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Two-stage data envelopment analysis: An enhanced Russell measure model

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Abstract— **Data envelopment analysis (DEA) is a non-parametric method in Operations Research and Economics for measuring the relative efficiency of peer decision making units (DMUs) that have multiple inputs and outputs. In many situations, DMUs can have a two-stage structure where the first stage uses inputs to produce outputs (called intermediate measures) that then become the inputs to the second stage. In recent studies on two-stage production processes, authors used the radial DEA models to measure the efficiency of the whole process and the efficiencies of individual two stages. In these models, due to the existence of intermediate measures, the usual procedure of adjusting the inputs or outputs by the efficiency scores for an inefficient DMU does not necessarily yield an efficient DMU. In this paper, we introduce a non-radial enhanced Russell measure (ERM) model on two-stage production processes by taking into account a relationship of the two stages. Unlike the radial two-stage DEA models, the new approach enables us to determine the efficient projections for inefficient DMUs within the framework of two-stage DEA. An example of the non-life insurance industry in Taiwan is applied to compare the new measure to a recent two-stage DEA model.**

Keywords- Data envelopment analysis; Decision making units; Efficiency; Two-stage; Enhanced Russell measure

I. INTRODUCTION

Data envelopment analysis (DEA) was first introduced by Charnes et al. [1] as a non-parametric technique in Operations Research and Economics for measuring relative efficiency and performance of each member of a set of related comparable entities, called Decision Making Units (DMUs). In many situations, DMUs can have a two-stage structure where the first stage uses inputs to produce outputs that then become the inputs to the second stage. The second stage thus utilizes these first stage outputs to produce its own outputs. We refer to the first stage outputs as intermediate measures. Here we assume that intermediate measures are the only inputs to the second stage. There are many studies on two-stage production processes. For example, Seiford and Zhu [2] developed a two-stage DEA approach for measuring efficiency of the profitability and marketability of US commercial banks. Zhu [3] applied the same two-stage process to assess the financial efficiency of the best 500 companies. Sexton and Lewis [4] studied the Major League Baseball performance in a two-stage process. Chen and Zhu [5] developed a linear DEA type model where each stage's efficiency is defined on its own production possibility set. Kao and Hwang [6] developed a different approach where the overall efficiency of the system can be decomposed into the product of the efficiencies of the two-stages. Chen et al. [7] presented a model similar to the Kao and Hwang's model, but in an additive form. These studies apply the radial DEA models for measuring efficiencies of each stage and whole system. On the other hand, as indicated by Chen et al. [8], in many two-stage DEA models including Kao and Hwang's approach, modifying the inputs and outputs for an inefficient DMU by the efficiency score is normally not sufficient to yield an efficient DMU.

The aim of this paper is to introduce a non-radial two-stage DEA model in enhanced Russell measure (ERM) formulation for measuring the overall efficiency of two-stage production processes. This approach takes into account the series relationship of the two stages in measuring the overall efficiency of the whole process. We will demonstrate that unlike the radial two-stage DEA models, the projected DMUs in this approach for inefficient DMUs are efficient. The data set consists of 24 non-life insurance companies in Taiwan is used to illustrate the new approach. The results are compared to those obtained from the Kao and Hwang's model.

The rest of this paper is organized as follows. Section 2 contains some preliminaries. Section 3 presents the general two-stage production process and the Kao and Hwang's model for two-stage processes. In Section 4, we propose an ERM model on two-stage processes. Section 5 presents the results in comparison of the new model with the Kao and Hwang's model using the data set of the non-life insurance industry in Taiwan studied by Kao and Hwang [6]. Finally, conclusions are provided in the last section.

II. PRELIMINARIES

Consider we have n DMUs, each uses m inputs $x_{ij}\ (i = 1,...,m)$ to produces s outputs $y_{rj}\ (r = 1,...,s)$. It is assumed that all inputs and outputs are non-negative. The production possibility set (PPS) is defined as the set of all inputs and outputs of a production technology in which outputs can be produced from inputs. Under the constant returns to scale (CRS) assumption the PPS can be represented as follows:

$$P_C = \left\{ (x, y) \,\middle|\, x \geq \sum_{j=1}^{n} \lambda_j x_j,\ y \leq \sum_{j=1}^{n} \lambda_j y_j,\ \lambda_j \geq 0,\ j = 1,...,n \right\},$$

where x_j and y_j are the input vector and output vector of DMU_j, respectively.

