

Accumulation of R&D Capital and Dynamic Firm Performance: a Not-so-Fixed Effect Model

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ABSTRACT. – Considering the observed patterns of R&D investment, we argue that a model which allows for a positive feedback from already acquired knowledge to the productiveness of current research, fits the empirical evidence better than the standard model that treats knowledge accumulation symmetrically with the accumulation of physical capital. We present an econometric framework consistent with a positive feedback in the accumulation of R&D capital. The empirical model is econometrically simple and less data-demanding than the standard framework. Our estimates show a significant positive effect of R&D on performance and a positive feedback effect from the stock of knowledge capital. We calculate the depreciation rate and the rate of return to knowledge capital for our alternative framework, and compare our estimated rates of return to results obtained within the standard framework.

Accumulation du capital de R&D et performance des entreprises : un modèle à effets presque fixes

RÉSUMÉ. – L'examen des évolutions des dépenses d'investissements en R&D des entreprises nous conduit à proposer un modèle qui permet un effet en retour du stock de connaissance déjà acquis sur la productivité du flux présent de recherche. Ce modèle paraît mieux adapté aux données que le modèle standard qui traite de l'accumulation du capital de connaissance à l'instar de celle du capital physique. Nous présentons une formulation économétrique avec un schéma d'accumulation du capital de connaissance (additif en logarithmes) impliquant un tel effet rétroactif positif; celle-ci a aussi l'avantage de la simplicité et d'être moins exigeante en matière de données sur la R&D que la spécification habituelle. Nos estimations montrent un effet positif significatif de la R&D sur la productivité, ainsi qu'un effet de rétroaction positif du capital de connaissance. Nous en déduisons un taux de dépréciation et un taux de rentabilité du capital de connaissance que nous comparons aux estimations correspondantes obtenues avec la formulation habituelle.

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1 Introduction

Over the last 10-15 years, we have seen an outburst of econometric research on R&D investment and productivity; see GRILICHES [1995] for a recent survey of the many insights that have emerged from this line of research. Much of this research follows the framework outlined in GRILICHES [1979]. In this paper we argue that this econometric framework should be modified and extended in various ways. In particular, considering the empirical evidence on the patterns of R&D investment, we argue that a model which allows for a positive feedback from already acquired knowledge to the productiveness of current research fits the empirical evidence better than the standard model that treats knowledge accumulation symmetrically to the accumulation of physical capital. Positive feedbacks in knowledge accumulation have recently been considered in the literature on macroeconomic growth by ROMER [1990], MILGROM, QIAN and ROBERTS [1991], and JONES [1995]. Their argument is that this feedback mechanism can explain the persistent differences in productivity between countries or industries, and why some industries or countries suddenly gain momentum and go through phases of high growth.

Our analysis is concerned with a related phenomenon at the micro level; how can we rationalize that some firms are persistently, often for a long period, more productive than other firms, as shown e.g. by BAILEY, HULTEN and CAMPBELL [1992]. Similarly, why do some firms persistently carry out considerable R&D, while other firms in the same industry never report any R&D investments? Empirically, it is widely observed that there are large differences in R&D effort across firms within narrowly defined industries, and that these differences in R&D effort are persistent over time. NELSON [1988] has pointed out that this co-existence of innovators and imitators - as he calls them - is a puzzle for the standard framework for productivity analysis at the micro level.

We argue that positive feedbacks in knowledge accumulation can be one explanation for the persistency of performance differences at the micro level, parallel to the cited arguments presented in the macro growth literature. The co-existence of innovators and imitators can within our framework be considered a consequence of the stochastic nature of knowledge production in combination with a positive feedback from past R&D success to the productiveness of current R&D. That is, a lucky draw in the R&D activity in one year tends to make R&D investments in the following years more productive and profitable. This positive feedback from past R&D success to the productivity of current R&D can explain how an innovation in a firm can stimulate the firm's R&D activity and start a cumulative process of several subsequent innovations and high productivity growth. Our alternative model of R&D accumulation tries to capture this cumulative nature of research.

The model presented below is attractive as it leads to an estimating equation which is empirically more tractable than the standard framework. In particular, one does not need to construct the knowledge stock variable which is often quite problematic since the calculation requires a long history

of R&D investments for each firm. Our empirical model also alters and augments the standard framework as presented in GRILICHES (1979, 1995) by explicitly incorporating the demand side and both process and product innovations.

We have estimated our model on a new data set that links R&D investment at the line-of-business level (within each firm) to plant level data on productivity. The results show that R&D investment is a significant determinant of dynamic performance and that the appropriate part of R&D capital depreciates quite rapidly.

The analysis presented here is in several ways an extension of the analysis presented in KLETTE [1996]: First, the present paper presents a formal analysis of optimal R&D investment when the accumulation process allows for the feedback mechanism in our alternative specification. Second, we present an empirical analysis of R&D investment to illustrate the empirical importance of our respecification. Third, the formal analysis of optimal R&D investment leads us to a formula for calculating the private rate of return to R&D investment. Finally, the empirical analysis in section 4 is carried out on a new data set that links R&D data at the line of business level to plant level data for the period 1980-92 (while KLETTE [1996], used only a single cross section of R&D data for 1989). This new, larger data set allows us to explore a number of specification issues and formal econometric tests that were not possible with the limited data set used in KLETTE [1996].

The rest of our paper is organized as follows: In section 2, we examine patterns of R&D investments. After discussing R&D investment in the standard model of knowledge accumulation, we present a dynamic programming analysis of optimal R&D investment for our alternative specification of the accumulation process. This theoretical analysis is confronted with empirical patterns of R&D investment in the second half of section 2. We proceed to the empirical analysis of R&D, productivity and performance in sections 3 and 4. For comparison, we start in section 3 with a standard analysis of R&D and productivity, following GRILICHES (1979, 1995) and HALL and MAIRESSE [1995]. Section 4 contains the main part of our analysis of R&D and performance, where we spell out the empirical framework and present the econometric results. We add some final comments in section 5.

2 Investment in R&D Capital and Performance

2.1. Persistent cross sectional differences in R&D investment: Theory

The standard framework treats the accumulation of knowledge capital in the same way as that of physical capital, using the “perpetual inventory”

specification as a common framework. Formally,

$$(1) \quad K_{it+1} = K_{it}(1 - \delta) + R_{it} ,$$

where K_{it} and R_{it} represent knowledge capital and R&D investment for firm i in year t ¹.

We will argue that the standard framework contradicts the widely observed pattern that the same firms tend to persistently carry out above (or below) average amounts of R&D, say, relative to their sales. This persistence in the differences in R&D intensities between firms within the same industry is hard to rationalize on the basis of a knowledge accumulation process as specified in equation (1). To clarify our point, assume a Cobb-Douglas production function,

$$(2) \quad Q_{it} = \Phi_{it} X_{it}^{\alpha^X} K_{it}^{\alpha^K} ,$$

where Q_{it} is output, Φ_{it} a productivity term, and X_{it} inputs. A firm's rate of return to knowledge capital can then be calculated as $\alpha^K Q_{it}/K_{it}$. This expression implies that if we consider two firms which differ only in their output-knowledge ratios at the beginning of a period, the firm with the lowest output-knowledge ratio should have the highest marginal return on its knowledge capital. Hence, one should expect the highest R&D-intensity for the firm with the lowest knowledge-output ratio at the beginning of the period². Our point is that the standard model, based on (1) and (2), is difficult to reconcile with widely observed patterns of *persistent cross-sectional differences in R&D-intensities* within the same industry. That is to say, it is difficult to rationalize the co-existence of high R&D-intensity firms with low R&D-intensity firms year after year within this model. See NELSON [1988] for an elaborate discussion of this question.

One possible resolution is to add convex adjustment costs for R&D capital to the model above. Firms starting with different initial conditions would then *slowly* converge towards the same ratio Q_{it}/K_{it} , with persistent differences in their R&D-intensities on their transition paths. However, given the relatively poor empirical performance of Euler equations for R&D investments we find it attractive to examine alternative models.

The treatment of heterogeneity is a more general problem with models such as (1) and (2). Heterogeneity is often captured by so-called fixed effects in empirical research on firm level data. While the presence of fixed effects can make the model consistent with the observed cross sectional differences in R&D activity, they are not very satisfactory. First, econometric studies of R&D and productivity based on models with fixed effects often give weak, if significant results, and the estimates are often not robust; see the survey by MAIRESSE and SASSENOU [1991]. Second, while our model suggests a mechanism generating persistent differences in R&D investment, models

1. It follows from (1) that this knowledge capital is a beginning-of-period capital.

2. Note that this result is valid even if firms differ in terms of productivity, Φ_{it} .

with fixed effects only account for such differences without offering any explanation how such differences have been generated.

