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The Innovation Performance and its Determinants of Korean Pharmaceutical Industry

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Abstract

The pharmaceutical industry has become one of the most powerful and potential industry for the economic growth in the world. Accordingly, many countries have increased research and development (R&D) investment with the goal of producing new drugs. As R&D in the pharmaceutical industry became increasingly important, so did the evaluation of the effectiveness and efficiency of expanding R&D investment. Evaluating and managing R&D efficiency are essential for enhancing the performance produced by R&D activities. However, only a few studies on evaluating R&D efficiency quantitatively have been conducted so far because of the complexity and uncertainty of R&D activity.

Therefore, in this paper I suggested the fuzzy DEA method which is useful for dealing with the uncertainty inherent in R&D data to evaluate R&D efficiency and applied it to Korean pharmaceutical firms. Additionally, the Malmquist index was employed to understand the R&D efficiency change over time and decomposed into the relative efficiency change and the technology change in order to determine the main factor for the R&D efficiency change.

According to these results, the R&D efficiency of Korean pharmaceutical firms had not improved for the period 2003~2006, but increased for the period 2007~2009. This R&D efficiency change mainly resulted from technology change rather than the relative efficiency change.

Ⅰ. Introduction

1. Backgrounds

The pharmaceutical industry has become one of the most powerful and potential industry for the economic growth in the world since its start in the 19th century. It employs many skilled workers, creates value-added, and contributes to the balance of trade each year. As such, its market size has dramatically expanded over years, too. In the year 2010, the sales of the pharmaceutical industry in the global market reached $856 billion and its annual average growth rate from 2003 to 2010 reached 8%.

Many countries have put a great emphasis on the growth of the pharmaceutical industry because of its importance for healthcare as well as for economic benefits. Particularly, the degree of huge investments in Research and Development (R&D) for developing new drugs is outstanding in the advanced countries such as the United States, the United Kingdom, Germany, and Japan.

Korea also considered the pharmaceutical industry as one of the growth engines for the national economy and has made an effort to encourage its growth. However, Korea has run into difficulties with the improvement of its competitiveness in the global market in the following respects.

First, the global pharmaceutical industry is dominated by a few multinational companies and their market power has become stronger. Korean pharmaceutical companies are very small in the scales of market, R&D activities and capital investment compared to the scales of the global leading companies. The pharmaceutical industry is capital intensive, which often causes Korean firms to be in a disadvantageous position in the global market.

Second, the efficiency of R&D investment has continuously decreased over time while patents of major original drugs have been expired. These made the global pharmaceutical industry a highly competitive business.

Third, the introduction of Good Manufacturing Practice (GMP) to Korean pharmaceutical companies is excluding unqualified small firms without a clearly defined and adequately controlled drug manufacturing process.

Forth, biotechnology has been combined with the process of drug development, and bio medical products are expected to dominate drug markets. As a consequence, pharmaceutical companies are challenged to successfully deal with new technology development and its application. In other words, innovation is a prerequisite for the growth of drug companies.

The pharmaceutical Industry is very dependent on the research and developments in finding new target materials and producing new drugs. To produce new drugs from R&D activities, it is most important for the pharmaceutical firms to undertake R&D effectively. Thus, this paper intends to develop R&D efficiency index that can be used to measure uncertain

R&D variables effectively and use the index to study R&D efficiency in the Korean pharmaceutical industry.

2. The Focus of this Paper

The amount of R&D investment with an objective of producing new drugs has increased in many countries. As the importance of R&D in the pharmaceutical industry has been raised, more emphasis has been put on evaluating the effectiveness and efficiency of R&D investment (OECD, 2004).

However, most previous literature has focused on how to increase R&D investment rather than how to evaluate and manage R&D efficiency (Wang & Huang, 2007). One of the main reasons for the paucity of the previous studies on R&D efficiency is the complexity of R&D activities. It is very difficult to define R&D input and output variables necessary for measuring R&D efficiency, because R&D activities are too complicated to specify. Besides, even when we find some useful input and output variables for describing R&D activities in the pharmaceutical industry, it is still hard to quantify the variables to reflect the real world situation.

Therefore, although there has been a lot of research discussing the impact of R&D investment on the economy (Mansfield (1988), Hartmann (2003), Timmer (2003)), only a few studies have recently dealt with measuring R&D efficiency quantitatively. Zhang et al. (2003) discussed the effect of the types of a firm's ownership on R&D efficiency in Chinese firms. Wang & Huang (2007) employed data envelopment analysis (DEA)

approach to measure and compare the relative efficiency of R&D activities in 30 selected countries. Hashimoto & Haneda (2008) applied the DEA/Malmquist index to measure the R&D efficiency of Japanese pharmaceutical firms and discussed its change over time at the industry level.

These studies are of value because the R&D variables necessary for calculating R&D efficiency were specified and the final efficiency values were calculated quantitatively. However, the question of how well the results reflect the real world situation of the pharmaceutical industry still remains there because uncertainty, commonly inherent in R&D data, was not considered. In the real world, R&D variables such as R&D expenditures and the number of researchers often include uncertainty because they vary based on different definitions or counting methods of R&D. In Korea, it has been very common for firms to report different figures for one R&D variable to the different survey agencies because of the differences among various R&D counting methods and R&D definitions. Hence, if this uncertainty, an attribute of R&D data, is not considered for measuring R&D efficiency, it is very difficult to evaluate R&D efficiency accurately.

In this regard, this study introduces the concept of fuzzy DEA approach to measuring R&D efficiency. Fuzzy DEA is an extended DEA method with fuzzy numbers. It can reflect the real world better because uncertain variables in the real world are expressed not as crisp values but as fuzzy numbers.

The fuzzy DEA method has been applied to various fields (Triantis (1998), Minola & Giorgino (2008), Guo (2009), Wu et

al. (2006)), but not yet to the field of R&D efficiency. Therefore, this paper may be a pioneering work on the application of the fuzzy DEA to measuring R&D efficiency. Furthermore, we intend to combine the fuzzy DEA method with the Malmquist index in order to discuss R&D efficiency change over time and to derive the main factors for the R&D efficiency change in Korean pharmaceutical firms.

This study has the following purposes: (1) to introduce the fuzzy DEA as a new method for measuring R&D efficiency with uncertain variables ; (2) to establish a methodology for applying the fuzzy DEA to measuring R&D efficiency ; (3) to evaluate R&D efficiency of Korean pharmaceutical firms by applying this method ; (4) to discuss R&D efficiency change of the selected firms by employing the Malmquist index method ; (5) to derive the main factor for the overall R&D efficiency change by decomposing the Malmquist index into the relative efficiency change and the technology change.