For measuring the relative efficiency of DMUs, there exist various models in DEA. The conventional DEA model was called CCR introduced by Chanes et al. [1] in 1978. The

CCR model is a radial model in which a proportional change of inputs or outputs is the main concern. The CCR model for measuring the efficiency of DMU_k, is indicated as follows:

$$
\begin{aligned}
&\theta^* = \min \theta \\
&\text{s.t.} \ \sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{ik}, \quad i = 1,\dots,m, \\
&\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{ik}, \quad r = 1,\dots,s, \qquad (1) \\
&\lambda_j \ge 0, \ j = 1,\dots,n, \ \theta \text{ free},
\end{aligned}
$$

where the optimal solution of θ^* is efficiency score. DMU_k is efficient if $\theta^*=1$ and inefficient if $\theta^*<1$.

The model (1) is the input-oriented CCR model where the purpose is to minimize input custom while keeping the level of current outputs. Similarly the output-oriented CCR model can be defined. The dual of model (1), which is called multiplier form, is given by:

$$
\begin{aligned}
&\theta^* = \max \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \\
&\text{s.t.} \ \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \ j = 1,\dots,n, \qquad (2) \\
&u_r, v_i \ge 0, \ r = 1,\dots,s, \ i = 1,\dots,m.
\end{aligned}
$$

Färe and Lovell [9] introduced the Russell measure model that, unlike the CCR model, is a non-radial and non-oriented model. Pastor et al. [10] revisited the Russell measure model and proposed a new non-radial measure called enhanced Russell Measure (ERM). The ERM model of DMU_k is defined as:

$$
\begin{aligned}
&\rho^* = \min \rho = \frac{\frac{1}{m}\sum_{i=1}^{m} \theta_i}{\frac{1}{s}\sum_{r=1}^{s} \phi_r} \\
&\text{s.t.} \ \theta_i x_{ik} \ge \sum_{j=1}^{n} \lambda_j x_{ij}, \qquad i = 1,\dots,m, \\
&\phi_r y_{rk} \le \sum_{j=1}^{n} \lambda_j y_{rj}, \qquad r = 1,\dots,s, \qquad (3) \\
&0 < \theta_i \le 1, \qquad i = 1,\dots,m, \\
&\phi_r \ge 1, \qquad r = 1,\dots,s, \\
&\lambda_j \ge 0, \qquad j = 1,\dots,n.
\end{aligned}
$$

The optimal solution of ρ^* is the SBM efficiency score. The DMU_k is ERM-efficient, if $\rho^*=1$ that is equivalent to $\theta_i^* = \phi_r^* = 1, \ \forall i, r$.

The input (output)-oriented ERM model can be defined by neglecting the denominator (numerator) of the objective function and ϕ_r^* (θ_i^*) of the left hand side of the constraints in model (3).

Note that as demonstrated by Pastor et al. [10] the efficiency score calculated by the ERM model is not greater than the efficiency score by CCR model. Also a DMU is ERM-efficient if and only if it is CCR-efficient.

III. Kao and Hwang Model

Consider a manufacturing process composed of a two-stage process as shown in Fig. 1. Suppose we have n DMUs, that each DMU_j (j=1,…,n) has m inputs x_{ij} (i=1,…,m) to the first stage and p outputs z_{dj} (d=1,…,p) from that stage. These p outputs then become the inputs to the second stage, and are referred to as intermediate measures. The outputs from the second stage are y_{rj} (r=1,…,s).

The CRS efficiency scores based on the multiplier form of the CCR model for the whole process and the two individual stages can be calculated as:

$$
\theta^* = \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}}, \ \theta_1^* = \frac{\sum_{d=1}^{p} w_d z_{dk}}{\sum_{i=1}^{m} v_i x_{ik}} \ \text{and} \ \theta_2^* = \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{d=1}^{p} \tilde{w}_d z_{dk}},
$$

where w_d , v_i , u_r and $\tilde{w}_d$ are unknown non-negative weights.

Kao and Hwang [6] proposed a two-stage DEA model where it is necessary for the weights associated with z_{dj} to be the same. Their model for measuring the overall efficiency of DMU_k can be shown as follows:

$$
\begin{aligned}
&\theta^* = \max \frac{\sum_{d=1}^{p} w_d z_{dk}}{\sum_{i=1}^{m} v_i x_{ik}} \times \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{d=1}^{p} \tilde{w}_d z_{dk}} = \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \\
&\text{s.t.} \ \frac{\sum_{d=1}^{p} w_d z_{dj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \ j = 1,\dots,n, \qquad (4) \\
&\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{d=1}^{p} \tilde{w}_d z_{dj}} \le 1, \ j = 1,\dots,n, \\
&u_r, v_i, w_d \ge 0, \tilde{w}_d = w_d, r = 1,\dots,s; i = 1,\dots,m; d = 1,\dots,p.
\end{aligned}
$$

It can be observed from the objective function of model (4) that the overall efficiency of DMU_k is the product of the efficiencies of the two stages. Note that model (4) can be applied only for the CRS cases.