2.1.1. An Alternative Specification of Knowledge Accumulation

A possible explanation for the observation that a high return on knowledge capital does not lead to R&D investments is that the relationship between R&D investment and knowledge capital is more complex than in equation (1). There is an alternative to the perpetual inventory model of capital accumulation that suggests that old capital and new investment are *complementary* inputs in the production of new capital. This view seems particularly relevant for the accumulation of knowledge capital, as noticed by GRILICHES [1979], HALL and HAYASHI [1989], ROMER [1990], JONES [1995] and KLETTE [1996]. The basic idea is that greater initial knowledge will tend to increase the amount of knowledge obtained from a given amount of R&D. The specific model of capital accumulation we will consider here was originally presented by UZAWA [1969], who attributed the idea to PENROSE [1959] ³.

Formally, we will assume that knowledge capital can be accumulated according to the equation ⁴

$$(3) \quad K_{t+1} = K_t^{(\rho-\nu)} R_t^\nu.$$

ν is a parameter capturing the productiveness of R&D in generating new knowledge, while ρ reflects scale economies in the production of knowledge. The interpretation of these parameters will be discussed further in section 4.1.3. We recognize that (3) has the rather extreme and unrealistic implication that a firm which stops its R&D in a single year will loose all its knowledge capital. A better specification is perhaps $K_{t+1} = K_t^{(\rho-\nu)}(R_t + c)^\nu$, where c is some positive parameter, but this respecification creates a non-linear estimation problem that we have not addressed in this paper. We will however add some further comments on this specification in section 4.

The firm maximizes its net present value; $V(K_0)$, given its initial knowledge capital stock (K_0):

$$(4) \quad V(K_0) = \max_{\{R_t\}} \sum_{t=0}^{\infty} \beta^t (\pi_t(K_t) - w_t R_t),$$

subject to the accumulation equation (3). β is the discount factor, $\pi_t(K_t)$ is the profit function conditional on the knowledge capital stock, excluding

3. Penrose and Uzawa put the model forward as a model of physical capital accumulation. Their argument was that physical capital investment requires organizational skills or capital as a complementary input, and organizational capital involves an accumulation process where past knowledge gives a positive feedbacks to the acquisition of new knowledge.

4. It can be shown that the log-linear specification is not essential for the argument below.

R&D investment cost, while w_t is the unit cost of R&D investment. For convenience, we have not included other kinds of capital or uncertainty in the model. This can be done without changing the argument; it only involves more notation.

As shown for instance by STOKEY and LUCAS (1989, ch. 4), under mild regularity conditions the value function satisfies the Bellman-equation:

$$(5) \quad V(K_t) = \max_{R_t} [\pi_t(K_t) - w_t R_t + \beta V(K_{t+1})],$$

where K_{t+1} is a function of K_t and R_t as specified in (3). Assuming strict concavity of the short run profit function (in K_t), the optimal R&D investment must satisfy the first-order condition:

$$(6) \quad -w_{t-1} + \beta V'(K_t) \frac{\partial K_t}{\partial R_{t-1}} = 0$$

Furthermore, as the Bellman equation (5) is supposed to hold for all initial knowledge capital stocks, we have that

$$(7) \quad V'(K_t) = \pi'_t(K_t) + \beta V'(K_{t+1}) \frac{\partial K_{t+1}}{\partial K_t}.$$

Eliminating the V 's from this equation by equation (6), we find that

$$(8) \quad \frac{1}{\beta} w_{t-1} \left(\frac{\partial K_t}{\partial R_{t-1}} \right)^{-1} = \pi'(K_t) + w_t \left(\frac{\partial K_{t+1}}{\partial R_t} \right)^{-1} \frac{\partial K_{t+1}}{\partial K_t}$$

Or, using (3), and rearranging some terms:

$$(9) \quad w_{t-1} R_{t-1} = \beta [\nu \pi'(K_t) K_t + (\rho - \nu) w_t R_t]$$

A common specification of the profit function implies that $\pi'(K_t) = \gamma S_t / K_t$, where S_t is sales (see KLETTE [1996]). In this case

$$(10) \quad \frac{w_{t-1} R_{t-1}}{S_t} = \beta \left[\nu \gamma + (\rho - \nu) \frac{w_t R_t}{S_t} \right].$$

Cross-sectional differences in sales are highly autocorrelated i.e. $S_{t-1} \simeq S_t$. Hence, equation (10) predicts that differences in the R&D intensity between different firms should be highly correlated over time. In section 2.2, we will provide empirical support for this prediction.

To summarize, the multiplicative model of knowledge accumulation considered in this section rationalizes why the same firms persistently invest above (or below) average in R&D. The main reason identified here is the intertemporal complementarity in the R&D activity; past experience makes current R&D effort more productive. We have formally shown that this mechanism leads to a pattern of persistent differences in R&D intensities between firms, a well known empirical pattern which is hard to rationalize in the standard framework.

2.2. Persistent Cross Sectional Differences in R&D Investment: Empirical Evidence

This section provides empirical evidence on two features of R&D investment behavior which motivate the alternative model of knowledge accumulation: The heterogeneity and persistence in R&D intensities.

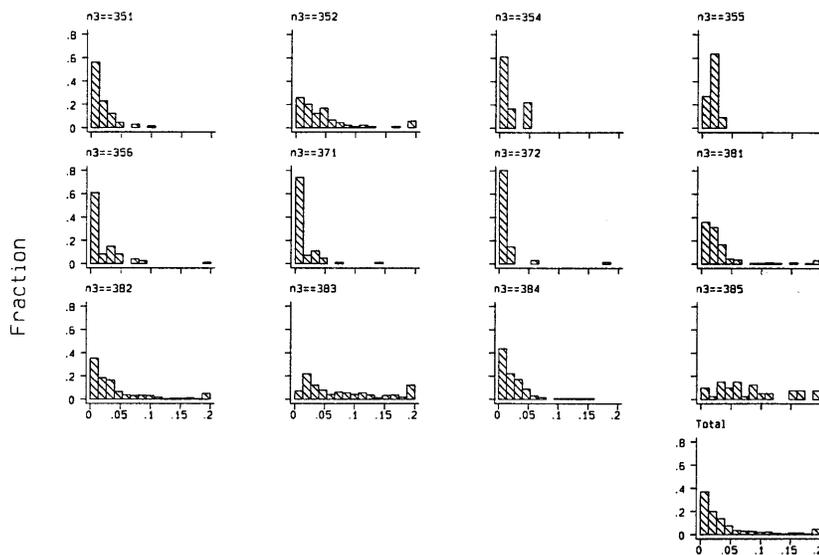
The empirical analysis is based on two primary data sources; the annual manufacturing census carried out by Statistics Norway and the R&D survey carried out by the Norwegian Research Council for Science and Technology (NTNF) until 1989 and by Statistics Norway from 1991. Our analysis covers the period 1980-92 and the following industries: “Chemicals”, “Mineral products”, “Basic metals” and “Metal products”. These industries account for almost all R&D in Norwegian manufacturing. Further details on our data sources and samples are given in the appendix.

One of the advantages with the Norwegian R&D data is that R&D is reported at the *line of business level within each firm*. The production data are reported at the plant level, and they have been aggregated to the line-of-business level for the analysis in this section where we will examine cross sectional and longitudinal patterns in R&D intensities.

Figure 1 shows the distribution of R&D intensities with the line-of-business within each firms as the unit of observation. The figure presents the

FIGURE 1

Distribution of R&D Intensities by Industry.



Notes: Observations at line of business level. Observations with no R&D not shown.

distribution of R&D intensities for each 3-digit industry and for the complete sample. We see from figure 1 that even within relatively narrowly defined industries there is a large amount of heterogeneity in R&D intensities. As COHEN and KLEPPER [1992] found, the distribution of R&D intensities is highly skewed in most industries, with a large fraction of the line-of-businesses reporting little or no R&D ⁵. There is a censoring problem for line-of-businesses that are not reporting R&D. Most of these firms are probably accumulating new knowledge, but often by other means than formal R&D. The firms without R&D create well-known problems for empirical analysis that we will return to in section 4.

Cohen and Klepper examined only a single cross section of firms. With a set of panel data, we can push the issue a step further. Table 1 shows that not only is the distribution of R&D intensities highly skewed; it is also the same firms that invest heavily in R&D year after year. Table 1 shows transition probabilities for categories of R&D intensities. The table shows that 90% of the plants which have no R&D in a given year, have no R&D two years later. More than 60% of the plants in the highest quartile of R&D plants are in this quartile two years later. This persistence in R&D intensities indicates that there are persistent differences in R&D investment opportunities across firms.