The remainder of this paper is organized as follows. The next section deals with the current state of the pharmaceutical industry in major countries. The third section introduces the fuzzy DEA method and compares it with the DEA method. The methodology for applying the fuzzy DEA method to evaluating R&D efficiency is reported in the forth section. The penultimate section provides the results from the fuzzy DEA analysis and the trend of R&D efficiency change, and discusses the characteristics of R&D efficiency of Korean pharmaceutical firms by employing the Malmquist index and its decomposition. Finally, some concluding remarks are made in the last section.

Ⅱ. The Current State of the Pharma-Ceutical Industry

1. Global Market

The biggest pharmaceutical market in the world is the United States and its market size reached $316 billion in the year 2009. Its market power is expected to be expanded continuously considering its high growth rates over time. The European market came to $238 billion in 2009 and the scale was the second biggest in the world. However, the market sizes of each European country were relatively smaller than the size of Japan.

Newly emerging markets such as Asia, Africa, and Australia are not so huge yet, but they are prospected to grow rapidly and to be more significant in the world market as IMS health forecasted its growth rate for 5 years from now as 14~17%.

As shown in Figure 1, Korean pharmaceutical industry is not advantageous in the market size. It ranked 15th in the global market in the year 2009 and is expected to be 13th in 2013.

<Table 1> Total Pharmaceutical Market by Region

unit : billion$

Region	2005	2006	2007	2008	2009
North America	261	286	299	304	316
Japan	68	64	66	77	90
France	32	33	39	43	41
Germany	31	32	37	42	42
United Kingdom	19	21	231	221	20
Italy	20	21	24	27	27
Other Europe	72	80	94	113	108
Latin America	32	36	42	48	49
ASIA/Africa/Australia	66	74	89	102	112
Total	601	645	714	778	807

Source : IMS Health(2010), IMS top-line

<Figure 1> Market Ranking by Countries

Source : IMS Health(2010), IMS top-line

Table 2 shows the global top 20 pharmaceutical companies and their sales. The united states have many leading companies such as Pfizer, GlaxoSmithKline, and Merck. The global top companies are expected to grow bigger through acquisition and merger (M&A) as shown in the case of the merger between Sanofi and Aventis.

<Table 2> Top 20 Pharmaceutical Companies

unit : million$

Rank	Firms	Country	sales
1	Pfizer	U.S.A	45,448
2	Sanofi-Aventis	France	38,773
3	Novartis	Swiss	38,455
4	GSK(GlaxoSmithKline)	U.K.	37,000
5	Roche	Swiss	35,933
6	AstraZeneca	Swiss	31,905
7	Merck	U.S.A	25,192
8	Johnson&Johnson	U.S.A	22,520
9	Ely Lilly & Co.	U.S.A	19,940
10	BMS(Bristol-Myers Squibb)	U.S.A	17,902
11	Abott Laboratories	U.S.A	16,486
12	Amgen	U.S.A	14,351
13	Takeda	Japan	14,082
14	Bayer	Germany	13,308
15	Teva	Israel	12,821
16	Astellas	Japan	10,417
17	Daichi-Sankyo	Japan	9,672
18	Novo Nordisk	Denmark	9,540
19	Eisai	Japan	8,274
20	Merck KGaA	Germany	7,434

source : Data Monitor(2010), Pharma Vitae Explorer/ Financial Analysis.

2. R&D Trend of Major Countries

(1) The United States

R&D investment of the pharmaceutical industry in the United States has dramatically increased over time. As shown in Table 3, the United States invested $ 45 billion in the pharmaceutical industry and it occupies most of the total R&D investment made by chemical industry.

R&D intensity is also very high, and 21.79% of the total sales was invested in R&D activities in the year of 2006. This figure shows that the United States places a great emphasis on the

<Table 3> R&D Investment of the Chemical & Pharmaceutical Industry in the U.S.A

unit : million$

	1991	1993	1995	1997	1999	2001	2003	2005	2007	2008
Chemical industry	14,648	17,521	17,613	19,131	21,026	17,892	23,001	42,995	55,572	52,449
pharma-ceutical industry	7,061	9,146	10,215	11,899	12,707	10,137	16,096	34,839	47,750	45,126

source : OECD, OLISnet.

<Table 4> R&D Intensity of the Chemical & Pharmaceutical Industry in the U.S.A

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	4.78	5.41	4.75	4.72	5.11	4.21	4.85	7.25	7.25
pharma-ceutical industry	11.08	13.07	12.86	13.13	11.77	8.04	10.94	21.29	21.79

pharmaceutical industry.

The ratio of pharmaceutical R&D investment to the total R&D in the U.S.A. also establishes the fact that the pharmaceutical industry is considered to be a growth engine for economy. The pharmaceutical R&D captured 15.7% of the total R&D in the United States in the year 2006.

As a result of a huge R&D investment in the drug industry, the United States is leading the pharmaceutical R&D activities in the world. As shown in Table 6, the R&D investment scale of the United States is 56% of the total R&D investment of the OECD countries in the pharmaceutical industry in 2006.

<Table 5> Ratio of Chemical & Pharmaceutical R&D Investment to the Total R&D in the U.S.A

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	12.52	14.92	13.33	12.14	11.42	8.86	11.46	19.01	18.71
pharmaceutical industry	6.04	7.79	7.73	7.55	6.90	5.02	8.02	15.40	15.71

<Table 6> Ratio of Chemical & Pharmaceutical R&D Investment of the U.S.A to The OECD Total

unit : %

	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	41.46	40.43	40.03	40.34	33.49	37.15	50.32	49.75
pharmaceutical industry	43.52	44.47	44.35	42.52	32.66	40.15	56.45	56.21

2. Germany

The scale of the R&D investment in Germany reached $5 billion in the year of 2008. It occupies almost half of the R&D investment of the total chemical industry. It shows more balanced R&D investment portfolio compared to the intensive R&D investment in the pharmaceutical industry in the United States.

R&D intensity of the pharmaceutical industry in Germany is relatively high and shows 10.41% in 2005. The R&D intensity to the total R&D decreased since 1993 and showed 7.31% in 1995. But it started to continue increasing steadily since 1997.

<Table 7> R&D Investment of the Chemical & Pharmaceutical Industry in Germany

unit : million$

	1991	1993	1995	1997	1999	2001	2003	2005	2007	2008
Chemical industry	6,124	5,834	6,599	6,120	6,067	5,296	7,163	7,913	9,123	10,193
pharma-ceutical industry	1,735	1,684	1,702	2,134	2,227	2,037	3,451	4,215	4,677	5,237

<Table 8> R&D Intensity of the Chemical & Pharmaceutical Industry in Germany

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005
Chemical industry	5.54	5.63	4.61	5.04	5.20	4.73	5.07	4.74
pharma-ceutical industry	10.16	9.60	7.31	9.56	9.68	9.20	10.84	10.41

<Table 9> Ratio of Chemical & Pharmaceutical R&D Investment to the Total R&D in Germany

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	19.84	19.06	18.07	18.78	16.94	16.29	16.70	16.46	17.17
pharma-ceutical industry	5.62	5.50	4.66	6.55	6.22	6.27	8.04	8.77	8.86

The scale of pharmaceutical R&D investment in Germany reached 8.86% of the total R&D in Germany. The ratio is about half of the chemical industry and relatively low compared to the figure of the United States. However, the ratio has increased over time, implying that the importance of the pharmaceutical industry has continued to increase.

