European Economic Review 30 (1986) 749–771. North-Holland

R&D, PRODUCTION STRUCTURE AND RATES OF RETURN IN THE U.S., JAPANESE AND GERMAN MANUFACTURING SECTORS

A Non-separable Dynamic Factor Demand Model*

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Received November 1983, final version received March 1985

The focus of this paper is an analysis of the production structure, the demand for factor inputs, and the rates of return in the manufacturing sector of three major industrialized countries, the United States, Japan and Germany. The analysis is based on a dynamic factor demand model with two variable inputs, labor and materials, and two quasi-fixed inputs, capital and R&D. Adjustment costs are explicitly specified. The demand equations are derived from an intertemporal cost-minimization problem formulated in discrete time. The adopted estimation methodology allows for non-separability in the quasi-fixed factors. The model is estimated using data from 1965–1966 to 1977–1978. Particular attention is given to the role of R&D. For all countries the rate of return on R&D is found to be higher than that of capital. Their respective magnitudes are similar across countries. Considerable differences in the input demand elasticities with respect to output and prices are observed; also, for all countries the speed of adjustment for capital is found to be higher than that for R&D.

*This study is an extension of an earlier paper of ours which assumed separability in the quasi-fixed factors and also considered a somewhat different set of variable inputs. That paper was presented at the Conference on Quantitative Studies on Research and Development in Industry, Paris, September 1983. We thank the participants of that conference for helpful discussions. We would also like to thank the editor and two referees of this journal for very helpful comments. We retain, however, full responsibility for any shortcomings. The financial support of the National Science Foundation, Grant PRA-8108635, and the Research Board of the Graduate School of the University of Maryland is gratefully acknowledged. We would also like to thank the computer centers of New York University and the University of Maryland for their support with computer time. Similar studies on other European countries are currently underway involving the authors and professor Angelo Cardani.

1. Introduction

The determinants of research and development (R&D) expenditures and their contributions to the growth of output and productivity have been analyzed extensively for the various U.S. industries.[1] The question of what are the rates of return on R&D investment[2] and the issue of lags between R&D expenditures, innovative activities and output growth in the various U.S. industries have also been active areas of research.[3] For other industrialized economies very few econometric studies are available that have explored the role of R&D. Also, most of the available studies are based on static equilibrium models and therefore do not adequately explore the intertemporal nature of some of the issues.

Against the above background we shall develop a dynamic factor demand model that takes explicit account of the adjustment costs inherent in the investment process and estimate the model using data for the manufacturing sectors of the U.S., Japan and Germany. These countries were chosen because they are the major economies among the OECD countries and provide a reasonable regional representation. The manufacturing sectors were selected because of their importance in the industrial structure of these economies and the availability of reasonable sets of data. Within the context of our dynamic model we shall explore the role played by labor, materials, plant and equipment capital, and R&D capital in the evolution of the structure of the production process of the manufacturing sectors of the three countries.

The dynamic factor demand equations of our model are derived directly from an intertemporal cost-minimization problem formulated in discrete time and based on a technology with internal adjustment costs. More specifically, the technology is assumed to be linear homogeneous. It is represented by a restricted cost function. Adjustment costs are separable, but as opposed to most empirical studies with explicit adjustment costs, the quasi-fixed factors are not assumed to be separable. Technical change is the outcome of R&D expenditures and therefore endogenous in our model. Plant and equipment capital are treated as quasi-fixed; because of the adjustment costs they will not adjust instantaneously to their optimal levels. Labor and materials are treated as variable.

Using our theoretical framework, we examine the evolution of the production process of the manufacturing sectors of the U.S., Japan and Germany. In particular we explore the short-, intermediate- and long-run responses of employment, materials, investment in plant and equipment and in research

[1] For a brief survey of contributions of R&D to growth of output and the determinants of R&D expenditures see Nadiri (1980) and Griliches (1980a).

[2] See Mansfield (1980) and Griliches (1980b) for a discussion of the rates of return on R&D in various U.S. sectors and industries.

[3] Pakes (1984) has recently examined the lags between R&D and patents.

and development to changes in relative prices and output; we also examine the extent of short-run disequilibrium from the long-run optimal stocks. Furthermore we formulate a concept of average net rates of return on the quasi-fixed inputs in the context of an intertemporal model and calculate these rates for capital and R&D for the manufacturing sectors of the U.S., Japan and Germany.

The paper is organized as follows: the theoretical and econometric specification of our model is given in section 2. In section 3 we present our estimation results and their interpretation. The differential responses of the inputs in the different countries to changes in input prices and output in the short, intermediate and long run are examined in section 4. In section 5 we formulate and calculate the average net rates of return on the quasi-fixed inputs. Concluding remarks and some suggestions for future research are given in section 6. The sources of the data used in estimating our model and details of the estimating equations are given in two appendices.

2. The model

The theoretical model underlying this paper is close to that of Denny, Fuss and Waverman (1981), and Morrison and Berndt (1981). Both of these papers specify their model in continuous time and then employ a discrete approximation of the continuous factor demand equations in their empirical investigation. Instead, we shall specify the entire model in discrete time. It turns out that the two approaches lead to different specifications. In the empirical application Denny et al. (1981) and Morrison and Berndt (1981) assume separability in the quasi-fixed factors. By adopting an idea of Epstein and Yatchew (1985) we will be able to relax this assumption and to estimate the model in a non-separable form.[4]

Consider a firm that employs two variable and two quasi-fixed inputs in producing a single output good from a technology with adjustment costs. More specifically, we assume that the firm's production process is described by the following generalized production function:

$$Y_t = F(V_t, X_{t-1}, \Delta X_t), \tag{1}$$

where Y_t is output, $V_t = [V_{1t}, V_{2t}]'$ is the vector of variable inputs and $X_t = [X_{1t}, X_{2t}]'$ is the vector of end-of-period stocks of the quasi-fixed factors. The vector $\Delta X_t = X_t - X_{t-1}$ represents internal adjustment costs in terms of foregone output due to changes in the quasi-fixed factors, i.e., $F_{|\Delta X|} < 0$. The production function satisfies standard assumptions with respect to the traditional factors V_t and X_{t-1} and is assumed to be concave in all inputs. This implies that the marginal products of the traditional factors of

[4]For an alternative approach towards the estimation of non-separable dynamic factor demand models useful for general cost of adjustment technologies and expectation formation processes, see Prucha and Nadiri (1982).

production are decreasing and that the marginal adjustment costs are increasing. The firm is assumed to face perfectly competitive markets with respect to its factor inputs.

