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R&D Activity in a Dynamic Factor Demand Model

A Panel Data Analysis of Small and Medium Size German Firms

Andrew J. Buck, Manfred Stadler*)

Abstract

The focus of this paper is an econometric analysis of the determinants of private firms' R&D activities in the context of a general dynamic factor demand model. Besides the traditional production factors we treat technological knowledge, endogenously determined by R&D expenditures, as a further input factor. While labour and materials are assumed to be variable, capital and know-how are considered as quasi-fixed. The dynamic demand equations for labour, capital investment and R&D which are derived from an intertemporal cost minimisation are estimated for a panel data set of small and medium size German firms. The data covers the period between 1978 and 1982 and includes 408 firms. It turns out that R&D activity depends on the underlying production structure as suggested by neoclassical theory. In addition, by introducing firm specific effects, we can show that firm size and market concentration influence innovative behaviour in accordance with the Schumpeterian hypotheses.

1. Introduction

Most empirical studies of firms' innovative behaviour have followed Schumpeterian lines of analysis. Private R&D expenditures were related to firm size, market share or market concentration ratios. The main issue of these studies was the identification of an optimal firm size or an optimal degree of concentration implying maximum innovative activity and hence economic growth (see, e. g., *Kamien – Schwartz*, 1982, for a survey). In modern production theory, however, R&D expenditures are considered as an investment in a stock of firm-specific technological knowledge similar to capital investment. Hence, if technological knowledge can usefully be treated as a production factor in its own right, R&D expendi-

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tures should depend not only on firm size and market concentration, but also on the relative prices of all factor inputs.

The objective of this paper is to examine the importance of the relationships between R&D expenditures and the demands for the other factor inputs capital, labour and materials. As is usual in modern production theory, our model is based on the approach of dynamic duality. We adapt a rather flexible restricted cost function to derive a system of dynamic interrelated factor demands. Following recent work of *Mohnen – Nadiri – Prucha* (1986), *Nadiri – Prucha* (1990A, 1990B), and *Bernstein – Nadiri* (1989), labour and materials are assumed to be variable, while capital and knowledge are treated as quasi-fixed. That is, while firms are able to adjust labour and materials instantaneously in response to a change in relative factor prices, they can adjust their stocks of capital and technological know-how only slowly and at some cost measured in terms of foregone output. In contrast to these earlier studies we allow for a more general production structure. In particular, we account for autonomous technological change due to knowledge not accumulated within the firms and use a non-homothetic cost function. Since we explicitly derive the demand functions by dynamic cost minimisation, our model belongs to the so-called "third generation models of dynamic factor demand" (*Berndt – Morrison – Watkins*, 1981).

The paper is organised as follows. In Section 2, the dynamic demand equations for labour, capital investment and R&D investment are derived from an intertemporal cost minimisation problem using a normalised restricted cost function. Section 3 contains a short description of the data and the econometric specification of our model. The estimation results of the interrelated factor demand system are presented in Section 4. Section 5 highlights the additional impact of market structure on the factor demands. Section 6 finally contains some concluding remarks.

2. The theoretical model of the production structure

We assume that the firms' production process for any period t can be described by a production function

$$(1) \quad Y_t = Y(\mathbf{V}_t, \mathbf{F}_{t-1}, \Delta \mathbf{F}_t),$$

where a single output, Y_t, is produced with variable and quasi-fixed inputs. The vector $\mathbf{V}_t = (L_t, Z_t)'$ represents the variable inputs, labour and materials. The vector $\mathbf{F}_t = (K_t, T_t)'$ represents the end of period stocks of the quasi-fixed inputs, capital and technological knowledge. The vector $\Delta \mathbf{F}_t = \mathbf{F}_t - \mathbf{F}_{t-1}$ accounts for internal adjustment costs in terms of foregone output due to changes in the stocks of the quasi-fixed factors.

As *Morrison – Berndt* (1981) and *Denny – Fuss – Waverman* (1981) have shown with formulations in continuous time, the intertemporal minimisation of the present value of the cost of producing a given flow of output subject to the production function constraint in *(1)* results in a normalised restricted cost function

$$(2) \qquad C_t = C(\mathbf{w}_t, \mathbf{F}_{t-1}, \Delta \mathbf{F}_t, Y_t, t),$$

where $\mathbf{w}_t$ is the vector of the variable input factor prices normalised by the price of one of the variable inputs. In our specification the price of intermediate goods is taken to be the numéraire. Thus, $\mathbf{w}_t$ is the wage rate divided by the price of intermediate goods and the variable normalised costs are $C_t = Z_t + \mathbf{w}_t L_t$. *Lau* (1976) has shown that *(2)* must satisfy certain regularity conditions in order to be an appropriate restricted cost function: It should be increasing in $\mathbf{w}$, $\Delta \mathbf{F}$ and Y, but decreasing in $\mathbf{F}$. Further, it should be concave in $\mathbf{w}$, but convex in $\mathbf{F}$ and $\Delta \mathbf{F}$.