The ratio of R&D investment of Germany to the total OECD was 6.14% in the year 2006 and it has decreased over time since 2005. This trend seems to be influenced by the rapid R&D increase of the United States. Meanwhile, the relative ratio of Germany in the pharmaceutical industry decreased although Germany has increased the scale of R&D investment.

<Table 10> Ratio of Chemical & Pharmaceutical R&D Investment of Germany to the OECD Total

unit : %

	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	11.66	11.08	11.48	11.21	11.60	11.18	8.59	8.84
pharma-ceutical industry	6.77	5.42	7.13	7.17	7.68	8.32	6.34	6.14

3. France

The R&D investment in the pharmaceutical industry in France has increased continuously over time, but, the growth rate has been slowed down in recent years. For example, the average annual growth rate of R&D investment from 1987 to 1997 had reached 11.67%, but the rate during the past decade was 5.91%, and it was further reduced by half by the end of the decade. However, the scale of the R&D investment has increased and reached about $ 5million in the year 2007.

The R&D intensity had risen during the 1990s and reached 9.71% of the total sales in the year 1999, but the ratio of R&D investment to sales was reduced during the 2000s.

The scale of pharmaceutical R&D investment in France reached 13.84% of the total R&D in 2006. It takes the greatest part of the R&D investment of the chemical industry. This figure This figure shows that the pharmaceutical industry is a major player in leading the R&D activities of the chemical industry in France.

<Table 11> R&D Investment of the Chemical & Pharmaceutical Industry in France

unit : million$

	1991	1993	1995	1997	1999	2001	2003	2005	2007
Chemical industry	2,930	3,188	3,967	3,655	3,829	3,402	4,908	5,497	6,928
pharma-ceutical industry	1,358	2,036	2,616	2,448	2,618	2,252	3,377	3,850	4,950

<Table 12> R&D Intensity of the Chemical & Pharmaceutical Industry in France

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005
Chemical industry	4.44	4.72	4.62	4.64	4.87	4.41	4.95	4.74
pharma-ceutical industry	6.63	8.84	9.41	9.49	9.71	8.06	8.52	8.49

<Table 13> Ratio of Chemical & Pharmaceutical R&D Investment to the Total R&D in France

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	16.52	16.89	18.17	18.75	19.27	18.30	20.10	19.64	19.24
pharma-ceutical industry	7.66	10.79	11.99	12.56	13.17	12.11	13.83	13.76	13.84

The ratio of the R&D investment of France to the total R&D investment of the OECD member countries was 5.19% in the year 2006 which is smaller than the ratio of Germany. The relative ratio of R&D investment of France during the 1990s maintained the level above 8% which was higher than the figure for the total OECD countries. Since 2005, however, the ratio fell close to 5%. This trend implies that the R&D activities in the pharmaceutical industry of France have relatively declined over time in relations to the average performance of the other OECD countries.

<Table 14> Ratio of Chemical & Pharmaceutical R&D Investment of France to the OECD Total

unit : %

	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	6.48	7.00	6.99	7.18	7.75	7.49	5.60	5.37
pharma-ceutical industry	8.33	8.76	8.34	8.57	8.83	7.96	5.43	5.19

4. Japan

The R&D investment in the pharmaceutical industry in Japan is the second biggest in the world. It reached $12 billion in the year 2008 and the scale is much bigger than the European countries'. Particularly, the recent R&D investment trend shows high and stable growth rate of R&D investment over time.

The R&D intensity marked about 9% during the 1990s, but the ratio of R&D investment to sales has increased since 2001 and reached up to 13.36 in the year 2005.

The ratio of pharmaceutical R&D investment to the total business R&D investment in Japan marked 8.81% in the year

<Table 15> R&D Investment of the Chemical & Pharmaceutical Industry in Japan

unit : million$

	1991	1993	1995	1997	1999	2001	2003	2005	2007	2008
Chemical industry	11,438	13,993	16,472	13,285	13,942	13,840	15,303	17,439	17,624	20,433
pharma-ceutical industry	4,361	5,639	6,803	5,311	6,053	6,672	7,622	9,506	10,645	12,478

2006. It embodies about a half of the R&D investment of the chemical industry. This figure suggests that the pharmaceutical industry is important in Japan, but R&D activities in other chemical industries are also vitalized.

The ratio of the R&D investment of Japan to the total ratio of the OECD member countries was 13.64% in the year 2006 and it has been reduced since 2003 slightly. This trend seems to be caused by a rapid increase of R&D of the United States and the relatively reduced ratio of Japan's R&D investment despite a trend of steady growth in its overall scale.

<Table 16> R&D Intensity of the Chemical & Pharmaceutical Industry in Japan

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005
Chemical industry	5.70	6.07	6.06	5.81	6.18	6.46	6.81	6.69
pharma-ceutical industry	9.38	9.49	9.75	9.26	9.68	10.63	11.19	13.36

<Table 17> Ratio of Chemical & Pharmaceutical R&D Investment to the Total R&D in Japan

unit : %

	1991	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	15.89	17.25	16.55	15.10	14.94	14.69	15.09	15.08	15.33
pharma-ceutical industry	6.06	6.95	6.83	6.04	6.49	7.08	7.51	8.22	8.81

<Table 18> Ratio of Chemical & Pharmaceutical R&D Investment of Japan to the OECD Total

unit : %

	1993	1995	1997	1999	2001	2003	2005	2006
Chemical industry	20.26	20.47	20.00	18.80	21.07	20.51	17.36	17.65
pharma-ceutical industry	16.41	16.04	14.25	14.24	17.49	15.78	13.10	13.64

5. Korea

The R&D investment in the pharmaceutical industry in Korea is very poor compared to those in advanced countries. It reached $0.5billion in the year 2008 and the scale is just 1.2% of the R&D investment of the United States. However, the growth rate of R&D investment from 2001 to 2008 in Korea reached 14.8% and was as high as the rate of the European countries.