IV. Enhanced Russell Measure (ERM) Model for Two-Stage Processes

In an effort to estimate the overall efficiency of DMU_k as a whole, first we use the ERM model for first stage and second stage. The models can be expressed as follows:

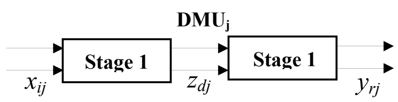

Fig. 1. Two stage production process.

$$\rho_1^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\theta_i}{\frac{1}{p}\sum_{d=1}^{p}\phi_d}$$

$$\begin{aligned}
\text{s.t. } & \theta_i x_{ik} \ge \sum_{j=1}^{n}\lambda_j x_{ij}, && i=1,\dots,m,\\
& \phi_d z_{dj} \le \sum_{j=1}^{n}\lambda_j y_{dj}, && d=1,\dots,p, \\
& 0<\theta_i \le 1, && i=1,\dots,m,\\
& \phi_d \ge 1, && d=1,\dots,p,\\
& \lambda_j \ge 0, && j=1,\dots,n.
\end{aligned} \tag{5}$$

and

$$\rho_2^* = \min \frac{\frac{1}{p}\sum_{d=1}^{p}\theta_d}{\frac{1}{s}\sum_{r=1}^{s}\phi_r}$$

$$\begin{aligned}
\text{s.t. } & \theta_d z_{dk} \ge \sum_{j=1}^{n}\mu_j z_{dj}, && d=1,\dots,p,\\
& \phi_r y_{rk} \le \sum_{j=1}^{n}\mu_j y_{rj}, && r=1,\dots,s, \\
& 0\le\theta_d \le 1, && d=1,\dots,p,\\
& \phi_r \ge 1, && r=1,\dots,s,\\
& \mu_j \ge 0, && j=1,\dots,n.
\end{aligned} \tag{6}$$

To connect the two sub-processes as a whole process, a model must describe this series relationship. Since, z_{dj} (d=1,…,p), the outputs of stage 1 are the inputs of the stage 2, we introduce the following constraints (called connecting constraints) for combining the two stages.

$$\sum_{j=1}^{n}\lambda_j z_{dj} = \sum_{j=1}^{n}\mu_j z_{dj},\ d=1,2,\dots,p.$$

Then, we propose the following programming problem for measuring the overall efficiency of DMU_k.

$$\rho_{overall}^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\theta_i}{\frac{1}{s}\sum_{r=1}^{s}\phi_r}$$

$$\begin{aligned}
\text{s.t. } & \theta_i x_{ik} \ge \sum_{j=1}^{n}\lambda_j x_{ij}, && i=1,\dots,m,\\
& \sum_{j=1}^{n}\lambda_j z_{dj} = \sum_{j=1}^{n}\mu_j z_{dj}, && d=1,\dots,p,\\
& \phi_r y_{rk} \le \sum_{j=1}^{n}\mu_j y_{rj}, && r=1,\dots,s, \\
& 0<\theta_i \le 1, && i=1,\dots,m,\\
& \phi_r \ge 1, && r=1,\dots,s,\\
& \lambda_j, \mu_j \ge 0, && j=1,\dots,n.
\end{aligned} \tag{7}$$

Note that model (7) is a nonlinear programming problem that can be converted into a linear programming problem by using the Cooper et al. [6] transformation as follows:

$$\rho_{overall}^* = \min \frac{1}{m}\sum_{i=1}^{m}u_i$$

$$\begin{aligned}
\text{s.t. } & \sum_{r=1}^{s}v_r = s,\\
& \sum_{j=1}^{n}\alpha_j x_{ij} \le u_i x_{ik}, && i=1,\dots,m,\\
& \sum_{j=1}^{n}\alpha_j z_{dj} = \sum_{j=1}^{n}\gamma_j z_{dj}, && d=1,\dots,p, \\
& \sum_{j=1}^{n}\gamma_j y_{rj} \ge v_r y_{rk}, && r=1,\dots,s,\\
& u_i \le \beta, && i=1,\dots,m,\\
& \beta \le v_r, && r=1,\dots,s,\\
& \alpha_j, \gamma_j \ge 0, && j=1,\dots,n,\\
& 0 \le \beta \le 1,
\end{aligned} \tag{8}$$

where $\beta^{-1} = \frac{1}{s}\sum_{r=1}^{s}\phi_r, u_i = \beta\theta_i, v_r = \beta\phi_r, \alpha_j = \beta\lambda_j$ and $\gamma_j = \beta\mu_j, \forall i,r,j.$

Theorem 1: *A DMU_k is overall efficient if and only if it is efficient for each two stages.*

Proof. The proof is clear and, hence, omitted. □

As indicated by Chen et al. [8], in the two-stage DEA models including the Kao and Hwang's approach, due to the existence of intermediate measures, the improved DMU for an inefficient DMU is normally not sufficient to yield an efficient DMU. We will show that under the new model the projected DMU for an inefficient DMU is efficient.

