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A Multi-Period Input DEA Model with Consistent Time Lag Effects

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일관된 지연 효과를 고려한 다기간 DEA 모형

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Most of the data envelopment analysis (DEA) models evaluate the relative efficiency of a decision making unit (DMU) based on the assumption that inputs in a specific period are consumed to produce the output in the same period of time. However, there may be some time lag between the consumption of input resources and the production of outputs. A few models to handle the concept of the time lag effect have been proposed. This paper suggests a new multi-period input DEA model considering the consistent time lag effects. Consistency of time lag effect means that the time delay for the same input factor or output factor are consistent throughout the periods. It is more realistic than the time lag effect for the same output or input factor can vary over the periods. The suggested model is an output-oriented model in order to adopt the consistent time lag effect. We analyze the results of the suggested model and the existing multi period input model with a sample data set from a long-term national research and development program in Korea. We show that the suggested model may have the better discrimination power than existing model while the ranking of DMUs is not different by two nonparametric tests.

Keywords : Data Envelopment Analysis, Multi-Period Input Model, Consistent Time Lag Effect

1. Introduction

Data envelopment analysis (DEA) presented by Charnes, Cooper, and Rhodes [3, 5] is a methodology to evaluate the performance of decision-making units (DMUs) by measuring the relative efficiency based on inputs and outputs of DMUs in a specific time period. There are various extensions of the original CCR model [7, 8, 12]. In particular, Banker et al. [2] suggested the BCC model to exhibit variable returns to scale. Many other models have been proposed to handle categorical input-output variables [1], weight restrictions [13] and ordinal input/output variables [7]. Beyond classifying DMUs into efficient and inefficient groups, researches for ranking DMUs in the DEA context has also been performed [4, 8, 9].

Generally, DEA models assumed that inputs in a specific period contribute to produce outputs in the same period. However, this assumption may not be valid in some fields like research and development (R&D) activity, marketing activity, or educational activity. That is, in some situations, a certain length of production lead time is required to produce outputs after the consumption of inputs. This kind of

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production lead time can be thought of as a time lag between the consumption of inputs and the production of outputs. In order to evaluate the efficiency under the time lag effects, Özpeynirci and Kökslan [11] developed a multi-period input model to calculate efficiency values of DMUs under the assumption of outputs of a period are the results of the inputs in previous periods prior to the specific output period. From another point of view, we can consider the situation such that inputs for a specific period can contribute to the outputs in several subsequent periods. From the point of view, Zhang and Jeong [15] suggested another time lag model, the multi-period output model.

The magnitude of time lag effect is expressed as the time lag weight of the models and the weights are determined to maximize the efficiency score of the DMUs respectively. As a result, the time lag effects for the same output or input factor can vary over the periods. But, it is more realistic for the magnitude of a time lag effect to be consistent for the same input or output factors, regardless of measuring period. To overcome the inconsistent time lag effects, Lee, Zhang and Jeong [10] developed a DEA model with consistent time lag effect by modifying the multi-period output model.

The inconsistency problem of time lag effects also exists in multi-period input model. Zhang [14] suggested the basic idea for a multi-period input model to consider consistent time lag effect even though it has some remained question. So, this paper tackled the question remained and suggest a modified version of the multi-period input model to handle the consistency of the time lag weight over different periods. The suggested model has the same time lag weight throughout the measured periods for each output factor.

In the next section, we briefly describe the existing time lag models and the consistent time lag model. Section 3 explains the conceptual difference between the multi-period input model and the consistent time lag model. A modified multi-period input model with a consistent time lag constraint will be given. In Section 4, we give a comparative analysis of the existing multi-period input model and the proposed model on a data set from a long-term R&D program in Korea.

2. Existing Time Lag Models and Consistent Time Lag Model

Let x_{ijt} and y_{rjt} denote the amount of input i and the amount of output r produced by DMU j in the period t, for $i = 1, \cdots, m$, $r = 1, \cdots, s$, $j = 1, \cdots, n$, respectively. Özpeynirci and Kökslan [11] proposed the following multi-period input model under the assumption that the output of a certain time period is produced by consumption of inputs in the current and several previous periods.