The small amount of R&D investment in Korea was mainly due to the low R&D intensity in the pharmaceutical industry as well as the small amount of the total R&D. As shown in

<Table 19> R&D Investment of the Chemical & Pharmaceutical Industry in Korea

unit : million$

	1995	1997	1999	2001	2003	2005	2007	2008
Chemical industry	707	624	439	663	819	1,320	1,969	1,699
pharma-ceutical industry	122	126	141	212	205	342	627	556

<Table 20> The Comparison of R&D Investment

unit : million$

	2001	2002	2003	2004	2005	2006	2007	2008	Growth rate
Germany	2,037	2,343	3,451	3,901	4,215	4,688	4,677	5,237	14.4%
USA	10,137	14,197	16,096	31,477	34,839	38,901	47,750	45,126	23.8%
Japan	6,672	7,702	7,622	8,377	9,506	10,068	10,645	12,478	9.4%
France	2,252	2,632	3,377	3,800	3,850	4,285	4,950	n.a.	14.0%
Korea	212	203	205	273	342	471	627	556	14.8%

<Table 21> R&D Intensity of the Chemical & Pharmaceutical Industry in Korea

unit : %

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Chemical industry	1.47	1.49	1.29	0.84	0.96	0.96	1.32	1.33	1.27	1.29	1.42
pharma-ceutical industry	1.08	1.15	1.09	0.69	1.52	1.08	2.02	1.71	1.66	1.98	1.99

the Table 21, Korean pharmaceutical firms invested only 1.99% of sales in R&D activities in 2005. It is very low compared to the R&D intensity of the advanced countries.

The ratio of pharmaceutical R&D investment to the total business R&D investment in Korea marked only 2.17% in the year 2006. It makes up only 28% of the R&D investment in the chemical industry. This figure shows that the R&D activities of pharmaceutical industry are poor in Korea and suggests that other chemical industries are more innovative in Korea.

<Table 22> Ratio of Chemical & Pharmaceutical R&D Investment to the Total R&D in Korea

unit : %

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Chemical industry	6.83	5.81	6.13	6.01	6.98	7.03	6.71	6.84	7.28	7.63
pharma-ceutical industry	1.38	1.01	1.97	1.35	2.23	1.96	1.68	1.84	1.89	2.17

Ⅲ. The Methodology for R&D Efficiency Measurement

1. Data Envelopment Analysis (DEA)

The Data Envelopment Analysis (DEA), since it was proposed by Charnes, Cooper & Rhodes (1978), is one of the most useful methods used to evaluate the relative efficiency of decision making units (DMUs) with multiple inputs and outputs in a production process.

In the CCR (Charnes, Cooper & Rhodes) model, a basic form of DEA, the relative efficiency of each DMU's production process is derived by dividing aggregated outputs by aggregated inputs as shown in equation (1).

$$\max_{\mu,\nu} \quad \theta = \frac{\sum_{r=1}^{s} \mu_r y_{rk}}{\sum_{i=1}^{m} \upsilon_i x_{ik}}$$

$$s.t. \quad \frac{\sum_{r=1}^{s} \mu_r y_{rj}}{\sum_{i=1}^{m} \upsilon_i x_{ij}} \leq 1 \quad (j = 1,2,...n) \qquad (1)$$

$$\mu \geq 0, \ \nu \geq 0$$

In this equation for measuring the efficiency of targeted

k^{th}DMU, x_{ij} is the amount of input i of the j^{th} DMU, y_{rj} is the amount of output r produced by the DMU, u_i, μ_r are the weights of input i and output r respectively, and n, m, s mean the numbers of DMUs, inputs, and outputs in order.

This model has been widely used for evaluating efficiency in various fields such as banking, education, and national economy (Denizer et al. (2007), Bougnol & Dula (2006), and Nasierowski & Arcelus (2003)) because it does not have to assume a functional form and is very useful for dealing with multiple outputs and inputs.

However, DEA is a frontier method very sensitive to outliers, allowing for small changes in data to cause significant changes in an efficiency frontier (Lertworasirikul, 2002). Therefore, when the variables include uncertainty as R&D data often do, the traditional DEA, in which input and output data are considered as crisp values, has difficulty measuring efficiency accurately.

2. The Fuzzy DEA

(1) Fuzzy Numbers

For a more accurate evaluation of efficiency with a given set of imprecise data, recently, the fuzzy set theory invented by Zadeh (1965) has been applied to DEA. Fuzzy set theory has the advantage of dealing with imprecise data by extending classical Boolean logic to real numbers (Al-Najjar & Alsyouf, 2003). In fuzzy set theory, all the fractions between 0 and 1 can represent partial truth while 1 represents true and 0 false

in Boolean logic (Moon & Lee, 2005). Hence, the variables with uncertainty can be effectively measured as fuzzy numbers, which are fuzzy sets whose membership function is $\mu_A(x) : R \rightarrow [0.1]$.

In this membership function which is a curve that defines how each imprecise data is mapped to a fuzzy number, the value of $\mu(x)$, called the membership value of x, means the probability that x belongs to the fuzzy set A. Fuzzy numbers can take various forms, but, the triangular fuzzy number is one of the most common forms whose membership function can be expressed as equation (2).

$$\mu_A(x) = \begin{cases} \dfrac{(x-l)}{(m-l)}, & \text{for } l \le x \le m \\ \dfrac{(x-r)}{(m-r)}, & \text{for } m \le x \le r \\ 0, & \text{otherwise} \end{cases} \qquad (2)$$

In this equation, l and r represent the lower and upper bounds of the fuzzy number A, respectively, and m is the modal value. In this case, the triangular fuzzy number can be denoted as (l,m,r).

(2) The Fuzzy DEA

The fuzzy DEA is an extended DEA model with fuzzy numbers. Therefore, using fuzzy numbers, we can transform the CCR model with uncertain variables into the fuzzy DEA as shown in equation (3). In this equation, $\tilde{x}_{ij}$ the fuzzy input

i consumed by the jth DMU, can be denoted as the fuzzy number $(x_{ij}^{l}, x_{ij}^{m}, x_{ij}^{r})$, and $\tilde{y}_{rj}$, the fuzzy output r produced by the DMU, as the fuzzy number $(y_{rj}^{l}, y_{rj}^{m}, y_{rj}^{r})$.

$$\max_{\mu,\nu} \quad \theta = \frac{\sum_{r=1}^{s} \mu_r \tilde{y}_{rk}}{\sum_{i=1}^{m} \upsilon_i \tilde{x}_{jk}}$$

$$s.t. \quad \frac{\sum_{r=1}^{s} \mu_r \tilde{y}_{rj}}{\sum_{i=1}^{m} \upsilon_i \tilde{x}_{ij}} \leq 1 \quad (j = 1,2,...n) \qquad (3)$$

$$\mu \geq 0, \quad \nu \geq 0$$

In this equation, $\sum_{r=1}^{s} \mu_r \tilde{y}_{rj} / \sum_{i=1}^{m} u_i \tilde{x}_{ij}$ is approximately less than or equal to one, because the parameters are fuzzy sets.