The production technology (1) can be described alternatively in terms of the normalized restricted cost function. Let $\hat{V}_t=[\hat{V}_{1t},\hat{V}_{2t}]'$ denote the cost-minimizing variable factor inputs needed to produce output Y_t conditional on X_{t-1} and ΔX_t and let W_t be the price of V_{2t} normalized by the price of V_{1t}; the normalized restricted cost function is then defined as $G(W_t, X_{t-1}, \Delta X_t, Y_t)=\hat{V}_{1t}+W_t\hat{V}_{2t}$. This function has the following properties: $G_{X_j}<0$, $G_{|\Delta X_j|}>0$, $G_Y>0, G_W>0$. Furthermore, $G(\cdot)$ is convex in X_{t-1} and ΔX_t, and concave in W_t.[5]

In the empirical analysis we take materials, M, and labor, L, as the variable factors and the stocks of capital, K, and R&D, R, as the quasi-fixed factors. R&D takes in our model the role of an (endogenously determined) index of technological change in place of the conventional time trend.[6] Given this interpretation it is important to note that R&D and capital are not assumed to be separable, i.e., our model allows for interactions between R&D, capital and the variable factors. We adopt the convention $V_1=M$, $V_2=L$, $X_1=K$ and $X_2=R$; W is then the real wage rate and the price of materials is taken to be the numeraire. The normalized acquisition price of capital and R&D will be denoted as Q^K and Q^R, and the depreciation rate of capital and R&D as δ_K and δ_R.

The functional form of the normalized restricted cost function used in our empirical analysis is as follows:

$$\begin{aligned}
G(W_t, X_{t-1}, \Delta X_t, Y_t) = {} & Y_t[\alpha_0+\alpha_W W_t+\tfrac{1}{2}\alpha_{WW}W_t^2]+\alpha_K K_{t-1}+\alpha_R R_{t-1}\\
& +\dot{\alpha}_K\Delta K_t+\dot{\alpha}_R\Delta R_t+\tfrac{1}{2}\alpha_{KK}(K_{t-1}^2/Y_t)+\tfrac{1}{2}\alpha_{RR}(R_{t-1}^2/Y_t)\\
& +\alpha_{KR}(K_{t-1}R_{t-1}/Y_t)+\tfrac{1}{2}\ddot{\alpha}_{KK}(\Delta K_t^2/Y_t)\\
& +\tfrac{1}{2}\ddot{\alpha}_{RR}(\Delta R_t^2/Y_t)+\ddot{\alpha}_{KR}(\Delta K_t\Delta R_t/Y_t)+\alpha_{WK}W_tK_{t-1}\\
& +\alpha_{WR}W_tR_{t-1}+\dot{\alpha}_{WK}W_t\Delta K_t+\dot{\alpha}_{WR}W_t\Delta R_t\\
& +\dot{\alpha}_{KK}K_{t-1}\Delta K_t+\dot{\alpha}_{RR}R_{t-1}\Delta R_t+\dot{\alpha}_{KR}K_{t-1}\Delta R_t\\
& +\dot{\alpha}_{RK}R_{t-1}\Delta K_t. \qquad (2a)
\end{aligned}$$

[5] See Lau (1976).

[6] For the use of R&D as an index of technology see, e.g., McMahon (1984). As an alternative to the present specification we could have introduced a time trend in addition to the R&D variable and interpreted time as our technology index. However, this leads to notions of R&D using and R&D saving technical change which seem difficult to interpret. Also, when a time trend was introduced the main empirical results did not change although some parameter estimates varied somewhat.

This functional form of a normalized restricted cost function was first introduced by Denny, Fuss and Waverman (1981), and Morrison and Berndt (1981). It can be viewed as a second-order approximation to a general normalized restricted cost function corresponding to a constant returns to scale technology.[7] As in the above references, we impose the parameter restrictions

$$\dot{\alpha}_K = \dot{\alpha}_R = \dot{\alpha}_{WK} = \dot{\alpha}_{WR} = \dot{\alpha}_{KK} = \dot{\alpha}_{RR} = \dot{\alpha}_{KR} = \dot{\alpha}_{RK} = 0, \qquad \ddot{\alpha}_{KR} = 0. \tag{2b,c}$$

Restriction (2b) implies that the marginal adjustment costs are zero in the steady state. Restriction (2c) implies separability in the adjustment costs. Contrary to the above references we do, however, not impose the restriction $\alpha_{KR}=0$, which would imply separability in the quasi-fixed factors.

The firm is assumed to hold static expectations on relative factor prices, output, the discount rate, r_t, and the corporate tax rate, u_t. In each period the firm is assumed to derive, for given initial stocks X_{t-1} and subject to the production function constraint (1), an optimal input path such that the present value of the future cost stream is minimized. Making use of the restricted cost function (2), we can state the firm's optimization problem in period t with respect to the quasi-fixed factors as

$$\min_{\{K_{t+\tau}, R_{t+\tau}\}_{\tau=0}^{\infty}} \sum_{\tau=0}^{\infty} \{[G(t+\tau) + Q_t^R I_{t+\tau}^R](1-u_t) + Q_t^K I_{t+\tau}^K\}(1+r_t)^{-\tau}, \tag{3}$$

where $G(t+\tau) = G(W_t, K_{t+\tau-1}, R_{t+\tau-1}, \Delta K_{t+\tau}, \Delta R_{t+\tau}, Y_t)$; further, $I_{t+\tau}^K = K_{t+\tau} - (1-\delta_K)K_{t+\tau-1}$ and $I_{t+\tau}^R = R_{t+\tau} - (1-\delta_R)R_{t+\tau-1}$. It is assumed that R&D expenditures can be expensed immediately. The optimization problem (3) is a standard dynamic programming problem.[8] The following set of Euler equations are necessary conditions for a minimum ($\tau = 0, 1, \ldots, \infty$):

$$-BX_{t+\tau+1} + [A + (2+r_t)B]X_{t+\tau} - (1+r_t)BX_{t+\tau-1} = a_t, \tag{4}$$

where

$$B = \begin{bmatrix} \ddot{\alpha}_{KK} & 0 \\ 0 & \ddot{\alpha}_{RR} \end{bmatrix}, \qquad A = \begin{bmatrix} \alpha_{KK} & \alpha_{KR} \\ \alpha_{KR} & \alpha_{RR} \end{bmatrix},$$

$$a_t = \begin{bmatrix} a_t^K \\ a_t^R \end{bmatrix} = -\begin{bmatrix} \alpha_K + \alpha_{WK} W_t + C_t^K \\ \alpha_R + \alpha_{WR} W_t + C_t^R \end{bmatrix} Y_t,$$

with $C_t^K = Q_t^K(r_t + \delta_K)/(1-u_t)$ and $C_t^R = Q_t^R(r_t + \delta_R)$. Thus unstable roots of the above set of second-order difference equations are ruled out by the trans-

[7] The normalized restricted cost function corresponding to a linear homogeneous technology is in general of the form $G(W, X_{-1}/Y, \Delta X/Y)Y$.

