0.92	0.94	1.16	0.96	1.00
1987	2.41	1.28	1.00	0.94	1.15	0.97	1.02
1988	2.49	1.42	0.90	0.96	1.17	0.99	1.05

Year 1982 $P = 1.00$.

Table C2. *Implied measures of sclae, capacity, and markups*

Year	Generalized scale ($AC^*/MC = \theta$)	Standardized scale ($AC/MC = \lambda$)	Markups ($P/MC = \omega$)	Generalized capacity ($AC^*/AC = \psi$)	Standardized capacity ($P/AC = \phi$)[a]
1950	1.22	1.27	1.39	0.96	1.10
1951	1.21	1.27	1.38	0.96	1.08
1952	1.22	1.26	1.36	0.97	1.08
1953	1.20	1.27	1.35	0.96	1.08
1954	1.24	1.26	1.35	0.98	1.07
1955	1.21	1.26	1.36	0.96	1.08
1956	1.22	1.25	1.34	0.98	1.08
1957	1.23	1.24	1.33	0.99	1.07
1958	1.25	1.23	1.32	1.01	1.06
1959	1.23	1.25	1.33	0.99	1.07
1960	1.23	1.25	1.34	0.98	1.06
1961	1.24	1.25	1.33	0.99	1.06
1962	1.22	1.25	1.33	0.98	1.07
1963	1.22	1.25	1.33	0.98	1.08
1964	1.21	1.24	1.34	0.99	1.08
1965	1.20	1.24	1.33	0.99	1.09
1966	1.20	1.23	1.32	0.99	1.08
1967	1.21	1.22	1.29	1.01	1.07
1968	1.21	1.21	1.27	1.02	1.06
1969	1.22	1.21	1.25	1.04	1.05
1970	1.24	1.20	1.23	1.05	1.02
1971	1.24	1.18	1.21	1.06	1.03
1972	1.22	1.16	1.21	1.07	1.05
1973	1.21	1.14	1.20	1.07	1.07
1974	1.20	1.10	1.17	1.11	1.06
1975	1.23	1.08	1.14	1.13	1.07
1976	1.22	1.08	1.13	1.13	1.05
1977	1.20	1.07	1.13	1.13	1.06
1978	1.20	1.06	1.12	1.13	1.06
1979	1.20	1.04	1.10	1.16	1.06
1980	1.21	1.04	1.07	1.17	1.02
1981	1.22	1.03	1.04	1.18	1.01
1982	1.24	1.05	1.04	1.17	0.98
1983	1.23	1.04	1.04	1.18	1.00
1984	1.22	1.04	1.05	1.15	0.99
1985	1.23	1.06	1.05	1.15	0.98
1986	1.23	1.06	1.06	1.18	1.01
1987	1.23	1.05	1.07	1.16	1.03
1988	1.22	1.03	1.09	1.18	1.05

[a] $P/AC = (P/MC)(MC/AC^*)(AC^*/AC)$.
$MC/AC = (MC/AC^*)(AC^*/AC)$.