In order to derive this solution, we cannot use a simple DEA solving method because it includes fuzzy sets. Therefore, several previous attempts have been made for solving fuzzy DEA models. Sengupta (1992) proposed the tolerance approach where fuzziness is incorporated into a traditional DEA model by defining tolerance levels. In Letrworasirikul (2002), fuzzy numbers were changed into crisp numbers first by the de-fuzzification method and then fuzzy DEA model was transformed into the DEA model. Kao & Liu (2000) applied the α-level based approach to solving the fuzzy DEA. In this study, fuzzy data were transformed to intervals using α-cuts and the interval

efficiency was suggested rather than crisp values at a given α-level.

In the fuzzy ranking method approach as shown in Guo & Tanaka (2001), fuzzy inequalities and equalities were expressed using the ranking method and then the fuzzy DEA model was transformed to the bi-level linear programming model. Additionally, the possibility approach discussed in Letrworasirikul (2003) transforms a fuzzy DEA model into a well-defined possibility DEA model using possibility measures.

In this paper, I intend to apply the defuzzification method to solving the fuzzy DEA because it is simple to handle and the final efficiency is expressed as an exact number which helps decision makers understand implications with ease.

Ⅳ. The Fuzzy DEA Method and its Application to R&D Efficiency

1. The Fuzzy DEA Application Method

The first step for applying the fuzzy DEA is to measure imprecise variables which include uncertainty by expressing them as approximate numbers or linguistic variables based on human beings' judgment. For example, the R&D expenditure of a firm can be measured as approximately one million dollars and the quality of research performance as a linguistic variable such as "good" and "bad." Specifically, using surveys with linguistic variables, whose values are words or sentences in a natural language, is one of the best methods for measuring imprecise variables. Because linguistic expression of values is more similar to how human thinking process work, it is likely to reduce and prevent the errors that may be caused by expressing the subjective judgment of human beings with cardinal or ordinal scales (Moon & Lee, 2005).

The linguistic variables gathered by a survey can be transformed into fuzzy numbers using a membership function for further calculations. If we employ the triangular fuzzy number as shown in the equation (2), a linguistic variable for an imprecise variable t, evaluated by a respondent I, can be denoted as a

fuzzy number $V_{it}=(v_{it}^{l}, v_{it}^{m}, v_{it}^{r})$ and the degree of accuracy of the respondent's judgment for that variable as $A_{it}=(a_{it}^{l}, a_{it}^{m}, a_{it}^{r})$. Next, the judgment of expert I for variable t is incorporated into one fuzzy number $F_{it}=(v_{it}^{l}\times a_{it}^{l}, v_{it}^{m}\times a_{it}^{m}, v_{it}^{r}\times a_{it}^{r})$ as shown in Moon & Kang (1999) as well as Moon & Lee (2005).

In order to transform this fuzzy number into a crisp value, several defuzzification methods, such as mean of maximum, center of area, α-cut, and total integral value, have been suggested. When we employ the total integral value method which is easy to handle (Liou&Wang, 1992), the fuzzy number is defuzzified as one crisp value, $f_t(t)$, by the equation (4).

$$f_i(t) = 0.5\left[\alpha(v_{it}^{l}\times a_{it}^{l}) + v_{it}^{m}\times a_{it}^{m} + (1-\alpha)(v_{it}^{r}\times a_{it}^{r})\right] \qquad (4)$$

In this equation, α represents the degree of optimism of a decision maker. If we assume he/she is neutral, we set it as 0.5.

Additionally, in order to aggregate the survey results from various experts for each variable, it is necessary to give a weight to each expert. In this study, the weights of experts were derived by their degree of confidence, that is, how confident they are of the overall survey. The stronger one respondent feels sure of the judgment, the higher his/her weight becomes. When we use mean operator which is most commonly used among a few methods such as mean, median,

max, min and mixed operators (Buckley, 1985) for this process, the degree of confidence of expert I can be calculated by the equation(5).

$$W_i = \left(\frac{\sum v_{it}^l \times a_{it}^l}{k}, \ \frac{\sum v_{it}^m \times a_{it}^m}{k}, \ \frac{\sum v_{it}^r \times a_{it}^r}{k} \right) \quad (5)$$

Next, we can defuzzify W_i into a crisp value by the total integral value method as shown in the equation (4) and then normalize it into the weight of the ith expert, W_i

$$w_i = norm\left\{ 0.5\left(\alpha \times \frac{\sum v_{it}^l \times a_{it}^l}{k} + \frac{\sum v_{it}^m \times a_{it}^m}{k} + (1-\alpha) \times \frac{\sum v_{it}^r \times a_{it}^r}{k} \right) \right\} \quad (6)$$

At last, the final defuzzified value of the variable t is calculated by the equation (7).

$$f(t) = \sum_i w_i f_i(t) \quad (7)$$

2. The Measurement of R&D Efficiency

(1) Selection of Variables

I applied the defuzzification method of the fuzzy DEA to evaluating the R&D efficiency of Korean pharmaceutical industry addressing the importance of R&D activities for the industry's economic performance. For this application, I defined a firm's R&D activity or operation that invest R&D inputs such as R&D expenditure and researchers, and produce final economic outputs

such as sales and net profit from an economic point of view. Therefore, I chose R&D expenditure and the number of researchers as R&D input variables, and sales and net profit as R&D outputs.

Next, I chose 11 Korean pharmaceutical firms which have the similarity of having more than 300 employees and showing intensive R&D investment (R&D expenditure are more than 3% of sales). The firms may represent Korean pharmaceutical industry because they include main large pharmaceutical firms that conduct R&D activities in Korea. The time period selected was from 1998 to 2009 because of the data availability. The data for the input and output variables were gathered from each firm's annual business report published on the website (http://dart.fss.or.kr). Among those variables, two R&D input variables were considered to contain uncertainty because they varied depending on the different source of the data.

(2) Measurement of Imprecise R&D Input Variables

In order to measure the two imprecise R&D input variables, I conducted two surveys with the persons in charge of the firms' R&D data reporting. The first survey was performed for measuring the maximum ranges of varied R&D input data with different degrees of uncertainty. This survey was sent to 50 persons in charge of the R&D data reporting in Korean pharmaceutical firms, with a request for the information on the maximum ranges of variation of those R&D data on average. A total of 35 persons replied.

According to this survey, the R&D expenditure varied by up to ± 20% of the value reported on firm's annual business reports and the number of researchers by up to ± 10% of the value. Therefore, I considered the maximum range of variations in the two variables as 20% and 10% respectively.

Next, I conducted the second survey in order to measure how certain the R&D input data on the reports were in selected firms. Questionnaires were sent out to 52 persons who were in charge of the R&D data reporting in each firm, and 42 responses were received.

