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Abstract:
Empirical research has established that there is a significant, positive relationship between productivity growth and R&D-expenditure at the firm level. Yet, while interesting, the conventional production function approach applied in such studies has some well known limitations. This paper attempts to provide new insights into three main issues: (i) Heterogeneity in production relationships, in particular differences in innovative opportunities, across firms are emphasized throughout. (ii) There tends to be a correlation between investment decisions and the error term in production function regressions (even when specified in a growth rate form), that will bias the estimated parameters. The paper handles this problem more carefully than usual, by dealing explicitly with uncertainty and expectation-errors by means of instrumental variable estimation. (iii) R&D is an investment activity which involves significant adjustment costs. This paper presents a new specifications of adjustment costs, where rapid changes in the R&D-program reduce the growth in knowledge capital. The results confirm the view that there are significant differences in innovative opportunities across firms (within narrowly defined industries). There is clear evidence that R&D-activity in a firm improves its performance. The results suggest that R&D-activities in competing firms will have a positive or negative effect on a firm's performance, depending on whether the firm is technologically advanced or not.

Keywords: R&D-investment, Knowledge accumulation, Spillovers, Productivity, Panel Data, Microdata

JEL classification: D24

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1 Introduction

By means of production function analysis, Griliches and other researchers have given clear evidence of a correlation between a firm's R&D-investment activity and its productivity performance[1]. This paper provides a somewhat extended framework for the econometric analysis of the relationship between R&D and firm performance. In particular, the analysis emphasizes differences in innovative opportunities between firms. The econometric model also stresses imperfect competition and the demand-expanding role of R&D. The econometric model is applied to a previously unexploited data set covering Norwegian "high-tech" companies in the period 1975-86.

The production function approach commonly applied to studies of the relationship between R&D and productivity, has some well known limitations. Several researchers have recently paid attention to the large amount of heterogeneity in production technology, prices and performance between firms and plants even within narrowly defined industries[2]. Studies of R&D-investment at the firm level suggest that such heterogeneity is particularly important when knowledge capital is included as a separate factor of production[3]. The econometric model presented in this paper imposes a minimum of parametric restrictions on the differences in innovative opportunities between firms[4]. The model attempts to infer heterogeneity in innovative opportunities from variations between firms in their past and present R&D-activity. The outcome of this inference is returned into a model of production in order to evaluate the informational contents of this measure of innovative opportunities. The results from this two-step procedure are encouraging in the sense that the estimates seem to reinforce the pattern of a positive relationship between R&D and firm performance, including both measures of productivity and profits more generally. Furthermore, the results show that this measure of innovative opportunities contains information about the nature of spillovers between firms, as well as on a firm's markup strategy.

[1]See Griliches (1988) and Mairesse and Sassenou (1991) for surveys of the econometric literature.

[2]See Griliches and Mairesse (1990) for a formal analysis of the (lack of) stability of the production function coefficients both longitudinally and cross-sectionally at the firm level. Pakes and Ericson (1989) and Olley and Pakes (1992) have also provided empirical studies that emphasize heterogeneity in efficiency and production relationships between firms within an industry.

The intensity version of the production function model, developed by Griliches (1979, 1986), allows for differences in innovative opportunities between firms. In fact, the intensity version can in some respects be considered a special case of the model presented in this paper.

[3]See Pakes and Schankerman (1984). Bound et al. (1984) and Scott (1984) have documented the large amount of variability of R&D-intensity across firms.

[4]Innovative opportunities is a concept that incorporates several aspects characterizing a firm's ability to obtain profits from its innovative efforts. In particular, the concept characterizes the firm's ability to generate new knowledge from its R&D-expenditures, as well as its ability to capture the profits from new knowledge. I do not attempt to identify the relative importance of the individual parts embedded in the notion of a firm's innovative opportunities. See Pakes and Schankerman (1984) for an elaborate discussion of different elements that affect a firm's innovative opportunities.

It is well known that production function parameters might be biased as a consequence of the correlation between factor inputs and productivity differences captured by the residuals. The usual approach is to deal with this problem by allowing for permanent efficiency differences between firms. This is done by estimating the production function in growth rate form. However, estimates based on growth rate regressions usually give much weaker support for a correlation between R&D and productivity, compared to estimation in levels. Furthermore, with the long panel data sets now widely available, allowing for permanent differences in productivity between firms might still leave an important dynamic endogeneity problem behind. That is, a positive correlation between R&D-investments and productivity growth might be evidence of both variables responding to favorable *changes* in demand or supply conditions, rather than a direct, causal relationship. The econometric framework presented in this paper attempts to handle this problem more carefully than usual, by explicitly estimating the production relationship in terms of an instrumental variable approach (GMM), and testing for the validity of the instruments.

Knowledge has some distinctive characteristics as a factor of production. This has been recognized at least since Arrow's seminal paper (Arrow, 1962)[5]. The non-rival nature of knowledge capital, suggests that scale economies and imperfect competition might be important characteristics of R&D-intensive industries. This perspective is supported by observations that high-tech industries are characterized by rapid, substantial and firm-specific changes in production technologies and product design. The model presented below stresses imperfect competition and allow for scale economies in production[6]. This model of imperfect competition provides a framework which is rich enough to incorporate both negative (pecuniary) externalities and positive spillovers from the R&D-effort of competing firms[7]. More interestingly, the estimates suggest that both positive and negative spillovers are important. Other researchers have paid much attention to the empirical significance of positive externalities of R&D-activities[8]. A new finding presented in this paper is that the net effect of R&D spillovers seems to be related to the (relative) technological level of the recipient firm of the spillovers. More precisely, the net

[5]See e.g. Romer (1990) for a recent discussion of the special characteristics of knowledge as an input in production.

[6]Griliches and Mairesse (1984) and Hall and Mairesse (1992) have also examined the R&D-productivity relationship in models with some emphasis on imperfect competition.

[7]Barzel (1968) and Hirschleifer (1971) were among the first economists to emphasize the possibilities of negative (pecuniary) externalities of knowledge production. During the last decade, there has been a rapidly expanding *theoretical* literature on patent races that emphasizes this aspect of knowledge production. However, the *empirical* literature on the relationship between R&D and performance has not paid attention to such negative spillover effects. See, however, Caballero and Jaffe (1993) for a recent exception.

[8]See Griliches (1992) for a survey of the econometric literature.

spillover effect is negative for a firm at an average technological level or below, according to the results presented in this paper. On the other hand, the positive spillovers dominate among the technologically more advanced firms[9]. Furthermore, I present evidence suggesting that there is a positive relationship between the technological level of a firm and the markup the firm charges on its products.

Significant cost differences are likely to prevail across firms within an industry where there are substantial and rapid changes in production technology and product design. With product differentiation and market power this will give rise to differences in output prices. The econometric model presented below pays attention to this possibility and the fact that the applied data set does not provide information about firm specific output prices. Hence, there will tend to be a difference between deflated sales and real output. Klette and Griliches (1992) emphasized the importance of this distinction when one tries to interpret estimated production function parameters[10]. The current paper extends this analysis to a model with R&D as a separate factor of production.

The paper is organized as follows: Section 2 presents the theoretical model of short-run producer behavior, relating deflated sales to factor inputs etc. The second half of section 2 presents a theoretical framework for the analysis of R&D-investment behavior. Section 3 discusses the empirical version of the model. The data are presented in section 4. Section 5 examines various aspects of efficient estimation, and tests of the econometric specification for this model. The empirical results are presented in section 6. Conclusions are provided in section 7.

2 The theoretical model

2.1 A model of short run producer behavior

This section presents a framework for production analysis that is a hybrid of non-parametric productivity analysis and the standard production functions[11]. In Klette (1994a), I have presented a detailed derivation of the model[12]. The model is based on the assumption of short-run profit maximizing behavior, and allow for scale economies and imperfect competition in the output market. The capital stocks are assumed to be (quasi-) fixed, when the firm solves its

[9]These conclusions are limited to the short run spillover effects (with 1-2 years lag).

[10]See Abbott (1991) and Dunne and Roberts (1992) for empirical evidence on the prevalence of variations in observed (real) prices in narrowly defined markets of various kinds.

[11]The framework presented here can be considered a generalization of the approach developed by Hall (1988, 1990). While Hall focuses on the estimation of markups in the absence of scale economies, the framework presented here permits a joint treatment of markups and scale economies.

