Assessment of Productive and Environmental Efficiencies of Japanese Industries

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Abstract

The global warming and climate change becomes a major policy issue in the world. To partly deal with the climate change issue from economics and business concerns, this study proposes a use of Data Envelopment Analysis (DEA) as a methodology for unified (operational and environmental) assessments. The proposed DEA approach has been long serving as an important methodology to evaluate the performance of various organizations. Recently, many researchers have applied DEA to various environmental issues. A contribution of the previous DEA studies was that they found the importance of an output separation into desirable (good) outputs and undesirable (bad) outputs (e.g., CO2 emission and air pollution substances from production activities). Acknowledging a contribution of these previous studies on DEA environmental assessment, this study classifies efficiency measures into the two categories according to the treatment of undesirable outputs: (a) productive efficiency and (b) unified efficiency under natural disposability. The first efficiency does not incorporate undesirable outputs in the performance evaluation, while the second measure incorporates them to the environmental assessment. Using a data set regarding the manufacturing industries of 47 prefectures in Japan, this study examines their productive and environmental efficiencies to obtain policy implications. The important empirical finding suggests that Japanese regional industries need to make their further efforts to reduce air pollution substances and increase energy efficiency.

Key Words: Environmental Assessment, Disposability, Energy Efficiency

1. Introduction

After the two oil crises in the 1970s, Japan diversified its energy sources through an increased use of nuclear energy, natural gas and coal to reduce the dependency on oil. Manufacturing industries, representing a majority of energy consumption in Japan, have worked on progressing energy conservation and improving energy efficiency. It is known that Japan has few energy resources, so depending on import for 96% of its primary energy supply. Even the nuclear generation is considered as domestic energy, the energy import dependency is still at 82%. Despite the efforts for energy conservation and increasing energy efficiency, oil still accounts for about 40% of Japan's primary energy supply and most of them come from the politically unstable Middle East region. As a result, the Japanese energy supply structure is vulnerable. See Energy White Paper [1].

Since the Great East Japan Earthquake in 2011, such efforts have become more important than before because all nuclear units stop their operations with an exception of only two units in 2013. Approximately 90% of electricity consumption in Japan is produced by fossil fuel power plants. Such conditions resulted in a tight relationship between demand and supply on electricity and increased import of fossil fuels from abroad. Currently Japan faces a major policy change on the energy that is directed towards more renewable resources and less dependency on nuclear power generation. The Japanese government has begun a new policy discussion on Basic Energy Plan regarding a future desirable energy mix.

Along with a shift to the new energy mix after the earthquake in 2011, Japan needs to pay attention to the climate change and global warming in the world. Since the Kyoto Protocol came into effect in 2005, Japanese government promoted environmental policy to reduce GHG (Greenhouse Gas) emissions from a use of fossil fuels. The manufacturing industries are important contributors to the growth of Japanese economy and they have been major contributors for Japanese regional economy. Meanwhile, they are major producers of GHG emissions such as CO2. In 2011, industry sector as a whole accounts for approximately 34% of CO2 emission. That is the largest among all sectors for the amount of CO2 emission, although its share gradually decreases over time. The introduction of CO2 emission trading scheme had been discussed, but that is not yet determined in Japan.

However, there is a voluntary institution within Japanese industries that continues to promote environmental protection. To achieve the environmental protection goals through global competition, the industries need to improve their productive efficiency and to satisfy environmental requirements in such a manner that they can balance between them for the development of a sustainable society. Under such a business condition, technology innovation in production is essential for Japanese industries. The technology innovation, arising from environmental constraints, is usually associated with an environment-friendly, energy-efficient production system, as discussed by Porter and van der Linde [2]. They stated that corporate efforts for improving the productivity of an entire manufacturing process under environmental regulations resulted in both improving productivity and environmental protection. The assertion is often referred to as "Porter Hypothesis" in corporate strategy.