[8] For a detailed derivation of the subsequent results see, e.g., Prucha and Nadiri (1981).

versality condition. The solution corresponding to the stable roots yields the following system of quasi-fixed factor demand equations in accelerator form:

$$\Delta X_t = M(X_t^* - X_{t-1}), \qquad X_t^* = A^{-1}a_t, \qquad M = \begin{bmatrix} m_{KK} & m_{KR} \\ m_{RK} & m_{RR} \end{bmatrix}, \tag{5}$$

where $X_t^* = [K_t^*, R_t^*]'$ is the stationary solution of (4) and where the matrix of adjustment coefficients M has to satisfy the following matrix equation:

$$BM^2 + (A + r_t B)M - A = 0. \tag{6}$$

Furthermore,

$$C = -BM = \begin{bmatrix} c_{KK} & c_{KR} \\ c_{KR} & c_{RR} \end{bmatrix} \tag{7}$$

is symmetric and negative definite. Unless we assume separability in the quasi-fixed factors (which corresponds to setting $\alpha_{KR} = 0$ and $m_{KR} = 0$) we cannot generally solve (6) explicitly for M in terms of A and B. We can, however, generally solve (6) for A in terms of B and M: $A = BM(M + r_t I)(I - M)^{-1}$. Let the real discount rate be constant over the sample period, i.e., $r_t = r$; then M can be viewed as a matrix of constants. The idea of Epstein and Yatchew (1985) is to estimate the elements of B and M rather than those of B and A.[9] To impose the symmetry of C we can also estimate B and C instead of B and M. Eqs. (6) and (7) imply (after some transformations) the following relatively simple and hence for the empirical implementation useful expressions:

$$\begin{aligned} A &= C - (1+r)[B - B(C+B)^{-1}B], \\ D &= -MA^{-1} = -B^{-1} - (1+r)(C - rB)^{-1} = \begin{bmatrix} d_{KK} & d_{KR} \\ d_{KR} & d_{RR} \end{bmatrix} \end{aligned} \tag{8}$$

with D symmetric. Substituting (8) into (5) we can write the demand equations for the quasi-fixed factors as:

$$\begin{aligned} K_t - K_{t-1} &= d_{KK}a_t^K + d_{KR}a_t^R + (c_{KK}/\ddot{\alpha}_{KK})K_{t-1} + (c_{KR}/\ddot{\alpha}_{KK})R_{t-1}, \\ R_t - R_{t-1} &= d_{KR}a_t^K + d_{RR}a_t^R + (c_{KR}/\ddot{\alpha}_{RR})K_{t-1} + (c_{RR}/\ddot{\alpha}_{RR})R_{t-1}. \end{aligned} \tag{9}$$

[9]The specification of the technology adopted by Epstein and Yatchew (1985) is somewhat different insofar as in their paper investment is assumed to be immediately productive. As a consequence, the expressions given in this paper are somewhat different from those given in the above reference.

The firm's demand equations for the variable factors can be derived from the normalized restricted cost function according to Shephard's lemma as $L_t = \partial G(t)/\partial W_t$ and $M_t = G(t) - W_t L_t$, which yields

$$L_t = [\alpha_W + \alpha_{WW} W_t] Y_t + \alpha_{WK} K_{t-1} + \alpha_{WR} R_{t-1},$$

$$\begin{aligned} M_t = {} & [\alpha_0 - \tfrac{1}{2}\alpha_{WW} W_t^2] Y_t + \alpha_K K_{t-1} + \alpha_R R_{t-1} + \tfrac{1}{2}\alpha_{KK}(K_{t-1}^2/Y_t) \\ & + \tfrac{1}{2}\alpha_{RR}(R_{t-1}^2/Y_t) + \alpha_{KR}(K_{t-1}R_{t-1}/Y_t) + \tfrac{1}{2}\ddot{\alpha}_{KK}(\Delta K_t^2/Y_t) \\ & + \tfrac{1}{2}\ddot{\alpha}_{RR}(\Delta R_t^2/Y_t). \end{aligned} \tag{10}$$

Our entire system of estimating equations thus consists of eqs. (9) for the quasi-fixed factors and (10) for the variable factors with α_{KK}, α_{RR}, α_{KR}, d_{KK}, d_{RR} and d_{KR} replaced by the expressions in c_{KK}, c_{RR}, c_{KR}, $\ddot{\alpha}_{KK}$ and $\ddot{\alpha}_{RR}$ as defined by (8). The explicit form for those expressions is given in appendix A. For the empirical estimation we add to the estimating equations a stochastic disturbance vector.

3. Empirical results

The data used to estimate the production structure and factor demands in the manufacturing sectors cover the period 1965–1977 for the U.S. and Germany and the period 1966–1978 for Japan. The sources of the data and the method of constructing the variables of the model are described in appendix B. Data on output, materials, capital and R&D are in constant 1970 prices. The estimation technique used was full information maximum likelihood. When necessary, a correction was made for first-order autocorrelation of the disturbances. All estimations were performed with TSP 4.0 at a tolerance level of 0.001.

The parameter estimates of the model are shown in table 1. The fit of the model is quite good, and the estimated coefficients are generally statistically significant. The R^2 for the labor equation is low for Japan; the individual parameter estimates vary, as expected, across countries. However, the important restrictions suggested by economic theory to insure the concavity conditions of the underlying technology are met in all cases, i.e., the parameters $\ddot{\alpha}_{KK}$ and $\ddot{\alpha}_{RR}$ are all positive, the parameters c_{KK}, c_{RR}, α_{WW} are all negative and the expressions $(c_{KK}c_{RR} - c_{KR}^2)$ are all positive. From the estimates in table 1 we can calculate estimates for m_{KK}, m_{RR}, m_{KR} and m_{RK} based on $M = -B^{-1}C$. Those estimates are reported in table 2. Several points are of interest with respect to these results.

First, the own-adjustment coefficient for R&D, m_{RR}, is by 40% to 60% lower in each country than the corresponding adjustment coefficient for

Table 1
Maximum likelihood parameter estimates of the cost of adjustment model for the total manufacturing sectors of the U.S. and Germany for 1965–1977 and of Japan for 1966–1978.[a]

Parameter	U.S.	Japan	Germany
α_0	1.39	1.23	1.33
	(19.05)	(6.19)	(19.32)
α_K	−0.94	−0.82	−0.52
	(−6.37)	(−8.39)	(−4.89)
α_R	0.08	−0.04	−0.06
	(1.99)	(−4.44)	(−2.32)
c_{KK}	−1.38	−1.19	−0.74
	(−9.48)	(−4.23)	(−4.44)
c_{RR}	−0.47	−0.15	−0.12
	(−3.59)	(−3.44)	(−2.21)
c_{KR}	0.20	0.01	−0.03
	(4.09)	(0.41)	(−1.19)
$\ddot{\alpha}_{KK}$	3.69	4.42	3.05
	(6.84)	(2.77)	(2.52)
$\ddot{\alpha}_{RR}$	2.06	1.38	1.45
	(2.74)	(2.83)	(1.43)
α_W	1.36	1.80	0.75
	(8.92)	(14.94)	(5.02)
α_{WW}	−1.20	−3.60	−0.52
	(−15.20)	(−17.38)	(−8.30)
α_{WK}	0.06	0.17	0.09
	(1.24)	(1.86)	(1.80)
α_{WR}	−0.19	−0.05	0.01
	(−3.93)	(−4.38)	(0.03)
M-equation: R^2	0.96	0.98	0.99
L-equation: R^2	0.80	0.52	0.89
K-equation: R^2	0.99	0.99	0.99
R-equation: R^2	0.99	0.99	0.99