For the empirical analysis we use a rather flexible form of the normalised restricted cost function. Following *Mohnen – Nadiri – Prucha* (1986) we relax the usual assumption of separability in the quasi-fixed input factors and estimate the model in a non-separable form. While *Nadiri – Prucha* (1990A, 1990B) allow for non-constant returns to scale by using a restricted cost function that can be interpreted as a second-order approximation to a general homothetic restricted cost function, we decided to use a non-homothetic cost function. We also account for autonomous technological advance which is conventionally represented by a time index (see *Chambers*, 1988, ch. 6). These additional variables are included in our cost function in a way similar to *Morrison's* (1988) Generalised Leontief restricted cost function. Thus, our specification of *(2)* takes the form

$$\begin{aligned}
(3) \qquad C_t = & \left(a_0 + a_w \mathbf{w}_t + \frac{1}{2} a_{ww} \mathbf{w}_t^2 + a_{wY} \mathbf{w}_t Y_t + a_{wt} \mathbf{w}_t t\right) Y_t + \\
& + a_K K_{t-1} + a_T T_{t-1} + c_K \Delta K_t + c_T \Delta T_t + \\
& + \frac{1}{2} \frac{a_{KK} K_{t-1}^2}{Y_t} + \frac{1}{2} \frac{a_{TT} T_{t-1}^2}{Y_t} + \frac{a_{KT} K_{t-1} T_{t-1}}{Y_t} + \\
& + a_{wK} \mathbf{w}_t K_{t-1} + a_{wT} \mathbf{w}_t T_{t-1} + a_{KY} K_{t-1} Y_t + a_{TY} T_{t-1} Y_t + a_{Kt} K_{t-1} t + a_{Tt} T_{t-1} t + \\
& + \frac{1}{2} \frac{b_{KK} (\Delta K_t)^2}{Y_t} + \frac{1}{2} \frac{b_{TT} (\Delta T_t)^2}{Y_t} + \frac{b_{KT} \Delta K_t \Delta T_t}{Y_t} + \frac{c_{KK} \Delta K_t K_{t-1}}{Y_t} + \frac{c_{TT} \Delta T_t T_{t-1}}{Y_t} + \\
& + c_{wK} \mathbf{w}_t \Delta K_t + c_{wT} \mathbf{w}_t \Delta T_t + c_{KT} \Delta K_t T_{t-1} + c_{TK} \Delta T_t K_{t-1} + \\
& + c_{KY} \Delta K_t Y_t + c_{TY} \Delta T_t Y_t + c_{Kt} \Delta K_t t + c_{Tt} \Delta T_t t .
\end{aligned}$$

At a stationary point, where ΔK and ΔT must equal zero, marginal internal adjustment costs have to be zero, too. In our case, the stationary conditions, $\left.\frac{\partial C_t}{\partial \Delta K_t}\right|_{\Delta K_t = 0} = 0$ and $\left.\frac{\partial C_t}{\partial \Delta T_t}\right|_{\Delta T_t = 0} = 0$, will hold for any w, K, T, Y and t only if the restrictions

$$\text{(4)} \quad c_K = c_T = b_{KT} = c_{KK} = c_{TT} = c_{wK} = c_{wT} = c_{KT} = c_{TK} = c_{KY} = c_{TY} = c_{Kt} = c_{Tt} = 0$$

are imposed (see, e. g., *Morrison – Berndt*, 1981, p. 348). Then our normalised variable cost function *(3)* reduces to

$$\text{(5)} \quad C_t = \left(a_0 + a_w \mathrm{w}_t + \frac{1}{2} a_{ww} \mathrm{w}_t^2 + a_{wY} \mathrm{w}_t Y_t + a_{wt} \mathrm{w}_t t\right) Y_t +$$
$$+ a_K K_{t-1} + a_T T_{t-1} +$$
$$+ \frac{1}{2} \frac{a_{KK} K_{t-1}^2}{Y_t} + \frac{1}{2} \frac{a_{TT} T_{t-1}^2}{Y_t} + \frac{a_{KT} K_{t-1} T_{t-1}}{Y_t} +$$
$$+ a_{wK} \mathrm{w}_t K_{t-1} + a_{wT} \mathrm{w}_t T_{t-1} + a_{KY} K_{t-1} Y_t + a_{TY} T_{t-1} Y_t + a_{Kt} K_{t-1} t + a_{Tt} T_{t-1} t +$$
$$+ \frac{1}{2} \frac{b_{KK} (\Delta K_t)^2}{Y_t} + \frac{1}{2} \frac{b_{TT} (\Delta T_t)^2}{Y_t}$$

Firms are assumed to hold static expectations on output, relative factor prices, and the discount rate, r. Thus, to derive the demand equations for the two quasi-fixed inputs, capital and technological knowledge, we have to solve the following intertemporal cost minimisation problem with respect to the quasi-fixed factors:

$$\text{(6)} \quad J(K, T, t) = \min_{\{K_{t+\tau}, T_{t+\tau}\}_{\tau=0}^{\infty}} \sum_{\tau=0}^{\infty} (C_{t+\tau} + p_{It} I_{t+\tau} + p_{Rt} R_{t+\tau}) (1 + r_t)^{-\tau}$$

s. t.

$$I_{t+\tau} = K_{t+\tau} - (1 - \delta) K_{t+\tau-1},$$
$$R_{t+\tau} = T_{t+\tau} - (1 - \mu) T_{t+\tau-1},$$

where I is real investment in physical capital, K, and R is real R&D expenditures for the accumulation of the firm-specific stock of knowledge, T. Further, p_I and p_R are the normalised acquisition prices of investment in capital and knowledge, respectively. Depreciation rates of capital and knowledge are denoted by δ and μ. The optimal time paths of investment and R&D must satisfy a set of necessary conditions given by the Euler equations ($\tau = 0, 1, 2, \ldots, \infty$):

