Department of Social Systems and Management

Discussion Paper Series

No. 1145

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by

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April 2006

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Tsukuba, Ibaraki 305-8573
JAPAN

Measuring the change in R&D efficiency of the Japanese pharmaceutical industry – revised*

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Abstract

This paper presents a DEA (Data Envelopment Analysis)/ Malmquist index methodology for measuring the R&D efficiency change of the Japanese pharmaceutical industry. Letting each of ten firms in each year be a separate DMU (Decision-Making Unit) and employing one input and three outputs in the DEA, and using the cumulative frontier shift component on average proposed in the Malmquist index analysis, we quite obviously show the industry-wide R&D efficiency change throughout the decade 1991-2000. The results empirically reveal that the R&D efficiency of the Japanese industry has surely gotten worse almost monotonically for the decade at least as to the pharmaceutical one.

Keywords: R&D efficiency change; Data envelopment analysis; Malmquist index; Japanese pharmaceutical industry

1 Introduction

This paper measures R&D efficiency of Japanese pharmaceutical firms and examines how R&D efficiency at the industry level has changed over time. R&D in firms, that can be considered as a stage prior to production, would be as important as production. But we have not quantitatively analyzed R&D efficiency so much as productivity. The lack of how to measure R&D efficiency would be the main reason. In considering the input and output of R&D, we cannot immediately specify what to be as the output, compared with R&D investment as the input. Geisler (1995) and Brown and Svenson (1998) list published articles, patents, new products, etc. as the output. That is, we cannot help considering not a single output but multiple outputs of the R&D. This multiplicity of

*This is a revised version of the paper: Hashimoto, A. and Haneda, S., Measuring the change in R&D efficiency of the Japanese pharmaceutical industry. Dept. Social Systs Mgmt Discussion Pap. Ser. 1128, Univ. Tsukuba, 2005.

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the output prevents from analyzing R&D efficiency by means of the ordinary production function, i.e., parametric, approach.

Thus it is not easy to measure R&D efficiency, so that we have seldom observed its chronological transition at the industry level. Has it gradually gotten better as incorporating some innovations into process like that productivity could be expected? For the recent Japanese industry, it might not or might have even worsened (Sakakibara and Tsujimoto, 2003). For also the pharmaceutical industry in the world, it is said that the R&D efficiency is recently in decline (Tollman et al., 2004). After all, the recent change in R&D efficiency has yet been elusive. Taking up the Japanese pharmaceutical industry, we verify whether the R&D efficiency has gotten better or worse for the decade 1991-2000.

In order to analyze the R&D efficiency, we employ *DEA (Data Envelopment Analysis)* (e.g., Charnes et al., 1994; Cooper et al., 2000). DEA is a non-parametric method that can measure the relative efficiency, i.e., *DEA efficiency*, of objects called *DMUs (Decision-Making Units)* with multiple *inputs* and multiple *outputs*. Although DEA could be applied to various fields other than the standard efficiency analysis (e.g., Hashimoto and Ishikawa, 1993; Hashimoto, 1996), the DEA characteristic that can deal with even multiple outputs has enabled to measure the efficiency of a novelty of DMU sets in also the original efficiency analysis. For example, Nasierowski and Arcelus (2003) recently measure the efficiency of 45 national innovation systems with two inputs and three outputs using DEA. However, we can find no DEA analyses of firms' R&D efficiency except for Honjo and Haneda (1998). They try to analyze the R&D efficiency of fourteen Japanese pharmaceutical firms with one input and two outputs for the period 1977-1991. Refining their analyses, we also preparatorily do DEA analyses using the panel data of ten pharmaceutical firms for 1991-2000. But we should note that the ordinary DEA cannot analyze as taking the *DEA efficiency frontier* shifting over time into consideration.

Then, we introduce *DEA/ Malmquist index* analysis (e.g., Färe et al., 1994; Thanassoulis, 2001) to examine time series change in R&D efficiency at the industry level. The Malmquist index can measure the ratio of DEA efficiencies in two different time periods with shifting DEA efficiency frontiers. Although we recently have some DEA/ Malmquist index applications, most of which are applied to productivity like González and Gascón (2004). The Malmquist index can be decomposed into two components: "catch-up" and "frontier shift". While the former measures how much closer to the frontier a DMU, i.e., a firm, moves, the latter does the movement of the frontier. Since the frontier is composed of the "DEA efficient" DMUs among all the firms in a time period, the frontier shift means the change at the industry level. Using this frontier shift, we devise to quite obviously display the R&D efficiency change of the Japanese pharmaceutical industry throughout the decade 1991-2000.

