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

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ABSTRACT

This paper presents a data envelopment analysis (DEA)/Malmquist index methodology for measuring the change in R&D efficiency at both firm and industry levels. Letting each of ten firms in each year be a separate decision-making unit, and employing one input and three outputs in a DEA case of R&D activity input–output lag, we measure "total factor R&D efficiency" change of Japanese pharmaceutical firms for decade 1983–1992 as defined by the period of R&D input. Decomposing Malmquist index into catch-up and frontier shift components and using "cumulative indices" proposed in this study, we evaluate R&D efficiency change for each firm and empirically show that R&D efficiency of Japanese pharmaceutical industry has almost monotonically gotten worse throughout the study decade.

1. Introduction

This paper measures R&D efficiency of Japanese pharmaceutical firms and examines how R&D efficiency at industry level has changed over time. R&D in firms, which 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 a main reason. In considering R&D activity input and output, 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 multiple outputs of R&D. This multiplicity of output prevents from analyzing R&D efficiency by means of 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 industry level. Has it gradually gotten better as incorporating some innovations into process as productivity could be expected? For the recent Japanese industry, it might not, or might have even worsened (Sakakibara and Tsujimoto, 2003). For also pharmaceutical industry in the world, it is said that 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 Japanese pharmaceutical industry, we verify whether R&D efficiency has gotten better or worse for the study period.

In order to analyze R&D efficiency, we employ *data envelopment analysis* (*DEA*) (e.g., Cooper et al., 2000). DEA is a non-parametric method that can measure the relative efficiency, i.e., *DEA efficiency*, of objects called *decision-making units* (*DMUs*) 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), its characteristic that is able to deal with multiple outputs has enabled measuring efficiencies of a novelty of DMU sets even in the standard analysis. For example, Nasierowski and Arcelus

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(2003) recently measure the efficiency of 45 national innovation systems with two inputs and three outputs. However, we can find no DEA analyses of firms' R&D efficiency except for Honjo and Haneda (1998). They try to analyze R&D efficiency of fourteen Japanese pharmaceutical firms with one input and two outputs for period 1977–1991. Refining their analyses, we also preparatorily do DEA analyses using panel data from ten pharmaceutical firms for the study period. But we should note that ordinary DEA cannot analyze as taking *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 industry level. The Malmquist index can measure the ratio of DEA efficiencies in two different time periods with shifting DEA efficiency frontiers. Although we have some DEA/Malmquist index applications (Färe et al., 1994; Coelli et al., 1998; González and Gasćon, 2004; etc.), they are all to productivity change. 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 movement of the frontier. Since the frontier is composed of "DEA efficient" DMUs among all firms in a time period, the frontier shift means change at industry level. Using this frontier shift, we devise to quite obviously display R&D efficiency change of Japanese pharmaceutical industry throughout the study period.

2. Input and output to measure R&D efficiency

To DEA-analyze R&D efficiency of Japanese pharmaceutical firms, we must select DEA input and output. 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. As the input, we straightforward employ *R&D expenditure* (billion yen a year). Rather, we measure the efficiency of activities appropriated as the R&D expenditure. This indicator also involves the concept of number of researchers as an R&D input.

For the output, we propose the following three dimensions: We first list *patents* (number of patent applications publicly published in a year) as a proxy of invention, i.e., an indicator directly reflecting level of R&D outcomes. Next, we consider the other phases of outcomes. R&D activities in firms can be divided into two: one aiming at "product innovation" and the other aiming at "process innovation." The former contributes sales increase through product discrimination, and the latter does profit increase through cost reduction (Odagiri, 1987). Considering two proxies of the product and process innovations, we employ *pharmaceutical sales* (10 billion yen a year) and *operating profit* (billion yen a year) as two additional outputs. Since the sales and profit can vary for the reasons (in-licensed new-products, marketing efforts, price regulations, etc.) other than R&D expenditure, the input, these might not be fittest as the output. But we use them because we could not find any better proxies of product and process innovations, and because the key contribution of the study is to evolve a methodology to measure R&D efficiency change with multiplicity of the R&D output.