(7) $$-b_{KK}K_{t+\tau+1} + [a_{KK} + (2+r_t)\,b_{KK}]\,K_{t+\tau} + a_{KT}T_{t+\tau} - (1+r_t)\,b_{KK}K_{t+\tau-1} = \\ = -[a_K + a_{wK}\mathbf{w}_t + a_{KY}Y_t + a_{Kt}t + p_{It}(r_t+\delta)]\,Y_t$$

and

(8) $$-b_{TT}T_{t+\tau+1} + [a_{TT} + (2+r_t)\,b_{TT}]\,T_{t+\tau} + a_{KT}K_{t+\tau} - (1+r_t)\,b_{TT}T_{t+\tau-1} = \\ = -[a_T + a_{wT}\mathbf{w}_t + a_{TY}Y_t + a_{Tt}t + p_{Rt}(r_t+\mu)]\,Y_t .$$

Equations *(7)* and *(8)* can be transformed into the matrix equation

(9) $$-B\,\mathbf{F}_{t+\tau+1} + [A + (2+r_t)\,B]\,\mathbf{F}_{t+\tau} - (1+r_t)\,B\,\mathbf{F}_{t+\tau-1} = \mathbf{v}_t ,$$

where the 2×2 matrices A and B and the 2×1 vector $\mathbf{v}$ are defined as

(10) $$A = \begin{bmatrix} a_{KK} & a_{KT} \\ a_{KT} & a_{TT} \end{bmatrix},$$

$$B = \begin{bmatrix} b_{KK} & 0 \\ 0 & b_{TT} \end{bmatrix},$$

$$\mathbf{v}_t = -\begin{bmatrix} a_K + a_{wK}\mathbf{w}_t + a_{KY}Y_t + a_{Kt}t + p_{It}(r_t+\delta) \\ a_T + a_{wT}\mathbf{w}_t + a_{TY}Y_t + a_{Tt}t + p_{Rt}(r_t+\mu) \end{bmatrix} Y_t .$$

Based on a model similar to that of *Epstein – Yatchew* (1985), it has been shown by *Mohnen – Nadiri – Prucha* (1986) and *Madan – Prucha* (1989) that the solution corresponding to the stable roots of a system like *(9)* can be equivalently expressed in feedback form as a flexible accelerator equation system

(11) $$\Delta\mathbf{F}_t = M(\mathbf{F}^* - \mathbf{F}_{t-1}),$$

where $\mathbf{F}^* = (K^*, T^*)'$ is the stationary solution of *(9)*,

(12) $$\mathbf{F}^* = A^{-1}\mathbf{v}_t ,$$

and where the 2×2 matrix M of own and cross-adjustment coefficients of the quasi-fixed input factors

(13) $$M = \begin{bmatrix} m_{KK} & m_{KT} \\ m_{TK} & m_{TT} \end{bmatrix}$$

has to satisfy the matrix polynomial

(14) $$BM^2 + (A + r_tB)\,M - A = 0.$$

The factor demand equations for capital and technological knowledge (but not for the variable labour demand function) look like the disequilibrium interrelated factor demand equations of *Nadiri – Rosen* (1969) and *Schott* (1978). However, the partial adjustment matrix M is exogenous in their approach, but is endogenously determined in our dynamic cost minimisation model.

The stationary levels $\mathbf{F}^*$ will rarely be reached due to stochastic shocks to demand. During the adjustment process the stocks will change due to the first-order difference equation system *(11)*. Inserting *(12)* gives

$$(15) \quad \Delta \mathbf{F} = D\,\mathbf{v}_t - M\,\mathbf{F}_{t-1}$$

with D defined as

$$(16) \quad D = M A^{-1}.$$

As long as we allow for non-separability in the quasi-fixed factors, we cannot explicitly solve for M in terms of A and B. Instead we will adopt the following strategy. First, we will empirically determine the elements of D and M in *(15)*. The matrices A and B are then calculated as

$$(17) \quad A = D^{-1} M$$

and

$$(18) \quad B = (A - AM)(M^2 + r_t M)^{-1}$$

to see whether the regularity conditions of our cost function are fulfilled.

According to *(15)* we get the following demand equations for the quasi-fixed factor inputs capital and technological knowledge:

$$\begin{aligned}(19) \quad K_t - K_{t-1} = & - d_{KK}[a_K + a_{wK}\mathbf{w}_t + a_{KY} Y_t + a_{Kt} t + p_{It}(r_t + \delta)] Y_t - \\ & - d_{KT}[a_T + a_{wT}\mathbf{w}_t + a_{TY} Y_t + a_{Tt} t + p_{Rt}(r_t + \mu)] Y_t - \\ & - m_{KK} K_{t-1} - m_{KT} T_{t-1}, \\ (20) \quad T_t - T_{t-1} = & - d_{TK}[a_K + a_{wK}\mathbf{w}_t + a_{KT} Y_t + a_{Kt} t + p_{It}(r_t + \delta)] Y_t - \\ & - d_{TT}[a_T + a_{wT}\mathbf{w}_t + a_{TY} Y_t + a_{Tt} t + p_{Rt}(r_t + \mu)] Y_t - \\ & - m_{TK} K_{t-1} - m_{TT} T_{t-1}.\end{aligned}$$

Further, applying Shephard's Lemma to *(5)*, we derive the labour demand equation

$$(21) \quad L_t = [a_w + a_{ww}\mathbf{w}_t + a_{wY} Y_t + a_{wt} t] Y_t + a_{wK} K_{t-1} + a_{wT} T_{t-1}.$$

The demand for intermediate goods could be calculated as $Z_t = C_t - \mathbf{w}_t L_t$. Since we have no data for the material inputs, we have to omit this equation. Thus, our entire system of estimating equations consists of the three factor demand equations *(19)* to *(21)*.