TABLE 1

Matrix of Transition Probabilities for Categories of R&D-Intensity.

<i>t</i>	<i>t</i> + 2					Total
	No R&D	1	2	3	4	
No R&D	2170 90.57	65 2.71	46 1.92	68 2.84	47 1.96	2396 100.00
1	42 25.93	98 60.49	17 10.49	4 2.47	1 0.62	162 100.00
2	38 30.89	24 19.51	42 34.15	16 13.01	3 2.44	123 100.00
3	29 18.95	3 1.96	20 13.07	73 47.71	28 18.30	153 100.00
4	21 14.69	1 0.70	4 2.80	26 18.18	91 63.64	143 100.00
Total	2300 77.26	191 6.42	129 4.33	187 6.28	170 5.71	2977 100.00

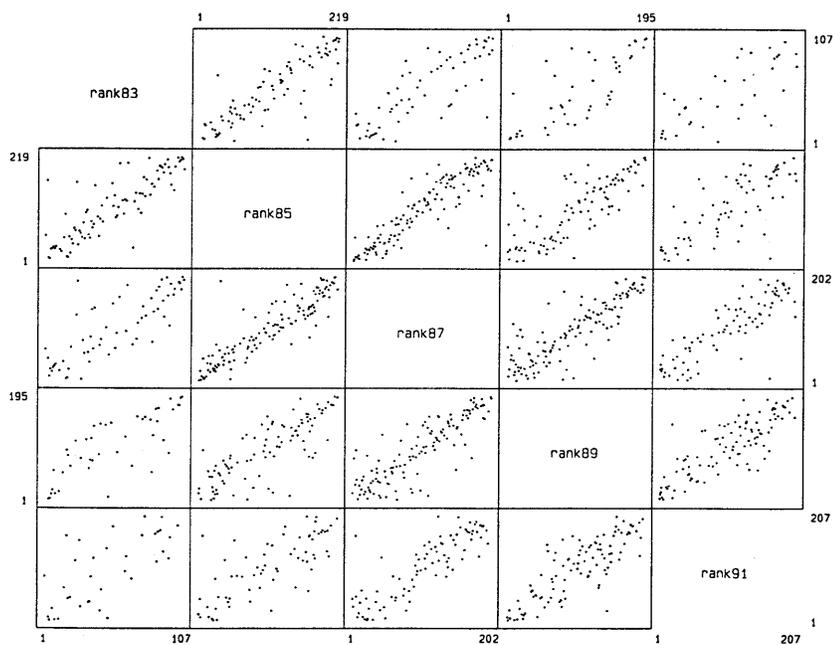
Another way to illustrate the same point is presented in figure 2; the figure shows ranks of R&D intensities in year *t* vs. year *t* + 2, ... , *t* + 8.

5. See also BOUND et al. (1984), KLETTE (1994b), and PAKES and SCHANKERMAN (1984).

The figure shows a positive autocorrelation pattern. For comparison, the analysis is repeated for physical capital investment intensities in figure 3. The autocorrelation pattern for fixed investment (intensities) is weak. A comparison of figures 2 and 3 shows that R&D investments are much more persistent than for physical capital investments. High persistence in the short run could also be explained by adjustment costs, as mentioned above. However, the fact that the degree of persistence is quite high over a large number of years for R&D suggests that standard convex adjustment costs are an inadequate explanation. The positive feedback effect incorporated in the model presented in section 2.1 is consistent with persistent differences in investment opportunities in R&D, cf. equation (10).

FIGURE 2

Ranks of R&D Intensities. Time t vs. $t + 2, t + 4, t + 6, t + 8$.

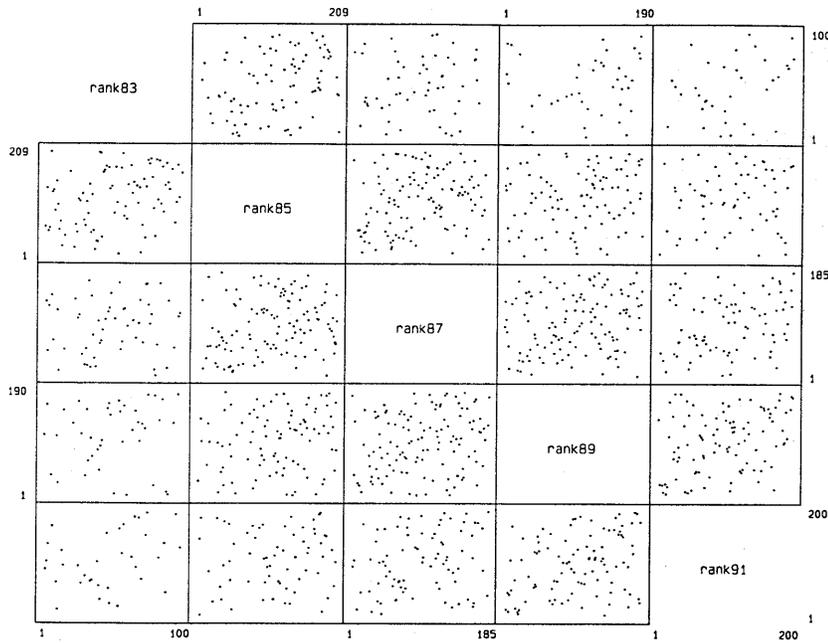


Notes: Observations at line of business level. Observations with no R&D not shown.

We noticed above that the positive feedback effect incorporated in the multiplicative model for capital accumulation was originally put forward as a model for physical capital investments by PENROSE [1959], UZAWA [1969]; see also SHEN [1970] who examined the empirical performance of the model. Our comparison of the patterns in figures 2 and 3 suggests that the positive feedback effect is much weaker in the accumulation of physical capital as compared to the case with R&D capital.

FIGURE 3

Ranks of Investment Intensities. Time t vs. $t + 2, t + 4, t + 6, t + 8$.



Notes: Observations at line of business level. Observations with no R&D not shown.

3 R&D and Productivity: a Standard Analysis

Before we present our main analysis, it is useful to present an econometric analysis of productivity and R&D based on the standard framework. By estimating some of the traditional models in the literature we want to illustrate two points: In the cross section, there is a positive relationship between R&D and productivity, while this relationship is quite weak in the longitudinal dimension.

In columns 1-8 of table 2 we estimate the output elasticity of the R&D capital stock, following the standard approach in the literature ⁶. The R&D capital stock is constructed by accumulating R&D investments according to equation (1) from an initial year. We assume a 15% depreciation rate for R&D and an R&D expenditure growth rate of 10% prior to the first

6. See GRILICHES (1979, 1995) and HALL and MAIRESSE (1995).

observation for each line of business (firm)⁷. The first six columns of the table give results for a log-linear (i.e. Cobb-Douglas) technology for two different measures of output, i.e. from estimating

$$y_{it} = \alpha + X_{it}\beta + \gamma k_{it} + e_{it},$$

where y_{it} is log output (either gross output or value added), X_{it} is a vector representing (log) capital and labor, as well as materials if output is measured by gross output. k_{it} is log of the R&D capital stock and γ is the parameter of primary interest.

Column (1) shows that R&D has a significant effect on value added. Including time and industry dummies as in column (2) gives almost identical results. A positive cross sectional relationship between productivity and the stock of knowledge capital has been found in a number other studies; see the surveys by MAIRESSE and SASSENOU [1991] and GRILICHES [1988, 1995]. In column (3), we see that when fixed effects are included, the relationship between R&D and productivity becomes weaker. This result is not surprising given the high persistence in R&D investments discussed above, and is well recognized in the literature (cf. the survey by SASSENOU and MAIRESSE [1991]). In columns (4) through (6) we repeat these regressions for a gross output specification of output. The (gross) output elasticities are similar to the estimates based on value added, but somewhat lower as expected.

The next two columns, (7) and (8) show similar results for a more general specification of the technology than the log-linear specification used in columns (1)-(6). Here we regress a productivity index on the stock of knowledge capital. This index of total factor productivity will be defined in section 4.1.2 below (cf. equation (18)). Again we find a significant relationship between R&D and productivity in the cross section, but R&D capital is insignificant when firm effects are included.

Finally in column (9) we regress productivity growth on R&D intensity. In this model the coefficient on R&D intensity can be interpreted as the private rate of return to R&D, see GRILICHES [1979]. We find essentially a zero rate of return. The implied rates of return for the estimates in columns (1)-(8) are presented in table 3. We will comment on these rates of return in section 4.5 below.