For these one input (R&D expenditure) and three outputs (patents, pharmaceutical sales, operating profit), we initially provide four data panels as follows: Each panel consists of 10 firms × 20 years. That is, the sample period is latest 1982–2001 and the 10 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 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 input and output data of the same year. We should consider that variations in input would cause observed variations in output of some years later. How many years would be the time lag between R&D expending and realization of its outcomes? Science and Technology Agency, Japan (1985) states that average years of the lag would be 8.08 for the Japanese pharmaceutical industry. Odagiri and Murakami (1992) estimate the lag 6–8 years. Based on these reports, we here employ 8 years, i.e., we use input data of a year together with output data of 8 years later. However, this input–output correspondence at intervals of 8 years would not so strict that we first compute 3 years moving averages being the middle year's values for the four indicators in the period 1982–2001, and obtain data panels for 1983–2000 (i.e., data of 1982 and 2001 are dropped). Merging the moving-averaged input data for 1983–1992 in the moving-averaged output data for 1991–2000, we reconstruct four data panels consisting of ten firms to analyze R&D efficiency for 10 years. Since the year of R&D efficiency should be defined as the year of R&D activity input in input–output lag cases, we consequently measure the efficiency in R&D activities of *decade 1983–1992* in spite of using the recent R&D data. For the time lag, we also tried 7 and 9 years lag cases. It should be noted that results of both cases had same tendency as the 8 years lag case this study adopts.

3. Preliminary DEA analyses of R&D efficiency

We preliminarily DEA-analyze R&D efficiency of Japanese pharmaceutical firms using panel data for the study decade 1983–1992 as defined by the period of R&D activity input. DEA model we employ is the *CCR* (Charnes et al., 1978) 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 linear program (LP):

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

where θ, λ_j = model's decision variables, n = number of DMUs, $y_j = [y_{1j}, \ldots, y_{rj}, \ldots, y_{tj}]$ = output vector for DMU j, y_{rj} = output r from DMU j, t = number of outputs, $x_j = [x_{1j}, \ldots, x_{ij}, \ldots, x_{mj}]$ = input vector for DMU j, x_{ij} = input i to DMU j, and m = 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 DMUs by solving LP (1) n times, setting each DMU as target DMU j_0 in turn. Here, DMUs j_0 with the optimum $g_{j_0}^* = 1$ 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 1983–1992 are shown in Appendix A. These analyses tell us the following: (1) Although Takeda and Yoshitomi are respectively the largest and smallest scaled firms measured by R&D expenditure, in Table A.1(1), both are judged DEA efficient in year 1992. This affirms the employment of CCR model assuming the constant returns-to-scale. (2) From the results of Table A.1(2) and (3), R&D efficiency of Japanese pharmaceutical firms do not seem to have gotten better for 1983–1992 at all. However, grasping exactly how R&D efficiency of the pharmaceutical industry has changed in this decade requires further approaches beyond ordinary DEA analyses.

4. Change in R&D efficiency for the study decade

To quantitatively show R&D efficiency change of the industry for the study decade 1983–1992, we here introduce a 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:

Fig. 1 presents a single input and output DEA case where DMU j_0 was at point A in period α, and line OCD represents the CCR DEA frontier. The input-oriented efficiency of DMU j_0 is then measured by PC/PA (<1, DEA inefficient). When point A is on the frontier, its score 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. The efficiency change in DMU j_0 can be measured by the ratio of its DEA score in period β to that in period α; however, the frontier has shifted, so that we must compute the geometric mean of ratios for the two frontiers in those same periods. This is the DEA (CCR input-oriented)/Malmquist index for

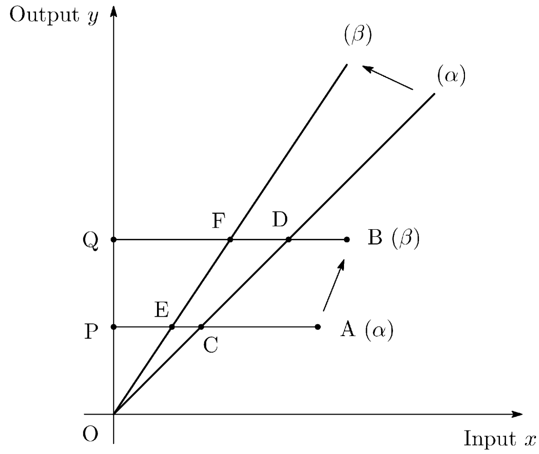

Fig. 1. DEA efficiency change with the frontier shifting over time.