The purpose of this study is to examine the productive and environmental performance of manufacturing industries in 47 prefectures (local government units in Japan which correspond to states in the United States). The examination reveals the importance of improved energy efficiency and environmental protection for the manufacturing industries in Japan to attain higher performance. In this study, the achievement of Japanese industries is measured by their unified (operational and environmental) efficiencies. For the research purpose, this study proposes a new use of DEA (Data Envelopment Analysis) environmental assessment, in which desirable and undesirable outputs are combined together under a disposability concept related to environmental strategy. See, for example, recent studies [3,4] for innovative uses of DEA in the area of energy policy and economics.

The reminder of this paper is organized as follows. Section 2 describes DEA environmental assessment as a managerial methodology for enhancing the productive and environmental performance of industries. Section 3 exhibits a data set regarding the manufacturing industries in the 47 prefectures. Section 4 summarizes our empirical results and discusses related policy implications. Section 5 concludes this study along with future research extensions.

2. Methodology

2.1 Previous Efforts on DEA Environmental Assessment

To combat the climate change, many previous studies proposes DEA as a methodology for environmental assessment. See, for example, [5-15] and many other articles published in the past decade. As discussed in the previous efforts, DEA was originally developed as a managerial methodology to evaluate the performance of various organizations in public and private sectors. A contribution of the previous studies in environmental assessment was that they separated outputs into desirable and undesirable ones. An important issue to be considered is how to unify these different outputs to assess the performance of organizations from their production and environmental concerns. See [15] that summarized more than 100 articles in environment and energy studies. As a result of their contributions, DEA environmental assessment can serve as an empirical methodology for planning and developing a sustainable society where economic prosperity can coexist with environmental protection. This study will fully utilize the research wisdom explored in the previous studies.

2.2 Natural Disposability

To discuss DEA environmental assessment, this study needs to describe a strategic concept related to environmental protection [16-18], which is referred to as "natural disposability", indicating that an organization decreases the directional vector of inputs to decrease the directional vector of undesirable outputs. Given the reduced vector of inputs, the organization increases the directional vector of desirable outputs as much as possible. This study considers the natural disposability as a negative adaptation to a change on environmental regulation because it does not invest for technology innovation but decreases inputs to cope with government regulation on undesirable outputs.

Figure 1 visually describes the relationship between desirable and undesirable outputs under natural disposability. The functional form (f) is expressed by g = f(b) where g and b stands for desirable (good) and undesirable (bad) outputs. The figure depicts the natural disposability to respond to a regulation change on an undesirable output. As in Figure 1, an organization reduces the amount of an input to decrease the amount of an undesirable output (from bn to br) until it satisfies the level of an undesirable output that is required by governmental regulation. Under the condition, the organization tries to maximize the desirable output as much as possible (from gn to gr) under natural disposability to enhance its productive and environmental unified efficiency.

