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DEA of Financial Statements Data: The U.S. Computer Industry

STEN THORE, GEORGE KOZMETSKY AND FRED PHILLIPS*
IC^2 Institute, The University of Texas at Austin, 2815 San Gabriel, Austin, TX 78705-3596

Abstract

DEA (data envelopment analysis) is a technique for determining the efficiency *frontier* (the envelope) to the inputs and outputs of a collection of individual corporations or other productive units. DEA is here employed to estimate the intertemporal productive efficiency of U.S. computer manufacturers, using financial data brought from earnings statements and balance sheets. The results indicate that a few corporations, including Apple Computer Inc., Compaq Computer Corp., and Seagate Technology were able to stay at the productivity efficiency frontier throughout the time period investigated. But not all successful corporations did; sometimes subefficiency (=disequilibrium) actually goes together with very rapid growth. A new Malmquist type productivity index is calculated for each corporation, measuring shifts of the estimated intertemporal efficiency frontier.

Keywords: DEA, Malmquist type productivity index

1. Introduction

The present study gauges the productive efficiency of U.S. computer companies, using the technique of data envelopment analysis (for surveys of DEA see Charnes and Cooper [1985], Banker et. al. [1989], and Seiford and Thrall [1990]). In the well-known fashion, DEA relates the performance of each company in the industry to a piecewise linear industry production frontier. The frontier is an empirically estimated production function, based on the inputs and outputs of the efficient companies.

The rationale of our approach is the microeconomic concept of an intertemporal production function. The range of individual products of the U.S. computer industry is considerable, encompassing mainframes, minicomputers, workstations, PC's, peripherals, and software. Each product goes through a typical life cycle (development—commercialization—maturation—technological obsolescence). The concepts of "inputs" and "outputs" should be understood with reference to the life cycles of individual product designs. The intertemporal production function can be thought of as a comparative static approximation to these time flows. The inputs encompass a flow of raw materials, labor, research and development, and services derived from capital investments. On the output side, there results a

*Sten Thore is the Gregory A. Kozmetsky Centennial Fellow, George Kozmetsky is the Director for the Institute, and Fred Phillips is the Research Program Director.

flow of current and expected future sales. The future sales are measured indirectly by financial indicators such as the current stock market capitalization of the corporation.

While many early applications of DEA were limited to nonprofit organizations (such as schools, military hospitals, post offices etc.), a growing literature deals with for-profit firms; for instance, several studies have been reported applying to the field of marketing, see Golany et al. [1990a–b], and Charnes, Cooper, Eechambadi et al. [1994]. Data envelopment of financial data was effected in a study of the solvency of commercial banks (Charnes, Cooper, Sun, and Huang [1990, 1994]). Smith [1990] rated 47 pharmaceutical firms using data brought from their annual financial statements, using average equity and average debt as inputs, and earnings, interest payments, and tax payments as outputs. Yue [1991] rated the ten top U.S. electronics companies and compared them with the performance of the ten top Japanese electronics companies.

For any corporation whose stock is traded publicly, there exists a wealth of data in the form of easily available standard corporate financial statements. In this article we employ such data— brought from the Dow Jones COMPUSTAT PC PLUS data base—to perform DEA calculations of the productive efficiency of the U.S. computer industry. That is, we employ financial proxies to measure productive efficiency. The calculations were carried out for the 44 largest computer manufacturers, using annual data for 1981–1990. An empirical efficiency frontier is estimated for each year. Section 2 tracks the time path of the frontier over the ten year period.

A subset of corporations is identified that consistently managed to achieve superior efficiency ratings. It includes Apple Computer Inc. which was given the rating 1.00 in nine out of ten years, and Compaq Computer and Seagate Technology which both rated 1.00 in seven out of eight years of observations.

A high rating of productive efficiency, however, does not itself guarantee success in the marketplace. It does not imply that a company experiences rapid growth of sales or market share, nor does it necessarily entail outstanding financial results such as substantial profits or a high stock market capitalization. Actually, some successful companies in the industry systematically scored low productivity ratings. In particular, we discuss the case of Sun Microsystems which consistently was subefficient since its introduction on Wall Street. We cite some theoretical justification for believing that extraordinary rapid growth may actually be associated with subefficiency and disequilibrium.

The relative productivity of a manufacturer can improve over time in several ways. A manufacturer located at the efficiency frontier will experience a productivity gain if the frontier is pushed outward. An inefficient manufacturer may gain in productivity simply by increasing its relative efficiency faster than the advance of the frontier. To systematize the measurement of these matters, a new Malmquist-type productivity index is proposed in Section 3. The new index extends earlier work by Caves, Christensen and Diewert [1982a–b], allowing for the possibility that production points are not necessarily located on the efficiency envelope. For related use of the Malmquist index in DEA work, see Fare, Grosskopf, Lindgren and Roos [1992 and 1994], see also Tulkens and Vanden Eeckaut [1991].

The usefulness of the new proposed index is illustrated in Section 4, as we employ the conventional efficiency ratings and the Malmquist index to discuss the shake-out that occurred in the U.S. computer industry during the decade. Old and established companies like IBM and Digital stagnated, others went under (Wang Laboratories), and new technology was spearheaded by startups like Silicon Graphics and Sun Microsystems. Some final comments are offered in Section 5.

2. Data Sources, Lists of Inputs and Outputs, Mathematical Formulation of the Model Used.

In all envelopment analysis, careful attention should be paid to the choice of inputs and outputs. In the present application the task is particularly challenging since a great number of potential variables are available in the COMPUSTAT data base. The variables to be discussed below are (in millions of dollars during the current fiscal year unless otherwise noted; the acronyms are those of the data base):

Costs of goods sold (COGS)
Capital expenditures (XCAP)
Expenditures on R & D (XRD)
Selling, general, and administrative expenditures (XSGA)
Labor force, in thousands of workers, at end of year (EMP)
Holdings of plant, property, and equipment, gross, at beginning of year (PPEGT)
Gross sales revenue (SALE)
Income Before Taxes (IB)
Market captialization of the stock, at end of year (MKVALF)