[a]The ratios of parameter estimates to asymptotic standard errors are given in parentheses. The R^2 values are the squared correlation coefficients between the actual variables (M, L, K, R) and their fitted values as calculated from the reduced form.

capital, m_{KK}. Second, the cross-adjustment coefficients m_{KR} and m_{RK} are much lower than the own-adjustment coefficients. Capital and R&D are found to be dynamic complements in the U.S. and in Japan and dynamic substitutes in Germany.[10] That is, if R&D is in excess demand in the U.S. and Japan, the adjustment in capital will slow down, and vice versa. In Germany, to the contrary, capital will compensate for R&D and vice versa in the adjustment

[10]See Nadiri and Rosen (1969) for a discussion of those concepts.

Table 2

Maximum likelihood estimates of own- and cross-adjustment coefficients of capital and R&D in the manufacturing sectors of the U.S., Japan and Germany.[a]

Adjustment coefficients	U.S.	Japan	Germany
m_{KK}	0.375	0.269	0.241
	(0.038)	(0.037)	(0.061)
m_{KR}	−0.055	−0.001	0.010
	(0.019)	(0.002)	(0.008)
m_{RK}	−0.098	−0.002	0.022
	(0.031)	(0.007)	(0.013)
m_{RR}	0.227	0.112	0.083
	(0.028)	(0.015)	(0.028)

[a]Asymptotic standard errors are given in parentheses.

towards the long-run equilibrium. We note that those results for Japan and Germany are only suggestive since for those countries m_{KR} and m_{RK} are not significantly different from zero in a strictly statistical sense.

Third, the cross effects have to be taken into account in the computation of the adjustment speed. We take as our measure of the adjustment speed the fraction of the difference between the long-run desired stock and the initial stock that is closed in the first period. Those measures, say $v_{Kt}=m_{KK}+m_{KR}(R_t^*-R_{t-1})/(K_t^*-K_{t-1})$ and $v_{Rt}=m_{RR}+m_{RK}(K_t^*-K_{t-1})/(R_t^*-R_{t-1})$, vary over time. Table 3 presents sample averages of these measures of the adjustment speed. The average adjustment speeds of table 3 differ markedly from the own-adjustment coefficients only in the case of U.S. manufacturing. These estimates imply that about 70% of the adjustment in capital is completed after four years, but that it takes much longer to adjust the stock of R&D. Our results seem compatible with previous findings for the capital stock. Mayer (1960) concluded from a survey of 276 U.S. companies that there was a lag of two to three years involved in plant investment and of seven to eight months in investment in equipment. Similar results were, e.g., obtained by Almon (1968), Berndt, Fuss and Waverman (1980), Bischoff (1969, 1971), Coen and Hickman (1970), Jorgenson and Siebert (1968), Jorgenson and Stephenson (1967), Morrison and Berndt (1981), and Nadiri and Rosen (1968). We obtain a mean lag for capital of about 2.8 years. Considerably less evidence exists on the adjustment of the stock of R&D to its desired level. Nadiri (1980), and Nadiri and Bitros (1980) obtained an own-adjustment coefficient for R&D between 0.16 and 0.32 on U.S. firm and total manufacturing data. Ravenscraft and Scherer (1982) estimated on 42 U.S. businesses over the 1970–1978 interval a mean lag of R&D on net pre-

Table 3
First-period adjustment in capital and R&D, average over the sample period.[a]

Adjustment speed in first period	U.S.	Japan	Germany
v_K	0.262 (0.043)	0.266 (0.001)	0.281 (0.113)
v_R	0.173 (0.016)	0.111 (0.000)	0.087 (0.003)

[a]The sample standard deviations are given in parentheses.

tax profits to range from four to six years. We obtain a mean lag in the adjustment of R&D of five years for the U.S.

Fourth, the adjustment coefficients of R&D differ among the manufacturing sectors of the three countries. In the U.S., R&D adjusts to its desired level somewhat faster than in the other countries. The pattern of adjustments of plant and equipment are quite similar, i.e., about 25% of the adjustment of the capital stock takes place in the first year.

Another interesting feature of the model to look at is the importance of short-run disequilibrium in factor holdings by comparing the short-run shadow prices from the long-run rental prices of the quasi-fixed inputs. The necessary conditions of the dynamic programming problem can alternatively be written as ($\tau=0,1,\dots,$)

$$(1+r_t)\frac{\partial G(t+\tau)}{\partial \Delta X_j}+\left[\frac{\partial G(t+\tau+1)}{\partial X_j}-\frac{\partial G(t+\tau+1)}{\partial \Delta X_j}\right]=-C_t^j, \qquad j=1,2.$$

It is evident that, in the long run, when adjustment costs are zero, the rental price of a quasi-fixed input is equal to the marginal variable cost reduction due to this input. But, in the short run, the marginal variable cost reduction (or the shadow price) of a quasi-fixed input has to compensate for both the user cost and the difference in marginal adjustment costs in two consecutive periods. In table 4, we present the estimates of the deviation of shadow from long-run rental costs as a percentage of long-run rental costs. In all countries, there is more disequilibrium in R&D than in capital, a finding consistent with the lower adjustment speeds of R&D. Of the three manufacturing sectors, the R&D investment in Japan was in much more disequilibrium over the sample period than in the other countries; in the German manufacturing sector the actual level of physical capital stock was close to its optimal level, while the actual stock of R&D was much further away from its optimal level; in the U.S. manufacturing sector the evidence

Table 4
Deviation of short-run (shadow) from long-run rental prices as percentage of long-run rental prices in the U.S., Japanese and German total manufacturing sectors.[a]

	U.S.	Japan	Germany
Capital	40	57	13
R&D [a]	66	119	107

[a]Sample averages, in percentages.

suggests considerably less disequilibrium in R&D than is the case for the other two countries.