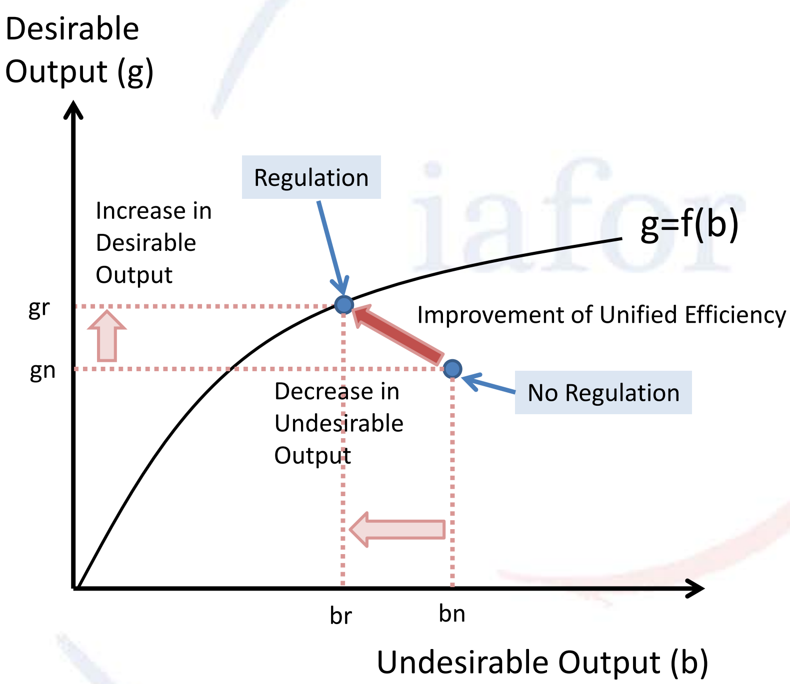

Figure 1: Natural Disposability

As discussed above, the concept on natural disposability originates from corporate strategy to adapt a regulation change on undesirable outputs. The natural disposability responds negatively to the regulation change because it does not invest in the production system for introducing technology innovation. This study is fully aware of an existence of other strategic alternatives in which firms respond positively to the regulation change by considering it as a new business opportunity, or they shift production facilities to a region and a country with less environmental regulation. However, this study excludes such strategic alternatives and focuses on the negative adaptation to the regulation change.

Finally, using an axiomatic expression, production technology to express natural disposability is formulated by the following two types of output vectors and an input vector, respectively [17, 18]:

$$P^n(X) = \left\{ (G,B) : G \le \sum_{j=1}^{n} G_j \lambda_j,\ B \ge \sum_{j=1}^{n} B_j \lambda_j,\ X \ge \sum_{j=1}^{n} X_j \lambda_j,\ \sum_{j=1}^{n} \lambda_j = 1,\ \lambda_j \quad 0 \right\}.$$

In the axiomatic expression, this study considers *n* DMUs (Decision Making Unit, e.g., corresponding to an organization in private and public sectors). $X \in R_{+}^{m}$ is an input vector, $G \in R_{+}^{s}$ is a desirable output vector and $B \in R_{+}^{h}$ is an undesirable output vector of each DMU. The subscript (*j*) stands for the *j*-th DMU and λ_j indicates the *j*-th intensity variable (*j* = 1, .. , *n*) that connects data points to construct a convex hull (part of an efficiency frontier) in a data domain.

2.3 Productive Efficiency

This study starts with describing a non-radial model to measure productive efficiency, or *PE* of the *k*-th DMU. Since this study employs the non-radial measurement, the level of inefficiency is determined by slacks. The operational efficiency does not consider an influence of undesirable outputs in the efficiency measurement, which is thus based on the fundamental framework of conventional production economics. The *PE* measure regarding the *k*-th DMU is obtained by the following non-radial model [19]:

$$\begin{aligned}
\text{Maximize} \quad & \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g \\
\text{s.t.} \quad & \sum_{j=1}^{n} x_{ij} \lambda_j + d_i^x = x_{ik} && (i = 1,\dots,m), \\
& \sum_{j=1}^{n} g_{rj} \lambda_j - d_r^g = g_{rk} && (r = 1,\dots,s), \qquad (1) \\
& \sum_{j=1}^{n} \lambda_j = 1, \\
& \lambda_j \ge 0 \ (j = 1,\dots,n),\ d_i^x \ge 0 \ (i = 1,..,m), \\
& \text{and } d_r^g \ge 0 \ (r = 1,\dots,s).
\end{aligned}$$

The two production factors are expressed by $X_j = (x_{1j}, x_{2j}, .. , x_{mj})^T$ and $G_j = (g_{1j}, g_{2j}, .. , g_{sj})^T$. The superscript "*T*" indicates a vector transpose. It is assumed that $X_j > 0$ and $G_j > 0$ for all *j* = 1, .. , *n*, where the inequality is applicable to all components of the two vectors.

Slacks regarding inputs and desirable outputs are specified by d_i^x (*i* = 1, .. , *m*) and d_r^g (*r* = 1, .., *s*), respectively in Model (1). A column vector of intensity variables are expressed by $\lambda = (\lambda_1, \dots, \lambda_n)^T$. They are used for connecting the input and output vectors by a convex combination. Since the sum of structural variables is restricted to be unity in Model (1), the production possibility set is structured under variable RTS (Returns to Scale).

The data ranges (R) in Model (1) are determined by the upper and lower bounds of the two production factors. They are specified as follows:

$$R_i^x = (m+s)^{-1}\left(max\left\{x_{ij} \mid j=1,..,n\right\} - min\left\{x_{ij} \mid j=1,..,n\right\}\right)^{-1} \text{ and}$$

$$R_r^g = (m+s)^{-1}\left(max\left\{g_{rj} \mid j=1,..,n\right\} - min\left\{g_{rj} \mid j=1,..,n\right\}\right)^{-1}.$$

After solving Model (1), the level of OE is determined by

$$\theta^* = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x*} \quad \sum_{r=1}^{s} R_r^g d_r^{g*}\right). \tag{2}$$

Here, slacks within the parentheses are obtained from optimality of Model (1).