2 Data to measure R&D efficiency

To DEA-analyze R&D efficiency of the Japanese pharmaceutical firms as DMUs, we must select inputs and outputs. DEA relatively evaluates how efficiently DMUs convert multiple inputs into multiple outputs. That is, any DMU producing more outputs with fewer inputs is judged relatively efficient. For the input, we straightforward employ *R&D expenditure* (billion yen a year) as an indicator involving also the concept of number of researchers. For the output, we propose the following three dimensions: We first list *patents* (the number of patent applications publicly published in a year) as a proxy of invention, i.e., an indicator directly reflecting the level of R&D outcomes. Next, we consider the other phases of outputs. R&D activities in firms can be divided into two: one aiming at "product innovation" and the other aiming at "process innovation". While the former contributes sales increase through product discrimination, the latter does profit increase through cost reduction (Odagiri, 1987). Corresponding to these phases respectively, we employ *pharmaceutical sales* (ten billion yen a year) and *operating profit* (billion yen a year) as the additional two outputs.

For these one input and three outputs, we initially provide four data panels as follows: Each panel is ten firms × twenty years. That is, the sample period is the latest 1982-2001 and the ten pharmaceutical firms are Takeda, Sankyo, Yamanouchi, Daiichi, Eisai, Shionogi, Fujisawa, Chugai, Tanabe and Yoshitomi. They are all big enterprises driving R&D and seem homogeneous as professional-medicine makers. Although we took the biggest thirteen pharmaceutical firms of Japan into consideration at the beginning, Kyowa-Hakko and Meiji-Seika were excluded because each firm's medicine sales did not reach to fifty percent of each whole sales. We also excluded Taisho because of its characteristic as a popular-medicine maker peculiar vs the other firms. We collect annual data to the one input and three outputs, for the ten firms in the period 1982-2001, from *Data Book* (Tokyo: Japan Pharmaceutical Manufacturers Association) and *NEEDS Database* (Tokyo: Nihon Keizai Shimbun, Inc.). The four indicators except for patents are all deflated to the 2001 value.

In DEA-analyzing R&D efficiency in a year, it is not appropriate to apply the input and output data of the same year. We should consider that variations in inputs would cause observed variations in outputs of some years later. How many years would be the time lag between the R&D expending and the realization of its outcomes? Science and Technology Agency (1985) states that the average years of the lag would be 8.08 for the Japanese pharmaceutical industry. Odagiri and Murakami (1992) estimate the lag six to eight years. Based on these reports, we here employ eight years, i.e., we use input data of a year together with output data of eight years later. However, this input-output correspondence at intervals of eight years would not so strict, that we first compute three-years moving averages being the middle year's values for the four indicators in the period 1982-2001. Merging the moving-averaged input data for 1983-1992 in the moving-averaged output data for 1991-2000, we reconstruct four data panels for the ten firms to analyze R&D efficiency for the decade 1991-2000. For the time lag, we also tried seven and nine years lag cases. It should be noted that the results of both cases had the same tendency of the eight years lag case this paper adopts.

3 Preliminary DEA analyses of R&D efficiency

We preliminarily DEA-analyze the R&D efficiency of Japanese pharmaceutical firms using the panel data for the decade 1991-2000. The DEA model we employ is the *CCR (Charnes, Cooper and Rhodes)* assuming the *constant returns-to-scale*. The CCR model in its *weak efficiency*, *input-oriented* and *envelopment* form to measure DEA efficiency (R&D efficiency) of target DMU j_0, $g_{j_0}(0 \leq g_{j_0} \leq 1)$, is formulated as the following LP (Linear Programming):

$$\begin{aligned} \text{Minimize} \quad & g_{j_0} = \theta \\ \text{subject to} \quad & \sum_{j=1}^{n} \lambda_j y_j \geq y_{j_0}, \end{aligned} \tag{1}$$

$$\sum_{j=1}^{n} \lambda_j x_j - \theta x_{j_0} \leq 0,$$
$$\lambda_j \geq 0,\ j = 1, ..., n,$$
$$(\theta \text{ unconstrained}),$$

where θ, λ_j = decision variables to LP, n = the number of DMUs, $y_j = [y_{1j}, ..., y_{rj}, ..., y_{tj}]$ = output vector of DMU j, y_{rj} = the amount of output r from DMU j, t = the number of outputs, $x_j = [x_{1j}, ..., x_{ij}, ..., x_{mj}]$ = input vector of DMU j, x_{ij} = the amount of input i to DMU j, m = the number of inputs. In our case, $m = 1$, input = (R&D expenditure), and $t = 3$, output = (patents, pharmaceutical sales, operating profit). We can find DEA efficiencies of all the DMUs by solving LP (1) n times, setting each DMU as target DMU j_0 in turn. Here, DMUs j_0 with the minimum $g^*_{j_0} = 1$ are judged *DEA efficient*, while the other DMUs j_0 with $g^*_{j_0} < 1$ are *DEA inefficient*.