4. Short-run, intermediate-run and long-run elasticities of factor demand

The examination of how inputs respond to changes in relative prices and output in the context of a dynamic model requires a careful formulation of the various concepts of elasticity. We distinguish between the short-run (SR), intermediate-run (IR) and long-run (LR) responses of inputs to the exogenous price and quantity shocks. The short-run elasticities measure the first-period responses, when the firm is adjusting its capital and R&D and consequently incurs costs of adjustment, but is operating with the initial levels of these stocks. The intermediate-run elasticities refer to the second-period responses, when the firm is still adjusting but operating at the stock levels after one period of adjustment. The long-run or steady-state elasticities refer to the responses after completion of the adjustment process, when the firm produces at optimal input levels.[11] We calculate various elasticities along the optimal adjustment path with respect to the unnormalized price of materials, w^M, and labor, w^L, the unnormalized price of capital, c^K, and R&D, c^R, and output. Let $\hat{X}_{t+\tau}=[\hat{X}_{1,t+\tau},\hat{X}_{2,t+\tau}]'$ with $\tau=0.1,\ldots,\infty$ be the optimal input sequence of the quasi-fixed factors defined by (5). We then have

$$\hat{X}_t=MX_t^*+(I-M)X_{t-1},\qquad \hat{X}_{t+1}=MX_t^*+(I-M)\hat{X}_t, \tag{11}$$

and $\hat{X}_{t+\infty}=X_t^*$. We refer to the elasticities of $\hat{X}_{jt}$, $\hat{X}_{j,t+1}$ and X_{jt}^* with respect to input prices and output as, respectively, the short-run, intermediate-run and long-run elasticities of the jth quasi-fixed factor. We denote them as $\varepsilon_{X_js}^S$, $\varepsilon_{X_js}^I$ and $\varepsilon_{X_js}^L$, where $s=w_t^M$, w_t^L, c_t^K, c_t^R and Y_t.

$$\varepsilon_{X_js}^S=\frac{s}{\hat{X}_{jt}}\frac{\partial\hat{X}_{jt}}{\partial s},\qquad \varepsilon_{X_js}^I=\frac{s}{\hat{X}_{j,t+1}}\frac{\partial X_{j,t+1}}{\partial s},\qquad \varepsilon_{X_js}^L=\frac{s}{X_{jt}^*}\frac{\partial X_{jt}^*}{\partial s}. \tag{12}$$

[11]Our definitions refer to the sequence of responses of the inputs at various stages of the adjustment process rather than to the mental experiments of allowing for more or less flexible responses.

Let $\hat{V}_{t+\tau}=[\hat{V}_{1,t+\tau}, \hat{V}_{2,t+\tau}]'$ be the sequence of optimal variable inputs associated with $\hat{X}_{t+\tau}$ for $\tau=0,1,\ldots,\infty$. Write (10) for $i=1,2$ more compactly as $\hat{V}_{it}=\phi_i(w_t^M, w_t^L, X_{t-1}, Y_t)$; we then have $\hat{V}_{i,t+1}=\phi_i(w_t^M, w_t^L, \hat{X}_t, Y_t)$ and $V_{it}^*=\hat{V}_{i,t+\infty}=\phi_i(w_t^M, w_t^L, X_t^*, Y_t)$. Analogously to above, we define the following short-run, intermediate-run and long-run elasticities of the ith variable factor with respect to input prices and output:

$$\varepsilon_{V_{is}}^S=\frac{s}{\hat{V}_{it}}\frac{\partial \hat{V}_{it}}{\partial s}=\frac{s}{\hat{V}_{it}}\frac{\partial \phi_i}{\partial s}\bigg|_{X_{t-1}},$$

$$\varepsilon_{V_{is}}^I=\frac{s}{\hat{V}_{i,t+1}}\frac{\partial \hat{V}_{i,t+1}}{\partial s}=\frac{s}{\hat{V}_{i,t+1}}\left[\frac{\partial \phi_i}{\partial s}+\sum_j\frac{\partial \phi_i}{\partial \hat{X}_{jt}}\frac{\partial \hat{X}_{jt}}{\partial s}\right]_{\hat{X}_t}, \tag{13}$$

$$\varepsilon_{V_{is}}^L=\frac{s}{V_{it}^*}\frac{\partial V_{it}^*}{\partial s}=\frac{s}{V_{it}^*}\left[\frac{\partial \phi_i}{\partial s}+\sum_j\frac{\partial \phi_i}{\partial X_{jt}^*}\frac{\partial X_{jt}^*}{\partial s}\right]_{X_t^*}.$$

Because the quasi-fixed factors do not adjust immediately to their long-run equilibrium values, some of the variable factors have to overshoot in the short run their long-run equilibrium levels. That is, the short-run output elasticities of some of the variable factors have to be larger than the long-run elasticities.

4.1. Price elasticities

The own-price elasticities of labor, materials, capital and R&D are reported in table 5. All the elasticities have the expected negative sign. In the U.S. and Japan the highest own-price elasticity among the different inputs is that of labor. In Germany, the two quasi-fixed inputs have their own-price elasticities higher than the variable inputs. The pattern of the own-price

Table 5
Short-run, intermediate-run and long-run own-price elasticities; U.S., Japanese and German manufacturing sectors, 1970.[a]

Elasticity estimate	U.S.			Japan			Germany		
	SR	IR	LR	SR	IR	LR	SR	IR	LR
ε_{M_wM}	−0.21	−0.22	−0.23	−0.18	−0.29	−0.49	−0.08	−0.14	−0.29
ε_{L_wL}	−0.48	−0.50	−0.85	−0.92	−0.93	−0.89	−0.24	−0.24	−0.42
ε_{K_cK}	−0.05	−0.09	−0.17	−0.13	−0.22	−0.39	−0.17	−0.30	−0.68
ε_{R_cR}	−0.04	−0.06	−0.15	−0.07	−0.11	−0.28	−0.10	−0.17	−0.55

[a]The following notation is used in tables 5–7: ε_{Z_s} is the elasticity of factor Z = materials (M), labor (L), capital (K) and R&D (R) with respect to s = price of materials (w^M), labor (w^L), capital (c^K), R&D (c^R) and output (Y). The symbols SR, IR and LR refer to the short-, intermediate- and long-run.

elasticities of the stock of R&D is, in general, similar to that of the capital stock, and the ranking of the countries does not change significantly. The materials factor responds the strongest to its own price in Japan. In general, the own-price elasticities are higher in Japan than in the U.S. For the U.S., where comparable studies of the adjustment-cost type exist [Berndt, Fuss and Waverman (1980), Morrison and Berndt (1981), Pindyck and Rotemberg (1983)], our estimates of the own-price elasticities are in line with those estimates, except for the own-price elasticity of labor which is somewhat higher than theirs.

The cross-price elasticities of inputs are shown in table 6. They reveal the following patterns: the cross-price elasticities are generally small except for the elasticities of labor with respect to the price of materials. The long-run cross-price elasticities of capital with respect to the price of materials and of R&D with respect to the price of labor are also fairly large. Materials seem to be, in general, substitutes for other inputs. Labor and R&D are substitutes, whereas labor and capital are complements in Japan and in Germany but substitutes in the U.S. Capital and R&D are complements in the U.S. and in Japan and substitutes in Germany, but the strength of these elasticities is quite weak.

