INSTITUT FÜR VOLKSWIRTSCHAFTSLEHRE

der

UNIVERSITÄT AUGSBURG

Detecting Technological Performance and Variety

An Empirical Approach to Technological Efficiency and Dynamics

by

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Beitrag Nr. 120

September 1994

Volkswirtschaftliche Diskussionsreihe

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September 1994

Acknowledgements:

We are very grateful to the "Stifterverband für die Deutsche Wissenschaft" who made it possible to relate our results on relative firm productivity to firm specific R&D expenditures. We are especially grateful to Christoph Grenzmann from the "SV-Wissenschaftsstatistik" at Essen who provided the technical assistance as well as the respective computations which are presented in chapter 3.3.

Moreover, we thank Jean Bernard for his critical remarks and suggestions on a previous version of this paper. Remaining errors are still our responsibility.

Finally, financial support by the European Commission for the SPES-project "Comparative Economics of R&D: The Case of France and Germany" as well as by the DAAD-programme PROCOPE is gratefully acknowledged.

1. Introduction

In this paper we present an investigation into the perceived heterogeneous performance of firms - as measured by efficiency indicators - within certain industrial sectors. Such analyses have a long standing tradition in public sector economics[1] as well as for the private sector[2] . The neoclassical explanation of such differences relies either on the concept of "market failures" - which is apparent in the concept of X-inefficiency[3] or in several oligopoly models in industrial organization[4] - or on such sources as product differentiation[5], spatial market fragmentation[6], and "institutional split"[7]. Inefficiencies measured on the basis of these approaches are mainly referred to as technical (and allocative) inefficiencies stating that a single given best-practice-technology is not used by its full potential throughout a sector.

Recent advances in the economics of technological change, however, increasingly stress that the observed industry structure may also be the result of the coexistence and competition of several different technologies[8]. Moreover, this diversity is even a major force pushing forward technological progress. Based on this socalled evolutionary approach the heterogenity of technologies in use implies that from a theoretical point of view technological inefficiency (where several different best-practice technologies are compared with each other) has to be distinguished from technical inefficiency (where a specific best-practice technology serves as yard stick). This implies that a variety of technological approaches, i.e. production functions, is to be expected and that economic determinants are of only secondary importance for further technical

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1 See for example Bös (1988), Hanusch/Cantner (1991), Cantner/Hanusch/Westermann (1994).

2 See for example Caves/Barton (1990).

3 See for example Crew/Jones-Lee/Rowley (1971), Leibenstein (1976), McCain (1975).

4 For inefficiencies accruing from entry barriers see for example Brandner/Spencer (1985), Mankiw/Whinston (1986). On the effects of excess capacity see Caves/Jarrett/Loucks (1979).

5 See for example Carlsson (1972).

6 See for example Moomaw (1981, 1985).

7 See Caves/Barton (1990).

8 See for example Dosi (1988), Nelson/Winter (1982).

advancements. Consequently, a variety of technological approaches may prevail within an industry and several technology leaders might be identified.

Based on this view of a technology dependent industry structure, the analytical procedure we employ has to take into account that contrary to traditional frontier-production analysis there may exist more than one best-practice technique. Since traditional neoclassical econometric approaches to frontier production functions determine only one best-practice technology - at least at the outset-, these methods are not suitable for our problem. Instead, we suggest a non-parametric approach, the linear programming approach[9] or the Data-Envelopment-Analysis (DEA)[10], to investigate technological performances and variety which neither needs a special type of production function nor relies on general equilibrium prices. Quite contrary, based on the broad definition of Leontief-type production functions this procedure allows to detect a large number of specific Leontief-functions each representing a certain "technology" defined and approximated by specific input ratios. Moreover, these functions can be compared with each other delivering a number of best-practice technologies as well as measures of technological/technical inefficiencies. These will be used to define certain technology fields with one or several technology leaders and a larger number of technologically/-technically backward firms.

This method has recently been used in empirical studies for the private sector such as in Thore/Kozmetsky/Phillips (1992), Berg/Forsund/Hjalmarsson/Suominen (1993), or Cantner/Hanusch/Westermann (1993), Bernard/Cantner/Westermann (1994).

Applying this method our empirical analysis focusses on the machinery and electronics sector in Germany respectively. We are able to detect several best-practice technologies as well as a measure for technological/technical inefficiency. Coupled with a traditional cluster analysis technology leaders can be assigned to specific "technology fields". Relating those results to the firm-specific R&D-capital stocks on the one side and to the

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9 For an overview see Färe/Grosskopf/Lovell (1993).

10 See Charnes/Cooper (1962, 1985). For an excellent overview see Charnes/Cooper/Lewin/-Seiford (1994).

patenting activities of the firms on the other, it is shown that these technology indicators are able to explain the intra-industry heterogeneity as measured by our inefficiency index.

In the following we proceed as follows. Chapter 2 delivers the theoretical foundation of our analysis. Moreover the DEA method is introduced which is well suited to perform an efficiency analysis within the theoretical framework of the modern approach to innovation and new technology. Chapter 3 delivers our results with respect to technological inefficiency which then are related to R&D capital stocks and patent activity in chapter 4. Chapter 5 concludes our investigation.

2. Theoretical Basis and Analytical Model

2.1 Technological Variety - A Theoretical Foundation

The modern theory of new technology and innovation attempts to explain differences or asymmetries among firms by their respective technological performance. The core of this approach is the emphasis on the fact that opportunities of and advances in technology (tend to) dominate any economic determinants of a firm's choice of technology.

Conventional neoclassical theory, however, does not share this view as there the path technological progress develops along is mainly determined by changes in relative factor prices where technological possibilities are open to all economic agents. Consequently, assuming a well functioning market mechanism heterogenity of firms within a sector is not to be expected. Diversity, nevertheless empirically observable, is then to be explained mainly by market failures.

This neoclassical concept of factor price induced technological progress has been challenged by the well-known Salter (1960) and Fellner (1961) critique. Salter (1960, p.43) notes that "... when labor costs rise, any advance that reduces total costs is welcome and whether this is achieved by saving labor or capital is irrelevant." Moreover, Ahmad (1966, p.345) states that "only technological considerations and not a change in the relative price of the factor may influence the nature of invention, even if there exists the possibility of choosing from different kinds of invention." Modern innovation theory attempts to develop these aspects further.