(MpI)

$$Max \quad \sum_{t=(PM+1)}^{T} \sum_{j=1}^{n} h_{jt} = \sum_{t=(PM+1)}^{T} \sum_{j=1}^{n} \sum_{r=1}^{s} u_{rjt} y_{rjt}$$

$$s.t. \quad \sum_{p=0}^{PM} \sum_{i=1}^{m} v_{ijt}^{p} x_{ij(t-p)} = 1, \ j = 1, \cdots, n; t = PM+1, \cdots, T$$

$$\sum_{r=1}^{s} u_{rjt} y_{rkt} - \sum_{p=0}^{PM} \sum_{i=1}^{m} v_{ijt}^{p} x_{ij(t-p)} \leq 0,$$

$$k = 1, \cdots, n; j = 1, \cdots, n; t = PM+1, \cdots, T$$

$$u_{rjt}, v_{ijt}^{p} \geq \epsilon, \quad \forall r, j, t, p$$

In (MpI), weight u_{rjt} represents the weight of output r of DMU j in period t, and weight v_{ijt}^{p} denotes the weight of input i consumed by DMU j in the p^{th} previous period from period t. Then the weight v_{ijt}^{p} reflects the time lag effect of the input i in the p^{th} previous period to the output r in period t. PM denotes the length of the periods in which the time lag effect is reflected.

Zhang and Jeong [15] developed the following (MpO) model from the viewpoint that input resources consumed in a specific period partially contribute to outputs produced in the following subsequent periods. That is, the efficiency score of the input in period t for DMU j can be measured by dividing the weighted sum of outputs produced during periods t, $t+1$, $\cdots$ $t+PM$ by the weighted input for period t.

(MpO)

$$Max \quad \sum_{t=1}^{T-PM} \sum_{j=1}^{n} h_{jt} = \sum_{p=0}^{PM} \sum_{t=1}^{T-Pm} \sum_{j=1}^{n} \sum_{r=1}^{s} u_{rjt}^{p} u_{rj(t+p)}$$

$$s.t. \quad \sum_{i=1}^{m} v_{ijt} x_{ijt} = 1, \ j = 1, \cdots, n; t = 1, \cdots, PM$$

$$\sum_{p=0}^{PM} \sum_{r=1}^{s} u_{rjt}^{p} y_{rk(t+p)} - \sum_{i=1}^{m} v_{ijt} x_{ikt} \leq 0,$$

$$k = 1, \cdots, n; j = 1, \cdots, n; t = 1, \cdots, T-PM$$

$$u_{rjt}^{p}, v_{ijt} \geq \epsilon, \quad \forall r, j, t, p$$

v_{ijt} is the weight of input i of DMU j in period t and μ_{rjt}^{p} is the weight of the output r of DMU j in period $t+p$. That is, u_{rjt}^{p} is the weight the DMU j assigns to the output r produced in the p^{th} following period after period t. the objective function is to maximize the total efficiency of all DMUs over period t to $t\text{-}PM$.

Lee et al. [10] suggested another multi-period output model (MpO-C) to consider a consistent time lag effects by the same time lag weights through the periods. The model is a new version of the multi-period output model whereby each output factor has the same time lag weight throughout the measurement periods.

(MpO-C)

$$max \quad \sum_{r=1}^{s}\sum_{p=0}^{PM}\left\{\sum_{t=1}^{T-PM} y_{rk(t+p)}\right\}u_r^p$$

$$s.t. \quad \sum_{i=1}^{m} x_{ikt}v_{it} = 1,\ t=1,\ \cdots,\ T-PM$$

$$\sum_{r=1}^{s}\sum_{p=0}^{PM} y_{j(t+p)}u_r^p - \sum_{i=1}^{m} x_{ijt}v_{it} \le 0,$$

$$j=1,\ \cdots,\ n; t=1,\ \cdots,\ T-PM$$

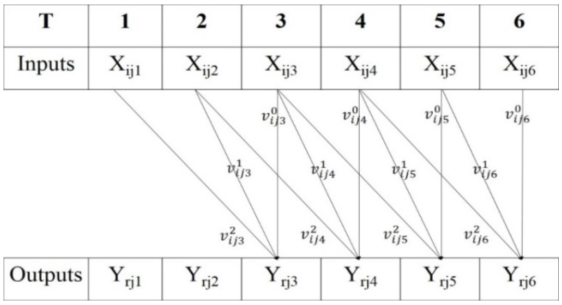
$$u_r^p,\ v_{it} \ge 0,\quad \forall\, i,\ r,\ t,\ p$$