Three DEA analyses of the ten pharmaceutical firms for the decade 1991-2000 are shown in Appendix. These analyses tell us the following: (1) Although Takeda and Yoshitomi are respectively the largest and the smallest scaled firms measured by the R&D expenditure, in Table A(1), both are judged DEA efficient in year 2000. This affirms the employment of CCR model assuming the constant returns-to-scale. (2) From the results of Tables A(2)-(3), the R&D efficiency of Japanese pharmaceutical firms do not seem to have gotten better for 1991-2000 at all. However, grasping exactly how the R&D efficiency of the pharmaceutical industry has changed in this decade requires further approaches beyond the ordinary DEA analyses.

4 Change in R&D efficiency for 1991-2000

To quantitatively show the R&D efficiency change of the industry for the decade 1991-2000, we here introduce the DEA/ Malmquist index analysis and apply the same data collected.

4.1 DEA/ Malmquist index analysis

DEA/ Malmquist index analysis measures the Malmquist (productivity) index (Malmquist, 1953) in the DEA frame:

In Fig. 1, a single input and output DEA case, DMU j_0 being evaluated was at point A in period α and line OCD shows the CCR DEA efficiency frontier. Then, the input oriented DEA efficiency of DMU j_0 is measured by PC/PA (< 1, DEA inefficient). When point A is on the frontier, the DEA efficiency is 1 (DEA efficient). Suppose that in period β ($\beta > \alpha$), DMU j_0 has moved to point B and the frontier itself has also shifted to line OEF. DEA efficiency change of DMU j_0 can be measured by the ratio of DEA efficiency in period β to that in period α, but the frontier has shifted, so that we compute the geometric mean of ratios as to the two frontiers in periods α and β. This is the DEA (CCR input oriented)/ Malmquist index of DMU j_0 between periods α and β

$$MI_{j_0}[\alpha, \beta] \equiv \left(\frac{QD/QB}{PC/PA} \cdot \frac{QF/QB}{PE/PA} \right)^{1/2}. \qquad (2)$$

Here, $MI > 1$ means gain in DEA efficiency of DMU j_0 from period α to β, while $MI = 1$ and $MI < 1$ mean the status quo and loss respectively.

Transforming formula (2), Malmquist index can be decomposed into two components as follows:

$$MI_{j_0}[\alpha,\beta] = \frac{QF/QB}{PC/PA} \times \left(\frac{PC}{PE} \cdot \frac{QD}{QF}\right)^{1/2} \tag{3}$$
$$= CU_{j_0}[\alpha,\beta] \times FS_{j_0}[\alpha,\beta]$$
$$= \frac{QF/QB}{PC/PA} \times \left(\frac{PC/PA}{PE/PA} \cdot \frac{QD/QB}{QF/QB}\right)^{1/2}. \tag{4}$$

As each term in the right hand side of formula (3) shows, CU indicates *Catch-Up* index, i.e, $CU > 1$ means that DMU j_0 has moved closer to the period β frontier than to the period α one. $CU = 1$ and $CU < 1$ mean that it has the same distance and that it has moved farther, respectively. FS indicates *Frontier Shift* index, and $FS > 1$ means gain in DEA efficiency frontier shift from period α to β measured from the location of DMU j_0, i.e., the frontier has moved so as to have the more output with the fewer input as shown in Fig. 1. $FS = 1$ and $FS < 1$ mean no change and loss respectively.

Since PE/PA in Fig. 1 is, for example, the DEA efficiency of the period α DMU j_0 measured by means of the period β frontier, we denote it as $\theta[D^\alpha, F^\beta]$. Then from formula (4),

$$MI_{j_0}[\alpha,\beta] = \frac{\theta[D^\beta, F^\beta]}{\theta[D^\alpha, F^\alpha]} \times \left(\frac{\theta[D^\alpha, F^\alpha]}{\theta[D^\alpha, F^\beta]} \cdot \frac{\theta[D^\beta, F^\alpha]}{\theta[D^\beta, F^\beta]}\right)^{1/2}. \tag{5}$$

In LP (1), letting x_j^α, $y_j^\alpha = x_j$, y_j in period α respectively, $\theta[D^\alpha, F^\alpha]$ can be obtained as the minimum of the following LP, the ordinary DEA model:

$$\begin{aligned} \text{Minimize} \quad & \theta \\ \text{subject to} \quad & \sum_{j=1}^{n} \lambda_j y_j^\alpha \geq y_{j_0}^\alpha, \\ & \sum_{j=1}^{n} \lambda_j x_j^\alpha - \theta x_{j_0}^\alpha \leq 0, \\ & \lambda_j \geq 0, \ j, ..., n, \\ & (\theta \text{ unconstrained}). \end{aligned} \tag{6}$$

$\theta[D^\beta, F^\beta]$ can also be obtained by the LP (6) replaced α by β.