Here, besides others a major point of criticism focuses on the standard neoclassical assumption that technological knowledge is considered as a public good which - in turn - implies technological uniformity between firms as core hypothesis.[11] Instead, the modern approach distinguishes between public knowledge on the one hand and private[12], often tacit technological knowledge on the other. It is this private good character of technological know-how which allows firms to develop along a certain technological path often described as cumulative, selective and finalized.[13] Consequently, although different firms belong to the same branch, although they are technologically tied to common - public good - principles and although they are engaged in the production of the same class of goods[14], they nevertheless differ with respect to their specific production technology.

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11 As a by-product, the use of a representative agent is justified on methodological grounds.

12 One could here also use the terminology of Nelson who uses "latent public" instead of "private".

13 See Dosi (1988).

14 This class of goods may either contain several more or less horizontally or vertically differentiated products, or may represent a homogeneous good produced with different production functions.

The reason for building up a private stock of technological knowledge leading to technological diversity is found in the conditions by which technological progress is accomplished on the firm level. Here, the technological capability a firm has been accumulating is determined by past investment, learning effects as well as own R&D engagements. And just by reverse causation, these capabilities are decisive for further successful technological improvements as well as successful adoption of new techniques developed elsewhere.[15] This implies (a) that further technological advances are mainly determined and constrained by the technique(s) a firm has been using in the past[16] and (b) that the firm's search for new solutions is characterized by bounded rationality and local learning effects. Technological progress which enhibits strongly cumulative effects is labelled "localized technological progress".[17]

A major consequence of this view is that relative factor prices play only a minor role in the development of new technologies. Employing the standard textbook isoquant only a (small) number of all techniques on an isoquant are practiced, and substitution processes - which are to be considered as resource using search processes - due to changes in relative factor prices are not costless. Therefore, if the technological opportunities of a firm are considerably high, search costs will be devoted to innovation, not to substitution.[18] In this case of local technological advances, the development path of a firm will be characterized by fairly constant factor input ratios indepen-

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15 Technological asymmetries among firms may also be responsible for a sometimes slow diffusion path of capital embodied innovations. "... the process of adoption of innovations is also affected by the technological capabilities, production strategies, expectations, and forms of productive organisation of the users." (Dosi/Pavitt/Soete (1990. p.119)).

16 With respect to the macro-level Abramovitz (1988, p.236) states: "... the capital stock of a country consists of an intricate web of interlocking elements ... built to fit together and it is difficult to replace one part of the complex with more modern and efficient elements without a costly rebuilding of other components". This of course implies that the more capital intensive a production is the more difficult and costly is the switching of techniques.

17 See Atkinson/Stiglitz (1969).

18 In fact such a behaviour is the core of the Salter critique.

dent of the prevailing relative factor prices. And even more, changes in the relative factor prices will not cause the transition to the new technology to be reversable, i.e. technological change is characterized by irreversibilities - at least in the short and medium run.

Based on this theoretical background we assume a special form of production structure on the sectoral level which we use for our empirical investigation:

(i) An industry consists of firms which employ different production functions, each one representing the respective firm specific technique. Since these techniques are the outcome of a localized technological progress, we consider the resulting techniques - at least in the short-run - to be of zero elasticity of substitution at the outset. This suggests to assume a Leontief-type production function. Firm diversity is then represented by a number of different Leontief-production functions, i.e. different factor input ratios.[19]

(ii) For the medium and long-run one still could assume a strongly localized technological[20] change which would imply the development path to be characterized by a constant factor input ratio. However, we do not need this restrictive assumption but we rather suggest a development path to be constraint within

[19] This modelling may take into account the claim put forward by Silverberg (1990) to abandon the traditional neoclassical production function altogether. In this respect the use of short-run fixed production coefficients has been used intensively in the theoretical literature as well as in simulation models.

[20] For the distinction between strong and weak localized technological change and its relation to the isoquant see Verspagen (1990).

elastic barriers.[21] The observation of an increasing mechanisation of the production processes is thus taken into account.[22]

With this formulation of a sector's production structure it is interesting to compare the firms of the sector with respect to their technological performance. Such an investigation has to take into account the following aspects:

(1) Due to different firm-specific technological approaches there may appear more than one best-practice technique. These techniques cannot necessarily be ranked as being better and worse.[23]

(2) Despite this, quite a number of practiced techniques can be ranked as unequivocally better or worse. These differences can be caused on the one hand by traditional technical inefficiency where inputs are not used efficiently given a specific technique. On the other hand, this can also be explained by technological inefficiency pointing to the fact that a comparably better technology is practiced elsewhere.

(3) With our assumption of short-run Leontief type production functions allocative (in-)efficiency is only a minor problem because a specific technique is optimal for a considerable range of relative factor prices. In fact, if only one best-practice Leontief-technology is in use, allocative inefficiency does not exist.[24]

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21 See David (1975).

22 See Dosi/Soete (1983), Dosi/Pavitt/Soete (1990).

23 This aspect is different from the one put forward for example by Dosi/Pavitt/Soete (1990, pp.114) where all techniques can be ranked unequivocally as better or worse.

24 In fact, the measure for inefficiency we compute below will consist of technological, technical and allocative inefficiencies. For a very dynamic sector, however, we consider technological inefficiencies as the major source. The other two inefficiencies will gain importance with increasing technological maturity.

Summarizing (1)-(3) our empirical analysis attempts to account (a) for the relative technological performance of firms and (b) for technological variety within a certain sector.

2.2 The Analytical Model

The analytical approach we apply is non-parametric and based on a linear programming procedure. In operations research and management science this analysis has become well known as the *Data Envelopment Analysis* (DEA)[25], whereas in the economics literature on frontier production functions it has diffused much more slowly.[26]
To ease the presentation, throughout the paper we will refer to this procedure as DEA.