3. Data and econometric specification

The derived dynamic factor demand model is estimated with panel data for 408 small and medium size German firms with not more than 2,500 employees. The data set includes employees, revenue, investment in capital and R&D expenditures. The period ranges from 1978 to 1982. The data for the first year is lost due to the construction of lagged variables. Hence the data falls in the period of the German recession following the second oil price shock. All firms can be related to 22 2-digit industries of the manufacturing sector. Therefore the panel data set was augmented by input and output price indices, concentration indices and interest rates. A detailed description of the data sources and the construction of all variables is given in the data appendix.

The stocks of capital and knowledge were constructed as the accumulated sum of past real investment and real R&D expenditures for each firm, i. e.,

$$(22) \quad K_t = K_0 + \sum_{\tau=1}^{t} I_\tau ,$$

$$(23) \quad T_t = T_0 + \sum_{\tau=1}^{t} R_\tau .$$

Since we have no data for firm specific depreciation we had to neglect the rates δ and μ in the computation of the stocks. The introduction of arbitrary depreciation rates did not change the main empirical results(1). The initial stocks K_0 and T_0 at period 1978 are estimated within the model as elements of the slope coefficients in the last two terms of equations *(19)* to *(21)*. The resulting values in *(22)* and *(23)* are certainly not very good proxies for the stocks. An alternative method to obtaining the benchmarks K_0 and T_0 is to divide real investment expenditures in 1978 by the depreciation rates and the estimated average growth rate of the corresponding stock for the years succeeding 1978 (see, e. g., *Nadiri*, 1980, p. 376). However, due to the many missing values at the beginning of our data set, we did not follow this line. For similar reasons we were not able to treat the stocks as weighted sums of investment (see *Griliches*, 1979).

To reduce the problem of heteroscedasticity, we divided all demand equations by output. Since we are primarily interested in the determinants of the factor demands, we decided to

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(1) *Nadiri* (1980), *Mohnen – Nadiri – Prucha* (1986) and *Bernstein – Nadiri* (1989) assume a depreciation rate for technological knowledge of 10 percent, *Jaffe* (1986) assumes one of 15 percent.

use the following estimation strategy. In a first step, we estimate the slope coefficients of all variables in the factor demands without restrictions. These coefficients are used in a second step to calculate the remaining coefficients of our cost function. Thus, the following system of input-output equations constitutes our basic empirical specification of the system of factor demands:

$$(24)\quad \frac{L_t}{Y_t} = \alpha_0 + \alpha_1 w_t + \alpha_2 Y_t + \alpha_3 t + \alpha_4 \frac{\sum_{\tau=1}^{t-1} I_\tau}{Y_t} + \alpha_5 \frac{\sum_{\tau=1}^{t-1} R_\tau}{Y_t} + \alpha_6 \left(\frac{1}{Y}\right)_t + u_{Lt},$$

$$(25)\quad \frac{I_t}{Y_t} = \beta_0 + \beta_1 w_t + \beta_2 Y_t + \beta_3 t + \beta_4 p_{It}(r_t + \delta) + \beta_5 p_{Rt}(r_t + \mu) +$$

$$+ \beta_6 \frac{\sum_{\tau=1}^{t-1} I_\tau}{Y_t} + \beta_7 \frac{\sum_{\tau=1}^{t-1} R_\tau}{Y_t} + \beta_8 \left(\frac{1}{Y}\right)_t + u_{It},$$

$$(26)\quad \frac{R_t}{Y_t} = \gamma_0 + \gamma_1 w_t + \gamma_2 Y_t + \gamma_3 t + \gamma_4 p_{It}(r_t + \delta) + \gamma_5 p_{Rt}(r_t + \mu) +$$

$$+ \gamma_6 \frac{\sum_{\tau=1}^{t-1} I_\tau}{Y_t} + \gamma_7 \frac{\sum_{\tau=1}^{t-1} R_\tau}{Y_t} + \gamma_8 \left(\frac{1}{Y}\right)_t + u_{Rt}$$

with the slope coefficients defined as

$$\alpha_0 = a_w,\ \alpha_1 = a_{ww},\ \alpha_2 = a_{wY},\ \alpha_3 = a_{wt},\ \alpha_4 = a_{wK},\ \alpha_5 = a_{wT},\ \alpha_6 = a_{wK} K_0 + a_{wT} T_0,$$

$$\beta_0 = -d_{KK} a_K - d_{KT} a_T,\ \beta_1 = -d_{KK} a_{wK} - d_{KT} a_{wT},\ \beta_2 = -d_{KK} a_{KY} - d_{KT} a_{TY},$$
$$\beta_3 = -d_{KK} a_{Kt} - d_{KT} a_{Tt},\ \beta_4 = -d_{KK},\ \beta_5 = -d_{KT},\ \beta_6 = -m_{KK},\ \beta_7 = -m_{KT},$$
$$\beta_8 = -m_{KK} K_0 - m_{KT} T_0,$$

$$\gamma_0 = -d_{TK} a_K - d_{TT} a_T,\ \gamma_1 = -d_{TK} a_{wK} - d_{TT} a_{wT},\ \gamma_2 = -d_{TK} a_{KY} - d_{TT} a_{TY},$$
$$\gamma_3 = -d_{TK} a_{Kt} - d_{TT} a_{Tt},\ \gamma_4 = -d_{TK},\ \gamma_5 = -d_{TT},\ \gamma_6 = -m_{TK},\ \gamma_7 = -m_{TT},$$
$$\gamma_8 = -m_{TK} K_0 - m_{TT} T_0.$$

The stochastic disturbance vector $(u_{Lt}, u_{It}, u_{Rt})'$ reflects optimisation errors or technology shocks. The error terms are assumed to be jointly normally distributed, with zero expected value, $E(u) = 0$, and with positive-definite symmetric covariance matrix, $E(u u') = \Omega$.