The questionnaire consisted of two parts. The first part was for evaluating the degree of certainty of each firm's R&D input data. In this part, I showed each respondent R&D data of his/her firms gathered from the annual business reports respectively, and asked them to reply how certain the stated R&D data were when they considered the other figures for the same input variables reported to the other survey agencies. For their answers, I presented linguistic expressions such as "very certain." Additionally, I asked them to check whether they thought that the true values in the real world situations for the two R&D input variables were larger than the stated R&D data.

The second part of the questionnaire was designed to measure the degree of confidence of the respondents in their answers. The respondents were asked to describe the degree of confidence in their judgment as the linguistic expressions such as "very certain," "certain," "medium," "not very certain" and "not certain at all."

(3) Defuzzification Procedures

The linguistic variables gathered by the survey were transformed into fuzzy numbers by triangular fuzzy numbers as shown in the equation (2).

After that, I derived the degree of certainty of each R&D input variable as crisp values $f_{\exp}$ and f_{res} from the triangular fuzzy numbers by the defuzzification method as discussed in the previous section (from the equation (4) to the equation (7)).

Next, the final value of R&D expenditure $L_{\exp}$ was calculated by the equation (8), where $B_{\exp}$ is an original value gathered from each firm's annual business report, and $f_{\exp}$ is a degree of certainty in R&D expenditure, and 0.2 corresponds to the maximum range of the variation in the variables caused by its uncertainty.

$$L_{\exp} = B_{\exp} \pm 0.2 \times B_{\exp}(1 - f_{\exp}) \tag{8}$$

I also determined the final value of the number of researchers, L_{res} as shown in the equation (9).

<Table 23> Triangular Fuzzy Number Corresponding to Each Linguistic Variable

Linguistic variable	Fuzzy number
Not certain at all	(0, 0, 0.25)
Not very certain	(0, 0.25, 0.5)
medium	(0.25, 0.5, 0.75)
certain	(0.5, 0.75, 1)
Very certain	(0.75, 1,1)

$$L_{res} = B_{res} \pm 0.1 \times B_{res}(1 - f_{res}) \quad (9)$$

In this equation, B_{res} and f_{res} are the original values from the annual business report and the degree of certainty respectively and 0.1 are the maximum ranges of variation.

V. Results

In order to calculate the R&D efficiency of the selected firms, I applied the final defuzzified R&D input data and output data to the DEA model shown in the equation (1). I considered the time lag between a R&D input and an economic output as 5 years based on the correlation results of those variables as it takes time for R&D inputs to be transformed into economic outputs. Consequently, I used input data for 1998~2004 and output data for 2003~2009 for deriving R&D efficiency.

<Table 24> R&D Efficiency of the Selected Firms by Years (Output Year Based)

Firm	2003	2004	2005	2006	2007	2008	2009
1	0.856	1	1	1	1	1	1
2	1	1	1	1	1	0.959	1
3	1	1	1	1	1	1	1
4	0.315	0.402	0.359	0.360	0.412	0.325	0.405
5	1	1	0.585	0.612	0.605	0.543	0.459
6	0.585	1	1	1	1	1	1
7	0.685	0.915	0.887	1	0.889	0.552	0.581
8	0.565	0.328	0.578	0.785	1	0.528	0.419
9	0.652	0.512	0.708	0.892	1	0.881	0.912
10	1	0.821	1	1	1	0.756	0.881
11	1	1	1	1	1	1	1
average	0.782	0.813	0.829	0.875	0.905	0.770	0.783

Table 24 shows the R&D efficiency of the Korean pharmaceutical firms by years. In this table, if a firm's score is 1, its R&D activity is considered to be efficient.

According to this Table, the average R&D efficiency scores of the selected firms by years varied from 0.782 to 0.905, and only two firms' R&D activities have remained efficient throughout the entire period.

To better understand the trend of firms' R&D efficiency, I employed the Malmquist index introduced by Caves et al. (1982). The Malmquist index is expressed as the geometric mean of DEA ratios of each time period with each technology in order to measure the efficiency change between the period t and the period t+1. Hence, when we denote a firm's DEA score of the time period t that invests input x^t, and produces output y^t with the technology t as $\theta^t(x^t, y^t)$, the Malmquist index of the i^{th} firm for measuring the R&D efficiency change between the time period t and t+1 can be expressed as the equation (10).

$$M_i = \left(\frac{\theta^t(x^{t+1}, y^{t+1})}{\theta^t(x^t, y^t)} \times \frac{\theta^{t+1}(x^{t+1}, y^{t+1})}{\theta^{t+1}(x^t, y^t)} \right)^{\frac{1}{2}} \quad (10)$$

In this equation, the first fraction means the DEA score ratio of the period t to the period t+1 with the technology t. The second fraction is that with the technology t+1. If the index value is more than 1, it means the R&D efficiency of the period t+1 improved compared with that of the period t.

In order to derive the main factor for this efficiency change, Färe et al. (1994) decomposed the index into two factors: the relative efficiency change and the technology change as shown in the equation (11) with the assumption of constant returns to scale (CRS) technology.

$$M_i = \frac{\theta^{t+1}(x^{t+1}, y^{t+1})}{\theta^t(x^t, y^t)} \left(\frac{\theta^t(x^t, y^t)}{\theta^{t+1}(x^t, y^t)} \times \frac{\theta^t(x^{t+1}, y^{t+1})}{\theta^{t+1}(x^{t+1}, y^{t+1})} \right)^{\frac{1}{2}} \qquad (11)$$

In this equation, the first fraction outside the parenthesis is the relative efficiency change and the inside of the parenthesis is the technology change between the two periods. If the first fraction is more than 1, it means that the relative efficiency of the i^{th} firm in the period t+1 is higher than that in the period t. Therefore, this term represents how narrow the efficiency gap between a firm and the most efficient firms becomes over time. On the other hand, the inside of the parenthesis shows the technology change between the two periods from each firm's point of view. If this value is higher than 1, the technology for transforming R&D input to economic output in the industry is considered to have improved. This term is related to the degree of improvement of the industrial technology.

Table 25 shows the Malmquist index of the selected firms calculated with the equation (10). In this Table, I considered the R&D efficiency level of 2003 as the reference value, 1, and derived the Malmquist index of each year compared to that of 2003 to show the trend of the index with ease. According to the Table, the annual average growth rates of each firm's

Malmquist index varied from -9.87% to +8.38%. Five out of eleven firms were found to have improved their R&D efficiency, two firms to have kept their efficiency unchanged, and four firms have had their efficiency get worse.