To summarize, our analysis based on the standard framework shows results similar to what comparable studies have found for other countries. R&D is positively correlated with productivity levels, while the longitudinal correlation between R&D and productivity growth is much weaker, in some cases even statistically insignificant. The basic message is that R&D firms are ahead and tend to stay ahead in terms of both R&D and productivity. The dynamic, econometric model we present in the next section fits very well with such a pattern.

7. See HALL and MAIRESSE (1995) for an extensive analysis of the sensitivity of the parameter estimates to changes in assumptions about this growth rate, the depreciation rate and other specification issues.

TABLE 2

Results for Log-linear Models with Standard R&D Capital Accumulation.

	Dependent Variable								
	ln(Value added)			ln(Gross output)			\hat{a}_t		$\Delta\hat{a}_t$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ln(Materials)				.556 (.007)	.528 (.007)	.485 (.011)			
ln(Capital)	.201 (.007)	.125 (.009)	.127 (.017)	.073 (.005)	.040 (.005)	.051 (.006)			
ln(Labor)	.819 (.008)	.903 (.010)	.781 (.023)	.349 (.006)	.423 (.008)	.397 (.014)			
ln(R&D Capital)	.066 (.005)	.053 (.005)	.018 (.007)	.036 (.002)	.030 (.002)	.004 (.003)	.018 (.002)	-.002 (.002)	
R&D Intensity									.004 (.020)
D(R&D Capital = 0)	.422 (.039)	.335 (.038)	.105 (.054)	.243 (.019)	.198 (.019)	.020 (.020)	.115 (.015)	-.005 (.017)	
D(R&D Int. = 0)									.000 (.003)
Time dummies	No	Yes	Yes	No	Yes	Yes	No	No	No
Industry dummies	No	Yes	No	No	Yes	No	No	No	No
Fixed effect	No	No	Yes	No	No	Yes	No	Yes	No
Adjusted R^2	.90	.91	.94	.97	.98	.99	.02	.52	.00
Observations	11289	11289	11289	11343	11343	11343	11343	11343	9970

Notes: R&D Intensity is defined as R&D investment divided by the average of output in period t and $t + 1$.

TABLE 3

Implied rates of return to R&D investments from models in table 2.

	ln(Value added)		ln(Gross output)		\hat{a}_t			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
For mean value of Output/R&D Capital	24%	22%	2%	51%	45%	6%	28%	-17%
For median value of Output/R&D Capital	6%	5%	1%	11%	10%	1%	6%	-4%

4 R&D, Productivity and Performance: the Not-So-Fixed Effect Model

4.1. R&D, Productivity and Dynamic Performance

This section will present a modification of the standard econometric model used to estimate the relationship between R&D and productivity.

The modification involves the R&D accumulation process discussed in section 2 as a replacement for the R&D stocks based on the perpetual inventory model. Our framework is attractive as the estimating equation is simple to implement, and the parameters have a structural interpretation. The presentation below follows KLETTE [1996] closely. Our framework is made up of three components: (i) a model of production; (ii) a simple specification of product demand; and (iii) the specification of knowledge accumulation, already discussed in section 2.

4.1.1. Production, R&D Capital and Process Innovations

The first component of the modified framework is a model of short-run producer behavior, a specification that is based on the assumption of short-run, profit-maximizing behavior, allowing for scale economies and imperfect competition in the output market. In this section, we will use the term firm without making any distinction between plants and the line of business within a firm. The distinction between the plant and the line of business (within the firm) will be introduced when we present the estimating equation in section 4.1.4.

Consider a firm that produces an output (Q_t) by means of the three inputs, labor, materials and capital, according to the production function $\Phi_t F(X_t)$, where X_t is a vector representing the three inputs (X_t^l , $l = L, M, C$). Let a hat above a variable denote logarithmic deviations from a reference input-output vector, (Q_{0t}, X_{0t}) ; i.e. $\hat{q}_t = \ln(Q_t/Q_{0t})$. We will refer to this reference point as the *reference firm*. We have dropped the index referring to the firm (the subscript “ i ”). It can be shown that the following relationship holds under quite general conditions ⁸:

$$(11) \quad \hat{q}_t = \sum_{l=L,M,C} \alpha_t^l \hat{x}_t^l + \hat{\phi}_t$$

where $\alpha_t^l \equiv [\partial \ln(F_t)/\partial \ln(X_t^l) + \partial \ln(F_{0t})/\partial \ln(X_{0t}^l)]/2$. $\hat{\phi}_t$ is the (logarithmic) productivity difference between the firm we consider and the reference firm.

With profit maximization, the output elasticity for a fully adjustable factor of production is equal to the markup (on marginal costs) times the factor’s cost share, assuming price taking firms in the *factor* markets (see KLETTE, 1994a, for details). It follows that

$$(12) \quad \alpha_t^l = \mu(\theta_t^l + \theta_{0t}^l)/2 \equiv \mu \bar{\theta}_t^l,$$

where θ_t^l is the cost for factor l as a share of revenue, for the firm we consider; θ_{0t}^l is the corresponding share for the reference firm. μ is the markup, i.e. the ratio of price and marginal costs. It is not reasonable

8. See KLETTE (1994a).

to assume capital to be fully adjusted in every period, so we should treat capital differently from the fully adjustable factors. If ϵ is the elasticity of scale, we have that the output elasticity of capital (α_t^C) can be expressed: $\alpha_t^C = \epsilon - \sum_{l \neq C} \alpha_t^l = \epsilon - \sum_{l \neq C} \mu \bar{\theta}_t^l$, where the last equality follows from (12). Inserting this expression and (12) into equation (11):

$$(13) \quad \hat{q}_t = \mu \sum_{l=L,M} \bar{\theta}_t^l (\hat{x}_t^l - \hat{x}_t^C) + \epsilon \hat{x}_t^C + \hat{\phi}_t$$

We will decompose the productivity term ($\hat{\phi}_t$) into two parts: One term reflects productivity differences due to differences in knowledge capital ($\alpha^K \hat{k}_t$), whereas the second term (\hat{u}_t) captures the remaining differences in productivity:

$$(14) \quad \hat{q}_t = \mu \sum_{l=M,L} \bar{\theta}_t^l (\hat{x}_t^l - \hat{x}_t^C) + \epsilon \hat{x}_t^C + \alpha^K \hat{k}_t + \hat{u}_t.$$

α^K is the output elasticity of knowledge capital. This parameter reflects the opportunities for *process innovation*.

4.1.2. Demand, R&D Capital and Product Innovations

As usual with firm level data, we do not have information about real output, only nominal sales⁹. We will now show how to reformulate equation (14) in terms of nominal sales instead of real output. Let us start with a demand function with price, knowledge capital and other demand shifters as its arguments. A firm's knowledge capital is assumed to affect demand through differences in product quality. Consider a (first order) log-linear expansion of the demand function around the reference firm¹⁰:

$$(15) \quad \hat{q}_t = \eta \hat{p}_t + \xi \hat{k}_t + \hat{d}_t,$$

where \hat{p}_t and \hat{k}_t are the firm's price and knowledge capital relative to the reference firm. η is the price elasticity of demand, while ξ is the elasticity of demand with respect to a change in the firm's relative "product quality". The parameter ξ also captures the relationship between knowledge and product quality. \hat{d}_t is a demand shifter. From the relationship $S_t = P_t Q_t$, it follows that $\hat{s}_t = \hat{p}_t + \hat{q}_t$. Using this relationship, we can eliminate the unobservable \hat{p}_t in equation (15):

$$(16) \quad \hat{q}_t = \frac{1}{\eta + 1} \hat{d}_t + \frac{\eta}{\eta + 1} \hat{s}_t + \frac{\xi}{\eta + 1} \hat{k}_t.$$

9. Deflated sales will not alter the argument as long as the deflation is based on industry wide deflators. See KLETTE and GRILICHES (1996) for a discussion in a slightly different context.

10. One might argue that knowledge capital affects the price elasticity of demand and not only the level of demand. This could be incorporated by allowing for interaction terms between \hat{p}_t and \hat{k}_t in (15). However, this extension of the model will substantially complicate the subsequent analysis and must be left as a topic for future research.

Optimal price setting implies a markup: $\mu = \eta/(1+\eta)$. Using this expression and combining (14) and (16) to eliminate the unobservable \hat{q}_t , we have that

$$(17) \quad \hat{s}_t = \sum_{l=M,L} \bar{\theta}_t^l (\hat{x}_t^l - \hat{x}_t^C) + \frac{\epsilon}{\mu} \hat{x}_t^C + \gamma \hat{k}_t - \frac{1}{\eta} \hat{d}_t + \frac{1}{\mu} \hat{u}_t,$$

where $\gamma = \alpha^K/\mu - \xi/\eta$ (notice that η , the price elasticity, is negative by definition). The two terms that make up the γ -parameter capture the effect of both process and product innovations.