We explain three alternative sets of inputs and outputs to be evaluated and compared:
(i) A Static One-period Production Function. Let there be one single period of analysis t, and use the notation

$$
\begin{aligned}
y_t &= \text{vector of outputs in period } t \\
x_t &= \text{vector of inputs in period } t \\
K_{t-1} &= \text{stock of real capital at beginning of period } t
\end{aligned}
$$

and consider the conventional one-period production function

$$y_t = f(x_t, K_{t-1}) \tag{1}$$

To measure the inputs and the outputs of (1), we propose the following variables for the DEA

inputs: COGS, XSGA, EMP, PPEGT
outputs: SALE, IB

All variables listed (except EMP) are measured in current dollars. We believe that dollar amounts are better indicators of the quantity and quality of high tech products than any measure of volume obtained by dividing by a price index. In the computer industry, volume indicators, such as the number of microchips or even the number of megabits of DRAM, at best tell only part of the story of the real attributes of the hardware. Indicators of the aggregate volume of software, such as the number of software programs sold are even less meaningful.[1]

(ii) An Intertemporal Production Function. This time, consider a multiperiod planning span $\tau = t, t + 1, \ldots, T$ extending from the present $\tau = t$ to the horizon $\tau = T$. We shall also need notation for the past, say $\tau = 0, 1, 2, \ldots, t - 1$ starting from some initial point $\tau = 0$. The intertemporal production function is written

$$y_\tau = f_\tau(x_\tau, K_0, K_1, K_2, \ldots, K_{\tau-1}; K_T), \ \tau = t, t + 1, \ldots, T \tag{2}$$

The planned output in any future time period $\tau \geq t$ depends upon the path of earlier capital formation $K_0, K_1, K_2, \ldots, K_{\tau-1}$, and also upon the target capital holding K_T at the planning horizon.[2]

To measure the inputs and the outputs of the intertemporal function (2), we propose the following variables for the DEA

inputs: COGS, XCAP, XSGA, EMP, PPEGT
outputs: SALE, IB, MKVALF

The input list now includes the variable XCAP being defined as the accumulation of capital during the fiscal year. As before, the variable PPEGT is K_{t-1}. Together, XCAP and PPEGT are taken as proxies of the entire path of capital. That is, given the inputs COGS, XSGA, EMP, PPEGT, it is postulated that a greater XCAP (signalling the presence of a more ambitious capital expansion program) will result in an increased future stream of sales, sales revenues, and profits.[3] The output list includes the variable MKVALF being interpreted as the value of the expected future profit stream, discounted to the end of the current fiscal year.

(iii) An Intertemporal Production Function with Accumulation of Technical Know-how. Taking one step further in the direction of accounting for the growth of a computer company over time, we introduce the additional notation

L_t = imputed stock of "technical know-how" at the end of period t
$L_t - L_{t-1}$ = expenditure on research and development in period t

That is, L_t is the imputed stock that accumulates in the form of expenditure on R&D. The intertemporal production function is amended to read

$$y_\tau = f_\tau(x_\tau, K_0, K_1, K_2, \ldots, K_{\tau-1}, L_0, L_1, L_2, \ldots, L_{\tau-1}; K_T, L_T), \quad \tau = t, t + 1, \ldots, T \tag{3}$$

The planned output in any future time period here depends upon the path of earlier capital formation, the earlier path of R&D, and also upon the horizon targets, both in terms of holdings of real capital and technical know-how.[4]

To measure the inputs and outputs of (3), we shall use the following variables for the DEA:

inputs: COGS, XCAP, XRD, XSGA, EMP, PPEGT
outputs: SALE, IB, MKVALF

The output list is the same as under (ii), but there is now one additional input explaining the expected future income stream: XRD.

To be included in our sample of U.S. computer companies, a company had to satisfy certain minimum requirements placed on the volume of its annual sales.[5] Over the decade, a total of 44 companies were at some time included in the sample.

Use mathematical notations as listed below:

$i = 1, \ldots, I$	index of inputs
$j = 1, \ldots, J$	index of outputs
$k = 1, \ldots, 44$	index of computer companies
$t = 1981, \ldots, 1990$	
$A^t = [a_{ik}^t]$	maxtrix of inputs at time t; the coefficient a_{ik}^t is the use of input i by company k at time t
$B^t = [b_{jk}^t]$	matrix of outputs at time t; the coefficient is b_{jk}^t the quantity of output j obtained by company k at time t
θ, ψ	efficiency ratios, to be determined
$\lambda^t = [\lambda_k^t]$	loadings of companies at time t, to be determined

Some smoothing over time was obtained by pooling the observations for any two consecutive years into a two-year window. In other words, *best practice* is defined as optimal practice in the light of the experience during the two last years.

Select one particular company to be rated (indexed "0"). The desired efficiency rating in year t, $t = 1982, \ldots, 1990$ is the optimal θ to be solved from the linear program (the CCR model of DEA, see Charnes, Cooper, and Rhodes [1978]).

$$\begin{aligned} &\min \theta \\ &\text{subject to } B^t\lambda^t + B^{t-1}\lambda^{t-1} \geq [b_{j0}^t] \\ &\theta[a_{i0}^t] - A^t\lambda^t - A^{t-1}\lambda^{t-1} \geq 0 \\ &\lambda^t, \lambda^{t-1} \geq 0 \end{aligned} \tag{4}$$

The purpose of program (4) is to compare the company to be rated with best practice, obtained as a linear extrapolation of all companies currently observed and observed during the immediately preceding year. That is, in any given year t we shall fit an efficiency frontier to the observations collected during the years t and $t - 1$. The extrapolation is achieved by giving each company k observed in a year t a loading λ_k^t and defining best practice input as the linear combination $A^t\lambda^t + A^{t-1}\lambda^{t-1}$ and best practice output as $B^t\lambda^t + B^{t-1}\lambda^{t-1}$.

As spelled out by program (4), the comparison between the company to be rated and best practice is carried out by attempting to contract all inputs equiproportionally, by the factor θ, while still generating at least the observed outputs. If no such radial contraction is possible so that the optimal contracting factor θ^* is unity, and if the inputs and outputs coincide with best practice, then the company is rated as efficient.

But if the optimal θ^* solved from the program is less than unity, the company is less than efficient and its efficiency ratio is said to be θ^*. It is then possible to shrink the use of all inputs equiproportionally by the factor θ^*, still obtaining at least the same amount of outputs.

