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Abstract:
Some well-known correlations between R&D and performance are given a somewhat new interpretation in this paper. I present an alternative model of knowledge accumulation, with some interesting and desirable properties. Perhaps the most attractive property is that it provides a simple and less data intensive framework for empirical studies of the relationship between firm performance and R&D. This property allows me to address some new aspects of this relationship combining two rich, new sources of firm and plant-level data. Among the substantial empirical findings are (i) R&D has a positive and significant effect on performance, (ii) the estimates suggest that the appropriable part of knowledge capital depreciate at a rate of 0.2, (iii) there are visible spillover effects of R&D across LBs within a firm (economies of scope in R&D), and (iv) there are significant spillovers in R&D across firms that belong to the same interlocking group of firms.

Keywords: Productivity, R&D, Corporate structure, Microeconometrics.

JEL classification: D24, O30.

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1 Introduction

This paper examines the relationship between R&D and firm performance using an unusually rich set of firm-level data. The data set allows us study this relationship at the line-of-business level within each firm[1]. This study also examines the extent to which knowledge can be productively transferred from one activity to another. The idea that knowledge gives rise to economies of scope has recently been emphasized by Jovanovic (1993). He explores to what extent this idea can explain the observed pattern of increasing diversification of U.S. firms. In contrast to most of the literature on corporate structure, which has emphasized the links between corporate structure and financial issues such as capital market imperfections[2], his analysis identifies interesting links between real effects and corporate structure. The current paper pursues a view similar to Jovanovic's, in that it identifies real (spillover) effects along borders defined by the corporate structure. The importance of scope economies in knowledge production has recently also been a focus of the growth literature. Such scope economies have been identified as an engine of economic growth in papers by Stokey (1988), Young (1991) and Lucas (1993). Whereas the importance of scope economies in knowledge production is well recognized, little is known about their empirical significance. This paper provides some direct, empirical evidence on this phenomenon.

In addition to identifying R&D at the line-of-business level within each firm, my data set also identifies which firm belongs to the same "interlocking group of firms"[3]. The R&D data have been merged to production data at the plant level. The merged data set is used to study the impact of R&D along various dimensions. The parameter estimates reveal significant spillover effects across different lines-of-business within a firm. Significant spillovers are also identified for activities, within a line of business, that are carried out by different firms within the same interlocking group.

These findings are obtained by a new framework for using microdata to study the relationship between R&D and performance. This framework should be useful beyond the application presented here. The framework explicitly recognizes the importance of heterogeneity between

[1] Previously, analysis at comparable level of detail has to my knowledge been presented only by Lichtenberg and Siegel (1991). An advantage of my data set is that the R&D data are disaggregated to the line-of-business level (like the production data). This is an advantage in comparison to the data set used by Lichtenberg and Siegel, in which only the production data were disaggregated to the line-of-business level.

[2] See e.g. Gertner, Sharfstein and Stein (1993).

[3] The Norwegian term is "konsern". An interlocking group of firms is characterized by a parent-company and all subsidiaries in which the parent owns a majority share of equity.

firms in terms of production costs and product characteristics (within narrowly defined industries). The model is consistent with the existence of market power, quasi-fixed physical capital and scale economies in production.

Perhaps the most interesting aspect of the empirical framework presented in this paper is the alternative specification of knowledge production. In what has become the standard model for empirical analysis of the relationship between R&D and performance[4], knowledge accumulation is treated symmetrically to the accumulation of physical capital (as modelled in the "perpetual inventory model"). This treatment of knowledge accumulation is critized in the next section. The alternative specification of knowledge accumulation, presented in this paper, not only overcomes some of this critiscm, but it also provides a simpler and less data-demanding empirical model. In particular, the (dynamic) estimating equation requires only a single cross section of the R&D variables. This is very useful for the empirical analysis presented below, as my R&D data set is only available for a single cross-section. The estimating model is nevertheless fully consistent with a situation in which there are substantial and persistent differences in performance between firms. In fact, one of the main ideas of the model is that differences in know-how give rise to such a pattern. Know-how can not be directly observed, but is treated as a latent variable which (possibly) depreciates over time. However, we observe R&D effort which is assumed to increase know-how in a stochastic sense. We can therefore observe a determinant of *changes* in know-how (with noise added). As I argue below, the model might be labeled "a not-so-fixed effect" model, as it resembles the "fixed effect" (or correlated effect) model introduced into the production function literature by Mundlak (1961) and Mundlak and Hoch (1965). But the effects - the productivity differences between firms - are not fixed over time, but tend to be less and less fixed (that is; correlated) as we consider periods further and further apart.

The analysis presented in the next section points out the deficiencies of the perpetual inventory model as a model of knowledge accumulation. One of the properties of my alternative model is that it is consistent with the observed pattern that R&D effort tends to be a reinforcing process. It is widely recognized that there are large differences in the R&D effort across firms within narrowly defined industries[5], and that these differences in R&D effort are persistent over time[6]. Nelson (1988) has emphasized that the "standard model" does not capture this phenomenon of the coexistence of "innovators" and "imitators". In the alternative specification,

[4]What I refer to as the standard model has been spelled out and discussed in much detail in Griliches (1979). See also Griliches (1986).

[5]See Bound et al. (1984), Klette (1992) and Schankerman and Pakes (1984).

[6]Hall, Griliches and Hausman (1986).

such an outcome is modeled as 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. In other words, the model captures a situation where a lucky strike in previous R&D has a positive impact on the incentives to increase subsequent R&D effort.

The paper is outlined as follows: Section 2 contrasts some properties of the "perpetual inventory model" as a model of knowledge accumulation with the alternative model applied in this paper. Section 3 displays the empirical model. The data set is presented in section 4. Econometric issues are discussed in section 5. Section 6 exhibits the empirical results. I give some concluding remarks in section 7

2 A criticism of the standard model

The standard framework for econometric analysis of the relationship between R&D, profits and productivity was presented in Griliches (1979). Mairesse and Sassenou (1991) have surveyed empirical studies in this tradition. Essentially, the model treats the accumulation of knowledge capital in the same way as that of physical capital. However, some of the peculiarities of knowledge accumulation have been recognized. In some studies, knowledge capital is recognized to be a partially non-excludable good, so that spillovers across firms are taken into consideration. Jaffe (1986) and others have carried out empirical analyses of this aspect of knowledge capital. Griliches (1979, 1992) discussed the findings and problems of such studies of knowledge spillovers. The point I want to emphasize here is that the excludable part of knowledge capital is treated in the same way as ordinary capital.

The particular aspect of the standard model on which I focus is the form of the capital accumulation equation for knowledge:

$$K_t = K_{t-1}(1-\delta) + R_{t-1}. \tag{1}$$

This is the "perpetual inventory" model of capital accumulation widely used in neoclassical capital theory. The lag between R&D investment (R_{t-1}) and the arrival of new knowledge capital (K_t) is assumed to be one year here, but that is not important. The important aspect of this formulation is the assumption of perfect substitutability between new R&D investment and old knowledge. This property implies that *cet.par.* a firm with more initial knowledge capital in a given period will carry out less R&D investment. Such a negative correlation runs counter to the well-established fact that differences in R&D investment between firms (within a given industry) tend to be highly positively correlated over time. That is, there is a widely observed pattern that firms which carried out an above average amount of R&D last year will also tend to do so this year and *vice versa.*

To clarify my point and ease the comparison with the alternative model I will consider below, it is useful to present this argument in a formal way. The firm maximizes its net present value; $V_t(K_t)$, given its initial knowledge capital stock (K_t):

$$V_t(K_t) = \max_{\{R_{t+s}\}} \sum_{s=0}^{\infty} \beta^s(\pi_{t+s}(K_{t+s}) - w_{t+s}R_{t+s}), \tag{2}$$

subject to the accumulation equation (1). β is the discount factor, $\pi_t(K_t)$ is the short run profit function conditional on the knowledge capital stock, excluding R&D investment cost, while w_t is the unit cost of R&D investment. For convenience, I have not included other kinds of capital or uncertainty in the model. This can be easily done without changing the argument; it only involves more notation.