Define the performance index:

$$(18) \quad \hat{a}_t \equiv \hat{s}_t - \sum_{l=M,L} \bar{\theta}_t^l (\hat{x}_t^l - \hat{x}_t^C) - \hat{x}_t^C.$$

Notice that this performance index can be calculated directly from observations on output, factor inputs and factor costs (cf. the right hand side of 17), as we have done in the empirical analysis we present below ¹¹. We can rewrite equation (17) in terms of the performance index (18):

$$(19) \quad \hat{a}_t = \left(\frac{\epsilon}{\mu} - 1 \right) \hat{x}_t^C + \gamma \hat{k}_t + \hat{\varepsilon}_t,$$

where $\hat{\varepsilon}_t = \hat{u}_t/\mu - \hat{d}_t/\eta$. Having calculated the performance index according to (18), we will now show how it can be embedded in an estimating equation to identify $(\rho - \nu)$, ν , γ and other parameters of primary interest ¹².

4.1.3. R&D Investment and the Production of Knowledge Capital

Knowledge accumulation is assumed to take place according to (3). Since the log-linear relationship is assumed to hold for all firms we have that:

$$(20) \quad \hat{k}_{t+1} = (\rho - \nu) \hat{k}_t + \nu \hat{r}_t + \hat{v}_t,$$

where \hat{v}_t captures stochastic elements in the innovation process. As above, a hat above a variable represents logarithmic deviations from the reference firm. Hence, the specification suggests that a firm's knowledge capital stock next year, measured *relative to the reference firm*, depends on its *relative* capital stock from the past, as well as the firm's *relative* R&D effort.

11. To calculate the right hand side of (18), we need to identify the reference firm. How this is done will be explained in section 4.2.1. The performance index (18) is essentially a Tornquist index for the Solow residual, except that sales (\hat{s}_t) has replaced real output (\hat{q}_t) in the Solow residual; see KLETTE (1996) for a discussion.

12. As we show below, it is only possible to identify ν and γ if we assume $\rho = 1$.

Note that though the accumulation equation for R&D capital collapses for zero R&D investment, our empirical analysis includes firms which do not report any R&D. We circumvent this problem by including a dummy variable for these firms. The interpretation is that these firms also accumulate knowledge, but not by means reported as formal R&D ¹³.

The term $(\rho - \nu)$ reflects the depreciation rate for the private (i.e. the appropriable) part of a firm's knowledge capital. Below, we will refer to $1 - (\rho - \nu)$ as the depreciation rate. $(\rho - \nu)$ determines *cet.par.* the speed of decay of a firm's knowledge advantage (or disadvantage) ¹⁴. As pointed out in section 2.1.1, the ρ parameter reflects scale economies in knowledge production, while the ν -parameter reflects the innovative opportunities of R&D effort. Hence, the two parameters ρ and ν reflect three different aspects of the process for generating R&D capital; scale economies in R&D, depreciation, and the potency of R&D in generating new knowledge. This suggests that a more general specification of the production function for R&D capital might be desirable. We must leave this as a topic for future research.

PAKES and ERICSON [1989], among others, have argued that firm specific stochastic elements in knowledge accumulation (in a broad sense) represent an important aspect of firm dynamics. The possibility of incorporating stochastic shocks in the knowledge accumulation process (cf. the last term in 20), in a clean and consistent way, is a benefit of the alternative framework here as compared to the standard ("perpetual inventory") framework.

It might be undesirable to impose the assumption that there is a one-year lag between R&D and new profit making knowledge, as in (20). It is not difficult to generalize the specification in (5) (and (20)) with a more flexible lag-structure, i.e. $K_{it+1} = K_{it}^{(\rho-\nu_1)} R_{it}^{\nu_1} R_{it-1}^{\nu_2} R_{it-2}^{\nu_3} \dots$. We will present some estimates with this more general specification below. However, as others have experienced before us, empirically it turns out to be hard to determine the appropriate lag structure, since R&D investments tend to be highly autocorrelated, as we showed in section 2.

4.1.4. The Estimating Equation: A Not-So-Fixed Effect Model

We can eliminate the unobservable knowledge capital stocks in equation (19) by using equation (20):

$$(21) \quad \hat{a}_{it} = (\rho - \nu)\hat{a}_{it-1} + \gamma\nu\hat{r}_{It-1} \\ + (\epsilon/\mu - 1)\hat{x}_{it}^C + (\rho - \nu)(\epsilon/\mu - 1)\hat{x}_{it-1}^C + \hat{\epsilon}_{it}.$$

13. As noticed above, an alternative way to handle firms that do not carry out R&D is to consider a knowledge accumulation process as discussed in section 2.1.1, where $K_{t+1} = K_t^{(\rho-\nu)}(R_t + c)^\nu$ (which creates a non-linear estimation problem).

14. See PAKES and SCHANKERMAN (1984) for a discussion of knowledge depreciation. More precisely, $(\rho - \nu)$ is the speed of decay for the *logarithm* of the knowledge capital stock relative to the reference firm.

The two last terms in (21) can be manipulated to reduce the multicollinearity problem between the variables representing the capital stock in two subsequent years ¹⁵:

$$(22) \quad \hat{a}_{it} = (\rho - \nu)\hat{a}_{it-1} + \gamma\nu\hat{r}_{It-1} + \lambda_1\hat{i}_{it-1} + \lambda_2\hat{x}_{it-1}^C + \hat{e}_{it}.$$

The two first terms on the right hand side of (22) capture the essence of our model, while the next two terms are included to control for market power and scale economies.

Equation (22) is our estimating equation incorporating the performance index which must be calculated according to (18). We have in this equation introduced a notation that distinguishes between plants and the line-of-business (within a firm) to which the plant belongs. The subscript i refers to a plant, while the upper case subscript I refers to the line-of-business within the firm to which the plant belongs. If a firm operates several plants within a line-of-business, we assume that they all have access to the same knowledge capital stock; see KLETTE [1996] for a related analysis of scope economies in R&D ¹⁶.

The difference equation (22) corresponds to a dynamic process where there are persistent differences in performance between plants, but not quite as persistent as in the fixed-effect case. The equation portrays a process where there is a tendency for differences in productivity to disappear with time, if there are no differences in R&D effort. Externalities, i.e. diffusion of knowledge is the cause for this tendency to converge, in our interpretation. Hence, the property that an above average firm tend to decline to average performance reflect only a relative decline rather than an absolute decline - in other words, the average level of performance is persistently improving. We should emphasize that this tendency to convergence only holds when there are no differences in R&D effort. We argued, however, in section 2 that there is a feedback mechanism built into this model that will give incentives to preserve (cross sectional) differences in R&D effort over time. This suggest that the model can rationalize persistent differences in performance between firms. A complete dynamic analysis of the model presented here requires an analysis of the two coupled difference equations (10) and (22), a task beyond the scope of this paper.

We notice that equation (22) is similar to equations widely studied and estimated within the standard framework. As noticed in KLETTE [1996], equation (22) picks up two correlation patterns which are not new or surprising; i.e. that productivity growth is positively related to lagged R&D, and negatively related to initial productivity. The contribution of the present framework is to show how these two patterns can be related within a fully specified *structural* model.

15. Use the approximation $x_{it}^C = \ln X_{it}^C = \ln(X_{it-1}^C + I_{it-1}) \simeq \ln X_{it-1}^C + (I_{it-1}/X_{it-1}^C)$, where we have introduced the variable $i_{it-1} = I_{it-1}/X_{it-1}^C$. The parameters should then be interpreted as follows: $\lambda_1 = (\epsilon/\mu - 1)$ and $\lambda_2 = [1 - (\rho - \nu)](\epsilon/\mu - 1)$.

16. See also ADAMS and JAFFE (1996). Notice that ADAMS and JAFFE (1996) do not have access to R&D broken down at the line-of-business level as we do.

4.2. Econometric Issues

4.2.1. Data and Variable Construction

Our data sources were briefly presented in section 2.2; more details are available in the appendix. In our empirical analysis we present estimates based on equation (22), with the plant as the unit of observation. One major reason why we have chosen the plant rather than the line-of-business within each firm, is that there is a significant amount of corporate restructuring going on among R&D intensive firms¹⁷. This makes it hard to keep track of the firms over time, while the problem is less severe for the plants which keep their identification number irrespective of the changes in ownership and the corporate structure.

To calculate the performance index (18), we have used the time-industry median values for output and each of the inputs in defining the reference plant (firm), cf. e.g. \hat{q}_t and \hat{x}_t^l in equation (11). That is to say, output and inputs are constructed as logarithmic deviations from the corresponding time-industry median values, and the factor shares θ_{0t}^l in (12) are also calculated as the time-industry median values.