So far the firms' demand decisions have been modelled without any consideration of firm or industry-specific characteristics. Indeed, the usual empirical work in this field does not make any attempt to account for either firm or industry fixed effects. However, the assumption that all firms behave identically with respect to their levels of factor employments may not be warranted. One would expect that firms as well as industries differ in their employment, investment and especially in their R&D behaviour due to different expectations, technological opportunities, appropriability of pioneer profits, market entry conditions, etc. (see *Nelson – Winter*, 1982). One of the major advantages of a panel data set over conventional cross-sectional or time series data sets is the possibility to account for those unobservable effects in a fixed or random effects model (see, e. g., *Hsiao*, 1986). Thus, we will compare our basic data pooling model with industry and firm fixed effects models which allow for specific time invariant differences between the industries or firms in our sample (for the estimating procedure see *Judge et al.*, 1985, ch. 13).

4. Empirical results

To estimate the coefficients of our factor demand system, we use the iterative Zellner efficient (IZEF) estimator without restrictions. The IZEF estimator yields parameter estimates that are numerically equivalent to those of the maximum likelihood estimator under the null hypothesis that our model is the correct characterisation of firm behaviour (see *Oberhofer – Kmenta*, 1974). All estimates were performed with RATS386. The estimation procedure converged by the second step in the basic model as well as in the two fixed effects models(2).

The estimated coefficients of the factor demand functions without fixed effects are reported in column 1 of Table 1. Keeping in mind the large size of the data set and the fact that we are using panel data, the fit of the demand models is quite good. In a previous study the single labour demand equation was estimated for various specifications (see *Flaig – Stadler*, 1988). The empirical evidence did not change very much in our simultaneous three equation approach. Labour demand depends significantly and negatively on its own normalised price, i. e., real wages. The positive signs of the quasi-fixed production factors imply that capital and knowledge inputs are complements to the labour input although the capital coefficient is not statistically significant. Increasing productivity of the labour input is evidenced by the negative coefficient on time. The latter result is apparent in the other two factor demand equations as well.

The investment equation is not terribly successful, but such equations seldom are. The factor prices are not significant. Most of the variation in investment is explained by autonomous technological progress, the inherited capital stock and output. The negative coefficient of the autonomous technological progress variable suggests the presence of increasing capital productivity among the small firms of the sample.

(2) We have also estimated the model parameters by non-linear least squares with the symmetry constraints imposed on D. The sign of all coefficients remained the same and with few exceptions the coefficients were all of the same order of magnitude. The results are available from the authors on request. All of the coefficients were significant at least at the 5 percent level.

Estimates of the parameters of the factor demand equations without fixed effects, with fixed industry effects and with fixed firm effects *Table 1*

	Without fixed effects	With fixed industry effects	With fixed firm effects
α_0 (10^{-2})	4.77 (4.62)	–	–
α_1 (10^{-2})	– 0.90 (– 3.68)	– 1.33 (– 0.99)	– 0.93 (– 3.02)
α_2 (10^{-8})	– 3.13 (– 11.23)	– 2.62 (– 10.67)	– 5.22 (– 12.85)
α_3 (10^{-4})	– 4.10 (– 3.21)	– 5.16 (– 4.52)	– 2.25 (– 6.09)
α_4 (10^{-2})	0.09 (0.67)	0.59 (4.89)	0.18 (3.56)
α_5 (10^{-2})	1.42 (6.51)	0.60 (2.96)	0.02 (0.21)
α_6	11.29 (4.43)	8.43 (3.76)	53.84 (16.79)
β_0	1.11 (8.95)	–	–
β_1 (10^{-2})	0.01 (0.00)	– 18.37 (– 1.22)	– 9.87 (– 0.97)
β_2 (10^{-8})	9.37 (3.42)	8.15 (2.99)	2.47 (0.18)
β_3 (10^{-2})	– 1.37 (– 8.77)	– 1.25 (– 7.13)	0.86 (5.82)
β_4 (10^{-4})	8.95 (1.36)	13.28 (1.43)	16.67 (2.64)
β_5 (10^{-4})	– 4.13 (– 0.55)	– 7.60 (– 0.94)	– 10.30 (– 1.87)
β_6 (10^{-2})	21.02 (16.67)	17.34 (12.94)	– 25.83 (– 15.59)
β_7 (10^{-2})	– 0.66 (– 0.30)	1.28 (0.57)	1.08 (0.33)
β_8 (10^{2})	1.59 (6.34)	1.73 (6.97)	9.46 (8.93)
γ_0	0.42 (12.56)	–	–
γ_1 (10^{-2})	3.48 (5.09)	– 8.76 (– 2.15)	2.78 (1.58)
γ_2 (10^{-8})	– 0.21 (– 0.28)	0.36 (0.49)	– 14.60 (– 6.34)
γ_3 (10^{-2})	– 0.54 (– 12.83)	– 0.53 (– 11.10)	0.04 (1.38)
γ_4 (10^{-4})	10.25 (5.78)	10.98 (4.37)	0.79 (0.74)
γ_5 (10^{-4})	– 3.16 (– 1.56)	– 6.23 (– 2.83)	– 0.25 (– 0.27)
γ_6 (10^{-2})	– 0.12 (– 0.36)	0.33 (0.90)	0.27 (0.94)
γ_7 (10^{-2})	30.89 (52.52)	29.63 (48.71)	– 2.21 (– 3.97)
γ_8	0.67 (0.10)	0.54 (0.08)	115.43 (6.35)
L equation: $\bar{R}^2$	0.20	0.39	0.38
I equation: $\bar{R}^2$	0.26	0.29	0.21
R equation: $\bar{R}^2$	0.76	0.77	0.09
N	1,151	1,151	1,151

Numbers in parentheses . . . t statistics.