2.4 Unified Efficiency under Natural Disposability

The research of [17, 18] has proposed the following model to measure the unified efficiency (UEN) of the k-th DMU under natural disposability after incorporating a vector of undesirable outputs or $B_j > 0$ where $B_j = \left(b_{1j}, b_{2j}, .., b_{hj}\right)^T$:

$$
\begin{aligned}
\text{Maximize} \quad & \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b \\
\text{s.t.} \quad & \sum_{j=1}^{n} x_{ij}\lambda_j + d_i^x = x_{ik} \qquad (i=1,...,m), \\
& \sum_{j=1}^{n} g_{rj}\lambda_j - d_r^g = g_{rk} \qquad (r=1,...,s), \\
& \sum_{j=1}^{n} b_{fj}\lambda_j + d_f^b = b_{fk} \qquad (f=1,...,h), \\
& \sum_{j=1}^{n} \lambda_j = 1, \\
& \lambda_j \geq 0 \ (j=1,...,n), \ d_i^x \geq 0 \ (i=1,..,m), \\
& d_r^g \geq 0 \ (r=1,...,s), \ \text{and} \ d_f^b \geq 0 \ (f=1,..,h).
\end{aligned} \tag{3}
$$

Since Model (3) measures unified (productive and environmental) efficiency, undesirable outputs are incorporated into the model. Slacks regarding undesirable outputs are specified by $d_f^b (f = 1,\ldots,h)$. Using the upper and lower bounds of inputs, desirable outputs and undesirable outputs, their data ranges are specified as follows:

$$R_i^x = (m+s+h)^{-1}\left(\max\left\{x_{ij} \mid j=1,..,n\right\} - \min\left\{x_{ij} \mid j=1,..,n\right\}\right)^{-1},$$

$$R_r^g = (m+s+h)^{-1}\left(\max\left\{g_{rj} \mid j=1,..,n\right\} - \min\left\{g_{rj} \mid j=1,..,n\right\}\right)^{-1} \text{ and}$$

$$R_f^b = (m+s+h)^{-1}\left(\max\left\{b_{fj} \mid j=1,..,n\right\} - \min\left\{b_{fj} \mid j=1,..,n\right\}\right)^{-1}.$$

Model (3) considers only negative deviations d_i^x (i = 1,…,m) to attain the natural disposability where all inputs decrease to improve the productive efficiency of the k-th DMU, while satisfying the regulation requirement on undesirable outputs. A unified efficiency score (θ^*) of the k-th DMU under natural disposability is measured by slightly modifying Equation (2), so becoming

$$\theta^* = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right), \tag{4}$$

where the inefficiency score and all slack variables are determined on optimality of Model (3). The equation within the parenthesis, obtained from the optimality of Model (3), indicates the level of unified inefficiency under natural disposability. The unified efficiency is obtained by subtracting the level of inefficiency from unity.

3. Data

Table 1 summarizes descriptive statistics of Japanese manufacturing industries. This study considers three inputs to produce both a desirable output and four undesirable outputs. The three inputs are the amount of labor, capital, and energy. The labor, as an input, is determined by the number of employees multiplied by the index of working hours, which is standardized by year 2000 (unit: index). The amount of capital, as another input, is a capital stock of private-sector firms multiplied by the rate of operation regarding capital assets, standardized by year 2000 (unit: index). The amount of energy is the final energy consumption (unit: 1,000 Terajoule).

A desirable output is the real GPP (Gross Prefecture Product, unit: 100 billion yen). Four undesirable outputs are the amount of carbon emissions (unit: 10,000 ton Carbon), SOx emissions (unit: 100 kNm3), NOx emissions (unit: 100 kNm3) and dust emissions (unit: 10 ton per annual).
All data sets constitute for each 47 Japanese prefecture for the year 2002, 2005 and 2008, each of which is related to manufacturing industries and non-manufacturing industries.