4.2.2. Instrumental Variables, Fixed Effects and GMM

Equation (22) can not be estimated directly by OLS since the equation contains a lagged dependent variable and the error term is autoregressive¹⁸, i.e. $\hat{e}_{it} \equiv \hat{e}_{it} - (\rho - \nu)\hat{e}_{it-1} + \hat{v}_{it}$. The estimation is instead carried out by instrumental variables, or more precisely by GMM.

The model is estimated in levels. As instruments for the lagged endogenous variable we use lagged values of output and employment in levels or growth rates (first differences). The preferred specification is based on growth in output and employment rather than their levels since the specification tests which we will present below indicate that the variables in levels are correlated with the error term. BLUNDELL and BOND [1995] have recently argued that growth rates can be quite powerful and attractive instruments in GMM-estimation with panel data. No instrument is used for the R&D variable, as it is assumed to be determined before the knowledge shock (and the performance shock) is revealed. As mentioned, both formal overidentification tests and estimates based on alternative instrument sets will be presented below.

17. GRILICHES and MAIRESSE (1984) discussed this problem with firm level data, and argued that the problem might significantly affect the estimated rate of return to R&D capital. One tends to lose many of the most successful R&D performers when constructing R&D capital stocks from past R&D expenditures, as many of the most successful R&D performers tend to restructure more often than other firms. A major benefit of the not-so-fixed effect model presented in this paper is that it only requires short panels of R&D investment. This is a useful property when we want to trace the performance of restructuring firms. KLETTE (1996) exploits and discusses this aspect of the not-so-fixed effect model.

18. See GRILICHES (1961).

As can be seen from the estimating equation (22), we are able to identify $(\rho - \nu)$ and $\gamma\nu$ which are the parameters required e.g. to calculate the rate of return to R&D investment, as we show below. If we assume constant returns to scale in knowledge production ¹⁹, i.e. $\rho = 1$, we can clearly identify γ and ν . There are some cross-coefficient restrictions that appear to provide a means for specification testing, and more efficient estimation of the parameters. However, one should notice that if the ratio between the scale elasticity and the markup (cf. ϵ/μ) changes between periods, this cross-coefficient restriction disappears.

4.3. The Potency of R&D and Persistent Performance Differences

4.3.1. Estimates from First Differences

The first results from our estimation of equation (22) can be found in table 4 ²⁰. For completeness, column (1) shows OLS results which for reasons explained above are biased. The instrument sets based on variables in levels, used in columns (2)-(4), are rejected in favor of instruments

TABLE 4

Dynamic performance and R&D. Eq. (22). One Year Differences, GMM-Results.

Dependent variable: \hat{a}_{t+1}

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
\hat{a}_t	.6604 (.0171)	.8828 (.0144)	.9342 (.0161)	.9310 (.0186)	.8248 (.0265)	.8497 (.0307)	.8461 (.0355)
\hat{r}_t	.0115 (.0021)	.0061 (.0013)	.0046 (.0013)	.0048 (.0013)	.0065 (.0017)	.0066 (.0015)	.0069 (.0017)
$\hat{\ell}_t$	.0311 (.0121)	-.0043 (.0095)	-.0109 (.0105)	-.0093 (.0111)	-.0028 (.0108)	-.0075 (.0117)	-.0062 (.0126)
\hat{x}_t^C	-.0025 (.0018)	-.0020 (.0009)	-.0015 (.0009)	-.0013 (.0010)	-.0022 (.0012)	-.0026 (.0012)	-.0028 (.0012)
D($R_t = 0$)	.0641 (.0144)	.0358 (.0090)	.0264 (.0087)	.0281 (.0089)	.0364 (.0111)	.0361 (.0109)	.0381 (.0113)
Obs	9991	9991	9991	9991	9991	9991	9991
Sargan/Hansen		p=.002	p=.016	p=.059	p=.000	p=.000	p=.000
IV	OLS	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-2,3,\dots}$ $q_{t-2,3,\dots}$	$n_{t-3,4,\dots}$ $q_{t-3,4,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-2,3,\dots}$ $\Delta q_{t-2,3,\dots}$	$\Delta n_{t-3,4,\dots}$ $\Delta q_{t-3,4,\dots}$

Notes: Robust standard errors in parentheses. Time, industry, age, foreign ownership and plant type dummies not reported.

19. Notice that this is a maintained hypothesis in the standard framework based on the perpetual inventory formula (1).

20. The estimates have been obtained by means of the GAUSS-program DPD, developed by Manuel Arellano and Steve Bond; see ARELLANO and BOND (1988).

in differences used in columns (5)-(7). The results in columns (5), (6) and (7) are quite similar and imply a depreciation rate of 15-18 percent, and a statistically highly significant, positive effect of R&D on next periods productivity ²¹.

In table 5 we try to explore the timing pattern of R&D by including several lags of R&D. From columns (5)-(7) it is clear that the lag structure is difficult to identify. It is not surprising that we encounter this well known problem given the persistence in R&D intensities found in section 2.2.

TABLE 5

Dynamic performance and R&D. Eq. (22). One Year Differences, GMM-Results, Extended R&D-lags.

Dependent variable: \hat{a}_{t+1}	
\hat{a}_t	.8310 (.0267)
\hat{r}_t	.0023 (.0039)
\hat{r}_{t-1}	.0026 (.0059)
\hat{r}_{t-2}	-.0013 (.0034)
\hat{i}_t	-.0088 (.0123)
\hat{X}_t^C	.0023 (.0012)
D($R_t = 0$)	.0101 (.0239)
D($R_{t-1} = 0$)	.0140 (.0366)
D($R_{t-2} = 0$)	-.0012 (.0228)
Wald test:	p=.156
$\hat{r}_t = \hat{r}_{t-i} = 0$	
Obs	8552
Sargan/Hansen	p=.011
IV	$\Delta n_{t-1,2,..}$ $\Delta q_{t-1,2,..}$

Notes: Robust standard errors in parentheses. Time, industry, age, foreign ownership and plant type dummies not reported.

4.3.2. Estimates from Longer Differences: Reducing Problems with Lag Specification

To reduce the problems with the lag specification, we have estimated the model for three year productivity differences. We recognize that even though

21. The No-R&D dummy is positive indicating that plants with high R&D drive this result.

the timing issue favor longer differences, problems with sample selection pulls in the opposite direction. The survival rate is lower for the no-R&D plants as we have documented in the working paper version of this paper; going to longer differences will consequently select a less representative group of no-R&D plants compared to the group of R&D plants.

The results based on the model for three year productivity differences can be found in table 6. The OLS results can again be rejected. There are large differences in the parameter estimate for the lagged dependent variable, when we compare the estimates based on instruments in levels (cf. columns. 2 and 3) with the estimates based on instrument in growth rates (cf. columns. 4 and 5). As the differences in these parameter estimates are large relative to their standard errors, it is clear that a formal Hausman test will reject the models based on instruments in levels. Our preferred specification is thus column (4) which implies an annual depreciation rate similar to what we found using one year differences, 18 percent ²², and a highly significant, positive effect of R&D on productivity.

TABLE 6

Dynamic performance and R&D. Eq. (22). Three Year Differences, GMM-Results.

Dependent variable: \hat{a}_{t+3}

	(1)	(2)	(3)	(4)	(5)
\hat{a}_t	.4476 (.0222)	.7176 (.0301)	.7989 (.0408)	.5576 (.0571)	.6206 (.0698)
$\ln(\sum R_t)$	.0160 (.0031)	.0102 (.0025)	.0086 (.0025)	.0136 (.0027)	.0127 (.0027)
$\sum \hat{a}_t$	.0263 (.0108)	.0040 (.0099)	-.0044 (.0110)	.0112 (.0111)	.0070 (.0124)
\hat{x}_t^C	-.0034 (.0026)	-.0030 (.0020)	-.0021 (.0020)	-.0046 (.0021)	-.0041 (.0021)
$D(\sum R_t = 0)$	.1017 (.0238)	.0655 (.0190)	.0555 (.0190)	.0883 (.0206)	.0819 (.0205)
Obs	7287	7287	7287	7287	7287
Sargan/Hansen		p=.018	p=.068	p=.001	p=.001
IV	OLS	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-2,3,\dots}$ $q_{t-2,3,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-2,3,\dots}$ $\Delta q_{t-2,3,\dots}$

Notes: Robust standard errors in parentheses. Time, industry, age, foreign ownership and plant type dummies not reported.