DEA allows to compute an index for relative technological/technical (in)-efficiency for each firm within a sample. The choice of a non-parametric approach helps to take account of technological variety by allowing for several parametrically different production functions. Principally this procedure relies on index numbers for productivity similar to the one used in traditional productivity analysis. For each firm j ($j=1,\dots,n$) a productivity index h_j is given by:

$$h_j = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \qquad (1)$$

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25 See Charnes/Cooper (1962, 1985), Charnes/Cooper/Lewin/Seiford (1994).

26 See Färe/Grosskopf/Lovell (1993).

y_{rj} is used for the r different outputs ($r=1,\ldots,s$) and x_{ij} refers to i different inputs ($i=1,\ldots,m$) of firm j. The parameters u_r and v_i are (variable) aggregation weights. Applying vector notation (1) looks as follows:

$$h_j = \frac{u^T Y_j}{v^T X_j} \quad . \qquad (2)$$

Here Y_j is a s-vector of outputs and X_j a m-vector of inputs of firm j. s-vector u and m-vector v contain the aggregation weights u_r and v_i respectively.

h_j in (2) (and (1)) is nothing else than an index for *total factor productivity*. The respective aggregation functions (for inputs and outputs respectively) are of a linear arithmetic type as also employed in the well-known Kendrick-Ott productivity index.[27] There, however, by special assumptions the aggregations weights, u_r and v_i, are given exogenously.

DEA does not rely on such assumptions, especially it is not assumed that all firms of the sample have a common identical production function. The specific aggregation weights are determined endogenously and can differ from firm to firm. They are the solution of a specific optimization problem (as discussed below), and therefore they are dependent on the empirical data of our sample. Critics often argue that a linear arithmetic aggregation nevertheless predetermines at least a special type of production function.[28] Here one can think of a Leontief-type production function.[29] Since the aggregation weights are determined endogenously and - as we will show below - can

27 See Kendrick (1956) and Ott (1959).

28 See also Chang/Guh (1991) p.217.

29 Leontief (1947) and Green (1964) have shown that a linear aggregation exists for a Leontief-type production function. Instead of a Leontief one could also use a linear production function.

be different among firms, at the end there exist a number of different specific production functions although they are of the same principal type.[30]

The basic principle of DEA is to determine the indexes h_j in such a way that they can be interpreted as efficiency parameters. The (relatively) most efficient firms of a sample should be characterized by a h of 1, all less efficient firms by a h of less than 1. The following constrained maximization problem is used to determine such a h-value for a specific firm l, $l \in \{1,\dots,n\}$, out of the sample:

$$\max\ h_l = \frac{u^T Y_l}{v^T X_l}$$

$$s.t.\ \frac{u^T Y_j}{v^T X_j} \leq 1;\quad j=1,\dots,n; \tag{3}$$

$$u, v > 0.$$

Problem (3) determines h_l of firm l subject to the constraint that the h_j of all firms of the sample are equal or less to 1. The constraints provide that h is indexed on]0,1]. Moreover the elements of u and v have to be strictly positive. This requirement is to be interpreted that for all inputs used and outputs there exists a positive value.[31]

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30. Employing parametric methods, e.g. the COLS or the EM-algorithm a specific production function is assumed. The coefficients of this function are estimated using the available data and the resulting production function is used to determine technical (in)-efficiencies of all the fims in the sample. This procedure, however, suggests that there is only one "*best-practice*"-technology (for an empirical investigation on the private sector see for example Green/Mayes (1991), Hanusch/Hierl (1992)). With DEA a number of "*best-practice*"-technologies can be determined.

31. This procedure is also known from activity analysis.

Since we employ linear arithmetic aggregation functions for inputs and outputs, (3) is to be rendered as a problem of linear fractional programming.[32] To solve such optimizations, there exist a number of methods where the best known is the one by Charnes and Cooper (1962). They suggest to transform (3) into a normal linear programm which then can be solved using the well-known simplex algorithm. This can easily be done, if one provides for the denominator in the objective function of (3) to be constant. By this, the fractional linear program can be dealt with like an (ordinary) linear program which reads as follows:

$$\begin{aligned} & \max \ \mu^T Y_l \\ & s.t. \\ & \mu^T Y - \omega^T X \leq 0 \\ & \qquad \omega^T X_l = 1 \\ & \qquad \mu, \omega > 0 \end{aligned} \tag{4}$$

Y_l and X_l are the r- and s-vectors of outputs and inputs respectively of firm l, Y and X are the $s \times j$-matrix of outputs and $m \times j$-matrix of inputs of all firms of the sample. In (4) the vectors μ und ω are the transformed aggregation weights which also have to be (strictly) positive.

Problem (4) represents a version of efficiency analysis which is known as the "Production"- or "Efficiency Technology"-form: Here, one attempts to maximize the output of firm l where input is normalized, the solution is to be positive, and the efficiency indexes[33] of all firms are restricted to $]0,1]$. The dual to (4) is known as the "Envelopment"-form since here a frontier function (containing several linear parts) can be

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32 An overview to linear fractional programming is given in Böhm (1978).

33 The ratios are stated here as differences which are not allowed to be positive.

determined. This obviously relates our analysis to the one of Farrell (1957). The corresponding dual programme reads then:[34]

$$\begin{aligned}
&\min\ \theta_l \\
&s.t. \\
&\qquad Y\lambda \geq Y_l \\
&\theta X_l - X\lambda \geq 0 \\
&\lambda \geq 0
\end{aligned} \tag{5}$$

The parameter θ to be minimized states to which percentage level the inputs of firm l can be reduced proportionally, in order to have this firm producing on the frontier function representing the best practice technologies. With $\theta=1$ the respective firm belongs to the efficient firms on the frontier. The j-vector λ states the weights of all (efficient) firms which serve as reference for firm l. For the efficient firm l (with θ-$=1$), we obtain $\lambda_l=1$ and $\lambda_j=0$, $j\#l$.