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

$$V_t(K_t) = \max_{R_t}[\ \pi_t(K_t) - w_tR_t + \beta V_{t+1}(K_t(1-\delta) + R_t)\ ]. \tag{3}$$

Assuming strict concavity of the short run profit function (in K_t), the optimal R&D investment (R_t^*) must satisfy the first-order condition[7]:

$$-\ w_t + \beta V'_{t+1}(K_t(1-\delta) + R_t^*) = 0 \tag{4}$$

If we consider two firms which differ only in their knowledge capital stocks (by an amount dK_t), it follows from this first-order condition that

$$\beta V''_{t+1}(\cdot)\ (dK_t(1-\delta) + dR_t^*) = 0. \tag{5}$$

That is, $dR_t^*/dK_t = -(1-\delta)$, if V'' is not zero. This can be restated

$$\frac{\hat{R}_t^*}{\hat{K}_t} = -(1-\delta)\frac{K_t}{R_t^*}, \tag{6}$$

[7]Lucas and Stokey (1989, ch. 4) show that if the short run profit function is strictly concave in the state variable, so is the value function. Consequently, strict concavity of the profit function is necessary for the model to satisfy the second-order condition associated with (4).

where a hat above an expression denote the logarithmic derivative; e.g. $\hat{R}_t^* = dR_t^*/R_t^*$. As anticipated, this analysis shows that there is a simple negative relationship between optimal R&D investment and the initial knowledge capital stock (K_t), if we start with an accumulation equation like (1).

The relationship suggests that we should observe a pattern of negative autocorrelation in $\log(R_t)$, or equivalently, a negative correlation between $\log(R_t)$ and the log of the knowledge capital stock. Such an autocorrelation pattern runs contrary to the observed pattern[8], which reinforces the doubt one might have about the appropriateness of (1) as an adequate formulation of knowledge accumulation. Some might argue that this exercise is too simple and that in reality there are other unobservable factors that offset this implication of the model. That is to say, the *cet.par.* claim made above is uninteresting. Ockham's razor provides the obvious counterargument: It is more satisfactory to search for a self-contained story more consistent with the basic facts, than to rely on unobservables which counter the unsatisfactory implications of the model. At least, Ockham's criterion is persuasive if the alternative, more consistent model provides an equally simple framework for analysis. As we shall see, the alternative model presented below offers a framework that is, in several respects, even simpler to implement empirically than the standard model.

2.1 An alternative model of knowledge accumulation

There is an alternative to the perpetual inventory model of capital accumulation that suggests that old capital and new investment are not perfect substitutes. The idea is that initial knowledge capital stock might have a positive effect on the incentives to carry out R&D. A similar effect, in the context of physical investment, was pointed out by Penrose (1959), and examined formally by Uzawa (1968). Hall and Hayashi (1987) and Romer (1990) have considered similar models in the context of knowledge accumulation. Griliches (1979) also suggests that such a formulation could be preferable. The basic idea is that greater initial knowledge will tend to increase the amount of knowledge obtained from a given amount of R&D.

Formally, the knowledge production function takes the form:

$$K_{t+1} = G(K_t, R_t) \tag{7}$$

with the (standard production function) properties that $G_K > 0, G_R > 0, G_{KR} > 0$ (while

[8] See e.g. Hall, Griliches and Hausman (1986).

$G_{KK} \leq 0$ and $G_{RR} \leq 0$). The subscripts denote the partial derivatives. Furthermore, in this theoretical section, I assume that $G(\cdot)$ is linear homogeneous, as is done by Uzawa (1968) and Hall and Hayashi (1987), but not by Romer (1990). The assumption of linear homogeneity in the knowledge production function will be relaxed in the empirical section. Notice that the standard model satisfies all these assumptions, except that in the standard case $G_{KR} = 0$. It is the sharp inequality in this cross-derivative that will alter the implications of the model, as we shall see below, and that corresponds to the assumption of less-than-perfect substitutes between old and new capital.

It follows from the stated assumptions that $K_{t+1} = K_t G(1, R_t/K_t) \equiv K_t g(R_t/K_t)$, where $g' > 0$ and $g'' < 0$.

The first-order condition from the Bellman equation, similar to equation (4), can in this case be written:

$$-w_t + \beta V'_{t+1}(K_t g(R_t^*/K_t)) \; g'(R_t^*/K_t) = 0. \tag{8}$$

Notice that the argument in the value function is changed according to the more general accumulation equation (7). Equation (8) can be rewritten:

$$\ln[V'_{t+1}(K_t g(R_t^*/K_t))] + \ln[g'(R_t^*/K_t)] = \ln(w_t/\beta). \tag{9}$$

By totally differentiating this equation with respect to K_t and R_t^*, we find that

$$\frac{K_t g V''_{t+1}}{V'_{t+1}} \left(\hat{K}_t + \frac{R_t^* g'}{K_t g}(\hat{R}_t^* - \hat{K}_t) \right) + \frac{R_t^* g''}{K_t g'}(\hat{R}_t^* - \hat{K}_t) = 0. \tag{10}$$

As before, a hat above an expression denotes the logarithmic derivative. The arguments of the value function and the g-function have been dropped for notational convenience. Denote $-(K_t g V''_{t+1})/V'_{t+1}$ by ω. ω is a measure of the concavity of the value function, and consequently is determined by the concavity of the profit function. ω is non-negative if the value function is concave, and zero if the value function is linear. Introducing ω, and collecting terms, we find that

$$\hat{R}_t^* = \left(1 + \frac{\omega}{\lambda}\right) \hat{K}_t, \tag{11}$$

where I have also introduced $\lambda \equiv (R_t^* g'')/(K_t g') - \omega(R_t^* g')/(K_t g)$. With a linear value function

($\omega = 0$), there is clearly a positive relationship between $\hat{R}_t^*$ and $\hat{K}_t$ [9].

In the special case considered by Hall and Hayashi (1987), where $G(R_t, K_t) = R_t^{\nu} K_t^{1-\nu}$, it is easy to show that $\lambda = \nu - 1 - \nu\omega$. It follows that $1 + \omega/\lambda = (1 - \omega\nu - \nu)^{-1}(1-\nu)(1-\omega)$, which is positive if ω is below unity, i.e. the value function is not too concave. In this case there is also a positive relationship between $\hat{R}_t^*$ and $\hat{K}_t$.

More generally, the sign of $\hat{R}_t^*/\hat{K}_t$ depends on whether $\omega + \lambda = \omega[1 - g' R_t^*/(K_t g)] + g'' R_t^*/(K_t g')$ is positive or negative. This sign is determined by the concavity of the value function, as well as the properties of the g-function up to its second derivative.

To summarize, the model of accumulation considered in this section suggests that the initial knowledge capital stock, that is, past R&D, may be positively related to the amount of current R&D investment, in contrast to the standard ("perpetual inventory") model. But the model does not unambiguously imply a positive relationship between past and current R&D, as this relationship depends on the shape of the value function and the knowledge production function ($G(\cdot)$). The point I want to make is that the model does not *per se* have the counterfactual implications of the standard model. In the empirical model to be presented below, I will elaborate on the specification of the knowledge production function.

2.2 On knowledge depreciation

The social value of knowledge capital can depreciate because of obsolescence. When we consider the private value of knowledge capital, where the focus is on the appropriable part of the knowledge stock relative to the firm's competitors, knowledge capital will also depreciate because competing firms imitate the ideas of an innovative firm[10]. In empirical studies of R&D it is not the absolute amount of knowledge capital which matters, but the relative amount of knowledge compared to the other firms in the sample.