While $\theta[D^\alpha, F^\beta]$ is obtained as the minimum of

$$\begin{aligned} \text{Minimize} \quad & \theta \\ \text{subject to} \quad & \sum_{j=1}^{n} \lambda_j y_j^\beta \geq y_{j_0}^\alpha, \\ & \sum_{j=1}^{n} \lambda_j x_j^\beta - \theta x_{j_0}^\alpha \leq 0, \\ & \lambda_j \geq 0, \ j, ..., n, \\ & (\theta \text{ unconstrained}), \end{aligned} \tag{7}$$

this forms the *DEA exclusion model* (Andersen and Petersen, 1993). Finally, we can obtain $\theta[D^\beta, F^\alpha]$ by also the DEA exclusion model (7) exchanged α and β.

4.2 Cumulative Malmquist index

Applying the data to LPs (6) and (7), and through formula (5), we can compute the catch-up $CU_{j_0}[\alpha, \beta]$, the frontier shift $FS_{j_0}[\alpha, \beta]$ and the Malmquist $MI_{j_0}[\alpha, \beta]$ indices. These indices for a year are usually compared to the preceding year, i.e., $\alpha = \beta$ - 1. However, such annually *successive* indices do not seem appropriate to see the chronological change throughout the sample period in the wide range of vision. Therefore, we propose to employ another index than the successive one. Tables 1-3 respectively show $MI_{j_0}[1991, \beta]$, $CU_{j_0}[1991, \beta]$ and $FS_{j_0}[1991, \beta]$, β = 1991, ..., 2000. They are all compared to the start year 1991. Since they involve their successive changes from the start year up to year β, we call them *cumulative* indices. Färe et al. [1994] and Coelli et al. [1998] use the sequential product of the annually successive indices to demonstrate the cumulated change. But, as the former authors state, the Malmquist index as well as the frontier shift one do not satisfy the circular test: e.g., $MI_{j_0}[\alpha, \alpha + 1] \times MI_{j_0}[\alpha + 1, \alpha + 2] \neq MI_{j_0}[\alpha, \alpha + 2]$. Therefore, we adopt the cumulative indices above instead of the sequential products. The cumulative index values when $\beta = 1991$ could be 1. Further, the MI, CU and FS indices themselves are also multiplicative, so that we employ geometric means, not arithmetic ones, as all the averages here.

The Malmquist index indicates the R&D efficiency change of a firm taking the R&D efficiency frontier shifting into consideration. We here note that the R&D efficiency frontier of a year is composed of the most efficient, i.e., DEA efficient, firms in R&D of the year. Thus Table 1 shows that the R&D efficiency of Japanese pharmaceutical firms has gotten worse in average at the annual rate 7.4% for the decade 1991-2000, and has in year 2000 dropped to fifty percent of the start year 1991. This implies a big loss in firms' R&D efficiency. We should note that all the ten firms have this decreasing R&D efficiency. The most worsened for this decade would be Tanabe while the least, Takeda.

The catch-up measures how much closer to the yearly R&D efficiency frontier a firm moves. For only the catch-up, six firms out of the ten except for Yamanouchi, Shionogi, Fujisawa and Tanabe have never gotten worse for this decade (Table 2). The cumulative catch-up is the ratio of R&D efficiency of a firm in year β to that in the start year 1991. Therefore, in Table A(1), the cross-section DEA efficiency of a year divided by that of year 1991 is the catch-up value of the year in Table 2. That is, for both Yamanouchi and Yoshitomi, the values in Tables 2 and A(1) are equal, and for Sankyo, for example, the values in Table 2 do not exceed $1/0.96 = 1.040$, i.e., its upper limit.

Picking up rows from Tables 1-3, we can draw a graph of the three cumulative indices for each firm. Fig. 2 for Sankyo and Fig. 3 for Takeda are examples: In Fig. 2, the catch-up shows that Sankyo has been on the R&D efficiency frontier on and after year 1993. Therefore, the Malmquist has moved as synchronized with the frontier shift, and has in year 2000 gone worsened to 57.4% of the start year, which has been due to the frontier shift backward. For Takeda (Fig. 3), as is mentioned before, the catch-up has gotten better since the start year and it has reached to the upper limit, i.e., Takeda has ridden onto the frontier, in year 2000. The cumulative Malmquist indices are also over 1 for 1992-1994, so that the R&D efficiency of Takeda had improved for this period compared to the start year. In this way, we can quantitatively show the chronological changes in a firm's R&D efficiency using the three cumulative indices.

4.3 R&D efficiency loss by the industry and innovative firms

The cumulative frontier shift index indicates the move of the industry's R&D efficiency frontier from the viewpoint (location) of each firm. Therefore, the *frontier shift on average*

(Table 3) could be an appropriate indicator to measure the R&D efficiency change at the industry level. The annual change rate 0.927 means that the R&D efficiency of the Japanese pharmaceutical industry has worsened at the annual rate 7.3% for 1991-2000. That is, the great R&D efficiency frontier shift backward, reverse to as shown in Fig. 1, has occurred between years 1991 and 2000.