Using the "Envelopment"-form of (5) it is easy to select efficient and inefficient firms directly. Principally, the Pareto-Koopmanns criterum is employed which allows to compare vectors. The linear programming procedure as performed by (5), however, may result in selecting a firm as DEA-efficient although it is clearly dominated by another firm on the frontier. This may happen when the parts of the frontier are parallel to one of the axes. To avoid such results the linear program in (5) has to be modified as follows:

[34] See Charnes/Cooper/Thrall (1986).

$$\begin{aligned} &\min \theta_l - \epsilon e^T s^+ - \epsilon e^T s^- \\ &s.t. \\ &\qquad Y\lambda - s^- = Y_l \\ &\theta X_l - X\lambda - s^+ = 0 \\ &\lambda, s^+, s^- \geq 0 \end{aligned} \tag{6}$$

This modification provides that for all firms, which are on the frontier ($\theta = 1$) but which are dominated by other firms of the frontier, the respective slacks (s^- for excess inputs and s^+ for output slacks) are taken into account in the objective function.[35] Vector e^T contains only elements 1.[36] ϵ is a positive constant smaller than any other variable of the program. This guarantees that slacks are only taken into account when a strictly convex envelope has already been determined.[37]

For efficiency analyses additional to θ one has therefore to take into account remaining slacks. Only then a clear-cut selection of efficient and inefficient firms is possible. For simple qualitative statements this procedure is sufficient.

For a quantitative analysis, however, it would be helpful to combine the proportional reduction θ and the remaining slacks into a single measure. This is done by a method suggested by Färe/Hunsacker (1986). As is known from index numbers for total factor productivity the input factors have to be aggregated in a single number. Applying

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35 The variable ϵ has to be smaller than any other measure of the optimization. This implies especially that first the frontier has to be determined and then the slack variables can enter the basic solution.

36 Of course, one should here distinguish two vectors e^T for inputs and output respectively which contain s and i elements respectively. To ease notation we do not take account of this. Further analysis is not affected.

37 This condition is equivalent to the statement that the aggregation weight or prices of the primal programme to be strictly positive.

DEA, the respective weights are given by the marginal productivities of the input factors of the reference firm. These marginal productivities are the solution of the primal program.

The ratio of the marginal productivities obtained here can be interpreted as the slopes of the linear parts of the frontier. Using the marginal productivities of the respective reference firm, one can compute for each firm a virtual input and a virtual slack. The ratio of both delivers the percentage of total slack for firm l. Correcting θ by this ratio delivers an adjusted aggregate measure of inefficiency, ι, which combines the possible proportional reduction in inputs with the remaining slacks. For our empirical analysis below we rely solely on ι.

3. Data Set, Procedure of Investigation and Empirical Results

3.1 Data Set and Procedure of Investigation

The data set we investigate contains time series data of 78 German machinery and 39 German electronic firms of different sub-branches. This data set is time consistent in the sense, that we have neither entries nor exits of firms over the whole period of investigation, 1985 to 1991. All firms under consideration are of the legal form "shareholder's company".

In order to compute the efficiency score "ι", we define some suitable variables for inputs and output:

As an output measure we construct a "total output" consisting of the sum of "total sales", "inventory changes", and "internal used firm services" from the profit&loss accounts. This output is deflated by a composed price index for German investment goods.

On the input side we distinguish between "capital", "labour", and "material". "Capital" is captured by the balance sheet position "fixed assets" (net value at the beginning of the year). Since we have no information about the age structure of capital this measure is not deflated. For "Labour" we compute the effective worker hours per year by multiplying the number of workers of a firm by an index of effective worker hours for the German machinery industry. "Material" consists of the deflated profit&loss position "raw materials and supplies".

We are certainly aware of the fact that in order to compute a measure for technical efficiency we should have used purely technical variables for the inputs or the output. For "Capital" input an ideal technical measure would be machine hours; for "Material" input we should have gathered data on the used raw materials in tons, pieces, etc.; for output "pieces of produced machines" would be an adequate technical measure.

In some cases these data are not available (machine hours), in others the variables are too heterogenous to be measured technically (output, material). So we have to replace or aggregate the real data by economic weighted values such as "sales" or "raw materials&supplies".

Our empirical analysis proceeds in three main steps. The first one is related (a) to the technological structure, (b) to the dynamics of this structure, and (c) to the aspect of technological variety. For this investigation the efficiency scores of DEA are used and interpreted.

In a second step our efficiency indices will be related to firm specific R&D. For this data we rely on a database of the Stifterverband. From our 78/39 firms above there are only 59 firms in machinery and 26 firms in electronics which have reported their R&D. Consequently, when using these data in our analysis we are forced to reduce our sample because we cannot distinguish whether the missing 19/13 firms have not reported to the Stifterverband or whether they have not invested in R&D at all.

Finally, we also relate our productivity results to the patenting activity of the firms. The respective patent data are drawn from the database of the European Patent Office. These data however do not cover the whole period of our investigation but only the years 1985 to 1988.

3.2 Technological/Technical Efficiency

According to our route of investigation in 3.1 the first step of our investigation attempts to answer the following questions on the productivity structure of our sample:

(1) Which are the efficient firms in a certain year?

(2) Is the set of efficient firms stable over time?

The results show that in a year by year analysis there are only three machinery and two electronics firms that are continously members of the efficient set. Other firms loose their leading position after some years or appear only for a short period on the frontier. The number of efficient firms is varying from 5 to 10 (3 to 8) firms per year with a slightly decreasing (increasing) tendency in the machinery (electronics) sector.

From this result we learn that the structure of the technological frontier changes quite rapidly. One can imagine some of the facets on the frontier to vanish and others to appear from period to period. We assume that only the technologically best firms stay and stamp the envelope for a longer time.