The point to note is that the standard model has not been able to empirically identify the depreciation rate, either in absolute or relative terms. Indeed, Mairesse and Sassenou (1991) and Hall and Mairesse (1993) have pointed out that the parameter estimates of the impact of the knowledge capital stock on productivity is insensitive to the choice of the depreciation rate. This result has the troublesome implication that the estimated net private rate of return to R&D, based on the coefficients from such regressions, are very sensitive to the assumption one

[9] Nothing in the derivation of (11) hinges on G_{KR} being strictly positive. It is a simple exercise to show that (11) is reduced to (6) when the knowledge production function is of the "perpetual inventory" form (1).

[10] Schankerman and Pakes (1984) discuss this issue.

makes about the depreciation rate. Considerable attention is paid to such estimates of rates of return to knowledge capital. Hence, it is desirable to obtain a model that does not rely heavily on outside and largely unavailable parameter estimates in order to identify the rate of return to knowledge capital and related variables of interest.

Unlike the standard model, the empirical model to be estimated below has the advantage that it is able to identify the depreciation rate of the appropriable part of the knowledge stock. That is, I will estimate *cet.par.* the speed of convergence towards the average firm for a firm which starts with, say, an above average knowledge stock. As will be shown, this is the depreciation rate that is required to estimate the value of the knowledge capital stock and the rate of return to this kind of capital.

3 The basic empirical model

3.1 The model of short-run producer-behavior

This section presents the applied framework for short run producer behavior, which is a hybrid of non-parametric productivity-analysis and an ordinary production-function[11]. In Klette (1993), I have presented a detailed derivation of the model. A brief summary of the derivation is given in appendix A. 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 ordinary capital stock is assumed to be (quasi-) fixed when the firm solves its short-run profit-maximization problem.

Although the unit of observation in the empirical section is a plant, it is still convenient to term the decision making unit the firm rather than the plant at this stage. The distinction between the model for the plant and that for the firm will be introduced later. The treatment of knowledge capital will also be discussed below.

In solving the short-run profit-maximization problem, the firm chooses the amount of labour and materials, and sets the output price. The formal expression of the model is (cf. appendix A)

$$\hat{q}_t = \mu \sum_{l=M,L} \theta_t^l(\hat{x}_t^l - \hat{c}_t) + \epsilon\, \hat{c}_t + \alpha\hat{k}_t + \hat{u}_t. \tag{12}$$

[11]The framework presented here is a generalization of the model in Hall (1988, 1990). While Hall focuses on the estimation of markups in the absence of scale economies, the framework presented here permits a simultaneous treatment of markups and scale economies.

In this discussion of the empirical model, a hat above a lower case variable denotes the logarithmic deviation from the reference firm of the corresponding upper-case variable. Q_t and X_t^l represent output and input "l" (labour and materials). The subscript "t" refers to year. μ is the markup and ϵ is the scale elasticity of the "ordinary factors" of production (labour, materials and ordinary capital). C_t and K_t correspond to ordinary capital (machinery and buildings) and knowledge capital. α is the output elasticity of the firm's own knowledge capital. This parameter reflects the opportunities for *process innovation.* θ_t^l is the cost of input "l" relative to the value of output. $\hat{u}_t$ represents differences in factor productivity not accounted for by the R&D capital variable.

3.2 Output versus deflated sales

Klette and Griliches (1992) have examined 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 when the firms compete in an imperfectly competitive environment, where prices will reflect idiosyncratic differences in cost. This feature of the economic environment seems *a priori* to be relevant to high-tech firms, operating in industries with rapid and idiosyncratic changes in technology and product design.

Consider a demand function $Q_t = Q(P_t, K_t, D_t)$, where P_t, K_t and D_t refer to price, knowledge capital and other demand shifters, respectively. A firm's knowledge capital will affect demand through improved product quality[12]. If we take a log-linear expansion of the demand function around the reference firm, we have

$$\hat{q}_t = \eta\hat{p}_t + \xi\hat{k}_t + \hat{d}_t, \tag{13}$$

where now $\hat{p}_t$ 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 opportunities for *product innovations.* $\hat{d}_t$ is a demand shifter. From the relationship between output and sales; $S_t = Q_tP_t$, we have that $\hat{s}_t = \hat{p}_t + \hat{q}_t$. This relationship can be used to eliminate the unobservable $\hat{p}_t$ in equation (13) to obtain

[12]Another way to think about this demand system is in terms of hedonic prices. The price that matters from a consumer's point of view is the price per quality-adjusted commodity-unit. We assume that the firm's knowledge capital affects its product quality. Consequently, the quality-adjusted price of a firm's output relative to that of its competitors will, *cet.par.*, be a decreasing function of its knowledge capital relative to its competitors. See Griliches and Mairesse (1984), Levin and Reiss (1988) and Nadiri and Bernstein (1988) for a related approach to modeling the effect of R&D.

$$\hat{q}_t = \frac{1}{\eta+1}\hat{d}_t + \frac{\eta}{\eta+1}\hat{s}_t + \frac{\xi}{\eta+1}\hat{k}_t. \tag{14}$$

Profit-maximizing behavior implies that the firm uses the markup factor $\mu = \eta/(1+\eta)$[13]. Using this relationship, and combining (12) and (14), we get the relationship

$$\hat{s}_t = \sum_{l=M,L} \theta_t^l(\hat{x}_t^l - \hat{c}_t) + \frac{\epsilon}{\mu}\hat{c}_t + \gamma\hat{k}_t - \frac{1}{\eta}\hat{d}_t + \frac{1}{\mu}\hat{u}_t, \tag{15}$$

where $\gamma = \alpha/\mu - \xi/\eta$. Notice that the two terms that make up the γ-parameter capture the effect of process and product innovations. Both terms contribute positivly to the parameter, as η is a price elasticity which takes on negative values by definition.

Define the Solow residual:

$$\hat{a}_t \equiv \hat{s}_t - \sum_{l=M,L} \theta_t^l(\hat{x}_t^l - \hat{c}_t) - \hat{c}_t. \tag{16}$$

Then (15) can be rewritten

$$\hat{a}_t = \left(\frac{\epsilon}{\mu} - 1\right)\hat{c}_t + \gamma\hat{k}_t - \frac{\hat{d}_t}{\eta} + \frac{\hat{u}_t}{\mu}. \tag{17}$$

This completes the derivation of the model of short-run producer behavior.

3.3 The accumulation of knowledge capital

As discussed in section 2, I will consider a new knowledge production function. Specifically, take the log-linear version of (7)[14]. Since the log-linear relationship is assumed to hold for all firms, including the reference firm, we can use the log-linear relationship in relative terms:

$$\hat{k}_{t+1} = (\rho - \nu)\hat{k}_t + \nu\hat{r}_t + \hat{v}_t \tag{18}$$

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 tomorrow, measured relative to the average competitor, depends on its relative capital stock from the past, as well as the firm's relative R&D effort.

[13] We assume that the number of firms are sufficiently large so that oligopolistic aspects of price setting behavior are negligible. See e.g. Klette (1994) for price setting rules in a simple model where both product differentiation and oligopolistic interactions are important.

[14] Hall and Hayashi (1988) used a similar formulation in their analysis of R&D investment behavior.

The specification in (18) allows for increasing (or decreasing) returns in the knowledge production function if ρ is larger (smaller) than one. If $(\rho - \nu)$ is smaller than one, the model suggests that there is a tendency for convergence. In this case, a firm that starts with above-average knowledge capital will gravitate towards the average firm if it carries out the average amount of R&D. In order to stay ahead in this case, the firm has to conduct an above average amount of R&D. If $(\rho - \nu)$ is larger than one, the model suggests a cumulative process, in which an above-average firm will depart more and more from the average firm, even if it invests the same amount of R&D as the average firm.