[12]See also Hall (1990, eq. 5.26).

short run profit maximizing problem. In solving the short run profit maximizing problem the firm chooses the amount of labour, materials and energy, and sets the output price. The formal expression of the model is

$$\hat{q}_{it} = \mu \sum_{l=L,M,E} \theta^l_{it}(\hat{x}^l_{it} - \hat{c}_{it}) + \epsilon\hat{c}_{it} + \alpha\hat{k}_{it} + \alpha'\hat{k}_{It} + \hat{a}_{it}. \tag{1}$$

A hat above a lower case variable denotes the growth rate (the logarithmic derivative) of the corresponding upper case variable. Q_{it} and X^l_{it} represent output and input "l". The superscript "l" refers to the variable inputs; labour, materials and energy. The subscript "it" indicates firm "i" in period "t". μ and ϵ are the markup and the scale elasticity of the "ordinary factors" of production (labour, materials, energy and ordinary capital). C_{it} and K_{it} correspond to ordinary capital (machinery and buildings) and knowledge capital. α and α' are the output elasticities of respectively the firm's own knowledge capital, and spillovers from the knowledge of the other firms in the industry. K_{It} is the R&D-capital of competing firms. θ^l_{it} is the cost of input "l" relative to the value of output. $\hat{a}_{it}$ represents growth in factor productivity (not accounted for by the R&D-capital variables).

The simplest way to think about the relationship in (1) is as a Cobb-Douglas production function in growth rates, where the output elasticities have been replaced by the revenue shares times the markup, and the capital share has been determined residually[13]. However, as have been discussed in Klette (1994a), the relationship holds more generally than the Cobb-Douglas case, when the revenue shares are constructed as explained below. The three last terms in (1) captures differences in productivity growth between firms.

2.2 Output versus deflated sales

Klette and Griliches (1992) have provided an extensive discussion of the biases that can arise in the estimation of firm level production models when output is proxied by deflated sales, based on a common deflator across firms. The biases occur in situations where the firms compete in an imperfectly competitive environment, and where prices will reflect idiosyncratic differences in cost. This feature of the economic environment seems *a priori* to be highly relevant to high-tech firms, operating in industries with rapid and idiosyncratic changes in technology and product design.

Klette and Griliches (1992) presented a simple approach to adjust for the fact that we observe

[13] i.e. using the property that the capital elasticity is given as $\epsilon - \mu\sum_{l=L,M,E}\theta^l_{it}$.

deflated sales rather than real output. Here I will extend that framework slightly, to allow for the possibility that the firm's knowledge capital will affect demand through improved product quality. That is to say, I will assume that the demand function facing the firm can be expressed as follows

$$Q_{it} = D_{it} \left(\frac{P_{it}}{P_{It}} \right)^{\eta} K_{it}^{\xi} K_{It}^{-\xi'}, \tag{2}$$

where P_{it}/P_{It} is the firm's price relative to its competitors, while K_{it} and K_{It} are the firm's versus the average competitors knowledge capital, as before [14]. D_{it} is a demand shifter. η is the price elasticity of demand, while ξ and ξ' are the elasticities of demand with respect to a change in the firm's and the average competitor's "product quality", respectively. Equation (2) says that the firm's own knowledge capital raises demand conditional on prices, while the knowledge capital of a firm's competitors reduces its demand (conditional on prices). If we employ the relationship between output and deflated sales[15]; $S_{it} = Q_{it}P_{it}/P_{It}$, equation (2) can be rewritten

$$Q_{it} = D_{it}^{1/(\eta+1)} S_{it}^{\eta/(\eta+1)} K_{it}^{\xi/(\eta+1)} K_{It}^{-\xi'/(\eta+1)}, \tag{3}$$

It follows that

$$\hat{q}_{it} = \frac{1}{\eta+1}\hat{d}_{it} + \frac{\eta}{\eta+1}\hat{s}_{it} + \frac{\xi}{\eta+1}\hat{k}_{it} - \frac{\xi'}{\eta+1}\hat{k}_{It} \tag{4}$$

Profit maximizing behavior implies that the firm uses the markup factor $\mu = \eta/(1+\eta)$. Using this relationship, and combining equations (1) and (4):

$$\begin{aligned} \hat{s}_{it} &= \sum_{l=L,M,E} \theta_{it}^{l}(\hat{x}_{it}^{l} - \hat{c}_{it}) + \epsilon(1+1/\eta)\hat{c}_{it} \\ &+ [\alpha(1+1/\eta) - \xi/\eta]\hat{k}_{it} + (\alpha' + \xi'/\eta)\hat{k}_{It} \\ &- 1/\eta\, \hat{d}_{it} + (1+1/\eta)\hat{a}_{it}. \end{aligned} \tag{5}$$

14 Another way to think about this demand system is in terms of hedonic prices. The price that matter from a consumer's point of view is the price per unit of quality. I will assume that the firm's knowledge capital affects its product quality. Consequently, the quality adjusted price of a firm relative to its competitors will , *cet.par.*, be a decreasing function of its knowledge capital relative to its competitors. See Levin and Reiss (1988) and Bernstein and Nadiri (1989) for a related approach to modeling the effect of R&D, using industry level data. However, neither of the two studies pays attention to the possibility of negative spillovers. Using industry level data limits the extent to which one can distinguish between negative and positive spillovers of R&D.

15 I assume that the common deflator is equal to the competitors' average price.

This completes the derivation of the model for short-run producer behavior. Section 3.3 will present an empirical version of this model.

2.3 The marginal revenue product of knowledge

Below I will need an expression for the marginal revenue product of knowledge capital in terms of the parameters in equation (5). Let $\Pi_{it}(K_{it})$ denote short run profit (operating surplus before investments) for the firm conditional on the knowledge capital stock K_{it}. In appendix A, I have shown that

$$\begin{aligned}\frac{d\Pi_{it}}{dK_{it}} &= \frac{d}{dK_{it}}[P_{it}Q(K_{it},P_{it}) - C(Q(K_{it},P_{it}),K_{it},\cdot)] \\ &= [\alpha(1+1/\eta) - \xi/\eta]\frac{P_{it}Q_{it}}{K_{it}} \qquad (6)\end{aligned}$$

That is to say, the coefficient in front of the growth in knowledge capital in the model in equation (5), is equal to the value share of R&D capital in output, evaluated at its nominal marginal product[16].

2.4 The R&D investment model

Let us now turn to the firm's investment activities. As above, $\Pi_{it}(K_{it})$ denotes profit (before investment) for firm i in period t, conditional on the knowledge capital stock K_{it}. Let R_{it} denote the investment in R&D, while p_t is the unit price of R&D-expenditure. The firm's investment problem is to find the R&D investment path, $\{R_{is}\}$, that solves

$$\max_{\{R_{i,t+s}\}} \mathcal{E}_{it}\sum_{s=0}^{\infty}\beta_t(s)[\Pi_{i,t+s}(K_{i,t+s}) - p_sR_{i,t+s}] \qquad (7)$$

subject to an accumulation constraint. $\beta_t(s)$ is the discount factor (e.g. $(1+r(t))^{-s}$). $\mathcal{E}_{it}$ is the expectation operator, conditional on the firm's information available at time "t".

I will assume that there are costs of adjustment for the knowledge capital stock. The applied model of adjustment costs reflects that investment are less effective in terms of generating new knowldege capital as the firm deviates from some "normal" investment level. For convenience, I will take the normal investment level to be equal to the level of depreciation. That is, the accumulation equation for R&D capital takes the form

[16]This relationship is the same as the relationship derived in more constrained production models applied to R&D-firms; see Griliches (1979, 1986). The derivation of this result is slightly more complicated in the present case, where I allow for endogenous prices.

$$K_{i,t+1} = K_{it}(1-\delta) + R_{it} - \frac{\gamma}{2} K_{it} \left(\frac{R_{it}}{K_{it}} - \delta \right)^2. \tag{8}$$

I have assumed that there is a one year lag between the R&D-investment and the time when the additional knowledge becomes productive. The appropriate choice of the lag length will be discussed further in section 6.1 . δ is the depreciation rate for knowledge capital, while γ is the cost of adjustment parameter. It follows that

$$\frac{dK_{i,t+1}}{dR_{i,t+1}} = 1 - \gamma \left(\frac{R_{it}}{K_{it}} - \delta \right). \tag{9}$$

The solution to the maximization problem in (7) must satisfy the (approximate) stochastic Euler equation (see appendix B for details):

$$\mathcal{E}_{it} \left[\beta_t \frac{d\Pi_{i,t+1}}{dK_{i,t+1}} \left\{ 1 - \gamma \left(\frac{R_{it}}{K_{it}} - \delta \right) \right\} - p_t^K \right] = 0. \tag{10}$$

p_t^K is a user cost, given by $p_t - \beta_t p_{t+1}(1-\delta) \equiv p_{t+1}\rho_t$, where ρ_t is the gross, real rate of return that the firm requires on its investments.

The specification of adjustment costs in (8) differs from the standard specification of adjustment costs in the literature on physical capital investment (and labor demand)[17]. The standard specification assumes that investment activities hamper productivity. Adjustment costs as specified in (8), on the other hand, consider adjustment costs that reduces the effectiveness of R&D-investment when a firm rapidly tries to increase its knowledge capital[18]. Notice that the standard specification of adjustment costs only give a contemporaneous loss in output, while adjustment costs as specified in (8) affect the R&D capital and thereby productivity for a number of years.