Fig. 4 is a graph of the cumulative frontier shift on average in Table 3. It shows that the R&D efficiency of the industry has gotten worse to under 70% of the start year 1991 in year 1995, the end of the first half, and has finally dropped to 50.6% in year 2000. Although there is observed the recovery in year 1998, we must say that the industry's R&D efficiency has almost monotonically been decreasing throughout the decade. Thus, we could quite obviously show how the industry-wide R&D efficiency has changed, which implies the great loss in R&D efficiency by the Japanese pharmaceutical industry for the decade 1991-2000.

For the decade with the R&D efficiency frontier almost annually shifted backward, what firms have made the frontier shift onward even temporarily? As such innovative firms, we designate DMUs j_0 in year β that satisfy the following conditions (Färe et al., 1994):

$$\text{a) } FS_{j_0}[\beta-1,\beta] > 1; \text{ b) } \theta[D^{\beta}, F^{\beta}] = 1; \text{ c) } \theta[D^{\beta}, F^{\beta-1}] > 1.$$

That is, those DMUs exist on the frontier judged "shifted onward from the preceding year" (conditions a and b) except for existing on the backward part in the crossed-frontiers case (condition c). Amongst the cross-section DEA efficient DMUs in Table A(1), which satisfy condition b), only three DMUs, Sankyo 1996, 1997 and 1998, satisfy also conditions a) and c). Therefore, we here note that Sankyo in the period 1996-1998 has been the innovative firm of the decade.

5 Summary and conclusions

This paper presented a DEA/ Malmquist index methodology for measuring the R&D efficiency change at the industry level. Using the cumulative frontier shift index proposed in the methodology, we could quantitatively show the time series change in the R&D efficiency of the Japanese pharmaceutical industry throughout the decade 1991-2000. We here found the great R&D efficiency loss by the industry for the decade and that the industry's R&D efficiency had dropped in year 2000 to fifty percent of the start year 1991, though several innovators had existed.

Why have the firms continued to spend money on the R&D despite that the R&D efficiency has not improved? It is considered that some factors beyond the efficiency might drive the R&D expenditure. Haneda and Odagiri (1998) indicate that R&D investment affects the value of firm. That is, firms might find another meaning of R&D expenditure than R&D itself. To examine this would require further studies. Anyhow, we could empirically reveal that the R&D efficiency of the Japanese pharmaceutical industry, whose change had seemed elusive, had surely been in decline for the decade 1991-2000.

Appendix

Solving DEA model (1) with one input and three outputs, we obtain DEA efficiencies $g^*_{j_0}$ shown in Table A. In this Table, value 1 indicates DEA efficient. Table A(1) shows the results of ten DEA cross-section analyses with ten DMUs (n = 10 firms), i.e., the cross-section DEA by year, treating each firm as a separate DMU. For example, in year 1996, both Sankyo and Fujisawa are the most efficient firms in R&D, while Yoshitomi has only 52% efficiency of these two best firms in the year. We find that Sankyo would have been most efficient in R&D because it is judged DEA efficient in eight years among the decade. On the contrary, half of the ten firms have never been DEA efficient throughout the decade.

Table A(2) shows the results of ten DEA time series analyses with ten DMUs (n = 10 years), i.e., the time series DEA (Cooper et al., 1995; Hashimoto and Kodama, 1997) by firm, treating each year as a separate DMU. For Shionogi, for example, 1991 and 1993 are its most efficiency years in R&D, while in year 2000, its R&D efficiency drops to 63% of these two best years of the firm. We find that 1991, the first year of the decade, is necessarily listed as the most efficient years in R&D to every firm. And only three firms, Takeda, Sankyo and Yoshitomi, have such years in also the last half of the decade, 1996-2000. Table A(3) shows the results of a DEA panel analysis with 100 DMUs (n = 100 = 10 firms $\times$ 10 years), i.e., the panel DEA treating each firm in each year as a separate DMU. We find that the efficiency frontier in this DEA is composed of only two DMUs, Yamanouchi 1991 and Yoshitomi 1991. These are the most efficient DMUs in R&D among the 100 and both are in the first year of the decade. Further, the average of DEA efficiencies of all the 50 DMUs in the first half of the decade, 1991-1995, is 0.68 as against 0.47 in the last half.