DMU j_0 between periods α and β, given in (2):

$$\mathrm{MI}_{j_0}[\alpha, \beta] \equiv \left(\frac{\mathrm{QD/QB}}{\mathrm{PC/PA}} \frac{\mathrm{QF/QB}}{\mathrm{PE/PA}} \right)^{1/2}. \tag{2}$$

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

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

$$\begin{aligned} \mathrm{MI}_{j_0}[\alpha, \beta] &= \frac{\mathrm{QF/QB}}{\mathrm{PC/PA}} \left(\frac{\mathrm{PC}}{\mathrm{PE}} \frac{\mathrm{QD}}{\mathrm{QF}} \right)^{1/2} \qquad (3) \\ &= \mathrm{CU}_{j_0}[\alpha, \beta] \mathrm{FS}_{j_0}[\alpha, \beta] \\ &= \frac{\mathrm{QF/QB}}{\mathrm{PC/PA}} \left(\frac{\mathrm{PC/PA}}{\mathrm{PE/PA}} \frac{\mathrm{QD/QB}}{\mathrm{QF/QB}} \right)^{1/2}. \qquad (4) \end{aligned}$$

As the first term in the right hand side (RHS) of formula (3) shows, CU expresses the *Catch-Up* index, i.e., CU > 1 suggests that DMU j_0 has moved closer to the period β frontier than to that for period α. CU = 1 and CU < 1 thus apply when the same distance, or more, have been covered, respectively. We define the second term on the RHS of formula (3) as the *Frontier Shift* (FS) index, where FS > 1 means a gain in the DEA frontier shift from period α to β as measured from DMU j_0. That is to say, the frontier has moved *onward*, generating more output but with less input (again, see Fig. 1). As in previous cases, FS = 1 and FS < 1 imply no change and loss (shift *backward*), respectively.

The catch-up and frontier shift are also called efficiency change and technical change, respectively (Färe et al., 1994). Since the Malmquist index in the context of production expresses total factor productivity change, it could be decomposed into "efficiency change at the level of the firm" and "industry-wide productivity change." We expect the former to capture production technology *diffusion* to firms and the latter, *innovation* of technology. In the context of R&D, the Malmquist index implies, as it were, "total factor R&D efficiency" change, so that we expect to the catch-up and frontier shift to capture diffusion and innovation of R&D technology, respectively.

Since PE/PA in Fig. 1 is, for example, the DEA score $\theta(g_{j_0})$ 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), we get:

$$\mathrm{MI}_{j_0}[\alpha,\beta]=\frac{\theta[D^\beta,F^\beta]}{\theta[D^\alpha,F^\alpha]}\left(\frac{\theta[D^\alpha,F^\alpha]}{\theta[D^\alpha,F^\beta]}\frac{\theta[D^\beta,F^\alpha]}{\theta[D^\beta,F^\beta]}\right)^{1/2}. \quad (5)$$

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

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

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

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

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

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

4.2. Cumulative Malmquist index

Applying the data to LPs (6) and (7), and through formula (5), we can compute the catch-up $\mathrm{CU}_{j_0}[\alpha,\beta]$, the frontier shift $\mathrm{FS}_{j_0}[\alpha,\beta]$ and the Malmquist $\mathrm{MI}_{j_0}[\alpha,\beta]$ 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 sample period in a wide range of vision. Therefore, we here propose another index than the successive one.