Particular attention should be given to the determinants of R&D activity. The factor equation modelling the demand for technological knowledge has the best fit of the three input factor equations. This results to a large degree from the positive influence of the available stock of knowledge. As in the investment equation, the cumulated stock of knowledge spurs further endeavours to advance the frontiers of knowledge. Such R&D behaviour is in accordance with the "success breeds success" hypothesis discussed by *Flaig – Stadler* (1992). As theoretically expected, the own R&D factor price index has a negative influence on R&D activity, while increases in either the user cost of capital or wages increase R&D intensity. Autonomous technological advance, which can result from inter-industry or intra-industry spill-overs of knowledge, seems to be a substitute for the firm's own research agenda. This result is consistent with the findings in *Bernstein – Nadiri* (1989) who explicitly emphasise spill-over effects.

It should be mentioned that both own adjustment coefficients, m_{KK} and m_{TT}, have negative signs. Thus, there is no evidence for a stable adjustment process. This shortcoming is probably caused by the weakness of our stock variables. However, it will be shown that with fixed firm effects the signs of these coefficients change and the magnitudes are quite plausible.

We specified the fixed effects models because we felt that there are probably differences across industries and firms which cannot be explained by the production structure alone. There is some evidence that R&D and capital investment are asymmetrically determined by different factors (see *Lach – Schankerman*, 1989). Certain industries with high technological opportunities are thought of as always being on the forefront of new technology while others are regarded as laggards. Further, there should be some differences in firms' creativity, intuition, experience and luck that are not part of the optimisation problem.

To test the overall significance of these differences, we employed the likelihood ratio (LR) test procedure. The LR test statistic is

$$LR = N\left[\ln|\hat{\Sigma}_{\omega}| - \ln|\hat{\Sigma}_{\Omega}|\right],$$

where $\hat{\Sigma}_{\omega}$ is the restricted estimator of the residual variance-covariance matrix, $\hat{\Sigma}_{\Omega}$ is the unrestricted estimator, and N is the number of observations in the pooled sample (see, e. g., *Berndt*, 1991, p. 467). The LR test statistic is asymptotically distributed as a χ^2 random variable with degrees of freedom equal to the number of parameter restrictions in the fixed effects models. There are 22 fixed industry effects and 408 fixed firm effects for each of our three factor demand equations. The calculated test statistic is 456.0 for the fixed industry effects model and 6,793.7 for the fixed firm effects model. The critical values of χ^2 (63) and χ^2 (1,221) at the 1 percent level are 92.0 and 1,338.9, respectively. Therefore, the null hypotheses of an unchanging structure of the demand functions for labour, investment, and R&D had to be rejected.

The coefficient estimates of the factor demands with industry and firm fixed effects are shown in columns 2 and 3 of Table 1. In the labour equations the results do not differ much. The influence of the lagged capital stock is now significant, too. On the other hand, output and wages in the fixed industry effects model and know-how in the fixed firm effects model are no longer statistically significant. The $\bar{R}^2$ rises in both models.

The fixed industry effects model for the investment equation shows similar results as in the model with no fixed effects, but in the fixed firm effects model some significant changes appear. The signs of the trend coefficient and of the lagged capital stock coefficient are changed. The own adjustment coefficient of capital, m_{KK}, now has the correct sign and a plausible magnitude of 26 percent. The $\bar{R}^2$ does not change very much in the three versions of the investment equation.

Table 2

Calculated values for the parameters of the cost function

	Without fixed effects	With fixed industry effects	With fixed firm effects
a_w (10^{-2})	4.77	–	–
a_{ww} (10^{-2})	– 0.90	– 1.33	– 0.93
a_{wY} (10^{-8})	– 3.13	– 2.62	– 5.22
a_{wt} (10^{-4})	– 4.10	– 5.16	– 2.25
a_{wK} (10^{-2})	0.09	0.56	0.17
a_{wT} (10^{-2})	1.14	0.61	0.03
d_{KK} (10^{-4})	– 8.95	– 13.28	– 16.67
d_{KT} (10^{-4})	4.13	7.60	10.30
d_{TK} (10^{-4})	– 10.25	– 10.98	– 0.79
d_{TT} (10^{-4})	3.16	6.23	0.25
a_K (10^{2})	– 12.45	–	–
a_T (10^{2})	– 53.82	–	–
a_{KY} (10^{-4})	– 2.16	– 64.13	– 38.34
a_{TY} (10^{-4})	– 6.95	–113.12	– 62.31
a_{Kt}	14.77	503.16	3.64
a_{Tt}	65.25	895.63	– 2.51
A positive-definite	Yes	Yes	Yes
B positive-definite	Yes	Yes	Yes
K_0 and T_0 positive	Yes	No	No

In the R&D equation with fixed industry effects there are some changes which are hard to explain. The wage coefficient has now the wrong negative sign. The insignificant coefficients of output and capital stock have changed the signs, too. In the fixed firm effects version, however, two interesting new results appear. First, similar to the investment equation, the own adjustment coefficient of technological knowledge, m_{TT}, now has a positive value of 2 percent within a year. That is, there exists a stable adjustment path converging to the long-run equilibrium. Due to the negative influence of the stock of knowledge the $\bar{R}^2$ has fallen drastically. The cross-adjustment coefficients m_{KT} and m_{TK} are insignificant, but the negative signs suggest that capital and knowledge will be dynamic complements rather than substitutes. This means that if R&D is in excess demand the adjustment in capital will slow down, and vice versa. These results are similar to those of previous comparable studies (see *Nadiri*, 1980, *Morrison – Berndt*, 1981, *Bernstein – Nadiri*, 1989). Secondly, all the coefficients of the factor prices are no more significant. Thus, input prices seem to be no important determinants of R&D if one controls for firm-specific effects.