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Table 1
Cumulative Malmquist index $MI_{jo}[1991, \beta], \beta = 1991, \cdots, 2000$

Firm	Year β									Annual change rate
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	
Takeda	1.000	1.065	1.000	1.003	0.874	0.858	0.818	0.832	0.811	0.906	0.989
Sankyo	1.000	0.949	0.897	0.815	0.778	0.787	0.845	0.842	0.695	0.574	0.940
Yamanouchi	1.000	0.920	0.834	0.758	0.705	0.653	0.535	0.486	0.454	0.465	0.918
Daiichi	1.000	0.943	0.848	0.760	0.657	0.606	0.548	0.543	0.517	0.516	0.929
Eisai	1.000	0.909	0.861	0.835	0.794	0.669	0.561	0.577	0.567	0.558	0.937
Shionogi	1.000	0.919	0.864	0.768	0.722	0.647	0.602	0.549	0.511	0.490	0.924
Fujisawa	1.000	0.895	0.870	0.898	0.793	0.645	0.465	0.459	0.394	0.366	0.894
Chugai	1.000	1.005	0.944	0.846	0.825	0.689	0.690	0.602	0.559	0.552	0.936
Tanabe	1.000	0.920	0.854	0.739	0.587	0.507	0.421	0.398	0.363	0.359	0.893
Yoshitomi	1.000	0.878	0.701	0.636	0.404	0.282	0.338	0.406	0.423	0.415	0.907
Average	1.000	0.939	0.864	0.800	0.699	0.612	0.562	0.552	0.514	0.502	0.926

Table 2
Cumulative catch-up index $CU_{jo}[1991, \beta], \beta = 1991, \cdots, 2000$

Firm	Year β									Annual change rate
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	
Takeda	1.000	1.182	1.275	1.387	1.332	1.479	1.461	1.330	1.316	1.543	1.049
Sankyo	1.000	1.000	1.040	1.040	1.040	1.040	1.040	1.040	1.040	1.040	1.004
Yamanouchi	1.000	1.000	1.000	1.000	1.000	0.996	0.796	0.696	0.739	0.870	0.985
Daiichi	1.000	1.025	0.998	0.984	0.919	0.917	0.827	0.826	0.927	1.011	1.001
Eisai	1.000	0.983	1.023	1.126	1.177	1.058	0.861	0.879	1.031	1.076	1.008
Shionogi	1.000	0.961	0.984	0.964	0.969	0.956	0.876	0.835	0.918	0.921	0.991
Fujisawa	1.000	1.002	1.165	1.243	1.243	1.243	0.959	0.899	0.899	0.900	0.988
Chugai	1.000	1.065	1.081	1.102	1.188	1.072	1.108	0.931	0.998	1.047	1.005
Tanabe	1.000	1.018	1.072	1.001	0.851	0.787	0.661	0.613	0.662	0.710	0.963
Yoshitomi	1.000	1.000	1.000	0.984	0.678	0.522	0.655	0.774	0.954	1.000	1.000
Average	1.000	1.022	1.061	1.076	1.022	0.975	0.900	0.864	0.934	0.994	0.999

(shaded) The upper limit for each firm. See Table A(1).

Table 3
Cumulative frontier shift index $FS_{jo}[1991, \beta], \beta = 1991, \cdots, 2000$

Firm	Year β									Annual change rate
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	
Takeda	1.000	0.901	0.784	0.723	0.656	0.580	0.560	0.626	0.616	0.587	0.943
Sankyo	1.000	0.949	0.863	0.784	0.748	0.756	0.812	0.809	0.668	0.551	0.936
Yamanouchi	1.000	0.920	0.834	0.758	0.705	0.656	0.673	0.698	0.614	0.534	0.933
Daiichi	1.000	0.920	0.849	0.773	0.715	0.661	0.663	0.658	0.557	0.510	0.928
Eisai	1.000	0.924	0.841	0.741	0.675	0.632	0.651	0.656	0.550	0.518	0.930
Shionogi	1.000	0.956	0.877	0.797	0.745	0.677	0.687	0.658	0.557	0.532	0.932
Fujisawa	1.000	0.893	0.747	0.722	0.638	0.519	0.484	0.511	0.438	0.407	0.905
Chugai	1.000	0.943	0.873	0.768	0.694	0.643	0.623	0.646	0.560	0.527	0.931
Tanabe	1.000	0.904	0.796	0.738	0.689	0.644	0.637	0.650	0.548	0.506	0.927
Yoshitomi	1.000	0.878	0.701	0.647	0.596	0.541	0.515	0.524	0.444	0.415	0.907
Average	1.000	0.919	0.815	0.744	0.685	0.627	0.624	0.639	0.551	0.506	0.927