These patterns of substitution and complementarity among inputs are in general accordance with the findings of some of the studies reported in the literature [see Mittelstädt (1983) for an excellent survey]. However, previous studies based on cost-of-adjustment models and U.S. data [Berndt, Fuss and Waverman (1980), Morrison and Berndt (1981), and Pindyck and Rotemberg (1983)] have found capital and labor to be complements. For the U.S., we obtain evidence to the contrary based on our model specification. More

Table 6

Short-run, intermediate-run and long-run cross-price elasticities; U.S., Japanese and German manufacturing sectors, 1970.[a]

Elasticity estimate	U.S.			Japan			Germany		
	SR	IR	LR	SR	IR	LR	SR	IR	LR
$\varepsilon_{M_w}L$	0.22	0.22	0.22	0.25	0.28	0.33	0.11	0.12	0.15
$\varepsilon_{M_c}K$	−0.01	0.01	0.02	−0.05	0.02	0.16	−0.01	0.03	0.15
$\varepsilon_{M_c}R$	−0.01	−0.01	−0.01	−0.01	−0.01	0.01	−0.01	−0.01	0.01
$\varepsilon_{L_w}M$	0.47	0.48	0.75	0.91	0.94	0.94	0.24	0.26	0.51
$\varepsilon_{L_c}K$		0.01	0.05		−0.02	−0.07		−0.01	−0.10
$\varepsilon_{L_c}R$		0.01	0.05		0.01	0.02		0.01	0.01
$\varepsilon_{K_w}M$	0.05	0.08	0.11	0.16	0.25	0.46	0.21	0.36	0.78
$\varepsilon_{K_w}L$	0.01	0.02	0.10	−0.02	−0.04	−0.07	−0.04	−0.07	−0.16
$\varepsilon_{K_c}R$	−0.01	−0.01	−0.05	−0.01	−0.01	−0.01	0.01	0.01	0.05
$\varepsilon_{R_w}M$	−0.04	−0.06	−0.11	0.01	0.01	0.04	0.03	0.05	0.08
$\varepsilon_{R_w}L$	0.11	0.19	0.45	0.06	0.10	0.26	0.01	0.02	0.03
$\varepsilon_{R_c}K$	−0.03	−0.06	−0.19	−0.01	−0.01	−0.02	0.05	0.05	0.37

[a]For notation, see table 5, footnote a.

research using alternative model specifications is needed to clear the evidence. Also the question of why the own- and cross-price elasticities of inputs vary among countries would require a clearly detailed analysis taking account of economic, social and political factors. Such analysis, although extremely pertinent and important, is beyond the scope of our present research.

4.2. Output elasticities

The output elasticities of materials, labor, capital, and R&D are shown in table 7. The long-run elasticities of the inputs are equal to unity, as is implied by the underlying linear homogeneous technology. The results indicate that, in all cases, materials respond very strongly in the short run to a change in output; the reason is that materials overshoot their long-run equilibrium value in the short run to compensate for the sluggish adjustments of the two quasi-fixed inputs. They slowly adjust toward their long-run equilibrium value as capital and R&D adjust. The short- and intermediate-run output elasticities of materials are somewhat higher in Japan, but, in general, the pattern of adjustment is remarkably similar among the manufacturing sectors of these countries.

Table 7
Short-run, intermediate-run and long-run output elasticities; U.S., Japanese and German manufacturing sectors, 1970.[a]

Elasticity estimate	U.S.			Japan			Germany		
	SR	IR	LR	SR	IR	LR	SR	IR	LR
ε_{MY}	1.17	1.10	1.00	1.53	1.36	1.00	1.29	1.21	1.00
ε_{LY}	0.83	0.82	1.00	0.97	1.02	1.00	0.51	0.53	1.00
ε_{KY}	0.33	0.54	1.00	0.34	0.55	1.00	0.28	0.48	1.00
ε_{RY}	0.16	0.31	1.00	0.23	0.39	1.00	0.20	0.35	1.00

[a]For notation, see table 5, footnote a.

The obtained results concerning the output elasticity of labor are interesting for their implications regarding labor productivity. The output elasticities of labor are lower in the short run than in the long run, denoting short-run increasing returns to labor. The results confirm the finding by Morrison and Berndt (1981) for U.S. manufacturing, and provide evidence to the same phenomenon for the manufacturing sectors of Japan and Germany. (Technically the phenomenon is based on the fact that $\partial L/\partial K^* > 0$ for all countries.) Part of the slowdown in labor productivity observed in the manufacturing sectors of these countries can therefore be explained by the fact that labor responds less than proportionately to a change in output. The productivity of labor has a cyclical movement; it increases in times of expansion and falls during recessions. Notice that the extent to which labor is sluggish in responding to a change in output varies from country to country. Labor appears to be the most sluggish in Germany, which may be a consequence of the high unionization rate. The obtained estimate for the short-run labor–output elasticity in Japan is comparatively high. This may in part be due to the dual structure of Japanese manufacturing [see Daly (1980)]. Small establishments abound in Japan (around 70% of the labor force working in manufacturing is employed in establishments with less than 300 people). Job security is much smaller in these small firms, which bear the cost of cyclical adjustment because of their subcontracting nature.

The output elasticities of capital and R&D are small in the short run, but they increase over time. The output elasticities of both quasi-fixed inputs are quite alike. On the whole the output elasticities of both the variable and the quasi-fixed factors exceed substantially their own-price elasticities discussed earlier. Also, in Japan factor inputs respond to changes in both relative prices and output much more than in the U.S. manufacturing sector.

5. Average rate of return on individual factors

In this section we define a measure for the rate of return of investment expenditures on an individual factor in period t. Because of adjustment costs, the firm's investment decisions are intertemporally connected. In defining the rate of return we hence have to be specific about the firm's behavior in future periods.

The maintained hypothesis in this paper is that the firm chooses its inputs such that it minimizes, for a given output stream, the discounted value of its costs. However, for expository reasons, consider for a moment a firm whose objective is to maximize the discounted value of its net profit stream. Let $R(X_{t-1}, \Delta X_t, V_t)$ denote the firm's net profits in period t. (Since price expectations are assumed to be static, prices have not been included in the argument list for notational simplicity.) We can then state the firm's objective as to choose its inputs such that it maximizes.

$$\sum_{\tau=0}^{\infty} R(X_{t+\tau-1}, \Delta X_{t+\tau}, V_{t+\tau})(1+r_t)^{-\tau}, \tag{14}$$

subject to the initial condition X_{t-1}. Let $\{\hat{X}_{t+\tau}, \hat{V}_{t+\tau}\}_{\tau=0}^{\infty}$ denote that maximizing input sequence.