Tables 1–3 respectively show $\mathrm{MI}_{j_0}[1983,\beta]$, $\mathrm{CU}_{j_0}[1983,\beta]$ and $\mathrm{FS}_{j_0}[1983,\beta]$, $\beta = 1983,\ldots,1992$. They are all compared to the *standard* year 1983, the start year of the study decade. Since they involve their successive changes from the standard year up to year β, we call them *cumulative indices*. Färe et al. (1994) and Coelli et al. (1998) use a sequential product of annually successive indices to demonstrate the cumulated change. But, as the former authors themselves state, the Malmquist index as well as the frontier shift index do not satisfy the circular test: e.g., $\mathrm{MI}_{j_0}[\alpha,\alpha+1]\times\mathrm{MI}_{j_0}[\alpha+1,\alpha+2]\neq\mathrm{MI}_{j_0}[\alpha,\alpha+2]$. To avoid this problem and to compute the cumulated change correctly, we employ the cumulative indices without the sequential product. The cumulative index values when $\beta = 1983$ could be all 1. Further, we should employ geometric means, not arithmetic ones, as the averages of MI, CU and FS indices because they are all multiplicative by nature. (See also Hashimoto et al., in press for the cumulative Malmquist index.)

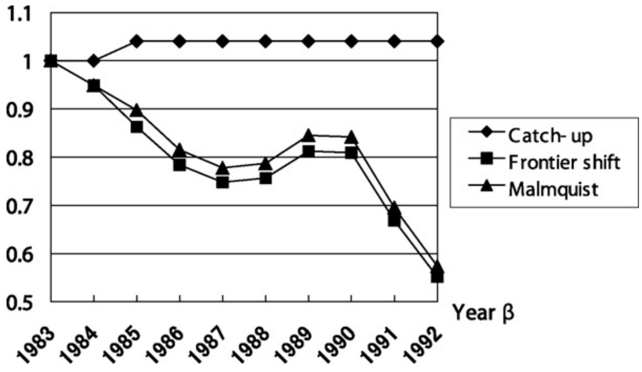

Fig. 2. Cumulative indices for Sankyo.

4.3. R&D efficiency change at firm level

The Malmquist index indicates the total factor R&D efficiency change of a firm over time. In that, DEA efficiency is measured with a yearly R&D efficiency frontier which is composed of most efficient, i.e., DEA efficient, firms in R&D of the year. The Malmquist index takes the frontier shifting into consideration. Thus Table 1 shows that R&D efficiency of Japanese pharmaceutical firms has gotten worse in average at the annual rate 7.4% for decade 1983–1992, and has in year 1992 dropped to fifty percent of the start year 1983. 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 index measures how much closer to the yearly R&D efficiency frontier a firm moves. Table 2 tells that Yamanouchi and Yoshitomi were on the frontier in the start year 1983, but in 1992, the former has dropped out of the frontier, i.e., is not most efficient in R&D. To the contrary, although both Takeda and Sankyo were not on the 1983 frontier, they have caught up to the frontier and are most efficient in 1992. The cumulative catch-up index is the ratio of R&D efficiency of a firm in year β to that in the start year 1983. Therefore, in Table A.1(1), the cross-section DEA efficiency of a year divided by that of year 1983 is the catch-up value of the year in Table 2. That is, for both Yamanouchi and Yoshitomi, values in Tables 2 and A.1(1) are equal, and for Sankyo, for example, values in Table 2 do not exceed 1/0.96 = 1.040, i.e., their upper limit, which means that the firm is on the R&D efficiency frontier. Table 2 also shows that the average firm has gotten farther at the annual rate 0.1% from the yearly R&D efficiency frontier. Thus we cannot find so great yearly-diffusion of R&D technology in this study decade.

Picking up rows from Tables 1–3, we can draw a graph of 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 1985. Therefore, the Malmquist has moved

Table 1
Cumulative Malmquist index $MI_{j_0}[1983, \beta]$, $\beta = 1983, \ldots, 1992$

Firm	Year β of R&D activity input										Annual change rate
	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	
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 $CU_{j_0}[1983, \beta]$, $\beta = 1983, \ldots, 1992$