3 The empirical model

3.1 Euler equations and heterogeneous innovative opportunities

A major question in the implementation of the Euler-equation for investment, is how to derive the marginal product of knowledge capital from observables. The approach chosen here is to rely on the relationship derived in section 2.3. One of the main ideas of this paper is to seek

[17]See e.g. Chirinko (1993) for a survey, and Chirinko and Fazzari (1994) for a recent empirical application.

[18]Hall and Hayashi (1989) and Klette (1994b) specify adjustment costs in a spirit similar to the one used in this paper. However, these studies also allow for stochastic elements in the accumulation equation. While stochastic elements in the accumulation equation are obviously relevant and interesting, they tend to complicate the analysis considerably, as explained by Pakes (1994).

a parameterization that allow for a fairly unconstrained heterogeneity in the returns to R&D investment across firms. More precisely, I have assumed that each firm has a separate value, to be estimated, for the expression $(\alpha(1+1/\eta)-\xi/\eta)$ (cf. equation (6)). Let me denote this parameter value by ν_i, where the subscript "i" is introduced to make explicit that this parameter is specific to firm "i". It follows that equation (10) can be rewritten

$$\mathcal{E}_{i,t-1}\left[\beta_{t-1}\nu_i\frac{S_{it}}{p_tK_{it}}\left(1-\gamma\left(\frac{R_{i,t-1}}{K_{i,t-1}}-\delta\right)\right)\right]=\rho_{t-1} \tag{11}$$

Taking the logarithm of both sides:

$$\ln\left(\frac{S_{it}}{p_tK_{it}}\right)=-\ln(\nu_i)-\ln\left[1-\gamma\left(\frac{R_{i,t-1}}{K_{i,t-1}}-\delta\right)\right]+\ln(\rho_{t-1}/\beta_{t-1})+v_{it}. \tag{12}$$

In this equation I have removed the expectation operator, and added a forecast error (v_{it}) to the right hand side of the equation. The properties of this forecast error will be discussed in section 5. I will need the following approximation

$$\ln\left(\frac{1-\gamma(R_{i,t-1}/K_{i,t-1}-\delta)}{1-\gamma(R_{i,t-2}/K_{i,t-2}-\delta)}\right)\approx-\gamma\left(\frac{R_{i,t-1}}{K_{i,t-1}}-\frac{R_{i,t-2}}{K_{i,t-2}}\right) \tag{13}$$

With this approximation, the first difference version of equation (12) can be written

$$\Delta\ln\left(\frac{S_{it}}{p_tK_{it}}\right)=\lambda_t+\gamma\Delta\left(\frac{R_{i,t-1}}{K_{i,t-1}}\right)+\Delta v_{it}, \tag{14}$$

where Δ is the first difference operator, while $\lambda_t\equiv\Delta\ln(\rho_{t-1}/\beta_{t-1})$. Efficient estimation of this model will be discussed in section 5.

3.2 The two step procedure

The idea is now to estimate the parameters of the model in equation (14). I will then use the relationship in equation (11) to predict the set of individual coefficients ν_i up to a set of parameters; ρ_t/β_t. That is, I am able to identify $\nu_i\beta_t/\rho_t$ on the basis of the results from the estimation of equation (14). By normalizing by the average value of $\nu_i\beta_t/\rho_t$ across firms in each period, I obtain an estimate of $\nu_{i0}\equiv\nu_i/\nu_0$, where ν_0 is the average revenue elasticity of R&D. The predicted value of ν_{i0} (denoted $\hat{\nu}_{i0}$) will be introduced into the model of short-run producer behavior in order to estimate ν_0 as well as other parameters of interest.

I have also used the estimates of ν_{i0} as a more general measure of the firms technological position. That is, a firm with a high value of ν_{i0} will be referred to as a technologically advanced firm.

Finally, one should notice that from equation (8), we have that

$$\begin{aligned}\ln(K_{it}/K_{i,t-1}) &= \ln\left(1+\frac{R_{i,t-1}}{K_{i,t-1}}-\delta-\frac{\gamma}{2}\left[\frac{R_{i,t-1}}{K_{i,t-1}}-\delta\right]^2\right)\\ &\approx \left(\frac{R_{i,t-1}}{K_{i,t-1}}-\delta\right)\left(1-\frac{\gamma}{2}\left[\frac{R_{i,t-1}}{K_{i,t-1}}-\delta\right]\right). \qquad (15)\end{aligned}$$

In the absence of adjustment costs (i.e. γ=0), this expression for the growth in (knowledge) capital is the familiar one from the perpetual inventory method. However, the presence of adjustment costs will reduce the growth in knowledge capital, when a firm is rapidly expanding its knowledge capital stock.

3.3 The empirical model of short run producer behavior

To apply the framework presented in section 2.2, I have to use suitable approximations for the variables expressed in continuous time. I have applied logarithmic differences for the growth rates, and the shares are approximated as for the Tornquist index[19]. The formal expression for the empirical model can be written

$$\begin{aligned}\Delta\ln(S_{it}) &= \sum_{l=L,M,E}\theta^l_{it}\Delta[\ln(X^l_{it})-\ln(C_{it})]+\epsilon(1+\frac{1}{\eta})\Delta\log(C_{it})\\ &+ \nu_0\left[\hat{\nu}_{i0}\Delta\ln(K_{it})\right]+\nu'\Delta\ln(K_{It})+\kappa\Delta\ln(H_{it}/N_{it})\\ &+ \lambda_I+\lambda_t+\Delta u_{it}. \qquad (16)\end{aligned}$$

$\hat{\nu}_{i0}$ is the estimate of the firm's relative innovative opportunities, constructed in the first stage of this procedure. ν' is short hand for $\alpha'+\xi'/\eta$. Notice that we can not sign the parameter ν' *a priori*, since the first part (the knowledge spillover) is positive, while the second part (the business stealing effect of a competitor's quality improvement) is negative. I have added a term $\kappa\Delta\ln(H_{it}/N_{it})$, where H_{it}/N_{it} expresses hours per employee. This term is meant to capture changes in capacity utilization, as well as (idiosyncratic) demand shocks more directly. λ_I and λ_t are industry and time dummies that account for common demand and productivity shocks across firms. Δu_{it} captures idiosyncratic *changes* in productivity and demand between period t-1 and t. Equation (16) can be rewritten

[19]That is, I am taking the average of the shares of the two periods used to construct the growth rates.

$$\begin{aligned}\Delta\text{TFP}_{it} &= (\epsilon[1+1/\eta]-1)\Delta\ln(C_{it}) + \nu_0\,[\hat{\nu}_{i0}\Delta\ln(K_{it})] \\ &+ \nu'\Delta\ln(K_{It}) + \kappa\Delta\ln(H_{it}/N_{it}) + \lambda_I + \lambda_t + \Delta u_{it}. \end{aligned} \tag{17}$$

The variable on the left hand side in this equation is the standard share weighted measure of total factor productivity growth (the Solow residual), but with deflated sales instead of real output.

4 The data sources and variable construction

The data sources used in this analysis is the annual census carried out by Statistics Norway, that have been merged with data from the R&D survey carried out by the Royal Norwegian Council for Scientific and Industrial Research (NTNF).

The sample is unbalanced with annual observations for the period 1975-86 (inclusive). The included companies are selected from the 3 most important R&D performing industries in Norwegian manufacturing. The three industry groups produce chemical products, machinery and electrical equipment, respectively[20]. In 1975 these industries carried out 67 percent of total private R&D in the manufacturing sector. The corresponding figure in 1985 was 76 percents; see table 1.A.

The sample includes only companies with at least 20 employees. Plants with incomplete reports for the variables needed in the estimation have been eliminated. Only "high-tech" firms are included. That is to say, only observations for firms reporting (non-zero) R&D-expenditures have been included. Details on variable and sample construction are presented in appendix C.

Summary statistics for the employed sample are reported in table 1.B. The R&D to sales ratio shown in this table represents the value of the R&D capital stock as a fraction of sales. "Electrical equipment" has a substantially higher R&D to sales ratio than the other two industries. The growth rates in output and R&D-capital show that the R&D-capital to sales ratio has increased in "Electrical equipments", while it has decreased in "Chemicals". However, one should keep in mind that this pattern is based on the assumption of a common rate of depreciation of knowledge capital (15 percents annually) across industries. In all three industries there is a clear movement towards a higher (physical) capital-labour ratio.

[20]The included ISIC-groups are 351, 352, 355 and 356 (Chemicals), 382 (Machinery) and 383 (Electrical equipment).

To estimate the R&D investment equations I have aggregated the data to the Line of Business (LB) level within each firm. There are three different groups of LBs in the sample, corresponding to the industry groups discussed above. The R&D data are reported separately for each LB, within each firm. This level of aggregation seems to be the relevant one for the investment decision making. For the analysis of short run producer behavior I have used plant as the unit of observation. By this choice I eliminate some of the problems of internal deliveries encountered when aggregating output and material inputs across plants within a company (line of business)[21]. The R&D variables merged to each plant are the same for all plants within each line of business (within each firm).