Table A
DEA efficiencies

(1) Cross-section DEA by year

Firm	Year									
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Takeda	0.65	0.77	0.83	0.90	0.86	0.96	0.95	0.86	0.85	1
Sankyo	0.96	0.96	1	1	1	1	1	1	1	1
Yamanouchi	1	1	1	1	1	1.00	0.80	0.70	0.74	0.87
Daiichi	0.88	0.90	0.88	0.86	0.81	0.81	0.73	0.73	0.81	0.89
Eisai	0.58	0.57	0.59	0.65	0.68	0.61	0.50	0.51	0.59	0.62
Shionogi	0.57	0.55	0.57	0.55	0.56	0.55	0.50	0.48	0.53	0.53
Fujisawa	0.80	0.81	0.94	1	1	1	0.77	0.72	0.72	0.72
Chugai	0.63	0.67	0.68	0.69	0.74	0.67	0.69	0.58	0.62	0.66
Tanabe	0.81	0.82	0.87	0.81	0.69	0.64	0.53	0.50	0.54	0.57
Yoshitomi	1	1	1	0.98	0.68	0.52	0.66	0.77	0.95	1

(2) Time series DEA by firm

Firm	Year									
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Takeda	1	1	0.97	0.97	0.87	0.86	0.85	0.90	0.91	1
Sankyo	1	1	0.98	0.88	0.86	0.90	1.00	1	0.82	0.67
Yamanouchi	1	0.96	0.88	0.80	0.75	0.67	0.57	0.52	0.50	0.50
Daiichi	1	0.95	0.88	0.81	0.75	0.68	0.62	0.61	0.62	0.62
Eisai	1	0.95	0.96	0.91	0.88	0.83	0.75	0.67	0.72	0.81
Shionogi	1	0.99	1	0.93	0.89	0.74	0.70	0.67	0.68	0.63
Fujisawa	1	0.95	1	1	0.99	0.83	0.80	0.72	0.63	0.56
Chugai	1	1	1	0.93	0.93	0.74	0.74	0.72	0.80	0.77
Tanabe	1	0.94	0.89	0.75	0.67	0.67	0.68	0.67	0.77	0.93
Yoshitomi	1	0.98	0.93	0.95	0.86	0.80	0.85	0.96	1	1

(3) Panel DEA

Firm	Year									
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Takeda	0.65	0.69	0.64	0.64	0.56	0.55	0.53	0.56	0.64	0.74
Sankyo	0.96	0.92	0.88	0.80	0.79	0.85	0.98	1.00	0.80	0.59
Yamanouchi	1	0.96	0.88	0.80	0.75	0.67	0.57	0.52	0.50	0.50
Daiichi	0.88	0.83	0.77	0.69	0.60	0.55	0.50	0.48	0.45	0.45
Eisai	0.58	0.53	0.52	0.48	0.46	0.39	0.34	0.33	0.32	0.33
Shionogi	0.57	0.53	0.50	0.44	0.41	0.37	0.35	0.32	0.29	0.28
Fujisawa	0.80	0.72	0.70	0.72	0.64	0.53	0.40	0.39	0.34	0.32
Chugai	0.63	0.62	0.59	0.52	0.50	0.41	0.39	0.37	0.35	0.34
Tanabe	0.81	0.74	0.69	0.60	0.49	0.43	0.37	0.33	0.30	0.30
Yoshitomi	1	0.89	0.73	0.66	0.44	0.35	0.45	0.51	0.53	0.53

(shaded) DEA efficient.

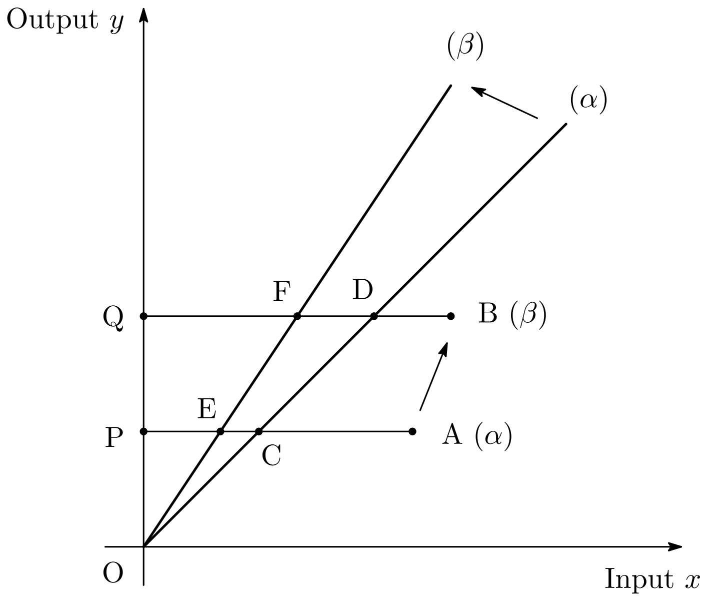

Fig.1. DEA efficiency change with the frontier shifting over time.