The estimated values were used to calculate the parameters in the factor demand equations *(19)* to *(21)*. Without the restrictions implied by the optimisation problem some of the equations are overidentified. For example, there are a number of ways to compute a_{wK} and a_{wT} from the estimated coefficients. To resolve the problem we projected the estimates onto the column space spanned by the restrictions implied by the theoretical model and calculated the parameter values presented in Table 2. These values were plugged into *(17)* and *(18)* to calculate elements of the matrices A and B. Since the calculated matrix A will not be symmetric and the calculated matrix B will not be diagonal as imposed in *(10)*, our regularity criterion will be that both calculated matrices are positive-definite. Indeed, all regularity conditions, as reported above, are satisfied in all three versions of our model. Thus, our restricted normalised cost function seems to be an appropriate description of the firms' underlying technology. Unfortunately, the estimated stocks at the beginning of our estimation period became negative in the fixed effects models. But, as already discussed, the estimated benchmark stocks are certainly not very good proxies for the real stocks.

5. Neoclassical firm behaviour and Schumpeterian hypotheses

So far we have argued that firms may treat technological know-how as a quasi-fixed factor of production. The firms will invest in R&D in pursuit of a growth path which minimises their discounted costs. We demonstrated that as an empirical matter our model is quite plausible. Indeed, in our model without fixed effects all factor prices influence R&D behaviour in the fashion suggested by neoclassical theory. Such optimising behaviour would hardly be contemplated in an evolutionary view of the firm. However, by taking into account individual effects due to unobserved variables, the impact of the system of relative input prices is no longer significant.

Therefore, our investigation does not end with an analysis of the neoclassical behaviour of firms in response to changing factor prices. A question which arises from the Schumpeterian hypotheses is whether there is a relationship between firm size and market concentration on the one hand and R&D activity on the other hand (see the surveys to this literature in *Kamien – Schwartz*, 1982, *Baldwin – Scott*, 1987, *Cohen – Levin*, 1989, and *Scherer – Ross*, 1990, ch. 17). To see whether the usual empirical evidence still holds after accounting for the firms' production structure, we decided to estimate the relationship between our firm fixed effects and firm size and market concentration. Our simultaneous equation framework is

(27) $\bar{\alpha}_t = a_{L0} + a_{L1} S_t + a_{L2} H_t + a_{L3} H_t^2 + \varepsilon_{Lt},$

(28) $\bar{\beta}_t = a_{I0} + a_{I1} S_t + a_{I2} H_t + a_{I3} H_t^2 + \varepsilon_{It},$

(29) $\bar{\gamma}_t = a_{R0} + a_{R1} S_t + a_{R2} H_t + a_{R3} H_t^2 + \varepsilon_{Rt},$

where $(\bar{\alpha}, \bar{\beta}, \bar{\gamma})'$ is the vector of firm fixed effects from the labour, investment and R&D equations. The error terms ε are assumed to be jointly normally distributed. The variables characterising the market structure are S for firm size, measured as the number of employees, and market concentration, H, represented by the Herfindahl index. The Herfindahl has been used instead of the more traditional concentration ratios since it includes data from all firms in the industry rather than just the largest firms which are certainly not in our sample of small and medium size firms.

The coefficient estimates of the market structure variables are shown in Table 3. There seems to be strong evidence that market structure matters even after controlling for the production theoretic variables. In particular, the fit of the labour equation is quite good. The fixed effects of the labour demand model depend significantly and positively on the firm size. Thus, labour demand is, in addition to the production structure effects, promoted by larger firms and inhibited by smaller firms. Further, there is significant evidence for an inverted U-shaped relationship between market concentration and the firm fixed effect coefficients from the labour demand equation. The maximum occurs at a Herfindahl index value of 0.056, which lies within the range of the various concentration indices of the industries in our sample.

In the investment equation we also derive a positive and significant influence of the firm size on investment, but the inverted U-shaped pattern of the market concentration effect is not significant.

Table 3

Firm fixed effects of the factor demand equations and market structure

	$\bar{\alpha}$	$\bar{\beta}$	$\bar{\gamma}$
a_0 (10^{-2})	2.83	– 66.36	– 3.82
	(144.88)	(–205.94)	(– 33.05)
a_1 (10^{-5})	0.77	4.72	2.73
	(31.26)	(11.60)	(18.74)
a_2 (10^{-6})	0.45	2.89	5.62
	(3.56)	(1.38)	(7.48)
a_3 (10^{-10})	– 0.40	– 5.50	– 5.37
	(– 2.33)	(– 1.93)	(– 5.24)
$\bar{R}^2$	0.47	0.10	0.28

Numbers in parentheses . . . t statistics.

Some results of particular interest arise for the R&D equation. In accordance with previous cross-sectional studies we derive a positive, monotonic relationship between firm size and R&D activity (see, e. g., *Soete*, 1979, *Link*, 1980, *Loeb*, 1983, *Meisel – Lin*, 1983). Several arguments in favour of this relationship are offered in the Schumpeterian literature: First, capital market imperfections could confer an advantage on large firms in securing external R&D finance. Secondly, due to economies of scope in production, large diversified firms may be able to exploit unforeseen technological advances more efficiently. Thirdly, there may be some complementary marketing activities or activities for gaining control over the channels of distribution which are more developed within large firms.