The data sources are as follows. The number of employees and the capital stock of private-sector firms are from the regional database of CRIEPI (Central Research Institute of Electric Power Industry). The index of working hours is obtained from the survey on a work force by Ministry of Internal Affairs and Communications and the monthly survey on labor statistics by Ministry of Health, Labor and Welfare. The index of rate of operation on manufacturing industries is obtained from statistics of rate of operation regarding capital for mining and manufacturing industries, prepared by Ministry of Economy, Trade and Industry. The data source concerning the amount of final energy consumption is the energy consumption statistics for each prefecture, prepared by Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry.

Table 1: Descriptive Statistics of Manufacturing Industries

Outputs and Inputs		Desirable Output	Undesirable Outputs				Inputs		
Variables		Real Gross Prefecture Product	Carbon Emissions	SOx Emissions	NOx Emissions	Dust Emissions	Labor	Capital	Energy
Unit		100 Billion JPY	10,000 ton Carbon	100 kNm3 (kilo-newton per cubic-meter) per Annual	100 kNm3 (kilo-newton per cubic-meter) per Annual	10 ton per Annaul	Index	Index	1,000 Tera Joule
2002	Avg.	22.3920	178.9503	25.0987	52.1242	83.8218	23.1470	69.3575	138.4510
	Max.	114.4226	1678.2387	138.5414	241.4170	336.1282	102.8552	341.4123	1031.8996
	Min.	1.9242	3.4962	0.8447	3.6130	3.4280	2.8959	6.6641	9.6391
	S.D.	24.0486	314.6423	28.5836	51.7796	80.0926	23.2401	68.2247	192.4770
2005	Avg.	26.6152	175.1315	22.2721	53.5589	80.9142	22.8297	78.4672	138.1335
	Max.	139.1626	1669.7059	107.2844	252.7304	353.3633	101.1612	398.2985	1026.8958
	Min.	1.9366	2.7995	1.0402	4.4471	3.9850	2.9795	7.7023	10.5616
	S.D.	28.5525	311.9574	23.8799	53.0294	81.2209	22.7059	77.0281	192.4507
2008	Avg.	27.9972	157.1507	16.1879	41.1374	64.8745	22.4823	77.5445	126.3314
	Max.	129.2511	1417.4103	75.2500	234.1000	296.4000	98.9933	402.2377	883.1531
	Min.	2.0585	2.5986	0.3300	1.0800	2.2000	3.1571	7.6103	10.9340
	S.D.	28.4268	274.4460	17.2381	46.3464	67.1028	22.1069	75.4925	170.6623
Total	Avg.	25.6681	170.4108	21.1862	48.9402	76.5368	22.8197	75.1231	134.3053
	Max.	139.1626	1678.2387	138.5414	252.7304	353.3633	102.8552	402.2377	1031.8996
	Min.	1.9242	2.5986	0.3300	1.0800	2.2000	2.8959	6.6641	9.6391
	S.D.	27.0024	298.9037	23.8197	50.4152	76.3195	22.5280	73.2690	184.2389

The real GPP is obtained from prefecture economic accounts prepared by Cabinet Office. The amount of carbon emissions is obtained from energy consumption statistics for each prefecture by Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry. The data source of other undesirable outputs: (a) SOx emissions, (b) NOx emissions, and (c) dust emissions; is the survey of air pollution substances conducted by the Ministry of Environment.

Table 1 indicates that the real GPP of Japanese prefectures increases over the observed period, while all undesirable outputs such as carbon emissions and two inputs (i.e., labor and energy) decrease during the same period in the manufacturing industries. An amount of capital increases over the observed period. This indicates that the Japanese manufacturing industries make their corporate efforts to improve their operational and environmental performance by decreasing the amounts of labor and energy inputs and increasing the amount of capital to introduce technology innovation.

4. Empirical Results

4.1 Efficiency Measures

Table 2 summarizes the two types of efficiency measures regarding manufacturing industries, which are measured by Models (1) and (3), respectively. Figure 2 visually describes the average efficiency in the three annual periods.