Firm	Year β of R&D activity input										Annual change rate
	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	
Takeda	1.000	1.182	1.275	1.387	1.332	1.479	1.461	1.330	1.316	$\boxed{1.543}$	1.049
Sankyo	1.000	1.000	$\boxed{1.040}$	$\boxed{1.040}$	$\boxed{1.040}$	$\boxed{1.040}$	$\boxed{1.040}$	$\boxed{1.040}$	$\boxed{1.040}$	$\boxed{1.040}$	1.004
Yamanouchi	$\boxed{1.000}$	$\boxed{1.000}$	$\boxed{1.000}$	$\boxed{1.000}$	$\boxed{1.000}$	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	$\boxed{1.243}$	$\boxed{1.243}$	$\boxed{1.243}$	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	$\boxed{1.000}$	$\boxed{1.000}$	$\boxed{1.000}$	0.984	0.678	0.522	0.655	0.774	0.954	$\boxed{1.000}$	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

$\boxed{}$ On the R&D efficiency frontier. See Table A.1(1).

as synchronized with the frontier shift after 1985 from the relation of formula (3), and has in year 1992 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 1992. The cumulative Malmquist indices are also over 1 for 1984–1986, so that total factor R&D efficiency of Takeda had improved for this period compared to the start year. In this way, we can quantitatively show chronological changes in a firm's R&D efficiency using the three cumulative indices.

4.4. R&D efficiency loss by the industry and innovative firms

While the catch-up CU_{j_0} and Malmquist MI_{j_0} express a move of firm j_0, the frontier shift FS_{j_0} expresses a shift of R&D efficiency frontier which is composed by firms relatively most efficient in R&D, not necessarily by firm j_0 itself. The R&D efficiency frontier is of the "industry," not of each firm. That is, the FS_{j_0} implies the industry's R&D efficiency frontier shift measured from the location (viewpoint) of firm j_0. Therefore, we here propose the average frontier shift index of all firms (Table 3), i.e., R&D efficiency frontier

Table 3
Cumulative frontier shift index $FS_{j_0}[1983, \beta]$, $\beta = 1983, \ldots, 1992$

Firm	Year β of R&D activity input										Annual change rate
	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	
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

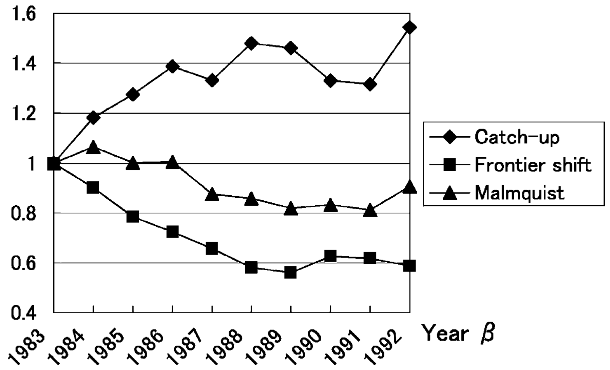

Fig. 3. Cumulative indices for Takeda.

shift as measured from the average firm, as an appropriate indicator to view R&D efficiency change at the industry level. Here, $\mathrm{FS}_{j_0} > 1$ means moving onward in the direction of more R&D outputs with fewer R&D inputs (e.g., a case that some R&D innovations have taken place). However, in Table 3, the annual change rate 0.927 means that R&D efficiency of Japanese pharmaceutical industry has worsened at the annual rate 7.3% for 1983–1992. That is, a great R&D efficiency frontier shift backward, reverse to as shown in Fig. 1, has occurred between years 1983 and 1992.

Fig. 4 is a graph of the cumulative frontier shift index on average in Table 3. It shows that R&D efficiency of the industry has gotten worse to under 70% of the start year 1983 in year 1987, the end of first half, and has finally dropped to 50.6% in year 1992. Although there was a recovery observed in year 1990, we must say that the industry's R&D efficiency has almost monotonically been decreasing throughout the decade. Thus, using the cumulative index, we could quite obviously show how the industry-wide R&D efficiency has changed, which implies a great loss in R&D efficiency by the Japanese pharmaceutical industry for the decade 1983–1992.