As the difference equation (18) shows, it is natural to interpret $(\rho - \nu)$ as a depreciation rate. It determines *cet.par.* the speed of evaporation of a firm's knowledge advantage (or disadvantage). The $(\rho - \nu)$ parameter depends on two basic properties of knowledge accumulation. If there are significant scale economies in R&D, this will suggest a high value of $(\rho - \nu)$. On the other hand, a substantial amount of spillover and diffusion of knowledge will pull this parameter in the opposite direction. The ν-parameter alone reflects the innovative opportunities of R&D effort.

In some industries, such as pharmaceuticals, it is unrealistic to assume a one year lag between R&D and new profitmaking knowledge, as in (18). However, I believe that the results presented below are not highly sensitive to the assumed lag length, since there tends to be a high degree of autocorrelation in relative R&D effort over time (cf. the discussion in section 2). The appropriate lag length in (18) will be a topic for future research, using data for several cross-sections of R&D data.

$\hat{v}_t$ is a stochastic term which reflects the importance of firm specific stochastic elements in the innovation processes[15]. Pakes and Ericson (1989) have argued that such firm specific stochastic elements in the knowledge accumulation (in a broad sense) represent an important aspect of firm dynamics. A basic motivation behind the framework outlined in the present paper, is to present a model that captures such shocks and, in particular, allows such shocks to have lasting direct and indirect impact on a firm's performance. That is to say, the model is set up so that a positive shock in knowledge accumulation will have a direct impact on the firm's performance. This will be a lasting impact due to the autoregressive process for the capital stock. But there is

[15]Here I will not elaborate on the extent to which such stochastic elements are due to variables that are unobserved to us as outside observers, or to which innovation involves inherently stochastic processes (even in the presence of complete information – whatever that means). The basic point is that even for the most complete data sets available (today or in the near future), a substantial stochastic component will remain in our empirical specification of the knowledge production function.

also an indirect effect on performance of such a knowledge shock, due to the increased incentives for R&D investment the shock may provide. This indirect effect will not be studied directly in this paper, but is on my agenda for future research modeling the pattern of R&D investment behavior.

The possibility of incorporating stochastic shocks in the accumulation model for knowledge capital in a clean way is a benefit of the alternative model as compared to the standard ("perpetual inventory") model. As we shall see below, my alternative model allows a simple elimination of the knowledge capital stock. This is desirable as stochastic shocks will make it impossible to construct an unbiased measure of the relevant knowledge variable[16].

3.4 The "not-so-fixed effect" model

Define the quasi-difference operator; $\tilde{\Delta} = 1 - (\rho - \nu)L$, where L is the lag-operator. If we apply this operator to equation (17), and eliminate the unobservable knowledge capital stock by equation (18), we obtain

$$\tilde{\Delta}\hat{a}_{it} = (\epsilon/\mu - 1)\,\tilde{\Delta}\hat{c}_{it} + \gamma\nu\,\hat{r}_{I,t-1} + \hat{e}_{it}. \tag{19}$$

Here I have introduced a subscript "i" to denote the plant under consideration. The subscript I refers to the line-of-business, within the firm to which the plant belongs. For a single-plant firm, the two subscripts "i" and "I" will refer to the same unit of observation, but for multi-plant firms this may not be the case. If a firm operates several plants within a line-of-business, this model assumes that they all have access to the same knowledge capital stock, apart from random noise buried in the residual. Implicitly, this formulation assumes the presence of scale economies in the *utilization* of knowledge capital. Such scale economies are analytically distinct from economies of scale in the *production* of knowledge capital, i.e. the scale economies in the $G(K_t, R_t)$-function. This distinction was emphasized by Fisher and Temin (1973). The residual ($\hat{e}_{it}$) captures the error term from the model of short-run producer behavior. Due to the quasi-difference operation, the error term will have a first-order moving-average structure if the untransformed residuals, (the $\hat{u}_t$ and $\hat{d}_t$ in (15)), are uncorrelated over time. $\hat{e}_{it}$ will also contain the error component from the knowledge production function ($\hat{v}_t$).

Equation (19) can be spelled out more completely:

[16] In the standard model, the problem is that we need the log of the capital stock, and it is this logtransformation that makes it impossible to create an unbiased measure of the required capital *variable* (i.e. the log of the capital stock).

$$\hat{a}_{it} = (\rho - \nu)\hat{a}_{i,t-1} + (\epsilon/\mu - 1)\hat{c}_{it} - (\rho - \nu)(\epsilon/\mu - 1)\hat{c}_{i,t-1} + \gamma\nu\hat{r}_{I,t-1} + \hat{e}_{it}. \tag{20}$$

This is the equation that has been estimated in this study. The model contains the standard fixed-effect model as a special case ($\rho - \nu = 1,\ \epsilon/\mu = 1$), if we disregard the way R&D investment enters the model. More generally, (20) portrays a model of plant (and firm) dynamics in which there are persistent differences in performance between plants, but not quite as persistent as in the fixed effect case, at least not if the leading firms do not continue their above average effort in R&D. Hence, one might label this model "a not-so-fixed effect model".

4 Variable construction and the data

The regressions are carried out on observations dated 1989 and 1990 for Norwegian manufacturing. There are 804 plants in the sample from 3 (2-digit) industries: Chemicals (ISIC 35), Metals (ISIC 37) and Machinery and equipment (ISIC 38). These industries carry out by far the largest share of R&D among the Norwegian manufacturing industries (about 94 percent of total manufacturing R&D). They also have the highest R&D intensities[17]. See table 1 for summary statistics on R&D in Norwegian manufacturing. Production data have been taken from the Manufacturing Time Series files, which contain the needed variables at the plant level (see appendix B for details), as well as the plant's company affiliation. We have eliminated plants with extreme value added per unit of labour or capital[18]. In addition to the observations entering the regression, the data set also contains additional lagged observations for the production variables, which are used as instruments[19]. Table 2 reports some summary statistics for the sample.

The R&D data have been taken from the Norwegian R&D survey in 1989, carried out by The Royal Norwegian Council for Research and Technology (NTNF). This survey is close to a census for all firms with more than 20 employees in the industries we consider. For firms with less than 20 employees, the coverage is less certain. Consequently, we have eliminated firms with less than 20 employees from our sample. The R&D data have been matched (manually) by company name and addresses[20]. The R&D data from 1989 have the great benefit, for our purpose, of containing information about whether the firm belongs to an interlocking group of firms. An interlocking group of firms is characterized by a parent-company owning and all subsidiaries in which the

[17] See Naas (1993) for an analysis of the pattern in R&D spending across industries and over the period 1985-89 (in Norwegian).

[18] "Extreme values" means more than 300 percent away from the median value within each 3-digit industry.

[19] Such lagged observations are easily available for the production statistics, but not for the R&D variables.

[20] I am grateful to G. Frengen and other people in Statistics Norway who helped me with this task.

parent owns a majority of equity. For firms belonging to an interlocking group (from now on often referred to only as "group"), the file provides an identification code for the group. The use of this information will be described in the next section. Another attractive aspect of this data source is that the file reports R&D disaggregated by line of business *within each firm*. The majority of firms report R&D in only one line of business; such a breakdown by line-of-business is still informative for firms that produce in several lines-of-business, as this breakdown helps us to identify the target line-of-business for the R&D activity.

The labour costs in the production data have been adjusted for R&D labour costs to avoid double counting. All production data are measured as deviations from (3-digit ISIC-code) industry-time average values.

4.1 The R&D variables and the search for spillovers

The degree of detail in the data allow us to address a number of issues by examining the impact of various R&D variables. The basic R&D variable refers to the amount of R&D done *within the line-of-business within the firm* to which the plant belongs[21]. Beyond this R&D variable, I have also considered other variables that possibly reflect the impact of R&D activities in other parts of the firm as well as the group. See figure 1, which illustrates the use of these variables. One set of regressions will consider the impact of R&D in other lines-of-business within the firm on the performance of a plant (cf. the impact of R&D in LB 37 in firm A, on plant 1). Another set of regressions will examine the impact of R&D carried out in other firms within the group (cf. LB 35 or LB 381 in firm B). The alternatives considered and their interpretations will be discussed in more detail when I present the regression results.