Table 2: Results of *PE* and *UEN*

Industries	Manufacturing Industries			
Year	2002	2005	2008	Total
Statistics	Productive Efficiency (PE)			
Avg	0.9384	0.9522	0.9646	0.9517
Max	1.0000	1.0000	1.0000	1.0000
Min	0.6860	0.7072	0.8331	0.6860
S.D.	0.0680	0.0605	0.0413	0.0583
Statistics	Unified Efficiency under Natural Disposability (UEN)			
Avg	0.8880	0.9076	0.9385	0.9114
Max	1.0000	1.0000	1.0000	1.0000
Min	0.4885	0.5155	0.7106	0.4885
S.D.	0.1189	0.1071	0.0754	0.1035

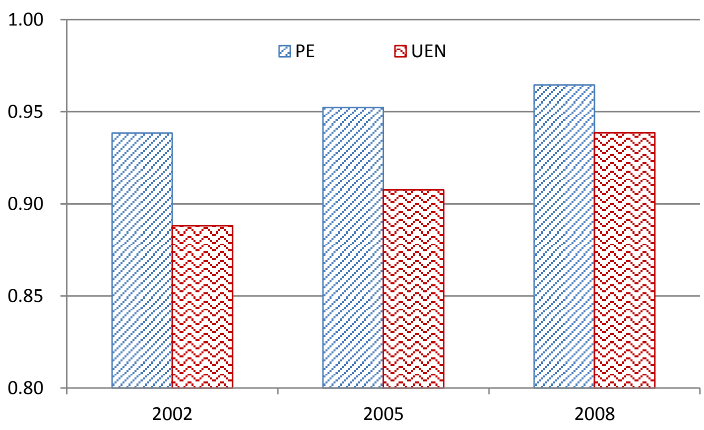

Figure 2: Efficiency Measures of Manufacturing Industries

The findings from Table 2 and Figure 2 are summarized as follows: First, two efficiency measures increased from 2002 to 2008. For instance, *PE* increased from 0.938 to 0.965 and *UEN* from 0.888 to 0.939 for the manufacturing industries in the three annual periods. This indicates that Japanese manufacturing industries made the corporate efforts for improving their performance on productive and unified efficiency. Second, the result indicated that the efficiency scores became lower when undesirable outputs, or environmental factors, were incorporated into the proposed DEA assessment. Furthermore, *PE* had the smaller variation among prefectures in a similar level of efficiency, than *UEN*. The result implied that manufacturing industries in all Japanese prefectures made similar level of efforts for improving their productive performance. In other words, the productive and environmental unified performance of Japanese manufacturing industries was less important than their productive performance.

4.2 Sources of Inefficiency

In this section, this study is interested in what production factors are sources of the inefficiency explored in Section 4.1. Since this study employs non-radial DEA models, each slack is related to each production factor and the slack directly links to a level of inefficiency. Thus, it is possible for us to identify the sources of inefficiency by examining the level of slacks regarding production factors. To explore the research concern, this study measures a ratio of each adjusted slack to the total sum of adjusted slacks. For example, the inefficiency related to each input i (i = 1,…,m) is expressed by

$R_i^x d_i^{x*} \Big/ \left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*} \right)$ for Model (1), and

$R_i^x d_i^{x*} \Big/ \left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*} \right)$ for Model (3).

The denominator of the above ratios indicates the level of inefficiency, which is expressed by the second term of the right-hand side of Equations (2) and (4), respectively.