Let θ^* (i), θ^* (ii), θ^* (iii) be the optimal efficiency ratings solved from program (4), using the sets of inputs and outputs denoted (i), (ii), and (iii) respectively. Noting that the set of inputs and outputs (iii) contains the set (ii), which in its turn contains set (i), one has by construction

$$\theta^* \text{ (i)} \leq \theta^* \text{ (ii)} \leq \theta^* \text{ (iii)} \tag{5}$$

Rating a particular company and starting out with the static measure θ^* (i), we are interested in finding out what happens when one moves from the static measure θ^* (i) to the dynamic measures θ^* (ii) and θ^* (iii). One possibility is that the rating then significantly improves—perhaps even increases to 1.0. If so, the company would seem to be well adjusted to a dynamic setting and the dynamic measure is superior to the static one. But if the improvement of the rating is slim or nonexistent, the static measure might just as well do and the dynamic measure offers no additional insight.

But these are just theoretical speculations. We now turn to the empirical evidence.

3. Tracking the Time Path of the Empirical Production Frontier

In presenting the results, we first turn to the efficiency leaders, those corporations that systematically obtained top scores in terms of their productive efficiency. They are listed in Table 1.[6] (The criterion for inclusion in the table is this: only one year of subefficiency θ^* (iii) < 1 is permitted. There are two reasons why a company may not be rated in a particular year: it may not yet have been introduced on Wall Street, or it may not meet the minimum sales requirement.(Among these eleven corporations, Apple and Compaq stand out. Apple was efficient in nine years over the decade, Compaq in seven. Furthermore, these extraordinary ratings remain the same for all three alternative sets of inputs and outputs. Whether the frame of reference is static theory or dynamic theory, they outperformed everybody else. Two companies, Conner and Quantum, show similar outstanding results, but for a shorter period of observation (Conner just 3 years, Quantum 5 years).

For all other companies in Table 1, the distinction between static and dynamic efficiency is crucial. If the frame of reference of the efficiency calculations is limited to a static production function, they did not perform spectacularly. Atari and Seagate were static efficient in only two years, Floating Point, National Computer, Silicon Graphics and Stratus in only one, Dell in none. The high productive efficiency of these companies becomes visible only when their entire dynamic adjustment is taken into regard.

In particular, we would like to stress that it is not enough to extend the static production function to the conventional dynamic alternative (ii). The XRD input variable (expenditure

Table 1. The efficiency leaders.

Apple Computer	(iii)	1981–88: 1.00 , 1989: 0.97 , 1990: 1.00
	(ii)	1981–88: 1.00 , 1989: 0.97 , 1990: 1.00
	(i)	1981–88: 1.00 , 1989: 0.97 , 1990: 1.00
Atari	(iii)	1986–89: 1.00, 1990: 1.0
	(ii)	1986: 1.00, 1987: 0.93, 1988–90: 1.0
	(i)	1986: 1.00, 1987: 0.89, 1988: 1.00, 1989: 0.93, 1990: 0.91
		NB: In 1990, Atari had negative IB[7].
Compaq Computer	(iii)	1983–88: 1.00, 1989: 0.998, 1990: 1.00
	(ii)	1983–88: 1.00, 1989: 0.97, 1990: 1.00
	(i)	1983–88: 1.00, 1989: 0.97, 1990: 1.00
Conner Peripherals	(iii)	1988–90: 1.00
	(ii)	1988–90: 1.00
	(i)	1988–90: 1.00
Dell Computer	(iii)	1988: 1.00, 1989: 0.94, 1990: 1.00
	(ii)	1988: 0.96, 1989: 0.88, 1990: 1.00
	(i)	1988: 0.96, 1989: 0.88, 1990: 0.99
Floating Point	(iii)	1983–85: 1.00
	(ii)	1983–85: 1.00
	(i)	1983: 1.00, 1984: 0.997, 1985: 0.95
National	(iii)	1984–88: 1.00, 1989: 0.99, 1990: 1.00
	(ii)	1984: 0.91, 1985–86: 1.00, 1987: 0.88, 1988: 0.84, 1989: 0.85, 1990: 1.00
	(i)	1984: 0.88, 1985: 1.00, 1986: 0.996, 1987: 0.86, 1988: 0.83, 1989: 0.84, 1990: 0.89
Quantum	(iii)	1984–85: 1.00, 1987–90: 1.00
	(ii)	1984–85: 1.00, 1987–90: 1.00
	(i)	1984–85: 1.00, 1987–90: 1.00
		NB: In 1987, Quantum had negative IB
Seagate Technology	(iii)	1983–84: 1.00, 1985: 0.79, 1986–90: 1.00
	(ii)	1983–84: 1.00, 1985: 0.79, 1986–87: 1.00, 1988: 0.91, 1989–90: 1.00
	(i)	1983–84: 1.00, 1985: 0.79, 1986: 0.98, 1987: 1.00, 1988: 0.91, 1989–90: 0.99
Silicon Graphics	(iii)	1989–90: 1.00
	(ii)	1989: 0.52, 1990: 1.00
	(i)	1989: 0.52, 1990: 1.00
Stratus	(iii)	1987: 1.00, 1988: 0.98, 1989–90: 1.00
	(ii)	1987: 1.00, 1988: 0.98, 1989: 0.997, 1990: 1.00
	(i)	1987: 1.00, 1988: 0.98, 1989: 0.997, 1990: 0.97

on R&D) is essential. Rating Silicon Graphics in 1989, only the full dynamic efficiency measure is able to reveal the optimal adjustment of this company. Anything less produces an efficiency rating of only θ^* (i) = θ^* (ii) = 0.52.

The DEA literature tends to identify the efficiency frontier with good and successful management. In an application to the world of high technology, such as ours, the concept of success becomes less clear-cut. DEA measures input-output efficiency, the proximity of an observed input-output point to the empirical production frontier. It measures how efficiently management is able to economize on its use of inputs in order to obtain a given list of outputs. As explained, this measurement can be carried out in a static or dynamic context. But there are other dimensions to success: productive inventiveness, marketing savvy, aggressiveness, growth, and appreciation of the stock price.

So, some care is needed to interpret our results. A high rating of productive efficiency does not guarantee that a corporation is expanding and growing, nor that it is doing well on Wall Street. Rather, the concept says something about management discipline: the ability of management to keep costs and expenditures under control in relation to outputs. Such discipline can be exercised in good times and in bad times alike.