Note that (MpO-C) is a model for a DMU k and (MpI) and (MpO) also can be decomposed to smaller models for each DMU. In (MpO-C) v_{it}^p denote the weight of input i of the DMU in period t and u_r^p is the weight of the output r of p^{th} following period after a certain period. Differ from (MpO), (MpO-C) has the same weights for the partial contribution to outputs in the following periods from input in a certain period. In the next section, we will see the consistent time lag effects in detail.

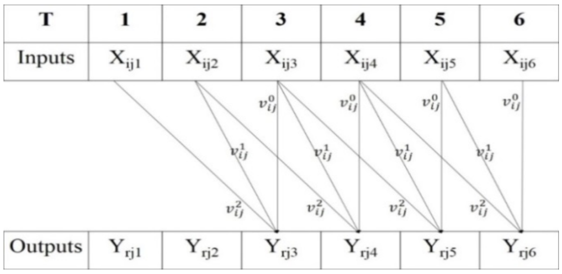
3. Multi-Period Input Model with a Consistent Time Lag Effect

3.1 Consistent Time Lag Effect

(MpI) assumes that the outputs in a period are produced by the consumption of the inputs in multiple previous periods. In the model, v_{ijt}^p is a weight value representing the contribution of input i consumed in period $t\text{-}p$ to outputs in period t for DMU j. <Figure 1> shows how the time lag weights in (MpI) reflect the time lag effects when PM = 2. Consider the output in periods 3. The output in period 3 is the results of partial contributions of the inputs from periods 1 to 3. v_{ij3}^2, v_{ij3}^1 and v_{ij3}^0 are the weights representing the time lag effects of period 1 to 3 for input i. Similarly, the output in period 4 is the result of the partial contributions



<Figure 1> Weights for Inconsistent Time Lag Effects of(MpI)



<Figure 2> Weights for the Consistent Time Lag Effects(MpI-C)

of the inputs from periods 2 to 4 and v_{ij4}^2, v_{ij4}^1, and v_{ij4}^0 represent the time lag effects. The weights for period 3 and 4 are determined independently. Thus, outputs of periods 3 and 4 can have different time lag weights for the same input despite having the same time lag periods. In other words, v_{ij3}^0, v_{ij3}^1, and v_{ij3}^2 and v_{ij4}^0, v_{ij4}^1, and v_{ij4}^2 can have different values even though they represents the time lag effects for the same input under the same time lag periods. However, it is more reasonable that the time lag effect for an input is constant regardless of the period if the length of time lag periods is the same. That is, we can assume that $v_{ij3}^p = v_{ij4}^p = v_{ij5}^p = v_{ij6}^p,\ p=0,\ 1,\ 2$ in <Figure 1> for the more reasonable consistent time lag effects.

<Figure 2> shows the weights for the consistent time lag effects. In the figure, the time lag effects from the inputs of periods 1 to 3 on the output of period 3, and the time lag effects from the inputs of periods 2 to 4 on the output of period 4 are the same for each time lag period p. The model based on the consistent time lag effects will be described in the next subsection.

3.2 Multi-Period Input Model with a Consistent Time Lag

(MpI) can be modified by replacing the time lag weights with the time lag weights in <Figure 2>. The new time lag weights force the time lag effect to be consistent. The following (MpI-C0) is a model to find the efficiency of DMU 0, under the consistent time lag effect.