5 Econometric issues

The error term in the "investment equation" (14) captures the forecast error. This forecast error will be correlated with news arriving between the time when the R&D-investment decision is made, and the time when the new knowledge becomes productive. Hence, valid instruments for estimation of this model can only be chosen among variables that the firm knew when it made its investment decision[22]. That is to say, in the first difference model in equation (14), I can only use variables dated t-2 and earlier[23].

The most efficient estimation technique, under the assumption that the demand and the supply shocks are serially uncorrelated (after we have taken out the fixed effects), is to make use of all the resulting moment restrictions. Hence, we should utilize all variables dated t-2 and earlier as instruments. This GMM technique is an efficient extension of the first difference

[21] Another widely applied alternative in such circumstances is to use value added as the output measure. However, value added as the measure of output does not fit well into the model of short run producer behavior applied in this paper.

[22] In the context of panel data, this instrumental variable method exploits orthogonality conditions of the form

$$\text{plim}_{N\to\infty}\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}v_{it}Z_{is}=0,\quad t\geq s,$$

where v_{it} denotes the forecast error and Z_{is} is an instrument, based on variables dated year s. However, as pointed out by Chamberlain (1984, p.1311), the rational expectation hypothesis does not ensure the validity of such orthogonality conditions if there are correlated shocks across firms (e.g. interest or exchange rate changes. Notice that T is assumed fixed when taking the limits. This is the relevant limit for most panel data sets.). Pakes (1994) discusses conditions under which the incorporation of time dummies (as in my model) will permit consistent estimates, using the orthogonality condition stated above. It is considered beyond the scope of this paper to provide a fully satisfactory solution to this problem. Here, I will follow the common practice in the panel data literature and lean on the stated orthogonality condition.

[23] If there are measurement errors in the R&D-investment figures – as is hardly avoidable – there will be serially correlated measurement errors in the R&D-capital stock figures. Serially correlated measurement errors in the R&D-capital figures will create biases when I use lagged R&D- investment and R&D-capital stock variables as instruments.

instrumental variable method suggested for dynamic fixed effects models by Anderson and Hsiao (1981). Arellano and Bond (1991) have given an exposition of the GMM method in the context of dynamic panel data models. The consistency of this method depends on the absence of serial correlation in the demand and supply shocks. The presence of serial correlation in the error terms is investigated using a test statistic developed by Arellano and Bond (1991). I will also report the test statistic corresponding to a general instrument validity test due to Hansen (1982)[24].

For the model of short run producer behavior we encounter related questions as for the investment model. As was pointed out in the derivation of the theoretical model, the error term in equation (17) will incorporate demand and productivity shocks in period t and t-1. The shocks dated t-1 will probably affect the investment decisions during period t-1. These investment decisions determine the growth in physical capital and R&D-capital from period t-1 to period t, given the assumption of a one year investment lag. More precisely, there will be a negative correlation between the growth in the capital stocks on the right hand side of equation (17), and the error term, causing a downward bias in the OLS estimates of this model. To avoid this bias, the model of short run producer behavior has also been estimated by the GMM-estimation method discussed above. The applied instruments have been chosen on a similar basis as for the R&D investment model. That is, instruments dated t-2 and earlier have been applied in the estimations. The application of the instrumental variable method will also reduce problems of random measurement errors.

6 Empirical results

6.1 The R&D investment model

The estimation results for the investment model (cf. equation (14)) are provided in table 2. Columns I-III present the results based on the whole sample, while the three last columns display the results for the three individual industries estimated separately. The results show a highly significant and fairly narrow set of estimates for the parameter of interest; the γ-parameter. Its estimated values range from 0.64 to 0.74 based on the whole sample. I will comment on the results for the individual industries below.

The test statistics for the model in columns I-III show no clear indication of misspecification.

[24]The GAUSS program applied in this paper is documented in Arellano and Bond (1988).

That is, there is no indication of second order autocorrelation in the residuals[25]. Such autocorrelation would be harmful for the validity of the applied instruments, as they are variables dated t-2 and earlier[26]. The test statistic for instrument validity provides no evidence of problems with the instruments.

Columns II and III present results from some slightly modified versions of the basic model. Column II omits the industry dummies. In column III I have attempted to address the question of whether there is more severe adjustment costs for firms *expanding* their R&D-program. That is to say, the R&D variable on the right hand side of that model is interacted with a dummy variable that is unity if the R&D-investment exceeds 15 percents of the R&D-capital stock, and zero otherwise. However, the results indicate no tendency for a higher adjustment cost *parameter* for the firms exceeding this limit.

Is a γ-estimate of 0.74 a large number? One way to illuminate this issue is to consider equation (15). Figure 1 shows $\ln(K_{it}/K_{i,t-1})$ for the applied set of observations, when γ is zero versus 0.74 . As shown in figure 1, only the extreme observations are substantially affected by the presence of a non-zero γ[27]. Two implications follow: For this value of γ (0.74) the approximations used in sections 2 and 3 should be quite harmless. Second, the bulk of the sample will not be much affected by the precise estimate of γ in the range of values reported in table 2.

To explore the stability of the model specification in general, and the γ-parameter in particular, the next three columns in table 2 exhibit the results from estimates on subsamples corresponding to the three industry groups Chemicals, Machinery and Electronic equipment. One of the results stands out, namely the result for Machinery. The overidentification test for this industry reveals beyond doubt that the applied instruments are invalid. Some experimental runs suggested that the explanation is that the timing of the R&D-variable on the right hand side of the model is incorrect for that industry. Replacing R&D-investment dated t-1 with the R&D-investment dated t-2 gave quite satisfactory results[28]. This finding suggests that the R&D-

[25]Notice that by taking first differences we introduce first order autocorrelation in the error term. Serial correlation in the forecast error will show up in higher order autocorrelation in the error term in equation (14).

[26]The applied instruments are, in addition to the dummy variables, sales dated t-2 and (3 periods) earlier and R&D dated t-3 and (3 periods) earlier. The application of R&D investment dated t-2 gave results that strongly suggested that it is an invalid instrument. An explanation is given below.

[27]A value of γ equal to 0.74 implies a value of 0.999 for the factor $(1-\gamma/2[R_{it}/K_{it}-\delta])$ at the sample mean (based on an R&D depreciation rate of 15 percents). This is clearly a negligible reweighting factor in equation (15). 0.90 is the corresponding value two standard deviations above the average R&D-growth rate, which is also a moderate reweighting factor.

[28]The estimated $R\&D_{-2}$-coefficient in this alternative specification is 0.500 with a standard error of 0.052. The test statistic for 2nd order autocorrelation is -1.02, while the test statistic for instrument validity has a value of

lag is closer to two than to one year for this industry. Hence, the results presented in column five suffer from an omitted explanatory variable that is included among the instruments. As an attempt to deal with this specification problem I have omitted the R&D variable dated t-2 from the instrument set in the estimation on the whole sample (cf. columns I-III).

Having obtained an estimate of γ (the value reported in column one has been applied), I can estimate firm specific values for the ν_{i0}-parameter. The distribution of the non-normalized values is presented in figure 2. The diagrams reveal that the distributions of the ν_i-parameters are skewed to the right for all industries. There are a few firms with exceptionally high ν_i-coefficients in each sector. This is particularly striking in "Chemicals" and "Machinery". The distribution is somewhat more uniform in "Electrical equipment". As was suggested by the numbers reported in tables 1.A and 1.B, "Electrical equipment" have considerably higher innovative opportunities than the other two sectors.

Figure 3 reconsider whether a γ-estimate of 0.74 as compared to zero, makes much difference. The figure plots pair-ways the two estimates of the ν_i-parameters based on a γ-value of zero versus 0.74. The estimated adjustment-costs give the highest revenue-elasticity of R&D (the ν_i's) a moderate boost, but the majority of the estimates are not much affected.

As discussed in section 3.3, I have normalized the estimates by their annual mean values. These normalized values were merged into the data set applied to the model of short run producer behavior.

6.2 Short run producer behavior: Basic results

Table 3 presents the basic findings from the estimation of the model for short run producer behavior. Columns I.A and I.B show the results we get when the estimates for the ν_i-parameters are not utilized, while columns II.A and II.B correspond to models incorporating these estimates. That is to say, the estimates in columns I.A and I.B are based on an assumption of a common revenue elasticity of R&D across firms, while this is not the case for the results presented in columns II.A and II.B.

The interesting finding in this analysis is that the estimates of the firm specific parameters (of the revenue elasticity of R&D) add significant information about the revenue generating effect of R&D. Without this information, there is no tendency of a significant relationship between

26.0, with 29 degrees of freedom. (The test statistic has a Chi-square distribution under the null hypothesis of valid instruments.)

growth in "total factor productivity"[29] and R&D investment (cf. columns I.A and I.B). As this model is formulated in first differences (annual growth rates), this disappointing finding conforms with the general experience with this kind of models[30].