One measure of success is market share (here: annual sales of a company divided by industry sales). During the decade, Apple increased its market share about sixfold, from 0.6 to 3.6%. Compaq was not far behind. Seagate also did well. Dell and Quantum both grew rapidly in 1988–90. But the others did not improve their market positions. National lost market share in 1987, Quantum in 1984–86. And the case of Atari is instructive. The last good year for Atari was 1987; from then on its sales fell in every single year as Nintendo took over the market for computer games. Atari ran up red ink in 1990 (negative IB) and the price of its stock on Wall Street collapsed. Yet, Atari remained efficient. Why? It downsized well, slashing inputs just as fast as its outputs were falling.

Turning now to the opposite end of the efficiency spectrum, several companies stayed inefficient throughout the entire decade (when not otherwise indicated, all calculations refer to the intertemporal efficiency ratings θ^* (iii)). They were Data General Corp (efficient in 1981), Digital, Hewlett Packard, NCR Corp, Unisys (efficient in 1981) and Wang Laboratories. The results for Data General, Digital and HP are exhibited in Figure 1. The results for the remaining three companies are shown in Figure 2. (In addition, there were

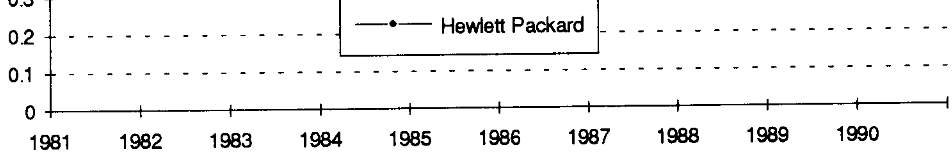

Figure 1. Efficiency ratings.

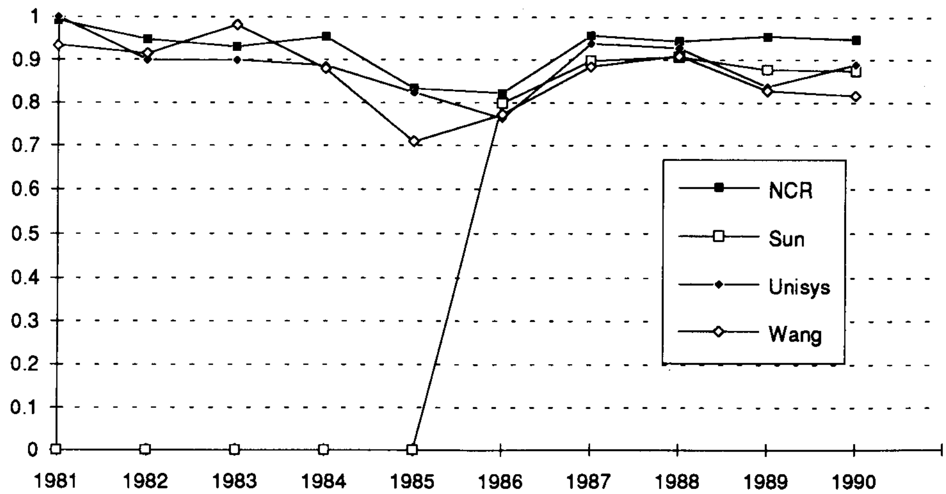

Figure 2. Efficiency ratings.

several all-inefficient companies that were present in the sample for a few years only. Sun Microsystems was one of them, see the discussion below. Sun is also shown in Figure 2).

Inspecting these two charts, one notices how the efficiency ratings in every case dipped to low levels in 1985 and/or 1986. These were the years when the computer industry was hit by a universal and sudden setback, with falling sales, falling prices, and layoffs. The efficiency leaders listed in Table 1 weathered the crises years well. The companies exhibited in Figures 1 and 2 took all bad hits. Conclusion: if a company is inefficiently managed already when market conditions are favorable, it is likely to run into even greater trouble when the market sours.

But again, productive and cost efficiency is only one dimension of the competitiveness of a company. By conventional measures, some of the companies exhibited in Figures 1 and 2 did quite well. Digital and Hewlett Packard were two companies of approximately the same size; each slowly expanded its market share over the decade, from a little below 7% to close to 9%. Unisys lost some market share in the early 1980s but blossomed during the difficult years of 1985–87. And then there was the remarkable performance of Sun Microsystems, one of the great stars of the industry. After its introduction on Wall Street in 1985, Sun Microsystems saw its sales multiply more than twentyfold during the next five years. (The accomplishments of Sun have been recorded by Hall and Barry, [1990].)

The obvious possibility must be considered that the systematic subefficiency of Sun actually was a *precondition* of its rapid growth. Or, putting it in slightly different terms, remembering that efficient points represent the static equilibrium frontier of neoclassical theory but subefficient points represent *disequilibrium*: the possibility that the very nature of rapid growth is disequilibrium. For theoretical considerations supporting such a notion, see Arthur [1989]. The DEA format of calculation for the first time provides an opportunity to test such assertions empirically.

Further insight into the very special nature of the time path that Sun followed during the decade can be gained by computing all three efficiency variants θ^* (i), θ^* (ii), and θ^* (iii). Rounded to two decimal places, all three efficiency measures coincided in every single year. For other inefficient companies, the degree of efficiency could be improved upon by moving from the static efficiency concept to the dynamic one. For Sun the inefficiency was structural.

Modern thermodynamics investigates physical dynamic systems that are engaged in disequilibrium paths *far from equilibrium* (see e.g. Nicolis and Prigogine, [1977].) The low efficiency values for Sun seem to indictate that this corporation, similarly, grew along a trajectory that was located far from equilibrium. One might infer this to mean that the Sun management consciously sacrificed cost efficiency in order to achieve rapid long term growth.

We have seen how some of the inefficiencies reported in Figures 1 and 2 actually went together with indisputable success in the marketplace. But they were the exceptions. Most of these companies experienced a static or declining market share. Digital lost terrain every year from 1984 and on, NCR in every year except 1986 and 1987. Unisys lost market share in 1982–85 and in 1988–90.

Wang Laboratories presents the most clearcut case of distress. After founder An Wang retired in 1984, this company ran into serious trouble (notice the bottom-low efficiency ratings in Figure 2). From 1986 to 1990 the company laid off more than a third of its labor force. Toward the end of the decade, the company suffered large losses (negative IB). The stock capitalization of this once flourishing company was virtually wiped out. (The plight of Wang has been chronicled in a popular book, see Kenney, [1992].)