With respect to the dynamics of the above described technological structure we ask the following questions:

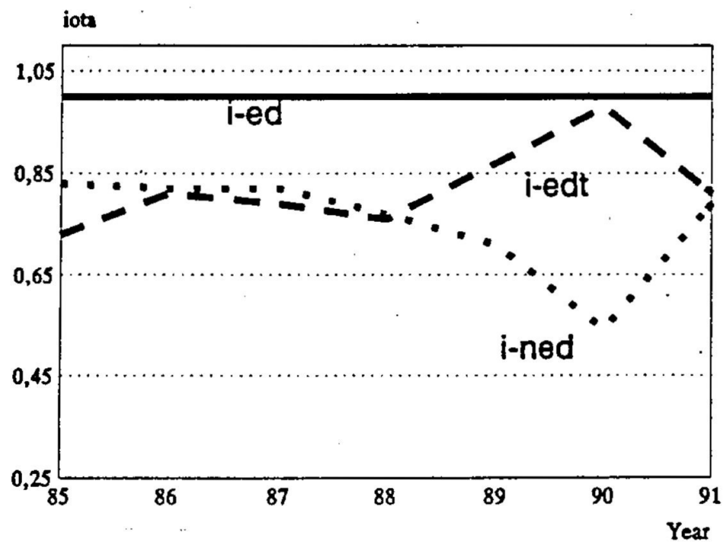
(4) Do the inefficient firms get closer to the frontier during time, i.e. is there a catch-up?

(5) Has there been something like technological progress driven by the efficiency leaders?

(6) Compared to the "all time best frontier" does the efficiency of the whole sector increase?

These questions lead to dividing the sample of firms in two sub-groups. The first one includes only the efficient firms, the other one consists of the not efficient firms. Figures 1a and 1b show the average "year-by-year" ι-value of the inefficient group (i-ned) together with the average "year-by-year" ι-value of the efficient firms (i-ed) (which, of course, has to be 1,0 by definition). To obtain a measure of the movement of the frontier we compute another average ι-value for the efficient sub-sample (i-edt) as a comparison with the "all-time-best-practice" frontier.

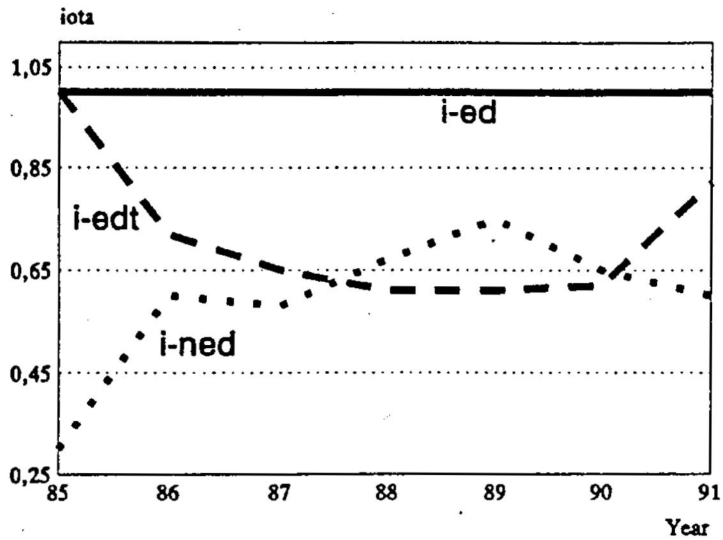
Figure 1a: Average Efficiency Series Machinery Sector



For the period from 1988 to 1990 figure 1a illustrates that the decreasing efficiency of the non-efficient machinery firms was mainly the result of an increasing efficiency of the frontier sample. In this period the pursuing firms were not able to follow the shifting of the frontier.

Quite a contrary result can be observed for the electronics sector in the same period (1988 to 1990). The increasing relative efficiency of the not-efficient firms is not an outcome of a efficiency movement of the frontier. This is obvious because from 1988 to 1990 the actual frontier's efficiency compared to the all-time-best-frontier does not

Figure 1b: Average Efficiency Series Electronics Sector



change.

With respect to the "all-time-best-practice" frontier for the efficient firms of both sectors (for the electronics sector at least from 1986) a slightly but obviously increasing tendency can be noticed. Consequently, the year-by-year efficiency leaders are pushing forward the technological development.

Another calculation not shown in the figures 1a and 1b is the following: The average ι values for the group of inefficient firms (calculated in the same way with reference to the "all time best practice" frontier) show as well an increasing trend from 0.49 (1985) to 0.55 (1991) for the machinery sector and from 0.30 (1985) to 0.37 (1991) for the electronics sector. Therefore, both sectors shifts towards more technical and/or technological efficiency.

Finally we want to take account of technological variety. The following four questions are adressed with respect to this issue:

(7) What are the differences between the efficiency leaders?

(8) Do the efficiency leaders define "technology fields" within one branch?

(9) How does the technological efficiency and importance of these "technology fields" develop over time?

As a concession to clearness and size of the analysis we present with respect to the intra-sector investigation only the results on the machinery firms.[38]

In the year 1985 we discover ten machinery firms with an ι-value of 1,0. Closer inspection of the input structure of these firms shows clearly that some of them differ extremely in the proportions of the use of the three inputs necessary to produce one unit of output. Such different proportions of inputs will help us to define different "technologies" - each one characterized by a certain input ratio and represented by a Leontief production function as stated in 2.1. The efficient firms #52 and #101 for example are the two opposite sides in the usage of "capital". Firm #52 and firm #193 mark the opposite ends of the "labor" use continuum. So it is obvious that there exists more than one efficient "technology" in order to produce the same group of goods (here: machinery goods).

The fact that we detect some firms applying extremely differing "technologies" (technicaly) very successfully, leads to the question whether it is possible to define them as the protagonists of different "technology fields". This seems adequate because the DEA method evaluates the non-efficient firms using the facets of the frontier built by linear combinations of the efficient ones. So we apply the λ values (see page 11) delivered by DEA to group the inefficient firms around the technology leaders. To verify this assignment defined by the DEA method, we additionaly ran a traditional cluster analysis using input ratios as factors. This delivers four different clusters of input ratios which we label "technology fields", F1 to F4. For these fields the DEA assignment is confirmed by 85 percent. Moreover, in three of the four clusters more than one efficient firms join the same "technology field".

With respect to the input ratios technology field F1 can be characterized as high capital-, low material- and medium labor-intensiv. In field F4 we find an extraordinary high material-intensity coupled with high capital-intensity and very low labor-intensity. An intensive use of labor, differing only in the extent (F2's labor intensity is two times

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[38] The results are of course available for interested readers from the authors.

higher), and a low capital/material ratio are the attributes of the clusters F2 and F3.