Assuming that the firm realizes the initial portion of the investment plan, the firm's net investment expenditures on (say) the first quasi-fixed factor are $Q_{1t}\Delta\hat{X}_{1t} = Q_{1t}(\hat{X}_{1t} - X_{1,t-1})$ where Q_{1t} is the acquisition price for capital good one. Clearly the expected returns on this investment (discounted by the opportunity rate r_t) are maximal only if the firm plans to follow the entire plan also with respect to the other factors. To calculate the net returns from this investment we have to compare these returns with the returns from an input sequence where that particular investment is not undertaken. To capture the entire effect of the firm's investment we assume that this alternative input sequence is conditionally optimal, i.e., optimal subject to the condition that the firm's investment in the first quasi-fixed factor in period t is not undertaken and hence zero. More formally, we consider as the alternative input sequence, say $\{\check{X}_{t+\tau}, \check{V}_{t+\tau}\}_{\tau=0}^{\infty}$, the input sequence that maximizes (14) subject to the constraint $\Delta X_{1t}=0$.[12] We now define as our rate of return the internal rate ρ that equates the present value of the differences in the two net return streams with the initial investment expenditure, i.e.,

$$Q_{1t}\Delta\hat{X}_{1t}=R(X_{t-1},\Delta\hat{X}_{1t},\Delta\hat{X}_{2t},\hat{V}_t)-R(X_{t-1},0,\Delta\check{X}_{2t},\check{V}_t)$$
$$+\sum_{\tau=1}^{\infty}\{R(\hat{X}_{t+\tau-1},\Delta\hat{X}_{t+\tau},\hat{V}_t)-R(\check{X}_{t+\tau-1},\Delta\check{X}_{t+\tau},\check{V}_{t+\tau})\}(1+\rho)^{-\tau}. \tag{15}$$

For an additional interpretation of the above definition, consider the special case of only one quasi-fixed factor. In this case the rate of return defined by (15) is identical to the rate obtained by specifying as the alternative policy that the firm maintains forever the quasi-fixed factor at its initial level, i.e., X_{t-1}, while choosing the variable inputs correspondingly optimal. To see this, note that in the case of one quasi-fixed factor $\check{X}_{t+\tau+1}=\hat{X}_{t+\tau}$ and $\check{V}_{t+\tau+1}=\hat{V}_{t+\tau}$ for $\tau\geqq 1$.[13]

In the case of a cost-minimizing firm, the input sequences $\{\hat{X}_{t+\tau}, \hat{V}_{t+\tau}\}_{\tau=0}^{\infty}$ and $\{\check{X}_{t+\tau}, \check{V}_{t+\tau}\}_{\tau=0}^{\infty}$ are established under the additional constraint that $F(V_{t+\tau}, X_{t+\tau-1}, \Delta X_{t+\tau})=Y_t$ for all $\tau\geqq 0$. We can still use (15) as our measure for the rate of return on investment. Note, however, that gross revenues will be identical for both input sequences. Hence in the case of a cost-minimizing firm we actually compare the difference in cost streams.

In table 8, we report the averages of the internal rates of return over the sample periods on the net investments in capital and R&D for the total manufacturing sectors in the U.S., Japan and Germany. These internal rates of return are net of depreciation and adjustment costs. Several interesting

[12] In case we want to calculate the rate of return on the last, say, 50 units, we have to make a comparison with returns attainable from an input sequence for which net investment in period t is $\Delta X_{1t}-50$.

[13] We note that our measure of the rate of return is consistent with traditional measures in the case of zero adjustment costs. A more detailed discussion is given in the previous version of this paper.

Table 8
Internal rates of return on the net investments of capital and R&D for total manufacturing in the U.S., Japan and Germany.[a]

	U.S.	Japan	Germany
Capital	10	13	9
R&D	11	15	13

[a]Sample averages in percentages.

points should be noted. First, the rates of return on R&D are higher than the rates of return on capital. This finding is consistent with the results of other studies [see Mansfield (1965) and Griliches (1980b)], although accounting for the depreciation and adjustment costs seems to reduce the difference between the two rates of return. Second, the rates of return are higher in Japanese manufacturing, particularly for R&D. A structural analysis of R&D spending, such as the one recently conducted by Piekarz, Thomas and Jennings (1984), could provide some clues to the international differences in the rates of return on R&D. For instance, one structural explanation concerns the financing of R&D. Japan has the lowest percentage of government financing. In 1975, only 1.7% of the gross expenditures on R&D performed by the manufacturing sector were funded by government in Japan, compared to 13.5% in Germany and 35.4% in the U.S.[14] What these numbers reveal is that the Japanese manufacturers cannot rely on government to do their R&D. This may suggest that in Japan managers are more motivated to direct their R&D efforts at profitable projects, whereas in the U.S. a great deal of R&D may be earmarked for social rather than private returns. Another explanation could reside in the industrial composition of R&D. Five industries account for the bulk of manufacturing R&D: machinery, motor vehicles, aircraft, chemicals and drugs, and electrical and electronic equipment and components. Over the period 1963–1977, these five industries accounted for 80% of all manufacturing R&D in the U.S., 85% in Germany, but only 65% in Japan. Germany had, of the three countries, the highest proportion of R&D in chemicals and drugs (27% of all manufacturing R&D), an industry where the payoff may be higher than elsewhere [see Griliches (1980b)]. The U.S. did most of its R&D in the aircraft industry (29%), an industry with high government investment and low returns [Griliches (1980)].

Finally, the approximate equality of the rates of return across countries is interesting, for it suggests that none of the countries is earning excessive

[14]See OECD, *International Statistical Year 1975*, DSTI/SPR/97-5, Paris, Table T.E. 2.1(A).

returns on its investment in plant and equipment and R&D exclusive of the depreciation and adjustment costs.

6. Summary and conclusions

In this paper we formulated a dynamic factor demand model with two variable inputs, labor and materials, and two quasi-fixed factors, plant and equipment and R&D. The model was estimated using data for the manufacturing sectors of three major industrialized countries, the U.S. and Germany for the period 1965 to 1977 and Japan for the period 1966 to 1978. The model was derived from an intertemporal cost-minimization problem formulated in discrete time. We note that no a priori restriction of separability in the quasi-fixed factors was imposed. The empirical results suggest that the adjustment cost model explains the behavior of inputs fairly well. In more detail the empirical results suggest that:

(*i*) It takes a considerably longer time for the stock of R&D to adjust to its optimum value than for the capital stock. Cross-adjustments between capital and R&D are significant only in the U.S.

(*ii*) The adjustment lags differ considerably among the manufacturing sectors for R&D but are similar for capital. We find an average lag of approximately three years for capital in the three countries. The average lag for R&D is about five years in the U.S., eight years in Japan and ten years in Germany. The results for U.S. manufacturing are similar to some evidence reported in the literature.