The sign pattern on the Herfindahl coefficients clearly produces a concave relationship between R&D intensity and market concentration. Maximum R&D activity occurs at a Herfindahl index value of 0.052 which lies in the middle of the concentration indices in our sample. This non-linear inverted U-shaped relationship was first discovered by *Scherer* (1967) and replicated, e. g., by *Scott* (1984) and *Levin – Cohen – Mowery* (1985). As Schumpeter argued, an oligopolistic market structure with some market power for the firms should be most conducive to innovative activity. On the one hand, firms in concentrated industries may more easily appropriate the returns from R&D investment. On the other hand, monopolistic industries may be characterised by X-efficiency as described by Leibenstein. In our sample, for example, the chemical and the electrical engineering industries seem to be too concentrated to achieve maximum technological advance.

6. Summary and conclusions

In this paper we developed a dynamic interrelated factor demand model with two variable inputs, labour and materials, and two quasi-fixed inputs, capital and technological knowledge. A system of factor demands for labour, capital, and knowledge was estimated in levels and with fixed industry and firm specific effects using a panel data set for small and medium size firms in the manufacturing sector of the FRG for the period 1978 to 1982.

The empirical results are encouraging for further work. Our non-homothetic restricted cost function with technological knowledge as an additional production factor seems to be an appropriate description of the firms' technology. The consideration of internal adjustment costs of capital and knowledge explains the behaviour of the factor demand equations fairly well. In particular, R&D activities respond to relative factor prices as suggested by neoclassical theory. However, these price effects disappear if individual effects are included in the analysis. There is strong empirical evidence that, in addition to the production theoretic elements, market structure matters in the factor demand as suggested by the Schumpeterian hypotheses.

The results of the model would undoubtedly improve with new data. It would be preferable to use a data set which discriminates between R&D activities devoted to product and process innovations. In addition, the use of data on innovative output would be superior to the use of innovation input data (see, e. g., *Acs – Audretsch*, 1990). There is also a need for increasing the length of the time series in order to construct better proxies for the stocks of capital and knowledge.

There are several topics for future work. For instance, our model is based on the restrictive assumption of static expectations for output and relative factor prices. Other forms of expectation could be taken into account (see *Pakes – Schankerman*, 1984, for the case of technological knowledge as the only quasi-fixed input). Another issue of importance is to explicitly analyse the relationship between a firm's own R&D activity and spill-overs due to R&D activities pursued by rivals in the same industry (intra-industry spill-overs) and by firms in other industries (inter-industry spill-overs).

7. Appendix: Data sources and construction

The annual data for the period 1978 to 1982 have been pooled from various sources. Basically, we used a panel data set for 463 firms in the manufacturing sector of the FRG as collected by the Institut für Gesellschaftswissenschaften of the University of Bonn (Prof. Albach). The set of variables reported in this data set includes employees, revenue, investment in capital, investment in R&D, and the industrial classification of the firms.

A total of 55 firms have been excluded from the sample. 42 firms were excluded because they reported sales and employment for fewer than three years. Most of these firms did not report their sales at all. The data of four firms had obvious data errors. The original intent of the survey was to learn about the R&D activities of firms with fewer than 2,500 employees. However, seven participating firms reported having more than 2,500 employees, so they also have been eliminated from the data set. One of the remaining firms was excluded because its revenue was twice as large as the next largest firm. In a scatterplot of employment versus revenue this firm was an obvious outlier. Finally, there was only one respondent from the shipbuilding industry, for which there are no adequate producer prices.

The industrial classification of the panel data enables us to add input and output price indices on the industry level. Data for nominal gross output, real value added, nominal intermediate input, the price index for capital investment, and average gross wages of employees are taken from the yearly disaggregated national income accounts of the Statistisches Bundesamt (Fachserie 18). The price indices for industry gross output are calculated as a weighted sum of the producer price indices of bundles of goods (Statistisches Bundesamt, Fachserie 17). The weights for the bundles of goods in each industry are obtained with the help of the disaggregated goods' input output table for 1982 (Statistisches Bundesamt, Fachserie 18, Reihe 2, Table 4.2). Dividing nominal industry gross output by the industry producer price indices yields the real industry gross output. The price index for intermediate inputs is derived by dividing nominal intermediate inputs by the difference between the calculated real gross output and real value added. The price indices for R&D expenditures are calculated as a weighted sum of the price indices for intermediate inputs, labour inputs and investment inputs. The weights are given by the shares of the corresponding expenditures in the industry R&D expenditure (Source: Stifterverband für die Deutsche Wissenschaft).

The Herfindahl indices of market concentration are taken from the Statistisches Bundesamt, Fachserie 4, Reihe S.9. For the interest rates we used the current yield on long-term bonds (Source: Deutsche Bundesbank).

Table 4

Industrial classification of firms

Industrial classification for the German current account		Number of firms
14	Chemical products	28
16	Plastic products	14
17	Rubber products	4
18	Stones and clay	17
19	Ceramic goods	4
20	Glass	6
21	Iron and steel	1
22	Non-ferrous metals	1
23	Foundries	11
25	Structural metal products	8
26	Mechanical engineering	74
28	Road vehicles	5
31	Electrical engineering	57
32	Precision and optical instruments	8
33	Finished metal goods	53
36	Wood products	24
37	Paper manufacturing	5
38	Paper processing	9
39	Printing and duplication	8
40	Leather products	4
41	Textile products	22
42	Clothing	14
43	Food and beverages	31
	Total	408

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Correspondence:

Manfred Stadler
Department of Economics
University of Augsburg
Memminger Straße 14
W-8900 Augsburg
F. R. G.