4. Measuring the development of productivity over time: A Malmquist type index.

In the preceding section, best practice in period t, $t = 1982, \ldots, 1990$ was determined as the point having inputs $A^t\lambda^{t*} + A^{t-1}\lambda^{t-1,*}$ and outputs $B^t\lambda^{t*} + B^{t-1}\lambda^{t-1,*}$ where the asterisk denotes the optimal value determined from program (4). Using a more compact notation, denote these inputs $[a_{io^{t*}}]$ and these outputs $[b_{jo^{t*}}]$. Let us now move one period ahead, to period $t + 1$. We pose the following question: how is this same best practice point doing in period $t + 1$? Is it still located on the envelope or has it now fallen behind? To find out, we shall *adjoin* the best practice point to the observations recorded in that period, and calculate its efficiency rating.

The answer will provide information about the possible advance of the envelope over time—that is, about the rate of increase of productivity over time. If the old best practice point is still located on the envelope, the facet of the envelope currently under investigation has not advanced. It remains the same (or it has actually retracted, see below). But if that former best practice point has fallen behind the current envelope, the envelope must now have shifted outwards. Productivity has increased. For instance, if the efficiency index of the former best practice point now turns out to be only 96%, and if productivity originally is put equal to 100, we shall say that productivity has increased to 100/96 = 104.2.

The calculations indicated involve forming and solving the program

$$\begin{aligned}
&\min \psi \\
&\text{subject to } B^{t+1}\lambda^{t+1} + B^{t}\lambda^{t} + [b_{j0}^{t*}\,\mu^{t}] \geq [b_{j0}^{t*}] \\
&\psi[a_{i0}^{t*}] - A^{t+1}\lambda^{t+1} - A^{t}\lambda^{t} - [a_{i0}^{t*}\mu^{t}] \geq 0 \\
&\lambda^{t+1}, \lambda^{t}, \mu^{t} \geq 0
\end{aligned} \tag{6}$$

where μ^t is the scalar loading attached to the adjoined best practice point.[8,9]

Put the productivity index in period t equal to Π_t. Then we shall calculate productivity in period $t + 1$ as the index

$$\Pi_{t+1} = \Pi_t / \psi^* \tag{7}$$

It is a Malmquist type index.

Notice that, by construction, the index (7) is monotonically increasing over time—it can stay unchanged or increase, but it cannot fall. If the technological frontier recedes, an earlier point of best practice will *a fortiori* remain efficient when rated at a later date (when the two-year window has been moved forward in time). In other words, the index (7) does not pick up possible decreases in productivity (extending over more than two years).[10]

The productivity index as defined and discussed above has its roots in earlier developments by Caves, Christensen, and Diewert [1982a]. Comparing two different firms k and l (or the same firm at two different time points k and l), these authors first define *the firm k Malmquist input index* as

> "... the maximum [factor] required to deflate the input vector of firm l ... onto the production surface of firm k, given that the output vector is that of firm k" (*ibid.*, p. 1396).

The firm l Malmquist input index is defined in an analogous manner. Next, they develop a productivity index by treating productivity differences as differences in minimum input requirements conditional on a given level of output. This view leads to a *Malmquist firm l input based productivity index*, defined as

> "the maximum input deflation factor such that deflated input for firm k ... and the firm k output vector lie on the production surface of firm l (*ibid.*, p. 1407)."

(In the parallel work 1982b, the same authors extended their analysis to a comparison of a larger number of firms.)

Our own treatment extends these concepts, allowing for the possibility of both optimal (on the envelope) and suboptimal (below the envelope) production behavior.

In recent articles, Fare, Grosskopf, Lindgren and Roos [1992, 1994] similarly set out to extend the same work by Caves, Christensen and Diewert to the case of possible inefficiency. They calculate their productivity index as the product of two factors: (i) the relative change of best practice as measured by the shifts in the efficiency frontier in period t and in period $t + 1$ and then averaged geometrically; and (ii) the relative change of the efficiency score between the two time periods. By contrast, our own approach gauges these two types of changes separately. (See also Forsund and Hjalmarsson, [1987].)

In spirit, the calculation of the efficiency measure ψ^* is related to the *advance of technical know-how* of conventional econometric productivity analysis. An empirical production function is estimated, relating a list of inputs to output. The advance of technical know-how is the change in output over time that cannot be ascribed to inputs but instead takes the form of an *unexplained residual* present in the econometric error term. Here, the advance of productivity is the contraction of frontier inputs over time, producing a given list of outputs.

The DEA calculation (6) establishes quite stringent criteria for a productivity gain: it is required that it be possible to reduce all frontier inputs equiproportionally. For a company that is already managed well, it may be difficult to accomplish such over-the-board reduction of all inputs. The following companies listed in Table 1 experienced no productivity gain at all: Apple, Atari, Compaq, Floating Point, and Stratus. Setting the Malmquist index (7) equal to 100 in the first year of calculations, it stayed at that figure throughout the decade. The production frontier remained static over time. For these few companies, then, assuming that their inputs in a future year were predetermined, one would be able to make an exact deterministic forecast of their outputs. There is no deviation from the frontier, neither below it nor above it.

To see how productivity gains interact with efficiency, turn now to the case of Amdahl Corp. illustrated in Figure 3. The top curve traces the value of the Malmquist type index Π over time (putting 1981 = 100). It shows the productivity development that Amdahl would have accomplished, had it all the time stayed at the efficiency frontier. The bottom curve traces the value of the product $\theta^*\Pi$ (where the value of θ^* has been brought from the solution of program (1)). This, then, is the productivity index that Amdahl *actually* achieved in each year.