(*iii*) The Japanese manufacturing sector was, over the sample period, further away from having optimal capital and R&D stocks than the U.S. and German manufacturing sectors.

(*iv*) The patterns of own- and cross-price elasticities of the inputs vary considerably among countries. The own-price elasticities are generally higher than the cross-price elasticities. There is mostly a substitutional relationship between the inputs. The exceptions are capital and labor in the Japanese and German manufacturing and capital and R&D in the U.S. and in Japan. The output elasticities of the inputs in the short and intermediate runs differ from each other and across countries. The materials input overshoots, in the short run, its long-run equilibrium value to compensate for the sluggish adjustments of the two quasi-fixed inputs; the output elasticities of the capital stock are larger than those of R&D in the short and intermediate runs; there are short-run increasing returns to labor. The Japanese manufacturing sector seems to have higher elasticities than the U.S. manufacturing sector and to display more flexibility.

(*v*) An interesting result is that the average net rates of return exclusive of the costs of adjustment and depreciation are similar for both R&D and capital in the manufacturing sectors of the three countries. The rate of return on R&D is somewhat greater than that on capital in each sector.

There are several issues that require further research. One is the relaxation of the assumption of constant returns to scale. Also our assumption of static expectations is restrictive. For a possible route to relax both assumptions see, e.g., Prucha and Nadiri (1982). Also, there is a need for increasing the span of time for the study by collecting new data for recent years and re-estimating the model. Furthermore, future studies may consider reporting confidence intervals for the elasticity estimates.

Appendix A

Explicit expressions for the elements of A and D in terms of the elements of B and C

Eq. (8) implies

$$\alpha_{KK}=c_{KK}-(1+r)[\ddot{a}_{KK}-\ddot{a}_{KK}^2(\ddot{a}_{RR}+c_{RR})/e],$$

$$\alpha_{RR}=c_{RR}-(1+r)[\ddot{a}_{RR}-\ddot{a}_{RR}^2(\ddot{a}_{KK}+c_{KK})/e],$$

$$\alpha_{KR}=c_{KR}-(1+r)\ddot{a}_{KK}\ddot{a}_{RR}c_{KR}/e,$$

$$d_{KK}=-1/\ddot{a}_{KK}-(1+r)[c_{RR}-r\ddot{a}_{RR}]/f,$$

$$d_{RR}=-1/\ddot{a}_{RR}-(1+r)[c_{KK}-r\ddot{a}_{KK}]/f,$$

$$d_{KR}=+(1+r)c_{KR}/f,$$

where $e=(\ddot{a}_{KK}+c_{KK})(\ddot{a}_{RR}+c_{RR})-c_{KR}^2$ and $f=(c_{KK}-r\ddot{a}_{KK})(c_{RR}-r\ddot{a}_{RR})-c_{KR}^2$.

Appendix B

Data sources and constructions

The data cover the total manufacturing sectors of the U.S., Japan and Germany. The period ranges from 1965 to 1977 for the U.S. and Germany and from 1966 to 1978 for Japan. The data have been assembled from various sources, as indicated below.

Labour. Employment (L) is measured in man-hours per year. The employment data for the U.S. and Germany are from the OECD (1981). Those for Japan are obtained from the Bank of Japan (1970 and 1981). For all countries the figures on hours worked are provided in International Labor Office (1980) and earlier publications.

Capital. The figures on net capital stock (K) are obtained from various sources. The capital stock series for the U.S. comes from the U.S. Department of Commerce (1982). For Japan, the gross capital stock series reported by the Economic Planning Agency (1977) is converted to a net capital stock series using the gross-to-net capital stock ratios contained in Denison and Chung (1976). The capital stock series for Germany is taken from Statistisches Bundesamt (1979). The 1977 figure is computed by the perpetual inventory method using the depreciation rate of 1976. The real and nominal gross investment series are taken from Statistisches Bundesamt (1978 and 1983). All capital stocks are measured as end-of-period stocks in 1970 prices.

Output. Output (Y) is measured as gross output at 1970 prices and is derived from two sources. For the U.S., the data are taken from Norsworthy and Malmquist (1983). For Japan, the data are spliced in the following way: for 1970–1978, the quantities are available from the United Nations (1983) and converted to the 1970 base; for 1966–1969, the Norsworthy and Malmquist (1983) data are used to construct the corresponding series, which are then linked to the United Nations series by the growth rates. For Germany, the observations for 1970–1977 are taken from the United Nations (1983); the figures prior to 1970 are obtained by deflating the unpublished nominal figures on materials (kindly provided by the National Accounts Division of the United Nations) by the materials price deflator and adding it to the real value added data.

Materials. Materials (M) come from the same source as output. The data on materials derived from Norsworthy and Malmquist (1983) are obtained by adding the energy to the non-energy materials data. Since materials include R&D, the real R&D expenditures are subtracted from materials to avoid double-counting.

R&D. The R&D stock (R) is constructed by the perpetual inventory method with a depreciation rate of 0.10. The benchmark is obtained from the first period R&D expenditure divided by the depreciation rate and the growth rate in real value-added. The nominal R&D expenditures are from the OECD (1979 and 1982b). The GNP deflator is used as a deflator for R&D. Real value-added figures are taken from the OECD (1982a) for the U.S. and Japan and from the United Nations (1983) for Germany.

Wage rate. Total compensations per hour worked (w^L) are obtained from the U.S. Department of Labor (1980).

User cost of capital. The user cost of capital (c^K) is constructed as $c^K = q^K(\delta_K + r)/(1-u)$, where q^K is the investment deflator, δ_K is the depreciation rate of the capital stock, r is the real discount rate and u is the corporate income tax rate. The nominal and real investment data used to compute the implicit investment deflator are from the same sources as the capital stock data. For Japan, we use the investment deflator for machinery and equipment published by the Bank of Japan (1981). The real discount rate is taken to be constant at 4%. The depreciation rates are obtained implicitly from the perpetual inventory formula, using the gross investment and net capital stock figures. Information on corporate income tax rates is provided by Pechman (1983) for the U.S., Pechman and Kaizuka (1976) for Japan, and for Germany by the laws of October 16, 1934 and August 31, 1976 published by the Federal Republic of Germany in, respectively, the Reichsgesetzblatt 1, p. 1031 and the Bundesgesetzblatt 1, p. 2597.

User cost of R&D. The user cost of R&D is constructed as $c^R = q^R(\delta_R + r)$, with an R&D depreciation rate of 0.10 and the GNP deflator for q^R.

Materials price. The price of materials (w^M) is measured by the implicit deflator computed from the real and nominal figures on materials. For the years prior to 1970 in Germany, the 'Index der Grundstoffpreise' published in Statistisches Bundesamt (1983) and prior issues is used as materials deflator.

For the data of different countries to be comparable, all currencies are converted to U.S. dollars, using the purchasing power parities for gross domestic income for 1970 computed by Summers, Kravis and Heston (1980).

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