Table 1 gives an account of the number of firms joining the four technology fields. It is evident that the main fields are F2 and F3 where the importance of the first is increasing, the one of the latter decreasing over time.

Table 1: Number of firms in each technology field (F1-F4)

field / year	F1	F2	F3	F4
85		5	73	
86		5	72	1
87		8	69	1
88	1	7	70	
89		9	69	
90	1	12	65	
91	2	13	63	

The average ι-value of the technology fields could give an account of the technological level of these fields.[39] Table 2 delivers these measures for each field and each year.

Table 2: Average ι for each technology field

year / field	F1	F2	F3	F4
85		0,666	0,517	
86		0,619	0,540	1,000
87		0,621	0,517	1,000
88	0,714	0,695	0,523	
89		0,625	0,539	
90	0,638	0,699	0,546	
91	0,846	0,694	0,557	

39 For this measure Forsund/Hjalmarrson (1987), Carlsson (1972).

Here, however, one has to be very cautious as (in a cross section comparision) this value tends to be higher for a lower number of firms. Taken this into account, comparing F2 and F3 suggests that the (average) technological level of F2 is constantly higher than the level of F3 with an increasing tendency for both. A reason for this result might be that we find technological progress in each of the fields, but F2 is more dense in the sense that the not efficient firms are closer to the leaders.

Table 3 shows the number of movements between the fields during the period 85-91. Evidently most of the movements occur between technology fields F2 and F3. This again furthers the observation that the technologies in F1 and F4 are rather extreme and cannot be easily applied by "outsiders".

Table 3: Movements between technology fields during the period 85-91

to from	F1	F2	F3	F4
F1		1		
F2	2		6	1
F3		16		
F4	1			

Table 4 gives an account of the development of the average ι-value, table 5 of the total ι-value of the moving firms. These numbers, however, have to be interpreted carefully. A switch over into technology field F3 from F2 leads to a slight of relative technological efficiency.

Table 4: Average ι development of moving firms

to from	F1	F2	F3	F4
F1		-0,453		
F2	0,329		-0,001	0,440
F3		0,019		
F4	-0,286			

A contrary result is found for a "jump" into F2 from F3. One reason for this is the fact that the gap between the technology leaders and the followers in F3 is larger compared to F2. A deeper investigation on why firms nevertheless change from F2 to F3 has to be accomplished in further steps. Economic reasons as well as reasons for dynamic efficiency have then to be considered. However, three of the six technology switches do fit into the concept of "elastic barriers" (David (1975)) where a switch into a considerable different technology is accompanyied by a loss of technological/technical efficiency.

Table 5: Total ι development of moving firms

to / from	F1	F2	F3	F4
F1		-0.453		
F2	0,657		-0,003	0.440
F3		0,298		
F4	-0,286			

3.3 Technological/Technical (In)efficiency and Technological Progress

In this chapter we focus on the relationship between the inefficiency measures obtained in the previous paragraph and proxy variables for the firm specific technological progress. Is the relative efficiency position of firms - at least partly - determined by its technological performance?

To make the latter concept operational for empirical analyses one can distinguish between technology input measures such as R&D expenditures and technology output indicators such as patents. We will use both in the following analysis, well aware of the apparent difficulties of both indicators to give an satisfactory account of the technological performance on the firm level. Let us start with R&D expenditures.

3.3.1 R&D-Expenditures and Relative Efficiency

In order to relate our ι-measures to R&D-expenditures we have to reduce the number of firms in the sample to 59 in machinery and 26 in electronics as described above. For this analysis we use traditional OLS where ι is the dependent variable and the R&D capital stock and other measures are independent. Some qualifications towards these measures have to be made.

The first one is related to ι when it is used in regression analyses in the following form:

$$\iota = Z\beta + \epsilon \tag{7}$$

Z is the matrix of independent variables and β is the vector of regression coefficients and ϵ is the vector of error terms.

Since the efficiency scores are restricted on]0.1] the error term ϵ is dependent on Z and thus biased and inconsistent estimates for β are to be expected. A proof of this is found in Holvad/Hougaard (1993).

In order to correct for this one has to look for a procedure transforming ι onto an unrestricted range. Holvad/Hougaard (1993) suggest the following:

$$\ln\left[\frac{1-\iota}{\iota}\right] \tag{8}$$

Consequently the dependent variable is unrestricted and OLS can be applied. For interpreting the regression results, however, one has to keep in mind that the sign of the estimates for the β values is related to the transformed and not the original ι, where the sign is just opposite.

In our estimation we related different independent variables with our efficiency measure. One of these is the R&D capital stock, RDS_t, which we use instead of yearly R&D expenditures, RD_t, for the following reasons:

(a) R&D expenditures cannot be expected to improve productivity at once but only after a certain lapse of time;

(b) technological progress is considered as a cumulative activity.

We suggest therefore that the technological level of a firm which is supposed to have a positive impact of productivity can be approximated by the accumulated R&D expenditures of the past. For this reason we calculate this stock for each firm by the perpetual inventory method where we apply degressive depreciation by a rate of 15%:[40]

$$RDS_t = RDS_{t-1} * 0,85 + RD_t \ . \tag{9}$$

The measured relative inefficiency of firms naturally has more than one determinant. Among others one should take into account measures of competitive conditions, product differentiation, geographical specifities, organizational influences and others more.[41] In the context of our analysis we are mainly interested in whether technological factors can be attributed to determine the relative position of firms. The following OLS results are therefore to be taken as to test the sign of the investigated relations rather than an estimate of a complete theoretical model. Therefore, we proceed step-by-step adding technological and other related variables. Here we include RDS/L as the R&D capital stock per labour; K/L, the capital/labour ratio takes into account the effects of an increasing mechanisation of the production process; RD/Y is the R&D intensity; the time variable ETP should cover not specified trend effects such as exogenous technical progress; finally in certain runs we include dummy variables DCL for the respective technology fields in order to catch technology specific fixed effects.