If we add the firm specific information about the potency of R&D, the R&D variable becomes highly significant[31]. The estimates presented in columns II.A and II.B suggest an average revenue elasticity of R&D around 0.03. To a first approximation[32], this value corresponds to a gross, real rate of return to R&D-investment around 18 percent, in order to be consistent with the mean value of the (non-normalized) ν_i-parameter estimates reported in figure 1.

Another finding from the specification that incorporates the estimated ν_i-parameters, is related to the externalities and spillover effects of R&D-investments. The row labeled "Industry R&D$_{-1}$" refer to the coefficient in front of the average growth of R&D-capital for all firms in the industry. The row labeled "Individual coefficient * Industry R&D$_{-1}$" report the coefficient for the same variable interacted with the measure of the firm's (relative) technological position (cf. $\hat{\nu}_{i0}$). The results suggest that an average firm experiences a negative effect of their competitors' (recent) R&D-effort. But as a firm becomes more technologically advanced, this effect changes sign. That is to say, a technologically advanced firm seems to experience a predominantly positive spillover effect of the (recent) R&D-investment of other firms in the industry. This result suggests that a firm has to be relatively technologically advanced to (rapidly) take advantage of the spillovers from other firms' R&D programs. Given the timing of these variables, I have added the terms 'recent' and 'rapidly' in parentheses. A question, which has not been explored here, is whether technologically less advanced firms obtain similar technological benefits from the R&D effort of other firms, but with a longer lag.

The estimates of the (ordinary) capital coefficient in table 3 suggests either that there are significant markups in this sample and/or that there are decreasing returns to scale (cf. the reduced form capital coefficient in equation (17))[33]. The estimated coefficient in front of hours per employee is negative and quite large. A negative (and large) coefficient is surprising if we

[29] I have put to term total factor productivity in quotes to empasize that this measure do not have purely the interpretation of productivity growth, since real output has been replaced by deflated sales.

[30] See e.g. Mairesse and Sassenou (1991) for a discussion of the literature and Hall and Mairesse (1992) for a detailed analysis of the different outcomes obtained by varying the data transformations when estimating the effect of R&D on productivity growth.

[31] The level of precision in these estimates are exaggerated, as they do not account for the stochastic elements in the estimated ν_i-parameters. However, adjusting the standard errors for this stochastic component is not trivial, and must be left for future work.

[32] That is, replacing the ρ_t/β_t by ρ_t.

[33] With constant returns to ordinary factors of production, the estimated capital coefficient suggests a markup on marginal costs around 6 percents.

believe that this coefficient picks up changes in capacity utilization and/or idiosyncratic demand shocks. However, this finding is surprisingly robust for Norwegian manufacturing (see also Klette (1991)).

The test statistics for 2nd order autocorrelation in the residuals show some tendency to positive serial correlation in the idiosyncratic demand and supply shocks. However, I can not reject the hypothesis of no serial correlation at a 5 percent significance level. The overidentification test does not provide any evidence to reject the validity of the instruments at conventional significance levels.

6.3 Short run producer behavior: Additional findings

Results reported in table 4 explore the relationship between R&D and producer behavior somewhat further. Column A.1 shows the outcome of OLS-regressions of the model with firm specific R&D-coefficients. As suggested in section 5, OLS gives downward bias in the estimated R&D-coefficients, explaining why the OLS parameter estimates are so close to zero.

In the models presented above there is a somewhat arbitrary assumption with respect to the R&D-lag. However, given the stability of the R&D-expenditures, this is probably not a major specification issue. This is confirmed by the results presented in column A.2. Column A.2 reports what happens if we alter the timing of the R&D-growth variable one year backwards. The R&D coefficients are robust with respect to such changes.

The last two columns in table 4 show estimates which explore the relationship between a firm's technological level and its markup behavior. The model in column A.3 addresses this issue by adding the interaction between capital growth and the firm specific R&D-coefficient. A positive coefficient suggests that technologically advanced firms face more elastic demand than other firms in the industry. However, the coefficient is very small, implying the effect is negligible. The price elasticity made up one part of the total revenue elasticity of R&D; recall that the measure of a firm's technological level is represented by the parameter $\nu = \alpha(1 + 1/\eta) - \xi/\eta$. I.e. both differences in the price elasticty (cf. η), the demand creating effect (ξ), and the cost reducing effect (α), can explain differences in a firm's technological level. Given that the price elasticity seems to be essentially uncorrelated with a firm's technological level, the results suggest that it is the demand creating (cf. the ξ-coefficient) and the cost reducing effects of R&D (cf. the α-coefficient) which differ between firms at different technological levels.

The last column examines whether there is more to a firm's markup behavior than product differentiation. If the firm uses a markup factor $\mu_i\eta/(1+\eta)$, with $\mu_i > 1$, then growth in variable inputs per unit of capital would show up on the right hand side of equation (17)[34]. The model in column A.4 introduces such an effect. In particular, the formulation allows the μ_i-parameter to be correlated with a firm's technological level. The result shows indeed a strong, positive and non-negligible correlation between the firm specific R&D- coefficient and the additional markup component. In other words, a technologically more advanced firm charges a higher markup. However, this higher markup is not a (direct) result of less price elastic demand. The results increase the magnitude of the coefficents capturing the technological spillovers and business stealing effects discussed in the previous section.

7 Concluding remarks and future research

This paper has presented a somewhat novel approach to the modeling of the relationship between a firm's R&D-investment, its productivity and profits. Three issues have been dealt with in more detail than is usual in production function studies. These are (i) the technological differences between firms, (ii) product differentiation and market power and (iii) the investment decision in R&D. The modeling framework presented here knits these three parts tightly together. The results suggest that this approach adds significant information useful in modelling the relationship R&D and firm performance. Of economic substance, the following findings have emerged:

- There are significant differences in innovative opportunities between firms. These differences are related to, and to some extent inferable from a firms R&D-investment behavior.

- Taking into account these differences in innovative opportunities, I find a strong, positive relationship between R&D-activity and firm performance, even in growth rates.

- The profit and productivity performance of a firm is significantly affected by the R&D-effort of competing firms. For a firm at an average technological level or below, there is a negative effect of the competitors' R&D-effort (a business stealing effect). For the technologically advanced firms, the positive spillover effects seem to dominate. (Notice, however, that this paper has only examined spillover effects in the short run.)

[34]Notice that the possibility that η differ across firms, was examined in column A.3. More precisely, I examined whether such differences were correlated with the estimated ν_{i0}- parameters. A similar correlation for the μ_i parameter is also the focus of the analysis in column A.4.

- There is no evidence suggesting that technologically more advanced firms to face a less elastic demand curve. However, I do find some evidence indicating that these firms charge a higher markup.

The demand side model presented in this paper is very crude. A more careful specification of this part of the model could be carried out, using more explicitly ideas and results from the hedonics literature and the more recent literature on product differentiation[35]. However, with the data I have available, I do not believe it is possible to get very far, since there is no information about product characteristics. But with a richer set of data, that includes product characteristics, there is clearly scope for progress along these lines.

The models examined in this paper have not paid attention to changes in innovative opportunities over time. However, the summary statistics presented in this paper and elsewhere, suggest that at least two of the "high-tech sectors" examined in the present study have experienced significant increase in the R&D to sales ratio over time. In the "Machinery" sector this holds for the industry as a whole, while it seems to be the case only among the R&D performing companies in the industry producing "Electrical equipment". To what extent these changes over time are due to improvements in innovative opportunities and to what extent other factors (e.g. financial conditions and industry restructuring) have created changes in the R&D-intensity, are interesting topics for future research.

[35]Recently, some empirical research has been carried out which merges ideas from the hedonics literature with theoretical models of product differentiation and imperfect competition. See Berry (1994) for a discussion and further references.