However, on the whole, the surveyed Korean pharmaceutical firms improved their R&D efficiency during the entire period judging from the fact that the annual average growth rate of the geometric mean of the Malmquist index was +0.3%. Particularly, the geometric mean of the Malmquist index has risen above 1.0 since 2009 although its value had fallen slightly

<Table 25> Malmquist Index of the Selected Firms (Output Year Based)

Firm	2003	2004	2005	2006	2007	2008	2009	Annual average growth rate
1	1	1.171	0.917	0.945	1.045	0.926	0.993	-0.11%
2	1	1.000	1.000	0.875	0.975	0.836	0.859	-2.50%
3	1	1.000	1.000	1.000	1.000	1.000	1.000	0.00%
4	1	1.089	1.262	0.864	1.112	1.135	1.472	6.66%
5	1	1.000	0.640	0.594	0.642	0.647	0.536	-9.87%
6	1	1.183	1.252	1.330	1.288	1.341	1.426	6.09%
7	1	1.127	1.143	1.144	1.050	1.024	1.021	0.35%
8	1	0.612	0.976	1.051	1.425	1.383	1.146	2.29%
9	1	0.839	1.271	1.268	1.857	2.366	1.621	8.38%
10	1	0.932	1.000	0.969	0.891	0.938	0.953	-0.80%
11	1	1	1	1	1	1	1	0.00%
Geometric mean	1	0.981	1.025	0.984	1.079	1.083	1.051	0.84%

compared to the level prior to 2008.

Next, I decomposed the Malmquist index into the relative efficiency change and the technology change with the equation (11). The relative efficiency change was calculated by the ratio of each year's DEA score to 2003's score, considered to be reference value 1, as shown in Table 26.

According to the Table, Firms 3 and 11 kept their efficiency status throughout the whole period. Firm 6 shows the highest annual average growth rate of the relative efficiency of 10.84%, followed in order by firms 9, 4, and 1. On the other hand, the

<Table 26.> The Relative Efficiency Change of the Selected Firms

Firm	2003	2004	2005	2006	2007	2008	2009	Annual average growth rate
1	1	1.084	1.084	1.084	1.089	1.089	1.089	1.43%
2	1	1	1	0.875	0.975	0.979	1	0.00%
3	1	1	1	1	1	1	1	0.00%
4	1	1.323	1.265	1.123	1.28	0.865	1.341	5.01%
5	1	1	0.587	0.623	0.667	0.534	0.462	-12.08%
6	1	1.582	1.694	1.785	1.679	1.781	1.854	10.84%
7	1	1.312	1.334	1.456	1.312	0.801	0.875	-2.20%
8	1	0.612	1.067	1.312	1.715	0.901	0.745	-4.79%
9	1	0.757	1.132	1.478	1.597	1.421	1.446	6.34%
10	1	0.84	1	1	0.891	0.811	0.895	-1.83%
11	1	1	1	1	1	1	1	0.00%
Geometric mean	1	1.013	1.074	1.116	1.155	0.972	0.982	-0.3%

relative efficiency of the other 4 firms became worse in 2008 compared with those in 2003. On the whole, the relative efficiency of Korean pharmaceutical firms decreased during the period. The geometric mean dropped from 1 in 2003 to 0.982 in 2009 and its annual average growth rate for a period between 2003 and 2009 was -0.3%. Particularly, the relative efficiency of most firms decreased rapidly in 2008 while it had increased generally until 2007.

On the contrary, the technology change shows the opposite trend to the relative efficiency change. As shown in Table 27, the technology of the Korean pharmaceutical industry was

<Table 27> The Technology Change of the Selected Firms

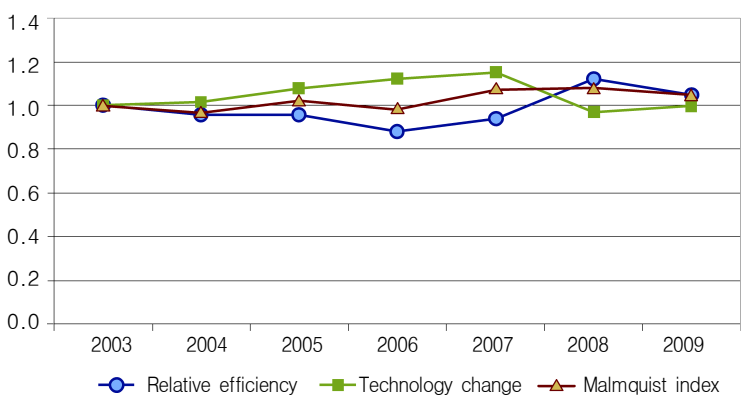
Firm	2003	2004	2005	2006	2007	2008	2009	Annual average growth rate
1	1	1.08	0.846	0.872	0.96	0.85	0.912	-1.52%
2	1	1	1	1	1	0.854	0.859	-2.50%
3	1	1	1	1	1	1	1	0.00%
4	1	0.823	0.998	0.769	0.869	1.312	1.098	1.57%
5	1	1	1.09	0.954	0.962	1.212	1.16	2.50%
6	1	0.748	0.739	0.745	0.767	0.753	0.769	-4.28%
7	1	0.859	0.857	0.786	0.8	1.278	1.167	2.61%
8	1	1	0.915	0.801	0.831	1.535	1.538	7.44%
9	1	1.108	1.123	0.858	1.163	1.665	1.121	1.92%
10	1	1.109	1	0.969	1	1.156	1.065	1.06%
11	1	1	1	1	1	1	1	0.00%
Geometric mean	1	0.968	0.954	0.881	0.935	1.114	1.046	0.76%

found to have improved as a whole. The geometric mean of the technology change went up to 1.046 in 2007 from 1 in 2003 and its annual average growth rate was 0.76%. In particular, the technology change value rose up to 1.114 in 2008, while it had been decreasing until 2007.

In order to discuss the overall R&D efficiency change and its main factor from an industrial point of view, I composite the geometric means of the Malmquist index, the relative efficiency change, and the technology change as shown in Figure 2.

As shown in this Figure, the R&D efficiency change of the Korean pharmaceutical industry shows different aspects between the period 2003~2006 and 2007~2009. During the period 2003~2006, the overall R&D efficiency did not improve compared with the reference year as the Malmquist index value indicates in the Figure. This was mainly due the decrease in

<Figure 2> The Geometric Means of the Malmquist Index and its Factors



the rate of technology change which offset the effect of relatively increasing efficiency during the same period. This implies that the industrial technology did not improve and new technology or innovation was not employed from an industrial point of view. However, the industrial technology seems to be disseminated from efficient firms to less efficient ones judging from the fact that the geometric mean of the relative efficiency increased rapidly. Therefore, it appears that the technology diffusion between firms, as opposed to technology innovation, was active at the industry level during this period.