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40 This is a rate very often used in empirical investigations where R&D capitals stocks are used. See for example Meyer-Krahmer/Wessels (1989) for the German manufacturing industry.

41 For a discussion of these aspects see for example Caves/Barton (1990).

For RDS/L, ETP we expect a negative coefficient because R&D and exogenous technical progress should improve the relative position of a firm with respect to the all-time best-practice frontier. RD/Y is expected to have a positive sign because the R&D expenditures in year t are assumed to increase productivity only in later years. The coefficient of K/L can have either sign, however, whenever process innovations are embodied in investment the sign should be negative.[42]

Tables 6 and 7 deliver our result for the coefficients, the t-values (in parenthesis) and the R^2 measures for various model variants in both sectors.

Table 6: Regression Results for the Machinery Sector

Variant	const.	RDS/L	K/L	RD/Y	ETP	DCL	R^2
1	6.666 (108.8)	-0.0059 (-7.306)					0.11
2	6.684 (109.1)	-0.0041 (-3.756)	-0.00001 (-2.556)				0.13
3	6.684 (108.5)	-0.0041 (-3.749)	-0.00001 (-2.553)	0.0002 (0.042)			0.13
4	6.761 (52.84)	-0.0040 (-3.661)	-0.00001 (-2.579)	0.0002 (0.048)	-0.0196 (-0.688)		0.13
5		-0.0064 (-6.126)	0.00003 (7.103)			3 sign.	0.39
6		-0.0063 (-5.951)	0.00003 (7.163)	0.0047 (1.331)	-0.0319 (-1.303)	3 sign.	0.40
7 only F2	3.163 (5.488)	-0.0340 (-4.493)	0.00008 (5.566)				0.49
8 only F2	3.923 (4.390)	-0.0332 (-4.281)	0.00008 (5.550)	0.0009 (0.119)	-0.1810 (-1.126)		0.51
9 only F3	6.305 (65.174)	-0.0052 (-6.280)	0.00003 (5.609)				0.18
10 only F3	6.372 (59.162)	-0.0050 (-6.035)	0.00003 (5.813)	-0.0019 (-0.256)	-0.0298 (-1.529)		0.19

For the machinery sector, considering variants 1 to 4, we find that the signs of RDS/L and K/L are both significantly negative which implies that a higher R&D capital stock

42 It would be interesting to include here investment data in order to take into account vintage effects. As yet, our data do not allow to take this into account.

per unit labour and a higher degree of mechanisation implies a higher relative efficiency score. The signs of RD/Y and ETP are as expected but the coefficients are not sigificant.

Including dummy variables (variants 5 and 6) for the 4 technology fields considerably improves the regression fit (R^2 improves from about 0,13 to 0,40) - only one of four dummies is insignificant at 5%. Additional runs specific to the two main technology fields F2 and F3 (variants 7 and 8, 9 and 10) repeat this result only partly. For F2 we get an even higher R^2 of about 0.50 and for F3 one sharply decreasing to 0,19. Again, the coefficients of RDS/L and K/L are siginificant; however the sign of the influence of K/L has changed implying that increased mechanisation within these technology fields leads to lower efficiency scores. A reason for this result is most probably that these two main technology fields within the machinery sector are characterized by a remarkable low K/L ratio (see point 3.2).

Table 7: Regression Results for the Electronics Sector

Variant	const.	RDS/L	K/L	RD/Y	ETP	DCL	R^2
1	7.600 (82.562)	-0.00047 (-3.964)					0,08
2	7.298 (32.090)	-0,00054 (-4.229)	0,00001 (1.453)				0.09
3	7.441 (34.620)	-0.00118 (-6.796)	0,00001 (0.693)	0.73618 (5,089)			0.21
4	7.432 (30.588)	-0.00118 (-6.748)	0.00001 (0.627)	0.73772 (5.037)	0.0034 (0.076)		0.21
5		-0.00116 (-13.09)	0.00001 (0.845)			sign.	0.81
6		-0,00119 (-14.01)	0,00001 (0.865)	0,4215 (1,600)	0,0269 (1.199)	sign.	0.82
7 only F4	7.410 (36.073)	-0,00117 (-20.34)	0,00001 (1.548)				0.85
8 only F4	7.193 (31.046)	-0.00117 (-21.195)	0.00001 (2.057)	2.802 (3.290)	0.0046 (0.199)		0.87
9 only F5	7.977 (74.36)	-0.0008 (-3.930)	0.00000 (0.151)				0.15
10 only F5	7.871 (67.86)	-0.003 (-4.358)	0.00001 (0,724)	1.317 (3,361)	0.0068 (0.497)		0.25

For variants 1 to 4 of the electronics sector the estimates for the RDS/L coefficient are significant and as expected negative. The mechanisation variable K/L is positive in sign but not significant. The estimate for R&D intensity shows a significant positive sign which is to be interpreted that increasing current R&D expenditures do not improve a firms relative position. Finally, exogenous technical progress is not sigificant here.

As in machinery, including dummies for the various technology fields improves the results considerably, R^2 increases to about 0,81. Investigating the most "crowded" technology fields "F4" and "F5" (characterized by comparably low K/L ratios of all technology fields within this sector) leads to a slight improvement for "F4" and a drastic decline in the regression fit of "F5".

Comparing both sectors we can conclude that in both the accumulated R&D capital stock has a considerable positive impact on the firms relative position towards the all-time best-practice frontier.[43] Moreover, the various technology fields have a specific (fixed) effect. Besides these common features, both sectors, however, differ with respect to the following:

(1) The different significance of the variable RD/Y in both sectors can be explained by the fact that electronic firms at the average invest five times more R&D per unit labour than machinery firms so that the effect on current year's position, i.e. relative efficiency, is here more severe and tends to dominate other factors.

(2) For the different result with respect to K/L the following explanation seems appropriate: The machinery sector - compared to electronics - is considered mostly as a sector purchasing technical progress embodied in investment where an increasing K/L and its effect on efficiency accounts for this.