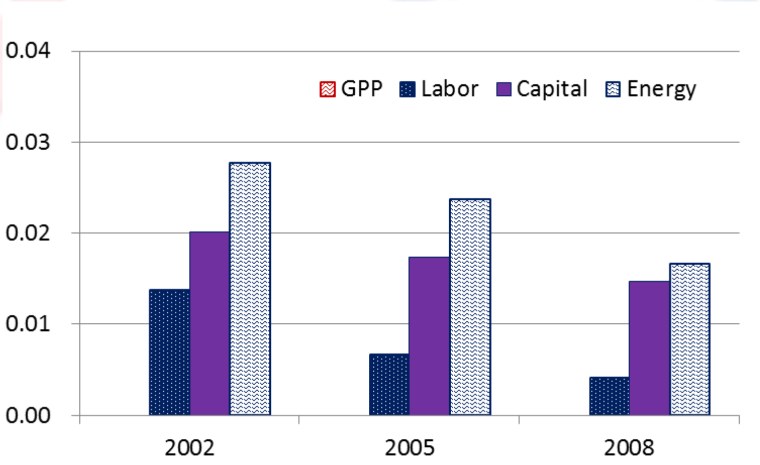

Figure 3: Slacks Used to Measure Productive Efficiency Measures

Figure 3 visually describes the average of each adjusted input slack to "productive inefficiency" from 2002 to 2008 on the manufacturing industries. The magnitude of the vertical axis in Figure 3 is standardized on the range from 0 to 0.04.

Figure 3 depicts that an amount of energy is the largest production factor to produce the productive inefficiency. This indicates that the level of energy efficiency is important for their operational performance.

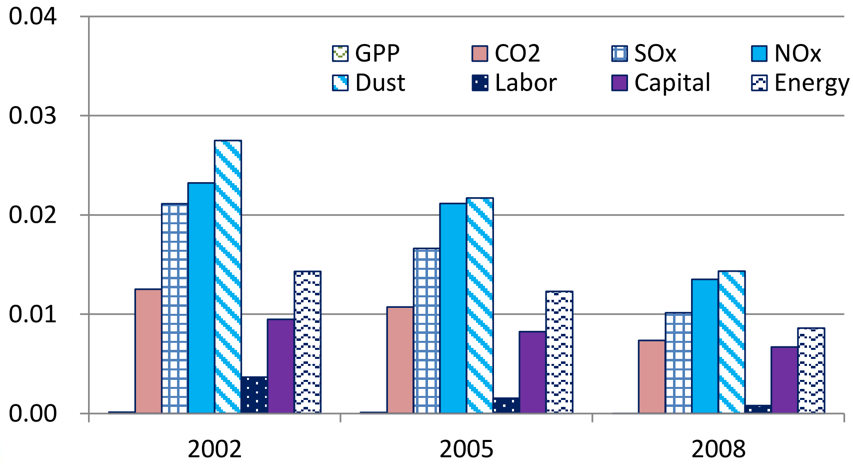

Figure 4: Slacks Used for Measuring Unified Efficiency under Natural Disposability

Figure 4 shows an annual change of slacks used to measure unified efficiency under natural disposability (*UEN*) on the manufacturing industries. It is easily found in Figure 4 that four undesirable outputs (i.e., CO2, SOx, NOx and dust emissions) dominate their unified inefficiency measures. The amounts of energy and capital still explain a significant part of unified inefficiency. Therefore, the reduction of undesirable outputs and capital, and the improvement in energy consumption are important measures for regional manufacturing industries to attain a high level of unified (productive and environmental) performance. Figure 4 visually describes that the manufacturing industries in some prefectures attain a high level of unified efficiency by controlling their undesirable outputs, energy and capital.

In summary, undesirable outputs produce a large difference in efficiency measures among prefectures, because some prefectures successfully manage the reduction of undesirable outputs, while the others do not. Such a difference among prefectures is also due to their energy and capital usages.

4.3 Regional Differences in Efficiency Measures

The data set used in this study consists of Japanese 47 prefectures. They are geographically classified into nine regions from north to south: (a) Hokkaido, (b) Tohoku, (c) Kanto, (d) Chubu, (e) Kinki, (f) Chugoku, (g) Shikoku, (h) Kyushu and (i) Okinawa.