On the other hand, during the period 2007~2009, the overall R&D efficiency improved compared with the 2003's as the geometric mean of the Malmquist index shows in Figure 2. This R&D efficiency improvement seems to result from a rapid technology change during the time period. In particular, the technology change value was highest in 2007 while the relative efficiency change fell down dramatically. This result implies that although technological innovation was introduced to this industry, many firms could not catch up with the new technology. Therefore, the efficiency gap between efficient firms and other firms became wider than before as shown in the decrease in the rate of the relative efficiency change. However, new technologies seem to have been disseminated in 2009 based on the fact that the technology change value began to decrease while the relative efficiency value increased.

Ⅵ. Concluding Remarks

This paper suggests the fuzzy DEA method for evaluating R&D efficiency in order to deal with imprecise R&D data effectively. This method was then applied to deriving R&D efficiency of Korean pharmaceutical firms. Additionally, the Malmquist index was employed for understanding the R&D efficiency change of the selected firms over time, and the overall R&D efficiency was decomposed into the relative efficiency change and the technology change.

According to the results, the overall R&D efficiency of the Korean pharmaceutical industry shows different aspects between the two periods: 2003～2006, 2007～2009. It had not improved for the period 2003～2006, but has become better during the second period. The main factor for this R&D efficiency change was found to be the technology change rather than the relative efficiency change. During the period 2003～2006, the technology change value did not increase and it was the main cause of the overall R&D efficiency retardation despite a higher value of the relative efficiency change. However, the rapid technology change during the period 2007～2009 was the driving force for increasing the overall R&D efficiency overcoming the fact that the relative efficiency gap between the frontier firms and the other firms, that could not catch up with new technology, became wider during this time.

This study is different from other previous studies in that I tried to deal with the uncertainty inherent in R&D data by employing the fuzzy DEA method and to apply it to evaluating R&D efficiency. This method is expected to be more useful for understanding the real world situation than the traditional DEA as it gives more accurate information to decision makers. Additionally, the results and insights gained from analyzing R&D efficiency change and deriving its main factors can help us understand the characteristics of R&D efficiency in the Korean pharmaceutical industry.

References

• Al-Najjar, B. and Alsyouf, I.(2003), Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making. *International Journal of Production Economics*, 84, 85-100.

• Buckley, J.J. (1985), Fuzzy hierarchical analysis. *Fuzzy Sets and Systems*, 17, 233-247.

• Bougnol, M.-L. and Dulá, J.H. (2006), Validating DEA as a ranking tool: an application of DEA to assess performance in higher education. *Annals of Operation Research*, 145, 1, 339-365.

• Caves, D., Christensen, L. and Diewert, E. (1982), The economic theory of index numbers and the measurement of input, output, and productivity. *Econometrica*, 50, 6, 1393-1414.

• Charnes, C. A., Cooper, W. W. and Rhodes, E.(1978), Measuring the efficiency of decision-making units. *European Journal of Operational Research*, 2, 429-444.

• Data Monitor(2010), Pharma Vitae Explorer / Financial Analysis.

• Denizer, C.A., Dinc, M. and Tarimcilar, M.(2007), Financial liberalization and banking efficiency : evidence from Turkey. *Journal of Productivity Analysis*, 27, 3, 177-195.

• Färe, R., Grosskopf, S., Norris, M., and Zhang, Z. (1994), Productivity growth, technical progress, and efficiency change in industrialized countries. *American Economic Review*, 84, 1, 66-83.

• Guo, P. and Tanaka, H. (2001), Fuzzy DEA: a perceptual evaluation method. *Fuzzy Sets and Systems*, 119, 149-160.

• Guo, P. (2009), Fuzzy data envelopment analysis and its application to location problems. *Information Sciences*, 179, 820-829.

• Hartmamm, G.C. (2003), Linking R&D spending to revenue growth. *Research Technology Management*, 46, 39-46.

• Hashimoto, A. and Haneda, S. (2008), Measuring the change in R&D

efficiency of the Japanese pharmaceutical industry. *Research Policy*, 37 , 1829-1836.

- IMS Health (2010), IMS top-line
- Kao, C. and Liu, S-T. (2000), Fuzzy Efficiency Measures in Data Envelopment Analysis. *Fuzzy Sets Systems*, 113, 3, 427-437.
- Lertworasirikul, S. (2002), Fuzzy Data Envelopment Analysis for supply chain modeling and analysis. Dissertation proposal in Industrial Engineering, North Carolina State University.
- Lertworasirikul, S., Fang, S.-C., Joines, J.A., and Nuttle, H.L.W. (2003), Fuzzy Data Envelopment Analysis (DEA): A possibility approach. *Fuzzy Sets and Systems*, 139, 379-394.
- Liou, T. S. and Wang, M. J. J. (1992), Ranking fuzzy numbers with integral value. *Fuzzy Sets and Systems*, 50, 247-255.
- Mansfield, E. (1988), Industrial R&D in Japan and the United States: A comparative study. *American Economic Review*, 78, 223-228.
- Minola, T. and Giorgino, M. (2008), Who's going to provide the funding for high tech start-ups? *R&D management*, 38, 335-351.
- Moon, J.-H. and Kang, C.-S. (1999), Use of fuzzy set theory in the aggregation of expert judgements. *Annalsof Nuclear Energy*, 26, 461-469.
- Moon, H.-S. and Lee, J.-D. (2005), A Fuzzy Set Theory Approach to National Composite S&T Indices. *Scientometrics*, 64,1,67-83.
- Nasierowski, W. and Arcelus, F.J. (2003), On the efficiency of national innovation systems. *Socio-Economic Planning Science*, 37, 215-234.
- OECD (2004), *OECD Science, Technology, and Industry Outlook*. OECD, Paris.
- OECD, OLISnet.
- Sengupta, J. K. (1992), A Fuzzy Systems Approach in Data Envelopment Analysis. *Computers and Mathematics with Applications*, 24,

8-9, 259-266.

• Timmer, M.P. (2003), Technological development and rates of return to investment in a catching-up economy: the case of South Korea. *Structural Change and Economic Dynamics*, 14, 405-425.

• Triantis, K. (1998), A mathematical programming approach for measuring technical efficiency in a fuzzy environment. *Journal of Productivity Analysis*, 10, 85-102.

• Wang, E.C. and Huang, W. (2007), Relative efficiency of R&D activities: A cross-country study accounting for environmental factors in the DEA approach. *Research Policy*, 36, 260-273.

• Wu, D., Yang, Z., and Liang, L. (2006), Efficiency analysis of cross-region bank branches using fuzzy data envelopment analysis. *Applied Mathematics and Computation*, 181, 271-281.

• Zadeh, L.A.(1965), Fuzzy sets. *Information and Control*, 8, 338-353.

• Zhang, A., Zhang, Y., and Zhao, R. (2003), A study of the R&D efficiency and productivity of Chinese firms. *Journal of Comparative Economics*, 31, 444-464.