(MpI-C_0)

$$Max \sum_{t=(PM+1)}^{T} h_{0t} = \sum_{t=(PM+1)}^{T} \sum_{r=1}^{s} \mu_{r0t} y_{r0t}$$

$$s.t. \quad \sum_{p=0}^{PM} \sum_{i=1}^{m} v_{i0}^{p} x_{i0(t-p)} = 1, \ t = PM+1, \cdots, T$$

$$\sum_{r=1}^{s} \mu_{r0t} y_{rkt} - \sum_{p=0}^{PM} \sum_{i=1}^{m} v_{i0}^{p} x_{ik(t-p)} \le 0,$$

$$k = 1, \cdots, n; t = PM+1, \cdots, T$$

$$\mu_{r0t}, v_{i0}^{p} \ge \epsilon, \ \forall i, r, p, t$$

Note that (MpI) has independent time lag weights for each DMU in each measuring period. Thus, (MpI) can be decomposed into smaller models for each DMU and period. But, (MpI-C_0) cannot be decomposed by the measuring period because the weight for the consistent time lag effects.

Unfortunately, (MpI-C_0) might have a feasibility problem in some cases. In the model, the linear system $\sum_{p=0}^{PM} \sum_{i=1}^{m} v_{ij}^{p} X_{ij(t-p)} = 1$ consists of $m(PM+1)$ variables and *T-PM* equations. When $m(PM+1)$ < *T-PM*, the linear system is over determined and then the system may have no solution.

Because of this feasibility problem, we need another approach to establish a new model to obtain efficiency values under the consistent time lag effect. The output-oriented model can be a useful approach to cope with the similar feasibility problem in DEA model [3]. The input-oriented approach is to maximize the weighted output given the weighted input, whereas the output-oriented approach is to minimize the weighted input given the weighted output. To make an output-oriented form of the multi-period input model with a consistent time lag effect, a reciprocal of efficiency q_{jt}. That is, the weighted input is minimized to maximize efficiency under the constraints setting the weighted output to 1.

(OMpI-C_0)

$$Min \sum_{t=PM+1}^{T} q_{0t} = \sum_{t=PM+1}^{T} \sum_{p=0}^{PM} \sum_{i=1}^{m} v_{i0}^{p} x_{i0(t-p)}$$

$$s.t. \quad \sum_{t=1}^{s} \mu_{r0t} y_{r0t} = 1, \ t = PM+1, \cdots, T$$

$$\sum_{p=0}^{PM} \sum_{i=1}^{m} v_{i0}^{p} x_{ik(t-p)} - \sum_{r=1}^{s} \mu_{r0t} y_{rkt} \ge 0,$$

$$k = 1, \cdots, n; t = PM+1, \cdots, T$$

$$\mu_{r0t}, v_{i0}^{p} \ge \epsilon, \ \forall i, r, p, t$$

Different from the input-oriented model, the above model is free from the feasibility problem, unless all output factors are zero for any period t = PM +1, ⋯, T. If a DMU has zero values for all output factors in a specific period, the efficiency of the DMU in that period should be zero, because the DMU produced no output in the period. Thus, we just exclude such periods for each DMU from the model.

4. Case Example

Lee et al. [10] used data on long-term national R&D programs. The data set consists of input and output data from a research center supported by a long-term national R&D program of the Korean government. The research center had 17 projects, and each project (DMU) had been supported financially for 10 years. There are four input factors and four output factors in the data set. The input factors are research fund (in millions of Korean won) and the number of PhD, MSc, and BSc researchers. The output factors are the number of published papers (SCI journals and non-SCI journals) and the number of applied and registered patents. <Table 1> shows sample input and output data from a project. We applied (MpI) and (OMpI-C) to the same data for the performance evaluation of the 17 projects under the consistent time lag effects with three different time lag periods, *PM* = 2, 3, and 4.