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

$$\text{(a)}\ \frac{\mathrm{FS}_{j_0}[1983,\ \beta]}{\mathrm{FS}_{j_0}[1983,\ \beta-1]} > 1; \quad \text{(b)}\ \theta[D^{\beta}, F^{\beta}] = 1;$$

$$\text{(c)}\ \theta[D^{\beta}, F^{\beta-1}] > 1.$$

Here, condition a is different from Färe et al. condition because we employ the cumulative indices unlike them. 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 crossed-frontiers case (condition c). Amongst the cross-section DEA efficient DMUs in Table A.1(1), which satisfy condition b, only two DMUs, Sankyo, 1988 and Sankyo, 1989, satisfy also conditions a and c. Therefore, we here note that Sankyo in period 1988–1989 has been the innovative firm in the decade.

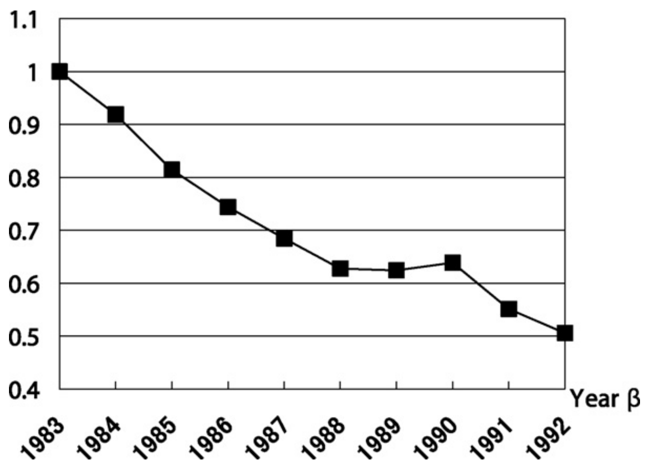

Fig. 4. R&D efficiency loss by the industry for the decade 1983–1992.

5. Summary and conclusions

This paper presented a DEA/Malmquist index methodology for measuring the change in total factor R&D efficiency of Japanese pharmaceutical firms. Using the Malmquist index decomposition into catch-up and frontier shift, we found that both diffusion and innovation of R&D technology had not taken place so much for decade 1983–1992. This study decade was defined by the period of R&D activity input in the 8 years input–output lag case. For the frontier shift especially, by means of the cumulative index proposed in this study, we could quantitatively show the time series change in R&D efficiency at industry level, which had empirically seemed elusive. That is, we found a great R&D efficiency loss by the Japanese pharmaceutical industry for the decade and that the industry's R&D efficiency had dropped in year 1992 to 50% of the start year 1983, though a few innovator firms existed.

The firms have continued to increase R&D expenditure every year despite that R&D efficiency has not improved. Possibly, firms might have found another meaning of R&D expenditure than R&D itself. (Haneda and Odagiri (1998) indicate that R&D investment affects the corporate value.) However, it is certain that there has been the lack of firms' R&D efficiency evaluation. The methodology presented in this study, which is able to measure the R&D efficiency change at both firm and industry levels, would provide useful information on firm's R&D activity management.

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Appendix A

Solving DEA model (1) with one input and three outputs, we obtain DEA efficiencies $g^{*}_{j_0}$ shown in Table A.1. In this table, value 1 indicates DEA efficient. Table A.1(1) shows the results of 10 DEA cross-section analyses with ten DMUs

Table A.1
DEA efficiencies

(1) Cross-section DEA by year

Firm	Year of R&D activity input									
	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
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 of R&D activity input									
	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
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 of R&D activity input									
	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
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

DEA efficient.

($n = 10$ firms), i.e., the cross-section DEA by year, treating each firm as a separate DMU. For example, in year 1988 of R&D activity input, 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 10 firms have never been DEA efficient throughout the decade.

Table A.1(2) shows the results of 10 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, 1983 and 1985 are its most efficient years in R&D, while in year 1992, its R&D efficiency drops to 63% of these two best years of the firm. We find that 1983, the first year of the study decade, is necessarily listed as the most efficient years in R&D to every firm. Moreover, only three firms, Takeda, Sankyo and Yoshitomi, have such years also in last half of the decade, 1988–1992. Table A.1(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, 1983 and Yoshitomi, 1983. 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 first half of the decade, 1983–1987, is 0.68 as against 0.47 in last half.

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