22. I.e., $0.18 = 1 - (.558)^{1/3} = 1 - .82$.

4.4. Parameter Stability Over Time and Across Industries

4.4.1. Differences over Time

It has been argued that the innovative opportunities and the potency of R&D has been declining over the last 10 to 20 years; see GRILICHES [1994] for a survey of this discussion based on evidence for the US. In Norway, it is well known that a number of the large firms in the R&D intensive electronics industry in Norway faced severe problems at the end of the 1980s, after some successful years in the early 1980s. KLETTE and FØRRE [1995] found that R&D intensive firms eliminated more jobs than other firms in the late 1980s, while the opposite was true in the first half of the 1980s. It is therefore interesting to know whether the potency of R&D investments has changed over the period we consider. The results in table 7 suggests, that if anything, R&D became more potent from 1987 onwards. The negative relationship between R&D and performance in terms of job creation documented in Klette and Førre, does not carry over when we consider performance in terms of productivity. Indeed, some of the improvements in performance and productivity for R&D firms might take the form of labor saving.

TABLE 7

Dynamic performance and R&D. Eq. (22). Three Year Differences, GMM-Results, R&D effects by time period.

Dependent variable: \hat{a}_{t+3}	
\hat{a}_t	.5530 (.0571)
$\ln(\sum R_t)D(81 - 86)$	.0132 (.0026)
$\ln(\sum R_t)D(87 - 91)$	.0157 (.0030)
$\sum \hat{\eta}_t$	.0117 (.0111)
\hat{x}_t^C	-.0047 (.0021)
$D(\sum R_t = 0)$	.0916 (.0206)
Obs	7287
Sargan/Hansen	p=.002
IV	$\Delta n_{t-1,2,..}$ $\Delta q_{t-1,2,..}$

Notes: Robust standard errors in parentheses. Time, industry, age, foreign ownership and plant type dummies not reported.

4.4.2. Differences Across Industries

We have examined differences in the effect of R&D across industries. Tables 8 and 9 present our results from estimating the model industry by industry. Table 8 is based on instruments in levels, while table 9 is based on instruments in difference form. The estimated R&D coefficients are quite similar in the two sets of estimates, while the estimated coefficients on the lagged dependent variable tend to be lower when we apply instruments based on differences. For most industries, a formal Hausman test based on this coefficient will tend to reject the specification in table 8.

TABLE 8

Dynamic performance and R&D. Eq. (22). Instruments in levels. Three Year Differences, GMM-Results by Industry.

Dependent variable: \hat{a}_{t+3}

Industry	(1) 351-352	(2) 354-356	(3) 37	(4) 381	(5) 382	(6) 383	(7) 384-385
\hat{a}_t	.6391 (.0149)	.5726 (.0355)	.7396 (.0208)	.5000 (.0493)	.7958 (.0392)	.6532 (.0271)	.6981 (.0374)
$\ln(\sum R_t)$	.0185 (.0012)	.0185 (.0040)	.0084 (.0021)	.0028 (.0060)	.0063 (.0037)	.0070 (.0026)	.0021 (.0042)
$\sum \hat{z}_t$	.0833 (.0104)	-.0009 (.0055)	.0695 (.0104)	.0168 (.0106)	.0001 (.0132)	-.0052 (.0106)	.0423 (.0175)
\hat{x}_t^C	-.0379 (.0021)	.0030 (.0028)	.0141 (.0022)	-.0122 (.0037)	.0040 (.0029)	-.0039 (.0035)	-.0025 (.0033)
$D(\sum R_t = 0)$	.1275 (.0123)	.1355 (.0307)	.0480 (.0159)	.0282 (.0462)	.0374 (.0303)	.0182 (.0215)	.0109 (.0312)
Obs	578	866	496	1451	1481	723	1488
Sargan/H.	p=.420	p=.390	p=.802	p=.253	p=.341	p=.296	p=.086
IV	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$	$n_{t-1,2,\dots}$ $q_{t-1,2,\dots}$

Notes: Robust standard errors in parentheses. Time, industry, age, foreign ownership and plant type dummies not reported.

The R&D coefficients presented in table 9 show that R&D investment is most important for performance in “Industrial chemicals and Pharmaceuticals” (ISIC 351-2) and “Plastic and petroleum products” (ISIC 354-6), while somewhat lower in the other industries. There are also significant differences in the depreciation rate of knowledge capital; cf. the coefficient on the lagged dependent variable. We find the lowest depreciation rate in “Metals” (ISIC 37) and the highest depreciation rate in “Plastic and petroleum products” (ISIC 354-6).

TABLE 9

Dynamic performance and R&D. Eq. (22). Instruments in differences. Three Year Differences, GMM-Results by Industry.

Dependent variable: \hat{a}_{t+3}

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Industry	351-352	354-356	37	381	382	383	384-385
\hat{a}_t	.4700 (.0129)	.2996 (.0296)	.8450 (.0313)	.4427 (.0511)	.7607 (.0489)	.7122 (.0323)	.4443 (.0509)
$\ln(\sum R_t)$	.0178 (.0013)	.0148 (.0034)	.0075 (.0021)	.0062 (.0061)	.0067 (.0046)	.0039 (.0025)	.0080 (.0046)
$\sum \hat{z}_t$	.1186 (.0107)	.0096 (.0073)	.0711 (.0056)	.0189 (.0106)	-.0045 (.0143)	.0070 (.0112)	.0521 (.0196)
\hat{x}_t^C	-.0382 (.0016)	-.0047 (.0027)	.0138 (.0029)	-.0128 (.0039)	.0031 (.0037)	-.0008 (.0041)	-.0064 (.0040)
$D(\sum R_t = 0)$	.1317 (.0128)	.0984 (.0262)	.0510 (.0131)	.0526 (.0463)	.0308 (.0371)	.0007 (.0219)	.0510 (.0332)
Obs	578	866	496	1451	1481	723	1488
Sargan/H.	p=.224	p=.161	p=.720	p=.599	p=.510	p=.347	p=.896
IV	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$	$\Delta n_{t-1,2,\dots}$ $\Delta q_{t-1,2,\dots}$

Notes: Robust standard errors in parentheses. Time, industry, age, foreign ownership and plant type dummies not reported.

4.5. Rates of Return to R&D Investments

In this section, we will illustrate how equation (10) and the estimated coefficients can be used to estimate the rate of return to R&D investments. Rearranging terms in (10), we find that

$$\beta = \frac{w_{t-1}R_{t-1}}{\nu\gamma S_t + (\rho - \nu)w_t R_t}$$

or since $\beta = 1/(1 + r)$:

$$(23) \quad r = \frac{\nu\gamma S_t + (\rho - \nu)w_t R_t}{w_{t-1}R_{t-1}} - 1$$

Using the parameter estimates presented above and the summary statistics in table 10, we can calculate the right hand side of this expression and thereby estimate the rates of return to R&D investments. The discount factor β in equation (10) reflects the required rate of return to R&D investments, and corresponds therefore to an *ex-ante* rate of return. However, the variables dated t in equations (10) and (23) refer to the expected values at time $t - 1$ (or more generally, at the time when the R&D investment decision for period $t - 1$ is made). Since we use realized rather than expected values in our estimates of the rate of return, it is more correct to consider this rate of return as an *ex-post* rate.

TABLE 10

Summary Statistics.

Variable	Sample	Obs.	Mean	Median	S.Dev.
\hat{a}_t	All	11343	-0.050	-0.055	0.183
	R&D plants	4316	-0.026	-0.038	0.178
	No R&D plants	7027	-0.066	-0.066	0.185
\hat{i}_t	All	11343	0.059	0.019	0.140
	R&D plants	4316	0.055	0.026	0.120
	No R&D plants	7027	0.061	0.014	0.150
\hat{x}_t^C	All	11326	9.557	9.502	1.793
	R&D plants	4316	10.586	10.530	1.706
	No R&D plants	7010	8.924	9.061	1.533
Employment	All	11343	108	48	189
	R&D plants	4316	185	93	269
	No R&D plants	7027	61	36	86
\hat{r}_t	R&D plants	4316	4.261	5.606	4.001
$w_t R_t / S_t$	R&D plants *	1609	0.126	0.038	0.982
$w_t R_t / w_{t-1} R_{t-1}$	R&D plants *	1187	1.248	1.094	1.310

Notes: * Observations at line of business level.

As we noticed in figure 1, the distribution of R&D intensities across plants is highly skewed. We therefore calculate rates of return for mean and median values of the R&D intensities as presented in the summary statistics in table 10. The resulting rates of return are given in table 11.

TABLE 11

Rates of Return to R&D investments.

	All Industries		Returns by Industry						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
			351-352	354-356	37	381	382	383	384-385
Mean value	9%	11%	8%	4%	23%	0%	19%	15%	2%
Median value	9%	6%	7%	-3%	11%	-8%	7%	2%	-5%

In the first column we use the estimate of the structural parameters in table 4, column (6). For a plant with the mean R&D intensity and mean R&D growth our results imply a rate of return of 9 percent. For median values of R&D intensity and R&D growth the return is also 9 percent.