The efficiency scores from each models when PM = 4 are shown in <Table 2>. In the results of the (MpI), the efficiency score of DMU A is 1 in all periods. In other words, DMU A is efficient in all periods. On the other hand, DMU A is not efficient in period 8 according to the efficiency

<Table 1> Sample Input and Output Data of a Project

Year	Input factors				Output factors			
	Fund	Researchers			Papers		Patents	
		PhD	MSc	BSc	SCI	Non-SCI	Appl.	Reg.
1	300	0	10	13	0	0	2	0
2	300	0	9	12	0	1	3	2
3	300	4	12	6	3	3	4	0
4	150	5	5	2	3	0	2	0
5	180	5	5	2	2	2	5	3
6	180	5	5	2	8	7	8	0
7	180	3	0	6	1	0	6	4
8	180	3	0	3	5	0	3	6
9	180	0	3	5	2	0	9	2
10	180	0	2	4	9	0	5	2

scores obtained from the proposed (OMpI-C). Let us consider efficiency values in period 5. All DMUs except DMU B and E are efficient, according to the (MpI) whereas only DMU A and K are efficient by (OMpI-C). Similarly, the number of efficient DMUs by (OMpI-C) is smaller than the number by (MpI) throughout periods. It's natural because the time leg weights are more restricted under the consistent time lag effects.

<Table 3> shows the average and range of 17 DMU's efficiency scores for each period by the two models. For all PM periods, average values obtained by the (MpI) are larger than the values by the (OMpI-C). On the other hand, the ranges of efficiency obtained by the (MpI) are smaller than the values obtained by the (OMpI-C). Thus, we may conclude that (OMpI-C) can discriminate DMUs better than (MpI) based on the efficiency scores.

<Table 2> Efficiency Values Obtained by (MpI) and (OMpI-C) when PM = 4

Model	DMU	Periods						Model	DMU	Periods					
		5	6	7	8	9	10			5	6	7	8	9	10
(MpI)	A	1.000	1.000	1.000	1.000	1.000	1.000	(OMpI-C)	A	1.000	1.000	1.000	0.998	1.000	1.000
	B	0.526	1.000	1.000	0.945	1.000	1.000		B	0.219	0.478	0.448	0.448	0.437	0.437
	C	1.000	1.000	1.000	0.998	1.000	1.000		C	0.401	0.388	0.289	0.509	0.259	0.383
	D	1.000	0.950	1.000	1.000	1.000	1.000		D	0.859	0.859	0.589	0.573	0.656	0.872
	E	0.437	0.698	0.451	1.000	1.000	1.000		E	0.238	0.238	0.418	0.397	0.397	0.397
	F	1.000	0.982	1.000	0.682	1.000	1.000		F	0.694	0.576	0.612	0.605	0.717	0.738
	G	1.000	1.000	1.000	1.000	1.000	1.000		G	0.567	0.786	0.806	0.989	0.796	0.793
	H	1.000	1.000	1.000	1.000	1.000	1.000		H	0.509	0.509	0.504	0.966	0.876	0.801
	I	1.000	1.000	1.000	1.000	1.000	0.836		I	0.799	0.528	0.531	0.785	0.785	0.789
	J	1.000	1.000	0.716	1.000	1.000	1.000		J	0.922	1.000	0.643	0.918	0.955	0.661
	K	1.000	1.000	1.000	0.997	0.508	1.000		K	1.000	1.000	0.504	0.260	0.259	0.359
	L	1.000	0.231	0.769	0.889	0.750	0.246		L	0.227	0.227	0.177	0.155	0.151	0.127
	M	1.000	1.000	1.000	0.666	1.000	1.000		M	0.223	0.346	0.346	0.327	0.204	0.999
	N	1.000	0.457	1.000	1.000	1.000	1.000		N	0.529	0.422	0.422	0.465	0.450	0.482
	O	1.000	1.000	0.469	0.572	0.560	0.551		O	0.535	0.460	0.420	0.297	0.296	0.314
	P	1.000	0.523	0.806	0.611	0.459	0.436		P	0.349	0.349	0.223	0.183	0.185	0.259
	Q	1.000	1.000	1.000	1.000	1.000	1.000		Q	0.643	0.643	0.643	1.000	1.000	1.000