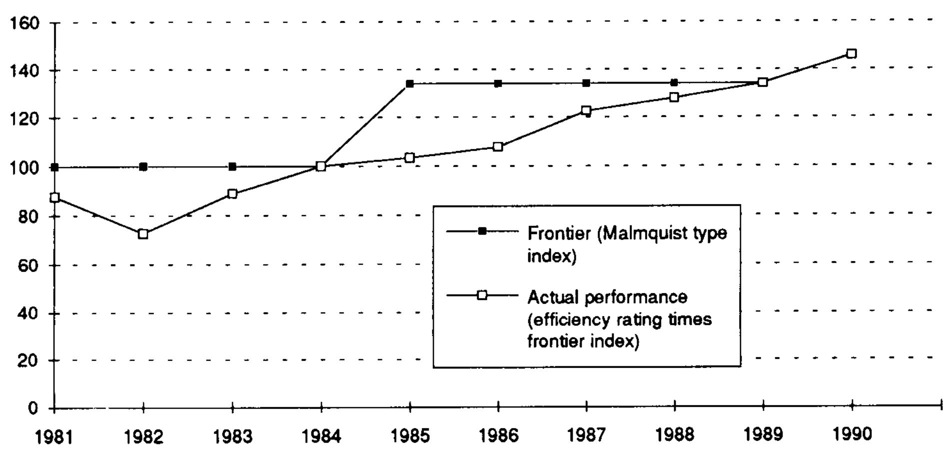

Figure 3. Amdahl Corp.

We have already in Section 2 identified a few companies that by conventional standards performed quite well, and yet obtained low efficiency ratings. Amdahl Corp is such a company. It expanded its sales in every single year, the sales volume multiplying about fivefold during the decade. The stock market reacted favorably. Amdahl's stock capitalization reached a peak in 1988. But the efficiency index remained low for most of the time period, reaching unity only in the three years 1984, 1989, and 1990.

As shown by the Malmquist productivity index (the top curve in Figure 3), the frontier ahead of Amdahl expanded outward in 1985, reaching $\Pi = 134.2$ in 1985. As a result, the index of actual performance $\theta^*\Pi$ (the bottom curve in the figure) rose that same year, and in every subsequent year. In other words, the low efficiency ratings in 1985–88 mask a solid improvement in productivity. Then, in 1989–90, something interesting occurs: Amdahl climbs back to the efficiency frontier and even pushes through it, raising it to 145.9.

Inspecting the companies making up the facets of the frontier ahead of Amdahl (the reference companies defining the frontier), the name of one company recurs every single year: Cray Research—the arch enemy of Amdahl in the supercomputer market. Up to 1985, Cray was the market leader, its Cray-1 system essentially being without head-to-head competition. During the ten years since its initial public offering on Wall Street, Cray stock had grown in value by a factor of over 100. It was the highest ten-year growth average of any publicly traded stock (see Berlin, [1987]).

The story of Amdahl and Cray as it unfolded during the 1980s is the drama of one low-efficiency climber pitted against a high-efficiency leader that faltered and slipped. Please compare Figure 3 (Amdahl) and Figure 4 (Cray).

The market share of Cray stagnated in 1987 and then fell in every single year. Its stock market capitalization amplified the declining prospects of the company, bottoming out in 1990 at a third of its 1986 peak. But, in terms of productive efficiency, the company remained excellently managed. The efficiency index stayed at 1.0 in eight out of ten years.

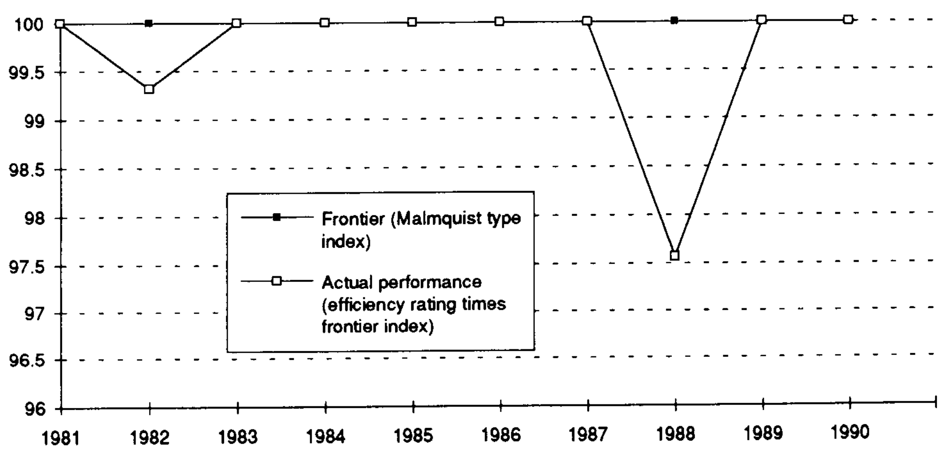

Figure 4. Cray Research.

The Malmquist index remained at 100.0 throughout the decade. The frontier never gave way. In other words, Cray showed consistently all the characteristics of an efficiency leader. And in times of adversity it still clung to the productivity frontier.

A few words should be said about IBM. The present application of DEA introduces a unqiue set of difficulties because of the great dispersion in size of the decision-making units rated. IBM is a giant company, responsible for about half of industry sales (the ratio slowly falling from 56% in 1981 to 46% in 1990). At the same time, more than half of the companies included in the sample in 1990 each rang up less than one per cent of industry sales.

As a consequence, it would make little sense in the DEA calculations to impose any constraints on the weights λ (other than nonnegativity). It is certainly necessary to permit the weights to become greater than unity; otherwise best practice for the larger companies would by construction be limited to a composite of other large companies. And, in particular, there would be no way IBM could ever become inefficient.

Yet, in the first round of calculations, IBM did come out efficient in every year. Suspecting that this result reflected the absolute size of the corporation rather than its efficiency, our attention soon was focused on the COGS input variable.[11] IBM manufactures a greater proportion of its inputs in-house than any other company. Its booked costs of goods sold, relative to sales, are therefore consistently lower. To eliminate this systematic advantage, we decided to carry out the IBM calculations without the COGS variable. The ratings for the ten years 1981 through 1990 then came out as 1.00, 1.00, 1.00, 0.75, 0.73, 0.60, 0.61, 0.56, 0.51, 0.58. Note the low values since 1986. The inputs could have been reduced by almost a half, still delivering the same outputs!

The relative decline of IBM becomes even more evidenct looking at its performance relative to the productivity gains at the frontier, see Figure 5. While IBM fell behind the frontier in 1984, the frontier surged ahead, reaching index 143.4 in 1987.