In our data set there are a number of firms that report no R&D. This causes our model to collapse for these observations, a problem well-recognized by researchers in this field. The standard interpretation of these zeros is that they reflect a censoring problem, and that all firms have some knowledge capital and are doing some new knowledge acquisition, but not necessarily in the form of formal R&D. I have used the standard fix-up for this problem by setting the log of the R&D variable equal to zero and adding a dummy variable that takes the value one for these firms, and zero otherwise. The interpretation of the dummy-coefficent is as the log of the average amount of knowledge acquisition for these firms, measured in R&D terms. We would expect these firms to do on average less knowledge acquisition than the R&D performing

[21] I am grateful to S.E. Førre who helped me with a detailed examination of possible errors in the industry classification of the reported R&D activities.

firms, which, since variables are measured relative to the average plant, translates to a negative coefficient for this dummy. An obvious alternative to this procedure is to restrict the sample to plants belonging to R&D performing firms. Experiments with this subsample gave similar parameter estimates, but less precision, as expected. Hence, the results below will be based on the more informative complete sample.

4.2 Some additional regressors

The basic model in equation (20) has been augmented in several ways. I have added a set of dummy variables that reflect the three different types of plants considered in these industries, "sole facilities in a single-plant firm", "parent facilities in a multi-plant firm" and "subsidiary facilities in a multi-plant firm". The motivation for introducing these dummies is that these types of plants may appear to converge to different average performance measures as they carry out different amounts of overhead activities. The regressions also contain dummy variables that reflect whether the firm is foreign-owned or not, and within two alternative intervals (20-50 percent vs. more than 50 percent foreign ownership)[22]. Industry dummies have not been introduced as all variables are measured relative to their time-industry means.

5 Econometric issues

Equation (20) can not be estimated directly by OLS, as the model contains a lagged dependent variable, and the error term is autoregressive of (at least) the MA(1)-form by construction[23]. The estimation is instead carried out by GMM[24]. The preferred regression is based on an instrument set consisting of capital and the number of employees dated t-1 and earlier, output dated t-2 and earlier, as well as the Solow residual dated t-3. The R&D variable is not instrumented, as it is assumed to be determined before the knowledge shock (and the performance shock) is revealed. I will present both formal overidentification tests and estimates based on alternative instrument sets below.

As the model is written in (20), there are some cross coefficient restrictions that appear to provide a means for specification testing, and more efficient estimation of the primary parameters of the model. 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.

[22]See Simpson (1994) for a study of the importance of foreign ownership using a larger set of the same data.
[23]See Griliches (1961).
[24]See Hansen (1982). GMM in my case, with only cross-sectional variations, is equivalent to the 2SIV-estimator suggested by White (1982).

6 The results

6.1 The basic model

Table 3 reports the basic results. The first column reports the preferred regression. The lagged dependent variable enters with a highly significant coefficient not very far from one. This result is consistent with the observation that productivity differences are highly persistent. However, the coefficient is significantly below one, and suggests a depreciation rate around 0.2 . The two capital variables have coefficents that are not significantly different from zero, which suggests that the scale coefficient and the markup are of similar magnitude (but not necessarily one!). The coefficient of R&D investment is highly significant and has the expected sign. The interpretation of the magnitude of this coefficient will be presented in the next section. The "No-R&D"-dummy is also highly significant. This estimate suggests that plants belonging to the "No-R&D"-firms tend to have a performance measure (Solow residual) 2.5 percent below the average. The "type of plant" dummies are not reported, but are highly significant. A joint test of both the R&D variable and the No-R&D dummy is reported under the horizontal line.

The GMM overidentification test, suggested by Hansen (1982), does not indicate that the model is misspecified. However, rather than relying entirely on the overidentification test as an omnibus specification test, I have examined a series of *a priori* interesting alternative specifications [25]. Column 2 reveals that nothing of substance hinges on the use of the GMM-estimator as compared to the 2SLS estimator. Column 3 demonstrates that even though the "type of plant" dummies are highly significant, dropping them does not seriously affect the parameters of interest. If we drop the dependent variable lagged three times as an instrument, the coefficent of the lagged dependent variable increases, while the coefficent of the R&D variables decreases. However, none of these changes results in coefficents outside the confidence interval of the preferred regression[26]. When I drop the lagged dependent variable as an instrument, I still find the R&D coefficients to be significant at standard significance levels. Adding the dependent variable lagged two times as an extra instrument, causes the overidentification test to reject, as reported in column 5. The last column shows what happens if we add industry dummies to the regression. As argued above, industry effects have been incorporated in one sense, as all vari-

[25] Cf. Newey (1985) for a discussion of the limitations of the GMM overidentification test as an omnibus specification test.

[26] A formal Hausman test on the other hand would clearly reject the first model. But as pointed out by Arellano and Bond (1991) among others, the Hausman-test based on (2-step) GMM-estimates has a serious tendency to overreject.

ables (sales, labour, materials etc.) are measured relative to their time-industry means. Though the R&D coefficient is insensitive to this change, other parameters are less so. In particular, the coefficient of the lagged dependent variable increases, both the capital coefficients turn highly significant, and the No-R&D dummy disappears. This pattern suggests at least two avenues for extending the model. One is to allow the scale/markup-ratios to differ across industries. The other is to let the coefficient of the No-R&D dummy to differ across industries, reflecting differences in their censoring levels. Experiments along these lines suggested that the model in this case is over-parameterized and not identifiable from the available sample. However, the R&D coefficient remained stable and significant in most of these regressions. The bottom line is that the preferred regression in column 1 seems reasonably stable across a set of alternative specifications. After presenting an interpretation of the magnitude of the R&D coefficient, the rest of the paper will present more regressions that extend this preferred specification of the model.

6.2 Interpreting the magnitude of the coefficients

In appendix C, I have shown that, for the model presented in section 3, the marginal (nominal) product of knowledge capital is given by

$$\frac{\partial \pi_{it}}{\partial K_{it}} = \gamma \frac{S_{it}}{K_{it}}, \tag{21}$$

where π_{it} and S_{it} denote the firm's profit and sales. Using the envelope theorem, and the fact that the (stochastic) Bellman equation[27] should hold for all values of the knowledge capital, yields

$$V'(K_{it}) = \frac{\partial \pi_{it}}{\partial K_{it}} + \beta E_{it}\left[V'(K_{i,t+1})\frac{\partial G_{it}}{\partial K_{it}}\right], \tag{22}$$

where the G_{it}-function now also captures the random component, in order to be consistent with the empirical model. $E_{it}[\cdot]$ is the expectation operator that conditions on the information available to firm i at time t. The first order condition for R&D investment can be written

$$w_{it} = \beta E_{it}\left[V'(K_{i,t+1})\frac{\partial G_{it}}{\partial R_{it}}\right] \tag{23}$$

Combining (21), (22) and (23), we find

[27] Cf. a stochastic version of (3). See Stokey and Lucas (1989, ch. 9) for a presentation of stochastic dynamic programming.

$$\frac{V'(K_{it})K_{it}}{S_{it}} = \gamma + \frac{(\rho - \nu)}{\nu}\frac{w_{it}R_{it}}{S_{it}} \tag{24}$$

In deriving (24), I used the log-linear functional form of the knowledge production function applied in the empirical section of this paper[28]. Unfortunately, I am not able to identify ρ, ν and γ separately in my regressions. But if we are willing to assume constant returns to scale in the knowledge production function, then it is easy to identify the parameters we need to evaluate (24) for our firms. Notice that constant returns to scale in knowledge production is a maintained hypothesis in the standard model (1). With constant returns to scale in the knowledge production function, the estimates in the first column in table 3 imply $\nu = 0.2$, and $\gamma = 0.07$[29]. That is to say, the value of the knowledge capital stock relative to a firm's sales is close to 0.07 for firms with very low (but positive) R&D intensities. The more R&D intensive firms have a substantially higher ratio, seen in the estimate of 4 for the slope coefficent of the last term in (24). Using the sample mean R&D intensity for all R&D performing plants suggests an average knowledge capital intensity around 0.51 . Electrical equipment (ISIC 383) alone, which is the most R&D intensive industry, has a mean knowledge capital to sales ratio of 1.12 . However, the large spreads in the observed R&D intensities across my sample suggest large variations in the knowledge-capital to sales ratio.