<Table 3> The Averages and Ranges of Efficiency Values

PM	Model		Periods							
			3	4	5	6	7	8	9	10
2	(MpI)	Avg	0.772	0.646	0.935	0.780	0.850	0.891	0.868	0.780
		Range	1.000	1.000	0.566	0.839	0.667	0.432	0.541	0.754
	(OMpI-C)	Avg	0.391	0.390	0.458	0.445	0.429	0.388	0.398	0.416
		Range	0.881	1.000	0.877	0.882	0.729	0.725	0.887	0.715
3	(MpI)	Avg		0.647	0.935	0.869	0.850	0.894	0.899	0.788
		Range		1.000	0.566	0.769	0.667	0.428	0.541	0.754
	(OMpI-C)	Avg		0.423	0.508	0.552	0.509	0.484	0.412	0.478
		Range		1.000	0.793	0.793	0.849	0.780	0.875	0.904
4	(MpI)	Avg			0.939	0.873	0.895	0.904	0.899	0.886
		Range			0.563	0.769	0.549	0.428	0.541	0.754
	(OMpI-C)	Avg			0.571	0.577	0.504	0.581	0.554	0.612
		Range			0.781	0.773	0.823	0.845	0.849	0.873

<Table 4> Summary of the Dependency Test between Ranks Under the Two Models

Period	Spearman's ρ			Kendall's τ rank correlation		
	PM = 2	PM = 3	PM = 4	PM = 2	PM = 3	PM = 4
3	**	N/A	N/A	**	N/A	N/A
4	***	***	N/A	***	***	N/A
5	**	**	*	*	**	*
6	***		**	***		*
7	**	***		*	***	*
8	*	***	***	*	***	***
9	***	***	***	***	***	***
10		*	***		**	***

*, **, *** indicate that H_0 can be rejected at 95%, 97.5%, and 99% significance levels, respectively.

We can rank the DMU's by the efficiency scores in each period. The ranking of efficient DMU is 1. Though (OMpI-C) has better to discriminate DMU's than (MpI), the rankings of DMU's obtained from two models may not different in stochastically. Thus, we did two nonparametric test, Spearman's test and Kendall's rank correlation test [6] to see whether the rankings obtained from the two models are different or not. The null hypothesis (H_0) of the tests is that the ranking obtained by the (MpI) and (OMpI-C) models are independent to each other. The test results on rank dependency are summarized in <Table 4>. The results show that H_0 can be rejected in both tests for most of the periods except one period for each time lag period PM. By Spearman's ρ test, the null hypothesis H_0 cannot be rejected only for period 10 when PM = 2, period 6 when PM = 3, and period 7 when PM = 4. By Kendall's rank correlation test, H_0 cannot be rejected only for period 10 when PM = 2 and period 6 when PM = 3. Thus, we can conclude that the ranking of DMU's by the suggested consistent time lag model (OMpI-C) is not different to the ranking by (MpI) though efficiency scores are different.

In conclusion, the efficiency values show that the proposed (OMpI-C) is better than (MpI) to discriminate efficient DMUs. However, the results of the two rank tests indicate that there is no significant difference in the ranking of DMUs from the two models.

5. Conclusion

In this, paper, we proposed a variation of a multi-period input model to evaluate the efficiency of DMUs considering the consistent time lag effects. The suggested model is an output-oriented model in order to adopt the consistent time lag effect in the multi-period input model. There are two underlying assumptions for calculating the efficiency scores of DMUs by the suggested model. The first one is that the outputs of a specific period are the results of partial contributions of inputs consumed in multiple preceding periods. The second one is that the time lag effect of each input factor is consistent throughout the entire evaluation period, regardless of the output period. A sample data set from a long-term Korean R&D program was used to investigate the characteristics of the suggested model. Two nonparametric tests were performed to compare the rankings obtained by the suggested model and an existing multi-period input model (MpI). As expected, the suggested model (OMpI-C) has better discrimination power than (MpI). Furthermore, the rankings of DMUs by (OMpI-C) and (MpI) are not significantly different. Thus, the suggested model (OMpI-C) considers more realistic time lag effect and has desirable properties for performance evaluation under the time lag effects.

The consistent pattern of time lag effects in R&D program data is dependent on the research domain. The domain-specific pattern of time lag effects can be used in future research in order to improve the suggested model. It is known that the input oriented and the output oriented CCR models for a single period give the same results. The theoretical analysis for the relation between multi-period input model and multi-period output model and the comparison of the results from the two models could be another future research.

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