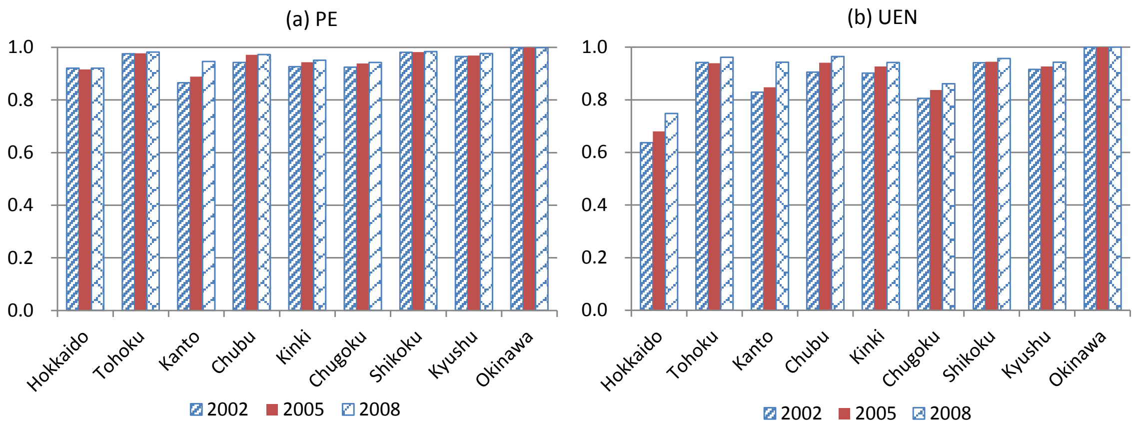

Figure 5: Regional Differences of Efficiency Measures in Manufacturing Industries

Figure 5 depicts the productive efficiency (*PE*) and the unified efficiency measure (*UEN*) of the nine regions. The left hand side of Figure 5 is related to the *PE*. The right hand side is for the *UEN* for the manufacturing industries.

The two efficiency measures exhibited different patterns among nine regions. For example, the regional variation on *PE* was relatively small, but the *PE* of Hokkaido was slightly lower than that of the other regions, whereas the other regions were almost same in the level of the *PE*. Shifting our interest from *PE* to *UEN*, the regional variations of *UEN* were larger than those of *PE* as discussed in Section 4.1, although there was a similar trend between *PE* and *UEN*. That is, Hokkaido was the lowest among the regions, followed by Chugoku with respect to both *PE* and *UEN*. The lower efficiency measures in Hokkaido and Chugoku implied that these areas may have a future potential to improve their unified efficiency measures by changing their industrial structures.

5. Conclusion

This study proposed the DEA models for the two efficiency measures such as *PE* and *UEN*. This study applied them to a data set, consisting of Japanese manufacturing industries in 47 prefectures. The measurement of *PE* did not incorporate undesirable outputs whereas those of *UEN* incorporated undesirable outputs in their assessments.

This study found four empirical results, which were summarized as follows. First, the *PE* and *UEN* in the manufacturing industry indicated an efficiency improvement from 2002 to 2008. Second, the level of efficiency decreased when the DEA model incorporated undesirable outputs. In particular, four undesirable outputs were major sources of inefficiency in *UEN*, which indicated there were wider variations among prefectures on controlling undesirable outputs, compared to the management efforts for increasing desirable outputs. The desirable output did not make a similar level of inefficiency. Meanwhile, the amount of energy was the largest source of inefficiency in *PE*. It also explained a large part of inefficiency in *UEN* for manufacturing industries. Third, the amount of capital caused a certain level of inefficiency in *UEN* of the manufacturing industries. Finally, Hokkaido and Chugoku were lower than the other regions in terms of efficiency. The difference in efficiency measures of the two regions with the others are larger in *UEN* than *OE*.

These findings suggest Japanese regional industries need to make their further effort to reduce air pollution substances. The improvement can be achieved by investing in technology innovation. Such an effort requires a certain amount of capital for the investment. In addition, it is true that the investment takes a time until its result appears, depending upon the condition of macro economy, an investment cycle and other regional factors. In particular, the manufacturing industries in Hokkaido and Chugoku have potential to improve their productive and environmental performance by introducing technology innovation. This study did not examine such a positive adaptation of industries to the regulation.

Although this study examined *PE* and *UEN* regarding Japanese regional industries, their industrial structures were different among regions. Each region has its intrinsic industrial structure. The difference influences the level of efficiency measures concerning each region, particularly when the assessment included environmental factors such as GHG emissions. Thus, it is necessary for this study to investigate the relationship between the level of efficiency measures and the industrial structure of regions. That will be an important future research task.

Finally, it is hoped that this study makes a contribution on DEA environmental assessment and Japanese regional study. We look forward to seeing future research extensions as discussed in this study.

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