6.3 Spillovers within group

Table 4 reports the regression results for my exploration of spillovers across plants that share a line-of-business, and belong to the same interlocking group of firms. Referring to figure 1, this set of regressions examines whether only the R&D in LB 35 within firm A affects the performance of plant 1, or whether the R&D within LB 35 within firm B also matters. In this analysis I am limiting the focus to spillovers to remain inside a given line-of-business within the group. The first column reports a regression in which we directly try to identify whether it is the R&D within the firm or the R&D within the group that affects a plant's performance. The iedntification is obtained by a regression that includes both the firm-LB and the group-LB R&D variables. To reduce the mulitcollineratiy problem, the variables are redefined as the firm-LB R&D variable, as against the difference between the firm-LB and the group-LB R&D variable. The results clearly suggest that it is the R&D within the firm rather than the group that matters. In fact,

[28] I.e. $K_{i,t+1} = V_{it}K_{it}^{\rho-\nu}R_{it}^{\nu}$, where V_{it} is a mean one, random component.

[29] ν is given as 1 (the assumed value for ρ) minus the coefficient in front the lagged Solow residual, while γ is the coefficient in front of R&D divided by our ν-estimate.

the regression seems to attach no weight to R&D effort outside the firm. To push this result a bit further, an alternative line of inquiry has been pursued in the next two columns. Column 2 uses within-firm (and within LB) R&D as the basic R&D variable, but adds to the regression a dummy that is one if there is R&D activity outside the firm but within its group-LB, and zero otherwise[30]. There are 53 observations with a non-zero dummy variable of this kind. The coefficient on the dummy variable is significant and suggests the presence of positive spillovers. The last column introduces an additional dummy variable that is similar to the dummy variable employed in the column 2 regression, but now with a threshold at 50 mill. Nkr rather than zero. 20 of the 53 observations with non-zero dummy in column 2 exceed this threshold[31]. The outcome of this regression clearly suggests that there is an identifiable, positive effect associated with this second dummy. That is to say, there seem to be strong spillovers across firms within a group and a given line of business, if the R&D effort is of a sufficient magnitude. A natural interpretation of this finding is that some of the groups have a central R&D laboratory that create innovations benefiting the whole group and not only the firm to which the laboratory belongs.

6.4 Economies of scope

The last set of results presented in table 5 consider spillovers across lines-of-business within the firm as well as within the group. I will label such spillovers economies of scope in R&D (in accordance with the definition in Panzar and Willig, 1981). As in the previous set of regressions, the approach is to introduce a set of dummy variables. The first column indicates that there is a positive, but insignificant, effect of R&D effort in other lines-of-business *within the firm*. The dummy variable that yields us this result is defined as one if there is some R&D activity in other lines-of-business within the firm. The lack of precision is not surprising as my sample has only 12 observations with non-zero dummy values in this case.

The next two columns consider economies of scope in R&D not only within the firm, but within the group. The second column shows the outcome when a dummy is introduced that is positive if the group undertakes R&D beyond the 5 mill. Nkr threshold and zero otherwise. The coefficient is of similar magnitude to the previous coefficient, and is estimated with more precision. The increased precision reflects a larger number of non-zero observations for this

[30] Cf. figure 1: If there is R&D activity in firm B, within LB 35, the dummy for plant 1 equals one.

[31] To reduce the multicollinearity problem between the two dummies I and II, the first dummy variable is set to zero when the second is one. This affects the interpretation of the coefficient of the second dummy.

dummy (72) in this regression. The last column suggests that the more R&D carried out in the other firms within the group, the larger is the benefit, as one might expect[32].

7 Concluding remarks and future research

The relationship between R&D and performance has been addressed with a new framework in this paper. This framework not only provides a new interpretation of well-established correlations in firm-level data; it also has allowed us to consider some new relationships. The empirical performance of the model is encouraging as it is able to capture and identify several phenomena of interest. The following substantial empirical findings have emerged from this study:

- R&D is a significant explanatory variable for performance at the firm (and plant) level.
- Non-R&D performing firms have, on average, a 2.5 percent lower performance measure (Solow residual) than the average of all firms.
- The rate of depreciation of the appropriable part of knowledge capital is estimated to be about 0.2 .
- There are visible (and significant) spillover effects of R&D across firms operating in the same line of business, and which belong to the same interlocking group.
- I also find some evidence suggesting that there are economies of scope in R&D across lines-of-business within a firm. Similar scope economies also seem to be working across firms that belong to the same interlocking group of firms.

The results presented in this paper are based on a short panel of observations. Most of the basic results presented above could be examined on longer panels and much larger data sets that are already available in many countries. I intend to pursue such research in the near future. Other results related to scope economies and spillovers require R&D disaggregated in a detail not often seen in other data sources. But the results presented in this paper hopefully encourage other researchers to search for rich data sets that could be used to address similar issues.

The model of knowledge accumulation presented in this paper has some interesting implications for the correlation in R&D investment over time, as well as cross equation correlations

[32] Regressions in which we pooled the information used in table 4 and 5 have been done; these regressions merged all the R&D undertaken outside the line-of-business for the plant under consideration. The results were similar to those reported in the last two columns in table 5.

in the error terms in the performance model (presented in this paper) and an R&D investment model. I intend to examine this pattern in future research in order to more conclusively discriminate between the standard model and the alternative presented here. Perhaps such an extension of the analysis will enable us to estimate the ρ-parameter, which captures the magnitude of scale economies in knowledge production. As recent research in growth theory has pointed out, identifying such a phenomenon could be important for understanding economic growth at various levels of the economy.

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Appendix A: The model of producer behavior

The starting point of this analysis is a differentiable production function for a technology with one output and a number of inputs[33]. Let us denote the production function as $Q_t = F(X_t)$, where X_t denotes the vectors of inputs and Q_t is output. Assume that the production function can be assumed to be a second order polynomial in log of the inputs, such as for the general translog production function. We do not assume constant returns to scale or a homothetic technology. Diewert (1976) has proved that in this case, for *any* two input-output vectors; (Q_{0t}, X_{0t}) and (Q_t, X_t):

$$\hat{q}_t + \sum_{l \in N} \alpha_t^l \hat{x}_t^l = 0, \tag{25}$$

where we use the notation that a hat above a variable represents the logarithmic changes, e.g. $\hat{q}_t = \ln(Q_t/Q_{0t})$ etc., and

$$\alpha_t^l \equiv \frac{1}{2}\left(\frac{X_{0t}^l}{F(X_{0t})}\frac{\partial F(X_{0t})}{\partial X_{0t}^l} + \frac{X_t^l}{F(X_t)}\frac{\partial F(X_t)}{\partial X_t^l}\right) \tag{26}$$

In our case the two input-output vectors will refer to two different plants in the same industry. That is to say, $\hat{x}_t^l$ will denote the percentage difference of input "l" between the plant in focus and a reference plant for a given year (t). N is the set of inputs. α_t^l is the average output elasticity of input l, where the average is constructed on the basis of the plant in consideration and the reference plant.