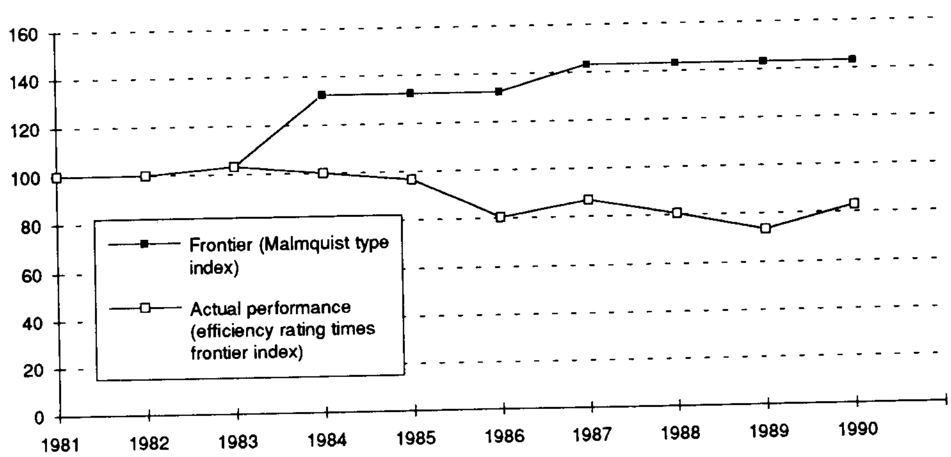

Figure 5. International Business Machines.

Which were the industry leaders ahead of IBM? In the common manner, the DEA calculations give detailed answers to that question. In 1990, best practice for IBM would have been a composite or amalgam formed as shown in Table 2 below. Note the large weights.

5. On the "Shake-out" in the U.S. Computer Industry during the 1980s.

The 1980s was a tumultuous time period in the U.S. computer industry, with many older established companies stumbling and a number of small aggressive startups making rapid advances. From a technological point of view, the decade witnessed on the one hand the maturing and eventual decline of the *big iron* (the mainframes), and on the other the advent of the personal computer and the computer workstation. The old mainframe companies had been capital-intensive, process-intensive, and reliant on high-volume manufacturing. The PC was more than just a new computer product; it wrought fundamental changes in the economics and structure of the computer industry. Value-added shifted toward design or architectural uniqueness and short product life cycles. The clash is sometimes referred to as the *downsizing* of the computer industry. Startups like Sun Microsystems, Compaq and Silicon Graphics maintained low overheads, outsourced many components to save R&D expenses, and recognized that time to market was their most significant weapon. Together with the PC revolution went a proliferation of peripherals (disk drives and printers) and software.

Employing the envelopment calculations explained in Section 2 and the new Malmquist productivity index in Section 3, we now identify some archetypes of corporate fortunes encountered in the industry. Consider these scenarios:

(i) A company moves up to the productivity frontier, breaks through it and establishes itself as a productivity leader (i.e., stays at the frontier). This is the archetype of the innovator who pioneers new efficient technology and who sets the new standards in the industry. Examples: Amdahl (breaking through the frontier in 1990), Quantum (breakthrough in 1989), Intergraph and Tandy (both breaking through in 1983).

(ii) A company stays at the productivity frontier all the time or most of the time. The productivity frontier remains static. Cases in point: Apple, Atari, Compaq, Floating Point, Stratus.

Notice that every single company identified as belonging to archetypes (i) and (ii) was a startup. They represented the new, the drive toward change, the advent of superior technology.

Table 2. Best practice of IBM in 1990.

Frontier Company (Reference Company)	Weight
Compaq	6.95
Conner	0.43
Dell	39.85
Quantum	10.54
Tandon	21.45

(iii) A company stays inefficient all the time or most of the time. The productivity frontier ahead of the company moves outward so that, relatively speaking, the position of the company is actually deteriorating. This is the archetype of the older established company that experiences difficulties adjusting to the new technological age. Examples: Data General (the frontier index Π in 1990 ending up at 115.8 but the Malmquist productivity index $\theta^* \Pi$ that same year actually having fallen to 96.6), Digital (108.0 and 95.1, respectively), Hewlett Packard (106.7 and 96.8, respectively), Unisys (111.0 and 98.7, respectively), Wang (105.3 and 86.9, respectively). Also, of course, IBM belongs to this list (143.4 and 82.9, resp.).

(iv) A company stays inefficient all the time or most of the time. The productivity frontier remains static. Examples: Sun Microsystems. We have already commented in some detail on this particular case.

6. Conclusion

It has been our intent to extend the conventional DEA calculations in several directions. The application involves an industry with rapidly changing technology, where the development of future manufacturing processes and future products is just as important as the implementation of current state-of-the-art technology. Accordingly, it seemed necessary to shift the emphasis of the DEA calculations from the estimation of a piecewise linear single period production function to an intertemporal production function.

A novel feature of our approach is the use of a standard financial data base to carry out the DEA calculations. In particular, we felt that data on R&D, and on the market capitalization of corporations could provide the desired links to the intertemporal dimensions of the production function.

The productive efficiency of a corporation was measured in relation to the production frontier enveloping all observed data points. We have argued that productivity can have two dimensions: a shift of the frontier itself, and an improvement of the performance of the corporation relative to the frontier. In the first instance, the observed input-output point of a corporation located at the frontier is inefficient relative to the observations in the next time period. The degree of inefficiency measures the productivity change.

In general, a corporation will exhibit inefficiencies both with respect to observations in the same time period and observations in the next period. Any recorded improvement in productivity can then be broken into two parts: improvements due to shifts of the frontier, and improved intra-period inefficiency ratings.

Correspondingly, we have calculated for each corporation a Malmquist type index (the index Π) that measures the rate of productivity change at the frontier, and an intra-period (in)efficiency index (denoted θ^*). The product $\theta^* \Pi$ incorporates the total productivity change arising from both sources.

Commenting finally on our empirical results, they strike us as both unexpected and offering new insights into the nature of efficiencies and subefficiencies in the rapidly changing world of high technology. We were able to identify a subset of companies that stayed consistently at the estimated intertemporal production frontier throughout the decade. In other words, an intertemporal production function existed and was attained by a few well managed companies. Furthermore, these companies happened to display no productivity shifts at all over time so that the intertemporal frontier actually remained static.

Another subset of companies stayed inefficient all the time. Remarkably, many of these companies displayed typical characteristics of success, such as rapid sales growth, increasing market shares, and increasing market capitalization. The conclusion seems inescapable that for many of these companies subefficiency was actually a preferred and conscious policy choice, sacrificing efficiency for growth.