These results are more or less consistent with the sector classification of Pavitt (1984). The electronics industry is there considered as rather science based relying very much

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43 Comparing also the magnitude of the respective coefficients does not lead to additional insights because the efficiency scores are a relative concept applicable only on a intrasectoral basis.

on own R&D efforts. The machinery industry, instead, is classified as production intensive with scale intensive and specialized suppliers. High capital intensities are a main feature of such productions.[44]

3.3.2 Patenting Activity and Relative Efficiency

We capture the patent activities of the firms in our sample by simply counting the number of patents they raised within a certain period for the German market. The data are taken from the 1991 publication of the INPADOC database by the "Ifo-Institut für Wirtschaftsforschung".[45]

Certainly aware of the well-known difficulties in accounting and weighting patents[46] we accept the rough procedure of Ifo and consider only those firms (a) who have applied for patents in at least two countries and (b) who had at least five applications during the years 1985-88. The relatively high costs for patenting abroad can be used as a yardstick (and lower bound) for the importance of the patents.

We are also aware of the fact that between patenting and a possible increase in productivity a certain lapse of time has to pass. This time lag should be not longer (or even shorter) than the one between R&D expenditure and productivity change. By comparing the patents of the years 1985 to 1988 with the efficiency measures of the year 1991, we lag our data between three and six years.

For the above mentioned period we select from our sample 24 machinery firms and 10 firms in the electronics sector with patent activities for Germany and at least one other country. This very small number and the fact that exactly weighting the patents was not

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44 "Technological leads are reflected in the capacity to design, build and operate large scale continuos processes, or to design and integrate large-scale assembley systems in order to produce a complex final product." See Dosi/Pavitt/Soete (1990, p.96).

45 See Faust/Buckel (1991).

46 See e.g. Pavitt (1985), Griliches (1990) or Kleinknecht (1993).

possible until now prevents us from performing regressions to relate them to efficiency measures. So we simply divide our sample in a patenting and a non-patenting group of firms and concentrate on the diferences between these subsamples. And even without a precisely measured relationship our results as stated in table 8 seem remarkable to us.

There it is shown that the average efficiency of the patenting firms is in both branches higher than the average efficiency of non-patenting firms. For the electronics sector even the percentage of technology leaders is three times higher in the patenting sample than in the non patenting group.

Table 8: Efficiency of Patenting and Non-Patenting Firms in 1991

	ELECTRONICS	MACHINERY
av. efficiency of patenting firms	0.46	0.61
av. efficiency of non-patent. firms	0.40	0.58
% of efficient firms within pat. firms	10%	0%
% of eff. firms within non-pat. firms	3%	4%

Finally we take account of the relevance of patenting for the respective technology fields in both sectors. Tables 9 and 10 give an overview.

Table 9: Patenting and Technology Fields in Machinery

techn. field	patenting firms	non-patenting firms	total	% patenting
F1	0	2	2	0
F2	6	7	13	46
F3	18	45	63	29
total	24	54	78	31

The main result for machinery is that technology field F2 with the highest average efficiency (see table 2) also leads in the percentage of patenting. This statement also applies to the electronics sector.

Table 10: Patenting and Technology Fields in Electronics

techn. field	patenting firms	non-patenting firms	total	% patenting
F1	0	3	3	0
F2	0	2	2	0
F3	0	2	2	0
F4	9	13	22	41
F5	1	9	10	10
total	10	29	39	26

This simple calculation supports the results for R&D in 3.3.1 above by indicating a positive correlation between patenting (as the ouput of R&D) and the relative efficiency of a firm and pointing on the differences between the two sectors. Again we find a slightly stronger link between patents (as the result of R&D) and the firm efficiency for the (science based) electronics sector. This outcome can be interpreted in different ways:

(1) In order to be in the top group of firms the performance with respect to technological progress is more important in the electronics sector than in machinery. This interpretation, however. does not take into account patent specific aspects.

(2) In this respect Scherer (1983) makes the point that the "propensity to patent" can differ between industries because of different expectations of the advantages of patenting. The respective propensities might differ between our two sectors, so that machinery relies more on other means of appropriation such as secrecy, first-mover-advantage, etc.

(3) Finally and related to the last point one might think of looking at the principle kind of innovation performed in both sectors. Levin et al. (1979) have stressed the fact that product innovation tend to get patented whereas for process innovations secrecy etc. are more appropriate means of protection. These aspects might be important for our results, since machinery might be more associated with process improvements, whereas electronics tends to develop new products.[47]

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47 Since our electronics sector includes also consumer electronics this argument is even more persuasive.

4. Conclusion

This paper delivers an empirical study on technological performance and diversity within the German manufacturing sectors "Machinery" and "Electronics" for the years between 1985 and 1991. Based on concepts from modern innovation theory we employ a non-parametric linear programming procedure, DEA, which allows (a) to compute an index for the relative technological and technical inefficiency of firms and (b) to determine certain technology fields differing by their relative use of input factors.

Our study shows that it is possible (a) to find a structure of technological inefficiencies characterized by several technological leaders and (b) to detect several technology fields which takes into account technological diversity. A dynamic analysis delivers (a) that the total efficiency of the sectors improves over time and (b) that there are differences among the respective technology fields.

In a second step these results are related to measures of firms' technological performance. We deliver that for both sectors the efficiency position of firms is determined by their technological performance. This result seems to be independent of whether we use the R&D capital stock as technology input measure or patenting activity as an technology output proxy.

Although our results do very much confirm the notion that technological progress is an important determinant of firm performance some qualifications necessarily have to be made. First, all what we know about the technology of a firm is deduced by a very rough procedure, e.g. technologies are distinguished by their factor input ratios. An analysis related to more technical aspects would be very much appreciated here. For future work we consider to use more information on the production structure as well as qualitative innovation data to improve our results. Second, quite crucial for our results is obviously how the factor "capital" is defined. Vintage effects, capacity utilisation, technical life cycle, etc. are not considered yet. Some improvement on this is expected whenever longer time series data completed with more reliable investment figures are available. Last but not least, the analysis of efficiency scores has to be worked on in order to distinguish between the top firms which are as yet not comparable ($\iota = 1$). Those improved measures might then help - in a longer times series analysis - to compare different technology fields and their comparative development directly.

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