Under profit maximization, the marginal revenue product of an input is equal to marginal cost for a fully adjustable factor of production. Let us assume that the firm determines inputs, considering input prices to be fixed[34]. It follows that

$$\frac{X_t^l}{F(X_t)}\frac{\partial F(X_t)}{\partial X_t^l} = \frac{W_t^l X_t^l}{(1/\mu)P_t Q_t} \qquad t = 1, 2 \tag{27}$$

where 'μ' is the ratio between price and marginal revenue (= marginal costs), while W_t^l and P_t are the prices of input i and the output. Combining (26) and (27), we have that the output elasticity for an adjustable input is

[33]This section borrows heavily from Klette (1993).

[34]This is clearly the case with standard price taking behavior. It is also true with a bargaining model where the unions and the firm negotiate about the wage rate, while the firm unilaterally determines the level of employment.

$$\begin{aligned}\alpha_t^l &= \frac{\mu}{2}\left(\frac{X_{0t}^l W_{0t}^l}{P_{0t}Q_{0t}} + \frac{X_t^l W_t^l}{P_t Q_t}\right) \\ &= \mu\theta_t^l \end{aligned} \tag{28}$$

where θ_t^l is the average cost share of input t for the reference plant and the plant in focus.

Various kinds of rigidities, input lags and expectational errors make it dubious to impute the marginal product of capital from observed prices on new equipment, interest rates etc. In productivity analysis of a competitive industry with constant returns to scale, this problem is dealt with by estimating the shadow price, and thereby the (shadow) elasticity of capital, as a residual. The case with imperfect competition and non-constant returns is almost as simple if we assume that we know - or can estimate - the overall scale elasticity to all factors. Denote this scale elasticity as η. Then we have that the output elasticity of capital (α_t^c), obeys the following relationships

$$\begin{aligned}\alpha_t^c &= \eta - \sum_{l \neq K} \alpha_t^l \\ &= \eta - \sum_{l \neq K} \mu\theta_t^l. \end{aligned} \tag{29}$$

The last equality follows from (28).

Using the expressions in (28) and (29), equation (25) can be rewritten

$$\hat{q}_t = \mu \sum_{l \in N} \theta_t^l(\hat{x}_t^l - \hat{x}_t^K) + \eta\hat{x}_t^K. \tag{30}$$

The empirical model

In our case, the explicit regression equation corresponding to the model derived above can be stated:

$$\hat{q}_t = \mu \sum_{l=M,L} \bar{\theta}_t^l(\hat{x}_t^l - \hat{c}_t)) \;+\; \eta\hat{c}_t \;+\; \alpha\hat{k}_t \;+\; \hat{u}_t. \tag{31}$$

The left hand side variable measures relative differences in output, while the right hand side variables refer to labour (L), materials (M) and capital (C). The subscript 't' refers to year. All relative differences refer to changes from the reference plant. This plant has been constructed as an average of the plants with TFP measures belonging to the 45 to 55 percentiles for each year and (2.5-digit) industry. E.g. the cost share for each input for the reference plant is computed as the as the average for these plants, while each of the inputs is given by their geometric mean. We have added a term; $\alpha\hat{k}_t$, which captures the productivity differences, due to the divergence in the knowledge capital between the plant under consideration and the reference plant. $\hat{u}_t$ reflects other sources of productivity differences.

Appendix B: Sample and variable construction

One of the data sources used in this analysis is the manufacturing census carried out annually by The Division of Manufacturing Statistics in 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. Price deflators for gross production (at seller prices), materials 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. An examination of the fire insurance values and a comparison with the investment figures reveal much noise in the fire insurance values. Hence, we have constructed a simple filter to pool the two sources of information about movements in the capital stock. Using the perpetual inventory method[35], we 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) in 1989. Aggregate R&D statistics based on the R&D survey are published in several publications from NTNF. An analysis of the pattern in the aggregate data across industries and the years 1985-90 is given by Naas (1993). The R&D data is reported separately for each line of business within each company. 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. That is to say, only companies with at least 20 employees were included in the sample

[35] I.e. using the formula

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

Appendix C: The shadow price of R&D capital

For a firm with knowledge capital stock K_t, short run profit is given by

$$\pi_t(K_t) = P_t Q_t - C(Q_t, K_t) \tag{32}$$

What is the increase in short run profits when we alter K_t? That is, we want to express the derivative of this expression with respect to K_t

$$\begin{aligned} \frac{d\pi_t}{dK_t} &= \frac{dP_t}{dK_t}Q_t + P_t\frac{\partial Q_t}{\partial P_t}\frac{dP_t}{dK_t} + P_t\frac{\partial Q_t}{\partial K_t} \\ &- \frac{\partial C(\cdot)}{\partial Q_t}\left(\frac{\partial Q_t}{\partial P_t}\frac{P_t}{dK_t} + \frac{\partial Q_t}{\partial K_t}\right) - \frac{\partial C(\cdot)}{\partial K_t} \end{aligned} \tag{33}$$

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

$$\begin{aligned} \frac{d\pi_t}{dK_t} &= \left(P_t - \frac{\partial C(\cdot)}{\partial Q_t}\right)\frac{\partial Q_t}{\partial K_t} - \frac{\partial C(\cdot)}{\partial K_t} \\ &= -\frac{1}{\eta}P\frac{\partial Q_t}{\partial K_t} - \frac{\partial C(\cdot)}{\partial K_t} \\ &= -\frac{\xi}{\eta}\frac{P_t Q_t}{K_t} - \frac{\partial C(\cdot)}{\partial K_t}. \end{aligned} \tag{34}$$

The first equality follows from the firm's markup rule, while the second follows from the properties of the demand system (cf. equation (13)). We 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

$$\frac{\partial X_t}{\partial K_t} = -\frac{\alpha}{\epsilon}\frac{X_t}{K_t} \tag{35}$$

where X_t represents ordinary inputs. Hence, with fixed factor prices (W)

$$\begin{aligned} \frac{\partial C(\cdot)}{\partial K_t} &= W\frac{\partial X_t}{\partial K_t} \\ &= -\frac{\alpha}{\epsilon}\frac{C(Q_t, K_t)}{K_t} \\ &= -\frac{\alpha}{\mu}\frac{P_t Q_t}{K_t} \end{aligned} \tag{36}$$

The last equality follows from the relationship $C(\cdot) = \epsilon/\mu \; P_t Q_t$, which can be derived from the definition of scale economies (from the cost side), and the firm's markup rule. Combining equations (34) and (36)

$$\frac{d\pi_t}{dK_t} = \left(\frac{\alpha}{\mu} - \frac{\xi}{\eta}\right) \frac{P_t Q_t}{K_t} \tag{37}$$

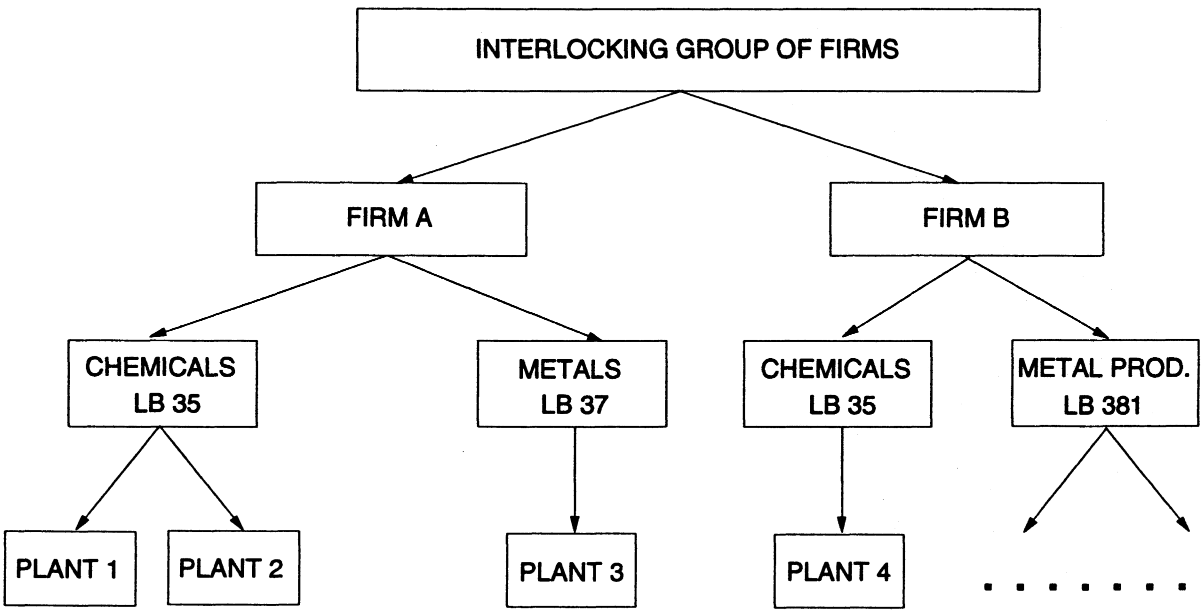

Figure 1: The relationship between "interlocking group", "firm", "line-of-business" and "plant"