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Appendix A: The shadow price of R&D-capital

Short run profit is given by

$$\Pi_{it}(K_{it}) = P_{it}Q_{it} - C(Q_{it}, K_{it}) \tag{18}$$

What is the increase in short run profits if we alter K_{it}? That is, I want to know how to express the derivative of this expression with respect to K_{it}

$$\begin{aligned} \frac{d\Pi_{it}}{dK_{it}} &= \frac{dP_{it}}{dK_{it}}Q_{it} + P_{it}\frac{\partial Q_{it}}{\partial P_{it}}\frac{dP_{it}}{dK_{it}} + P_{it}\frac{\partial Q_{it}}{\partial K_{it}} \\ &- \frac{\partial C(\cdot)}{\partial Q_{it}}\left(\frac{\partial Q_{it}}{\partial P_{it}}\frac{P_{it}}{dK_{it}} + \frac{\partial Q_{it}}{\partial K_{it}}\right) - \frac{\partial C(\cdot)}{\partial K_{it}} \end{aligned} \tag{19}$$

The first, second and forth term on the right hand side add to zero, given that the firm maximizes profits (cf. the Envelope theorem). Collecting the remaining terms, we find that

$$\begin{aligned} \frac{d\Pi_{it}}{dK_{it}} &= \left(P_{it} - \frac{\partial C(\cdot)}{\partial Q_{it}}\right)\frac{\partial Q_{it}}{\partial K_{it}} - \frac{\partial C(\cdot)}{\partial K_{it}} \\ &= -\frac{1}{\eta}P\frac{\partial Q_{it}}{\partial K_{it}} - \frac{\partial C(\cdot)}{\partial K_{it}} \\ &= -\frac{\xi}{\eta}\frac{P_{it}Q_{it}}{K_{it}} - \frac{\partial C(\cdot)}{\partial K_{it}}. \end{aligned} \tag{20}$$

The first equality follows from the firm's markup rule, while the second follows from the properties of the demand system (cf. equation (2)). I have defined α and ϵ as the output elasticities of the firm's transformation function with respect to knowledge capital and ordinary inputs, respectively. It follows by the Implicit Function Theorem that

$$\frac{\partial X_{it}}{\partial K_{it}} = -\frac{\alpha}{\epsilon}\frac{X_{it}}{K_{it}} \tag{21}$$

where X_{it} represents ordinary inputs. Hence, with fixed factor prices (w)

$$\begin{aligned} \frac{\partial C(\cdot)}{\partial K_{it}} &= w\frac{\partial X_{it}}{\partial K_{it}} \\ &= -\frac{\alpha}{\epsilon}\frac{C(Q_{it}, K_{it})}{K_{it}} \\ &= -\alpha(1 + 1/\eta)\frac{P_{it}Q_{it}}{K_{it}} \end{aligned} \tag{22}$$

The last equality follows from the relationship $C(\cdot) = \epsilon(1+1/\eta)P_{it}Q_{it}$, which can be derived from the definition of scale economies (from the cost side), and the firm's markup rule. Combining equations (20) and (22)

$$\frac{\partial \Pi_{it}}{\partial K_{it}} = [\alpha(1+1/\eta) - \xi/\eta]\frac{P_{it}Q_{it}}{K_{it}} \tag{23}$$

Q.E.D.

Appendix B: The stochastic Euler equation

The problem is to solve the optimization problem

$$\max_{\{R_{is}\}} \mathcal{E}_{it} \sum_{t=0}^{\infty} \beta_t(s)[\Pi_{i,t+s} - p_s R_{is}] \tag{24}$$

subject to

$$K_{i,t+1} = K_{it}(1-\delta) + R_{it} - \frac{\gamma}{2} K_{it} \left(\frac{R_{it}}{K_{it}} - \delta \right)^2 . \tag{25}$$

As shown by e.g. Stokey and Lucas (1989, ch. 9.5), a necessary condition for a solution to this problem is that R_{it} solves the problem [36]:

$$\max_{R_{it}} \left(-p_t R_{it} + \mathcal{E}_{it} \beta_t [\Pi_{i,t+1} - p_{t+1} R_{i,t+1}] \right) \tag{26}$$

subject to equation (25), and imposing the restriction that $R_{i,t+1}$ varies with R_{it} such that $K_{i,t+2}$ is fixed, i.e. that

$$K_{i,t+1}(1-\delta) + R_{i,t+1} - \frac{\gamma}{2} K_{i,t+1} \left(\frac{R_{i,t+1}}{K_{i,t+1}} - \delta \right)^2 = \text{constant} \tag{27}$$

Eliminating $K_{i,t+1}$ by combining equations (25) and (27), and totally differentiating with respect to R_{it} and $R_{i,t+1}$, gives the following result

$$\begin{aligned} 0 &= (1-\delta) dR_{it} \left[1 - \gamma \left(\frac{R_{it}}{K_{it}} - \delta \right) \right] \\ &+ dR_{i,t+1} \left[1 - \gamma \left(\frac{R_{i,t+1}}{K_{i,t+1}} - \delta \right) \right] \\ &- dR_{it} \left[1 - \gamma \left(\frac{R_{it}}{K_{it}} - \delta \right) \right] \frac{\gamma}{2} \left[\left(\frac{R_{i,t+1}}{K_{i,t+1}} \right)^2 - \delta^2 \right] . \end{aligned} \tag{28}$$

Rearranging terms, we find that

$$\begin{aligned} \frac{dR_{i,t+1}}{dR_{it}} &= -\frac{(1-\delta)[1-\gamma(R_{it}/K_{it}-\delta)] - \gamma/2[(R_{i,t+1}/K_{i,t+1})^2 - \delta^2]}{1-\gamma(R_{i,t+1}/K_{i,t+1}-\delta)} \\ &\simeq -(1-\delta)\left(1 - \gamma \left[\frac{R_{it}}{K_{it}} - \frac{R_{i,t+1}}{K_{i,t+1}} \right] \right) \\ &\simeq -(1-\delta) \end{aligned} \tag{29}$$

[36]Given appropriate regularity conditions on functional forms and the stochastic shocks, spelled out in Lucas and Stokey.

The approximations are valid when (net) investments ratios are small, and net investments vary slowly over time. The economic interpretation of this approximation, is that the firm neglects the possibility of reducing adjustment costs in the next period, by increasing the current R&D-capital stock. This will be commented on in section 6.1.

Solving the maximization problem in equation (26) and using the relationships (25) and (29), we find the approximate stochastic Euler equation

$$\mathcal{E}_{it}\left[\beta_t \frac{d\Pi_{i,t+1}}{dK_{i,t+1}}\left\{1-\gamma\left(\frac{R_{it}}{K_{it}}-\delta\right)\right\}-\left[p_t-\beta_t p_{t+1}(1-\delta)\right]\right]=0 \tag{30}$$

Q.E.D.

Appendix C: Sample and variable construction

One of the data sources used in this analysis is the annual census carried out by Statistics Norway. A detailed description of the data set is provided by Halvorsen et.al. (1991).

The output measure is gross output adjusted for duties and subsidies. Labour inputs are represented by man hours. For the years before 1983, only manhours for blue collar workers are available. Wage payments are recorded separately for blue and white collar workers. I have estimated a total index for manhours by adjusting the recorded number of manhours by a factor (1 + Wages(white collar)/Wages(blue collar)). Price deflators for gross production (at seller prices), materials, energy and capital (at buyer prices) are taken from the Norwegian National Accounts. Wage payments comprise salaries and wages in cash and kind, other benefits for the employees, taxes and social expenses levied by law. The capital input variable employed is based on investment figures and the total reported fire insurance value for buildings and machinery [37]. Using the perpetual inventory method[38], I have constructed three different estimates of the capital (C_{it}) on the basis of observations for fire insurance values and investment figures for the years t, t-1 and t+1. The final estimates of the capital value for each year is obtained by taking the mean value of three different estimates. The empirical model assumes that it is the capital stock at the beginning of the year which determines the flow of capital services in that year.

The data source for the R&D-data is the R&D survey carried out by the Royal Norwegian Council for Scientific and Industrial Research (NTNF). Aggregate R&D statistics based on the R&D survey are published in several publications from NTNF. The data is reported separately for each line of business within each company.

The data was only available as print-outs, and one substantial task has been to record them into machine-readable form. Another major task in this research project was to merge the R&D-data together with the production data. The data has been (manually) merged at the company level, on the basis of Company names and locations. Recording and merging of the R&D-data were carried out for the years 1975, 1977, 1979, 1981, 1983 and 1985. For the intermediary years, total R&D-expenditures were linearly interpolated for each line of business. To avoid

[37] An examination of the fire insurance values and a comparison with the investment figures reveal much noise in the fire insurance values. Hence, I have constructed a simple filter to pool the two sources of information about movements in the capital stock.

[38] I.e. using the formula

$$C_{it} = C_{i,t-1}(1-\delta) + 0.5(I_{it} + I_{i,t-1}).$$

double counting, the manhours and labour costs in the production statistics were corrected for R&D-expenditures[39].

The median (hourly) wage rate was used as deflator for the R&D-expenditures. The R&D-capital stocks were estimated on the basis of a perpetual inventory method, assuming 15 percent annual depreciation and a pre-sample growth rate in R&D-expenditure of 5 percents (cf. Griliches and Mairesse, 1984, and Hall and Mairesse, 1992). Ideally, we should have iterated the construction of the capital stock, taking into consideration the adjustment costs. However, as suggested by the results reported in section 6, such an iteration process would not create any significant changes.

The employed, merged sample is an unbalanced sample of annual observations for the period 1975-86 (inclusive). Only companies with at least 20 employees were included in the sample[40]. Firms with a growth in R&D-capital exceeding 50 percents were eliminated[41].

[39] More than 80 percent of the R&D-expenditures were reported in the NTNF-survey as labour costs.

[40] According to NTNF, the R&D survey should be close to a census for companies with more than 20 employees. For smaller companies the sampling is more selective. To reduce the problem of sample selection bias, I have chosen to truncate the sample.

[41] The approximations applied in the derivation of the empirical model in this paper are not valid for firms with extremely rapid changes in their R&D-program. However, experiments with less strict trimming with respect to the R&D-variable suggested that the results were not very sensitive to the truncation point.