In the next column we use the estimate of the structural parameters in table 6, column (4). For a plant with the mean R&D intensity and mean R&D growth our results imply an annual rate of return of 11 percent. For median values of R&D intensity and R&D growth the return is 6 percent. We also give results for each industry using the structural parameters from table 9.

Considering the estimated private rates of return in table 11, they are quite low compared to estimates based on the standard model; see GRILICHES [1994, 1995]. The rates of return in table 11 are much closer to normal rates of return e.g. on physical investment²³ than the estimates that Griliches refers to. Taking the estimates in table 11 at face value, they e.g. suggest significantly smaller imperfection in the capital market than previous estimates.

In table 3, we have presented estimates for the rate of return to R&D investments based on the standard model. We can use these estimates to make a more clear cut comparison of the rate of return derived from the standard framework to the estimates based on our alternative specification. The results in columns 4-6 in table 3 are *a priori* most comparable to those we have presented in table 11²⁴. We must recognize that the rates of return in table 3 are *gross* rates and should be adjusted for depreciation to be comparable to the results in table 11. Considering the rates of return for the mean output-R&D capital ratio in columns 4 and 5 in table 3, the estimates are much higher than the estimates in table 11. This is true even if we subtract a 15 percent depreciation rate from the estimates in table 3 (i.e. the depreciation rate used to construct the R&D capital stocks). It is, however, evident that the rates of return to R&D investment presented in table 3 are not very robust and that allowing for fixed effects in the estimation (as in columns 3, 6, 7 and 8) has a very dramatic effect on the rates of return. This is to a large extent also true for the estimates in table 11 based on our alternative specification. The lack of robust estimates of rates of return to R&D has been observed in a number of similar studies; see the survey by MAIRESSE and SASSENOU [1991].

A striking pattern in table 11 is the large differences in the rates of return between industries. Since these are *ex-post* rates of return, this variation might reflect a substantial amount of randomness in the innovation process, that we also emphasized above. Similarly, the mean rate of return to R&D investment is much higher than the estimates for the median line of business. This suggests a distribution of rates of return skewed to the right. That is to say, a low fraction of firms experience rates of return to R&D that are sufficiently high to pull the average rate of return substantially above the median. This result is related to SCHANKERMAN and PAKES [1986] who also found that the value of innovations, measured by the value of patents, is highly skewed with a few very profitable innovations and a large fraction that are close to worthless. Clearly, the variations in our estimated rates of return to R&D investment could also reflect a problem with our framework.

Before we pull the interpretation of our estimates too far we should point out a caveat that our model shares with the standard framework. It is clear from equation (23) that a firm with sufficiently low R&D investment (cf. the denominator) relative to its sales, will have a high rate of return to its R&D (even if its planned R&D investment in the next period is zero). A

23. The rate of return on physical capital investment has been estimated to around 7 percent for the Norwegian economy.

24. Since both are based on gross output rather than value added.

similar problem is present in the standard model where the rate of return to R&D capital is estimated as proportional to the ratio of sales to R&D capital; a firm with little R&D capital, i.e. little past R&D investment will therefore have a high rate of return and vice versa. We find this implication of the model puzzling and it might reveal a problem with the log-linear specification where the marginal product of knowledge capital is proportional to the average product of knowledge capital. Alternatively, a respecification of the knowledge production function as suggested in section 2.1.1 (and footnote 13) might reduce the problem. This issue deserves further analysis before too much is made out of estimated rates of return to R&D investment.

5 Conclusions

The point of departure for our analysis are some well known observations on the empirical patterns of R&D investment and productivity: First, there are substantial cross sectional differences in R&D activity within narrow industries, and these cross sectional differences tend to be quite persistent over time. Second, there are quite strong cross sectional correlations between R&D and productivity, while the longitudinal correlations are much weaker. We have argued that the first observation questions the validity of the standard framework for R&D productivity studies that treat the accumulation of knowledge capital as identical to the accumulation of physical capital (based on the perpetual inventory model). We also argued that the empirical pattern of R&D investment can be better accommodated by a simple, alternative accumulation process for R&D capital that allows for a positive complementarity between already acquired knowledge and current R&D in the generation of new knowledge ²⁵.

The second step in our analysis shows how this alternative specification of knowledge accumulation leads to a simple, structural and dynamic econometric model, where next year's performance (roughly speaking, productivity) depends on current performance and current R&D activity. We have estimated this model on a new data set, where plant level production data have been linked with R&D data broken down by product line within each firm. Our empirical framework merges the cross sectional and the longitudinal patterns identified in the second observation mentioned above, and permits a structural interpretation of the estimated coefficients. We find that the appropriable part of R&D capital depreciates quite rapidly, with an

25. We have shown that intertemporal complementarity in R&D can rationalize the observed persistency in R&D. However, persistency in R&D does not necessarily imply persistency in innovations. Indeed, Geroski, Van Reenen and Walters (1996) have shown, on the basis of innovation data for UK, that there is little persistence in *large* innovations. There might be a high degree of persistence in smaller innovations, while the persistence in major breakthroughs and innovations is low.

estimated annual depreciation rate around 18 percent on average. We should point out that this high rate of depreciation of the appropriable part of R&D capital suggests significant spillover effects according to our model. Our estimates also show that R&D investment has a significant effect on firm (or plant) performance, but the estimated private rates of return to R&D investment is substantially lower than the rates of return found in many of the studies surveyed by GRILICHES [1995]. However, we point out a puzzle or problem with our estimates of the rate of return to R&D investment that we have not managed to resolve. That is, the rate of return to R&D investment is estimated to be very high for firms that invest very little in R&D relative to their sales. This implication of the model is due to the assumption of diminishing returns to knowledge capital for all values of this capital, an assumption or property that our alternative specification shares with the standard framework.

The estimated model did not incorporate the R&D investment equation. An obvious extension of the empirical analysis presented in this paper will be to estimate the R&D investment equation (equation 9 or 10) jointly with the not-so-fixed effect model (equation 22).

• Data sources

Our empirical analysis uses merged data from the Manufacturing Statistics and R&D surveys. The Manufacturing Statistics of Statistics Norway is an annual census of all plants in the Norwegian manufacturing industry. See HALVORSEN et al. [1991] for documentation. From this source we use information on outputs and other inputs than R&D. The unit of observation in the analysis is the plant, so to each plant we merge the R&D expenditures at the line of business level within each firm.

Information about R&D expenses at the line of business level of each firm is obtained from R&D surveys for the years 1982, -83, -84, -85, -87, -89 and -91. This survey was carried out by the Norwegian Research Council for Science and Technology (NTNF) until 1989 and by Statistics Norway in 1991. See SKORGE et al. [1996] for definitions and industry level figures.

• Sample construction

Our analysis covers the period 1980-92 and the following industries: “Chemicals” (ISIC 35)²⁶, “Basic metals” (ISIC 37) and “Metal products” (ISIC 38). These industries account for almost all R&D in Norwegian manufacturing²⁷.

Since the coverage of the R&D survey is quite low for firms with less than 20 employees, our analysis covers only plants that belong to firms with at least 20 employees in at least one year in the sample period. Note that the analysis also includes plants which report no R&D. Since we use lagged variables as instruments when estimating the model, we limit the analysis to plants where we have at least four consecutive years of observations.

• Variable construction

Output is measured as the value of gross production corrected for taxes and subsidies. Inputs are labor (man hours), materials including energy, rentals and fire insurance value of capital. Constructing our performance index, all nominal variables are deflated using industry level deflators from Norwegian national accounts.

In addition to investments, each plant reports the fire insurance values and rental costs for machinery and buildings. We have constructed a simple filter to eliminate some of the noise that is known to exist in the fire insurance values. The capital values have been transformed to rental costs by a

26. We have not included “Petroleum refining” (ISIC 353) in our analysis, as it is a sector with a very low R&D intensity (in Norway).

27. In 1991, these industries accounted for 91 per cent of total R&D expenditures in manufacturing.

standard user cost formula, to account for the differences in depreciation between buildings and machinery and to make it possible to sum these costs together with the reported rental costs of capital. The final measure of capital for year t is the mean of capital values at the end of years $t-2$, $t-1$, and t

The R&D variable includes all intramural and extramural R&D expenditures. The R&D expenditures are deflated with a wage deflator. To avoid double counting of the R&D inputs, we have pulled out R&D labor from the man hours before constructing the performance measure. Finally for the three years without a R&D survey, we interpolate R&D expenses plant by plant.

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