Finally, we have shown how a proposed new Malmquist type productivity index can help to characterize the dynamic performance of the observed computer companies. We were able to demonstrate how it is possible to assemble information about efficiency and productivity change (as measured by the new index) to understand the wrenching confrontation in the industry between older technology that was rapidly becoming obsolete on the one hand, and new aggressive micro-processor based technology on the other. Certainly, our brief discussion on the subject cannot be the last word on the matter. But the analytical potential of the proposed new index should be evident.

Acknowledgments

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Notes

1. The difficulities of constructing price indices for high tech products are notorious. See Triplett [1986] and Cole et al. [1986]. Reich points out that the transition to a high tech economy also means a transition from volume to value. See Reich [1991], Ch. 7 ("From High Volume to High Value").
2. For precursors to the formulation (2), see Koopmans [1957] and Dorfman, Samuelson, and Solow [1958], Ch. 12 ("Efficient Programs of Capital Accumulation"); modern formulations typically draw on control theory, see e.g. Sethi and Thompson [1981], Ch. 5. The particular formulation employed here subsumes that the quality of physical capital K_t evolves over time, so that each vintage of capital needs to be distinguished separately. The initial condition determining y_τ is therefore not just the initial capital stock K_{t-1} but the entire path of earlier physical capital $K_0, K_1, K_2, \ldots, K_\tau$.
3. Assume that the currently observed time period (a fiscal year) spans the unit time periods $\tau = t, t + 1, \ldots, t'$ with $t < t' < T$. Summing (2) over $\tau = t, t + 1, \ldots, t'$, one finds

$$\Sigma y_\tau = f(x_t, x_{t+1}, \ldots, x_{t'}, K_0, K_1, K_2, \ldots, K_{t'-1}; K_T) \tag{2a}$$

In words, total output Σy_τ is a function of the time path of inputs $x_t, x_{t+1}, \ldots, x_{t'}$ and of the time path of capital $K_0, K_1, K_2, \ldots, K_{t'-1}$. Next, approximate (2a) by

$$\Sigma y_\tau = f(\Sigma x_\tau, K_{t-1}, K_{t'} - K_{t-1}; K_T) \tag{2b}$$

The approximation from (2a) to (2b) involves replacing the path of consumption during the fiscal year $x_t, x_{t+1}, \ldots, x_{t'}$ by total consumption Σx_τ, and representing the entire path of capital $K_0, K_1, K_2, \ldots, K_{t'-1}$ by initial capital K_{t-1} and investment during the year $K_{t'} - K_{t-1}$.

4. Early estimates of a Cobb-Douglas type production function with accumulation of an imputed stock of R&D were reported in Terleckyj [1974]. Several later studies on R&D expenditures and productivity growth have been carried out by E. Mansfield, see e.g., his survey article [1987].
5. To participate in our sample of U.S. computer companies, a company had to satisfy three criteria: (i) SIC codes 3570–72 and 3577; (ii) Only domestic companies were included; (iii) In order to avoid vast discrepancies between very large companies and quite small ones, each company was required to meet the following minimum sales volumes: 1981–85: 100 million dollars, 1986–87: 150 million dollars, 1988–89: 200 million dollars, 1990: 250 million dollars. The number of companies qualifying in each year was: 16 (1981), 19 (1982), 24 (1983), 27 (1984), 30 (1985), 29 (1986), 32 (1987), 33 (1988), 37 (1989), 36 (1990).
6. Since we used a two-year window, two different efficiency values can be computed in each year for each company: one calculation for the first year in the two-year window, and one calculation for the second year in the window. Only the latter results are shown.
7. The observations of the output variable IB were in a number of instances negative (a company operating at a loss). It is usually assumed that all observations in the standard DEA format need to be nonnegative; some widely available software for DEA does not run with negative outputs. However, there seems to be no difficulties in principle to extend the DEA format to accommodate the presence of negative outputs, see Golany and Thore [1993]. Thus, the negative observations were employed on line with the others. However, we decided to further qualify the DEA model (4) to include the condition that best practice output at all times be nonnegative ($B^t \lambda^t + B^{t-1} \lambda^{t-1} \geq 0$). In many cases with negative outputs, this nonnegativity constraint turned out to be non-binding. But when it does bind, the optimal efficiency value θ^* can become greater than unity, signalling that one or several negative outputs are creating trouble. See further *ibid.*
8. Without the two-year "window", program (6) simply reads

$$\begin{aligned}
&\min \psi \\
&\text{subject to } B^{t+1}\lambda^{t+1} + [b_{j0}^{t*}\mu^t] \geq [b_{j0}^{t*}] \\
&\psi[a_{i0}^{t*}] - A^{t+1}\lambda^{t+1} - [a_{i0}^{t*}\mu^t] \geq 0 \\
&\lambda^{t+1}, \mu^t \geq 0 \qquad (6a)
\end{aligned}$$

   There is something to be said for this formulation, because the reference point for firm 0 is here calculated from a wholly different set of data points.
9. Program (6) applies as long as actual performance in period t falls short of best practice, i.e., the optimal $\theta^* < 1$. But if actual performance in period t equals best practice, a mathematical complication occurs. Adjoining best practice in period t to the observations in period $t + 1$ would then produce a DEA program where one and the same observation is present twice and the DEA calculations becomes degenerate. The obvious remedy is to eliminate one of the two identical presences of the same point—Because of the modifications of the DEA calculations thus made necessary (see also the comments in Note 7), standard DEA software could not be used. Instead, we wrote our own software programmed in the GAMS mathematical programming code.
10. Although we shall not pursue these possibilities here, the possible decline of productivity could presumably be established in the following manner. Rather than adjoining ($[a_{io}^{t*}]$, $[b_{jo}^{t*}]$) to the observations in period $t + 1$, one may ask whether that same point now lies inside, on the frontier, or outside the convex set spanned by those observations.
11. Searching for the culprit causing the apparent efficiency at all times, we constructed a modified DEA program (4) multiplying each input by a binary 0–1 variable, say z_i^t, $i = 1, \ldots, I$. We also adjoined the constraint $z_1^t + z_2^t + z_3^t + z_4^t + z_5^t + z_6^t \geq 5$. This modified program, then, searches for the lowest possible θ^*, kicking out one (but not more than one) input. Solving the program by the 0–1 ZOOM code (being part of the GAMS software package), it kicked out COGS in every single year.

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