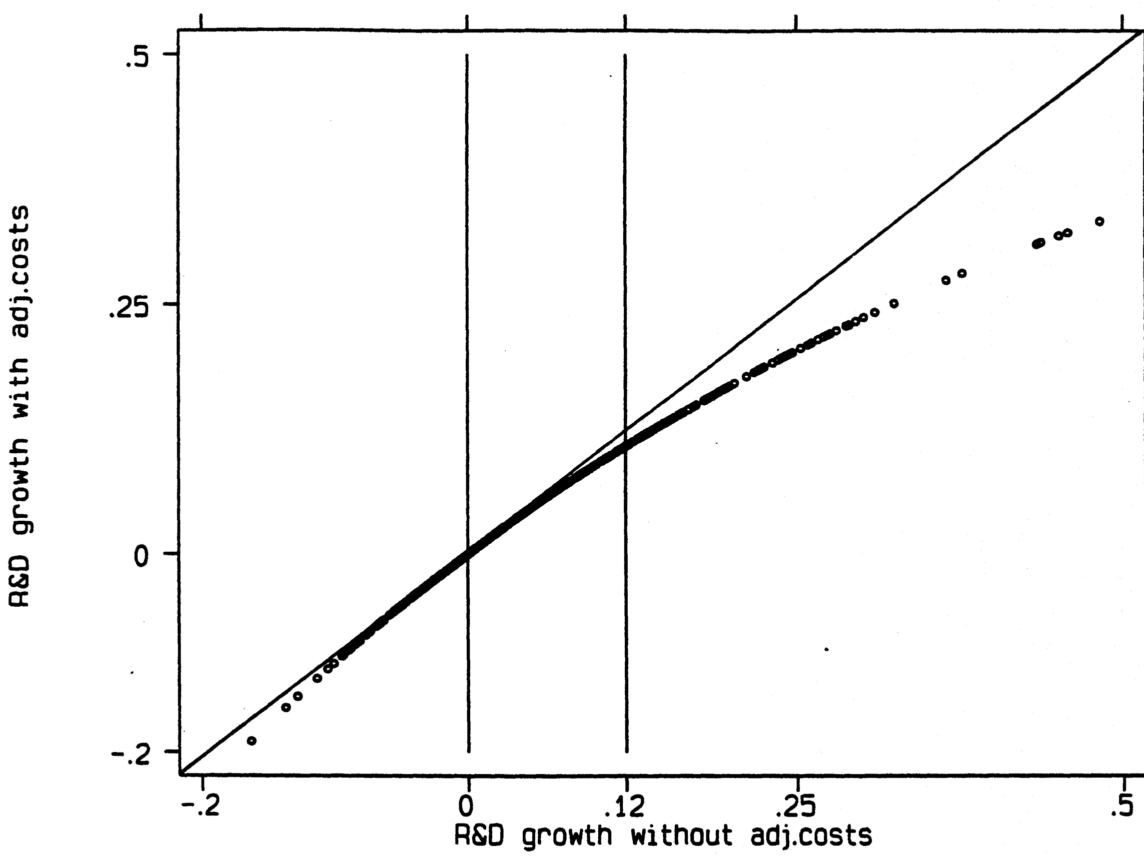

Figure 1: Growth in R&D-capital accounting for adjustment costs versus growth in R&D-capital neglecting adjustment costs.

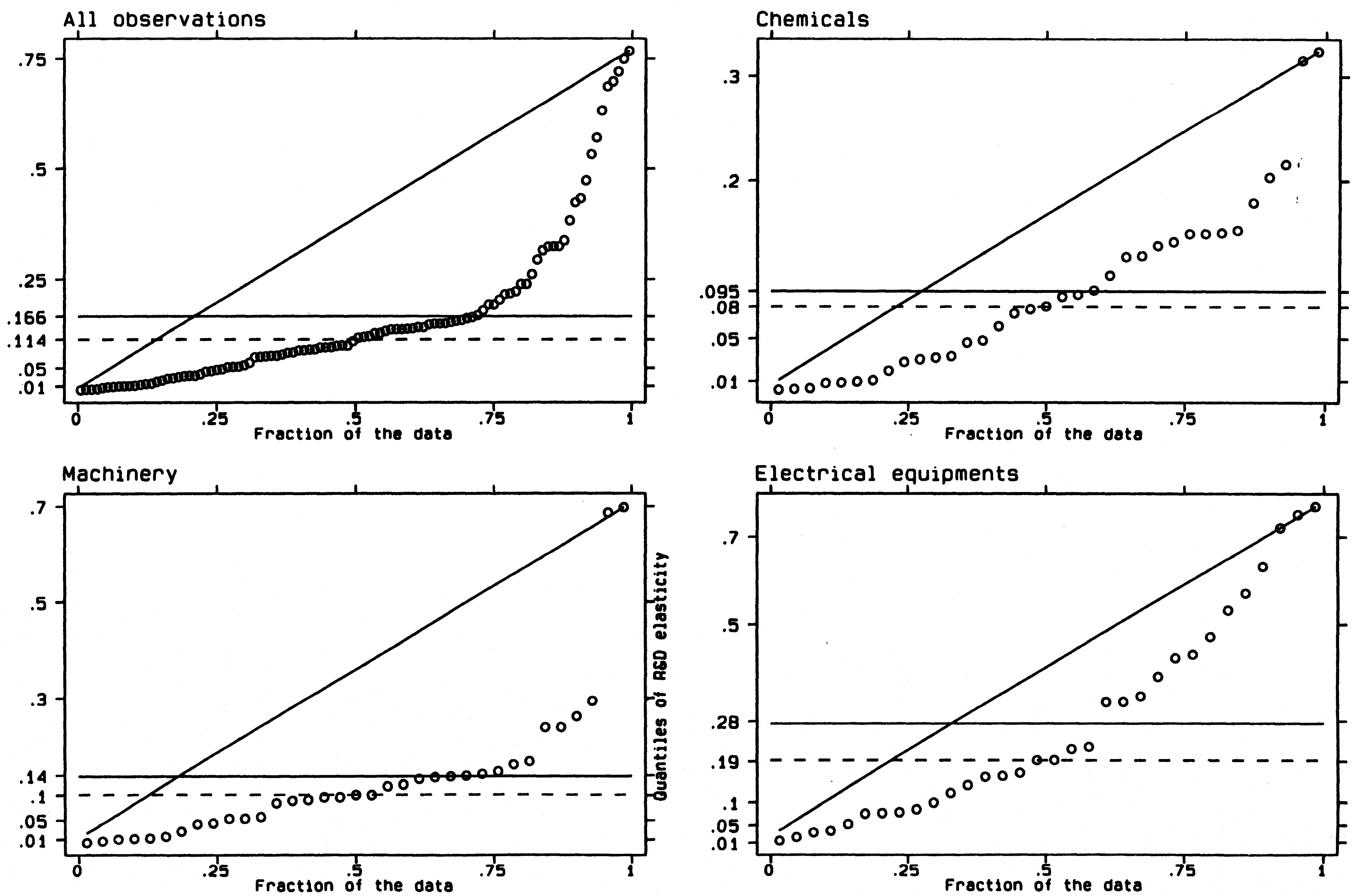

Figure 2: The distribution of estimated revenue elasticities of R&D-capital. The dotted lines report the median value, while the solid (horizontal) lines refer the mean.