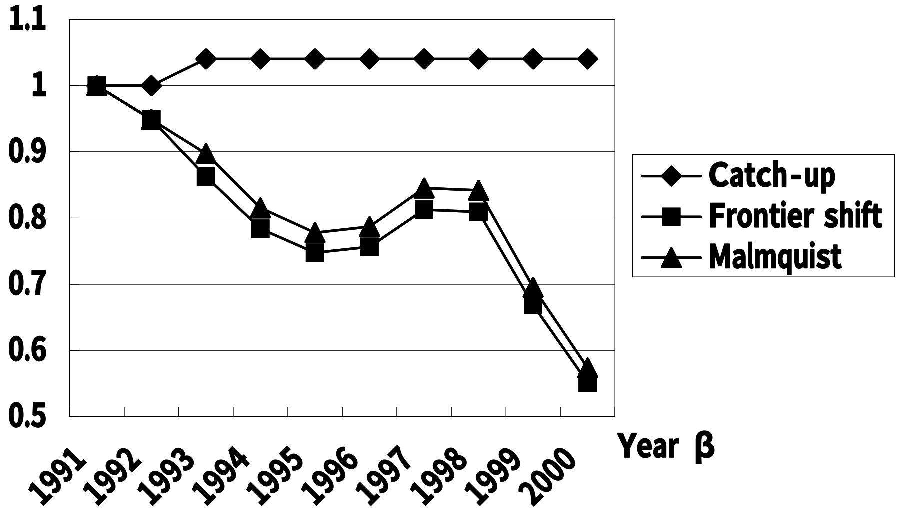

Fig. 2. Cumulative indices for Sankyo.

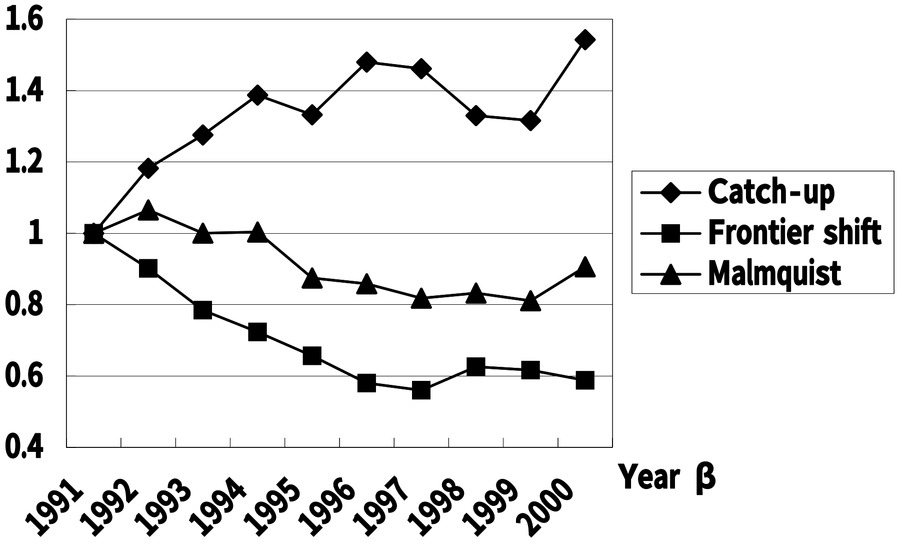

Fig. 3. Cumulative indices for Takeda.

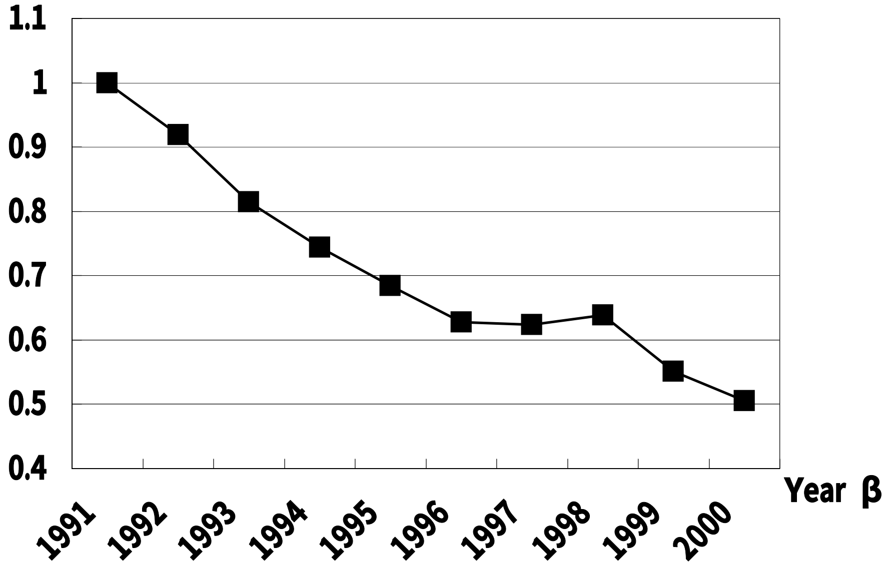

Fig. 4. R&D efficiency loss by the industry for 1991-2000.