Table 1: Summary statistics on the R&D variables. 1989

			R&D-intensity			R&D-expenditures*	
	R&D-plants	Non-R&D-plants	Mean	Median	Inter quart. range	Median	Inter quart. range
All industries	196	608	0.111	0.042	0.097	2.7	7.7
El. equipment	40	53	0.262	0.249	0.257	3.4	9.0
Chemistry	51	105	0.096	0.021	0.082	3.4	9.0

Footnote:
* Mill. Nkr.

Table 2: Summary statistics for the production variables. 1990. Mean values, standard deviations in parentheses.

	Employment	Value added per employee*	Capital intensity	Labour share	Material share	Obs.
All plants	106	287	2.89	0.349	0.559	804
	(168)	(152)	(4.37)	(.182)	(.165)	
Non-R&D-plants	73	254	2.76	0.379	0.543	608
	(97)	(102)	(4.81)	(.186)	(.170)	
R&D-plants	208	387	3.31	0.255	0.607	196
	(271)	(223)	(2.51)	(.128)	(.135)	

Footnote:
* 1000 Nkr.

Table 3: Basic regressions. GMM-estimates. Dependent variable: Solow residual.

	Basic results	2SLS[4)]	No dummies	Drop lag. dep. var.as IV	Include extra IV	Add ind. dummies
Solow residual$_{-1}$	0.800***	0.786***	0.808***	0.862***	0.870***	0.909***
	(.046)	(.038)	(.046)	(.053)	(.039)	(.049)
Capital	0.036	0.041	0.038	0.031	0.005	-0.140***
	(.032)	(.032)	(.032)	(.033)	(.029)	(.036)
Capital$_{-1}$	-0.037	-0.042	-0.039*	-0.033	-0.006	0.133***
	(.031)	(.030)	(.030)	(.031)	(.028)	(.035)
R&D$_{-1}$	0.014***	0.011***	0.012***	0.009**	0.010***	0.011***
	(.004)	(.005)	(.004)	(.005)	(.004)	(.005)
"No R&D$_{-1}$" dummy	-0.025***	-0.026**	-0.022**	-0.021**	-0.016**	-0.010
	(.011)	(.012)	(.011)	(.011)	(.010)	(.009)
Type of plant[1)]	X***	X***		X***	X***	X***
R&D-effects[2)]	13.76***	10.25***	9.87***	6.49**	9.00**	6.26**
	(2)	(2)	(2)	(2)	(2)	(2)
Overident. test[3)]	9.96	-	9.60	2.40	15.17**	12.21*
	(6)		(6)	(5)	(7)	(6)
RMSE	0.110	0.110	0.111	0.112	0.111	0.112
Obs.	804	804	804	804	804	804

Footnotes:

Robus standard errors in parentheses.

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

1) Regression includes dummies for plant type and foreign ownership

2) Chi-square test of the joint significance of the R&D variables (DOF in parentheses)

3) Hansen's (1982) overidentification test (DOF in parentheses)

4) Standard errors are not robust to heteroskedasticity

Table 4: Spillovers across firms within group. GMM-estimates. Dependent variable: Solow residual.

	Weight-test	Dummy-test I	Dummy-test II
Solow residual$_{-1}$	0.802***	0.800***	0.800***
	(.047)	(.047)	(.047)
Capital	0.034	0.037	0.044
	(.035)	(.032)	(.034)
Capital$_{-1}$	-0.036	-0.039	-0.045
	(.033)	(.031)	(.032)
$R\&D^{LB}_{-1}$ 1)	0.014***	0.012***	0.012***
	(.004)	(.004)	(.004)
$(R\&D^{GLB}_{-1}-R\&D^{LB}_{-1})$ 2)	0.002		
	(.008)		
"No $R\&D^{LB}_{-1}$" dummy	-0.025***	-0.018**	-0.019**
	(.011)	(.010)	(.011)
Dummy I for $R\&D^{GLB}_{-1}$ 3)		0.029**	0.002
		(.017)	(.019)
Dummy II for $R\&D^{GLB}_{-1}$ 4)			0.070***
			(.030)
Type of plant 5)	X***	X***	X***
R&D-effects 6)	13.98***	14.41***	17.23***
	(3)	(3)	(3)
Overident. test 7)	10.01	9.78	10.02
	(6)	(6)	(6)
RMSE	0.110	0.110	0.110
Obs.	804	804	804

Footnotes:
Robus standard errors in parentheses.
*** Significant at 1 percent level
** Significant at 5 percent level
* Significant at 10 percent level
1) R&D at the line of buisness level
2) Difference between R&D at group versus firm level
3) Dummy equal to one if there is positive R&D outside firm, but within groups and the same line of business.
4) Dummy equal to one if R&D outside firm, but within group exceeds 50 Mill. Nkr.
5) Regression includes dummies for plant type and foreign ownership
6) Chi-square test of the joint significance of the R&D variables (DOF in parentheses)
7) Hansen's (1982) overidentification test (DOF in parentheses)

Table 5: Economies of scope in R&D. GMM-estimates. Dependent variable: Solow residual.

	Economies of scope within firm	Economies of scope within group I	Economies of scope within group II
Solow residual$_{-1}$	0.799***	0.800***	0.799***
	(.047)	(.046)	(.047)
Capital	0.040	0.038	0.041
	(.033)	(.032)	(.034)
Capital$_{-1}$	-0.041*	-0.040	-0.042
	(.031)	(.031)	(.032)
R&D$^{LB}_{-1}$ 1)	0.012***	0.011***	0.010**
	(.005)	(.004)	(.004)
"No R&D$^{LB}_{-1}$" dummy	-0.024**	-0.014*	-0.015*
	(.011)	(.010)	(.010)
Dummy for R&D$_{-1}$ 2)	0.031		
	(.026)		
Dummy I for R&D$_{-1}$ 3)		0.033**	0.024*
		(.016)	(.016)
Dummy II for R&D$_{-1}$ 4)			0.049**
			(.028)
Type of plant 5)	X***	X***	X***
R&D-effects 6)	12.55***	15.09***	15.24***
	(3)	(3)	(4)
Overident. test 7)	9.55	9.78	9.82
	(6)	(6)	(6)
RMSE	0.110	0.110	0.110
Obs.	804	804	804

Footnotes:

Robus standard errors in parentheses.

*** Significant at 1 percent level

** Significant at 5 percent level

* Significant at 10 percent level

1) R&D at the line of buisness level
2) Dummy equal to one if R&D in other lines of buisness within firm is positive
3) Dummy equal to one if R&D in other lines of buisness within group exceeds 5 Mill. Nkr.
4) Dummy equal to one if R&D in other lines of buisness within group exceeds 50 Mill. Nkr.
5) Regression includes dummies for plant type and foreign ownership
6) Chi-square test of the joint significance of the R&D variables (DOF in parentheses)
7) Hansen's (1982) overidentification test (DOF in parentheses)

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