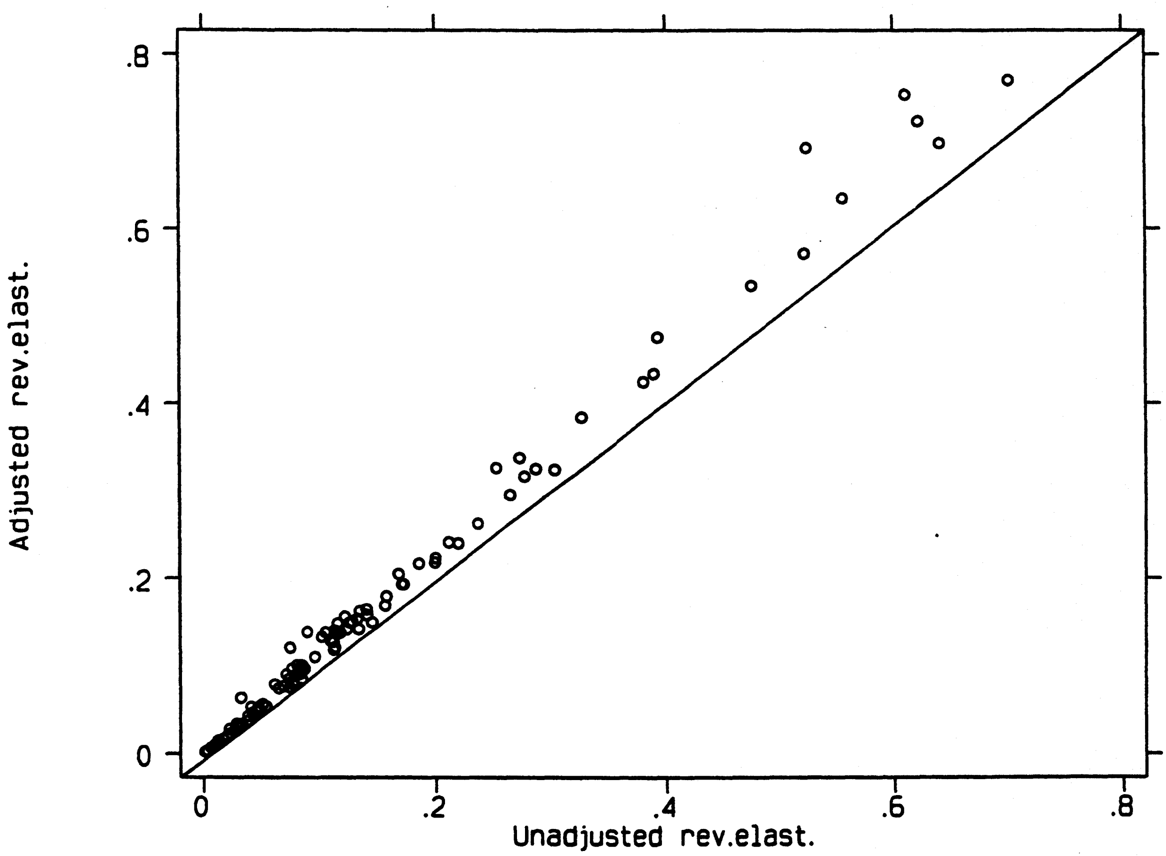

Figure 3: The estimates of the revenue elasticities of R&D with and without adjustment costs.

Table 1.A: R&D-expenditures and sales in Chemicals, Machinery and Electrical equipments.
All figures as percentage share of total manufacturing[1]

	3 sectors together	Chemicals[2]	Machinery	Electrical equipments
R&D-expenditures				
1975	67	20	15	32
1985	76	19	28	29
Sales				
1975	33	15	12	6
1985	45	21	19	5

[1] Excluding Manufacture of food, beverages and tobacco.
[2] These figures includes the sector Manufacture of products of petroleum and coal (ISIC code 354), which is excluded from the study.

Table 1.B: Summary statistics for sample used in regressions.
Growth rates and value shares in percents

	All sample		Chemicals		Machinery		El.equip.	
Variables:	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std. dev.
Growth rates								
Output	1.3	20.8	1.5	22.4	1.2	19.8	1.0	19.1
TFP	0.2	12.1	0.5	13.3	0.3	11.5	-0.4	10.7
Hours	-1.7	17.4	-2.1	16.8	-1.0	16.9	-1.6	18.6
Phys.capital	5.4	30.0	4.7	34.5	3.2	21.8	3.2	26.9
R&D capital	0.4	12.6	-1.5	10.7	0.2	13.0	3.2	11.9
#empl./plant	247	319	266	351	184	217	274	337
R&D/sales[1]	15.8	22.5	11.1	13.3	14.7	30.5	22.6	20.3
# Obs.	981		438		254		289	
# plants	145		64		43		38	
# LBs	102		35		35		32	

[1] R&D capital as a percentage of sales.

Table 2: "Investment equations".
GMM-estimates[1]. Variables are in first differences. Dependent variable: ln(Sales/R&D-stock). Sample periode: 1978-86. 122 Line of Businesses

Explanatory variables:	All observations[2]			Chem.[3]	Mach.[3]	El.eq[3]
	I.	II.	III.	IV.	V.	VI.
Lagged R&D-growth	0.735 (.137)	0.640 (.130)		0.601 (.114)	1.328 (.105)	1.122 (.191)
Lagged R&D* Dummy[4]			0.688 (.111)			
Time dummies	X	X	X	X	X	X
Industry dummies	X		X			
2.nd order autocorr.[5]	-1.16	-1.10	-1.19	0.146	-0.257	-0.377
Overidentification test[6]	66.4 (55)	68.3 (57)	71.4 (55)	26.0 (26)	364.9 (26)	20.8 (18)
Obs:	710	710	710	303	272	257

[1] Asymptotic standard errors robust to general cross-section and times series heteroskedasticity are reported in parentheses.
[2] The instruments are ln(sales) from t-2 and earlier, and R&D-growth dated t-3 and earlier.
[3] The instruments are ln(sales) and R&D-growth dated t-2 and earlier.
[4] The dummy variable is unity if R&D-expenditure as a fraction of R&D-stock exceeds 15 percents.
[5] This test statistic has a N(0,1)-distribution. See Arellano and Bond (1991) for a detailed exposition.
[6] This test statistic has a Chi-square distribution. The degrees of freedom are shown in parentheses. See Hansen (1982) and Arellano and Bond (1991) for details.

Table 3: Model of short run producer behavior. Basic results.
GMM-estimates[1]. Variables are in first differences. Dependent variable: Growth in "total factor productivity"[2]. Sample periode: 1978-86. Number of plants: 145. All models include time and industry dummies

Explanatory variables	I.A	I.B	II.A	II.B
ln(Capital)	-0.054	-0.054	-0.055	-0.060
	(.004)	(.005)	(.004)	(.006)
ln($Capital_{-1}$)	0.008	0.008	0.008	0.007
	(.001)	(.001)	(.001)	(.001)
R&D	0.004	0.004		
	(.004)	(.006)		
Indiv.coef. * R&D			0.030	0.032
			(.005)	(.006)
Industry $R\&D_{-1}$	0.006		-0.198	-0.270
	(.032)		(.037)	(.037)
Indiv.coef.* Industry $R\&D_{-1}$				0.135
				(.012)
ln(Hours/employee)	-0.232	-0.232	-0.229	-0.249
	(.012)	(.012)	(.005)	(.012)
2nd order autocorr.[3]	-1.648	-1.602	-1.680	-1.633
Overidentification test[4]	122.3	122.2	125.6	127.0
	(122)	(121)	(122)	(120)
Obs:	691	691	691	691

[1] Asymptotic standard errors robust to general cross-section and time series heteroskedasticity are reported in parentheses. The applied instruments are ln(capital), ln(R&D) ln(Industry-R&D), ln(hours) and ln(employees) dated t-2 and earlier, inaddition to the time and industry dummies. The longest lag applied in the instrument set is t-5.
[2] See equation (17).
[3] This test statistic has a N(0,1)-distribution. See Arellano and Bond (1991) for details.
[4] This test statistic has a Chi-square distribution. The degrees of freedom are shown in parentheses. See Hansen (1982) and Arellano and Bond (1991) for details.

Table 4: Model of short run producer behavior. Alternative specifications.
Variables are in first differences. Dependent variable: Growth in "total factor productivity"[1]. Sample periode: 1978-86. Number of plants: 145. All models include time and industry dummies

Est. method	A.1 OLS[2]	A.2 GMM[2,3]	A.3 GMM[2,3]	A.4 GMM[2,3]
ln(Var.inputs/capital)				-0.018 (.009)
Indiv.coeff.* ln(Var.inputs/capital)				0.058 (.003)
ln(Capital)	-0.073 (.026)	-0.060 (.006)	-0.059 (.017)	-0.018 (.005)
Indiv.coeff.* ln(Capital)			0.001 (.0002)	
ln($Capital_{-1}$)	0.012 (.018)	0.006 (.001)	0.008 (.002)	0.012 (.002)
Indiv.coeff. * R&D	0.003 (.024)		0.028 (.006)	0.019 (.006)
Indiv.coeff. * $R\&D_{-1}$		0.031 (.004)		
Industry $R\&D_{-1}$	-0.144 (.171)	-0.168 (.037)	-0.196 (.037)	-0.487 (.036)
Indiv.coef.* Industry $R\&D_{-1}$	0.039 (.100)	0.104 (.013)	0.134 (.012)	0.326 (.022)
ln(Hours/employee)	-0.134 (.060)	-0.250 (.012)	-0.229 (.015)	-0.304 (.017)
2nd order autocorr.[4]	-1.630	-1.676	-1.627	-1.683
Overidentification test[5]		125.7 (121)	121.2 (119)	126.7 (118)
Obs:	691	691	691	691

[1] See equation (17).
[2] Asymptotic standard errors robust to general cross-section and time series heteroskedasticity are reported in parentheses.
[3] The applied instruments are ln(capital), ln(R&D), ln(Industry-R&D), ln(hours) and ln(employees) dated t-2 and eralier, in addition to the time and industry dummies. For the model in column A.4 we also included ln(Variable inputs/capital) dated t-2 and earlier. The longest lag applied in the instrument set is t-5, except for last model where the limit was t-4.
[4] This test statistic has a N(0,1)-distribution. See Arellano and Bond (1991) for details.
[5] This test statistic has a Chi-square distribution. The degrees of freedom are shown in parentheses. See Arellano and Bond (1991) for details.

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