Suppose that, a DMU_K is inefficient and an optimal solution to model (7) be $\lambda_j^*, \mu_j^*, \theta_i^*, \phi_r^*$. Then, we have a formula for improvement, which is called the ERM-projection as follows:

$$\begin{aligned}
& x_{ik}^* \leftarrow \theta_i x_{ik}, && i=1,\dots,m,\\
& y_{rk}^* \leftarrow \phi_r y_{rk}, && r=1,\dots,s, \\
& z_{dk}^* \leftarrow (\sum_{j=1}^{n}\lambda_j^* z_{dj} = \sum_{j=1}^{n}\mu_j^* z_{dj}), && d=1,\dots,p.
\end{aligned} \tag{9}$$

Theorem 2: *The improved DMU_k defined by (9) is overall efficient.*

Proof. Suppose that an optimal solution of the improved DMU_k calculated by model (7) is $\lambda_j', \mu_j', \theta_i', \phi_r'$. Then, we have

$$x_{ik}^* \theta_i' = \sum_{j=1}^{n} \lambda_j' x_{ij}, i = 1,...,m,$$

$$y_{rk}^* \phi_r' = \sum_{j=1}^{n} \mu_j' y_{rj}, j = 1,...,s.$$

By inserting amounts of x_{ik}^* and y_{rk}^*, we have

$$(\theta_i x_{ik})\theta_i' = x_{ik}\theta_i'\theta_i = \sum_{j=1}^{n} \lambda_j' x_{ij}, \ i = 1,..., m,$$

$$(\phi_r y_{rk})\phi_r' = y_{rk}\phi_r'\phi_r = \sum_{j=1}^{n} \mu_j' y_{rj}, \ r = 1,..., s.$$

Corresponding to these constraints the overall efficiency is:

$$\rho_{overall}' = \frac{\frac{1}{m}\sum_{i=1}^{m} \theta_i'\theta_i}{\frac{1}{s}\sum_{r=1}^{s} \phi_r'\phi_r}.$$

If any $\theta_i' \, (i = 1,..., m)$ or $\phi_r' \, (r = 1,..., s)$ be less than one, then it holds that

$$\rho_{overall}' < \rho_{overall}^*.$$

This contradicts the optimality of $\rho_{overall}^*$. Therefore, we have $\theta_i' = \phi_r' = 1, \ \forall i, r$. Hence, the improved DMU is overall efficient. □

So far the discussion is based upon the assumption of CRS. The proposed model holds under the assumption of variable returns to scale (VRS) by adding the convexity constraint, namely $\sum_{j=1}^{n} \lambda_j = 1$, into models.

V. NUMERICAL EXAMPLE

In this section, the new approach is applied to the 24 Taiwanese non-life insurance companies as studied by Kao and Hwang [6]. They divide the production process of the non-life insurance industry into two stages: premium acquisition and profit generation. The inputs to the first stage are operational expenses and insurance expenses, and the outputs from the second stage are underwriting profit and investment profit. There are also two intermediate measures between the two stages, namely direct written premiums and reinsurance premiums. The data are provided in Table 1. The efficiency of the first stage evaluates the performance in marketing the service of insurance while the efficiency of the second stage evaluates the performance in generating profit from the premiums.

In order to compare the results with the input-oriented CCR model proposed by Kao and Hwang [6], we employ the input-oriented ERM model under the assumption of CRS. By applying the input-oriented version of models (5), (6) and (7), the efficiencies of the first stage, second stage and the whole process of the 24 non-life insurance companies are calculated. The results are shown in Table 2. According to Theorem 1, because none of the insurance companies perform efficiently in both the stages, none of them perform efficiently for the whole process. It can be observed from Table 2 that for most DMUs the efficiency of the first stage is higher than the second stage. This exhibits that the low efficiency score for the whole process is caused by the low efficiency score of the second stage.

Table 3 reports the rankings of the efficiency scores based upon our approach and Kao and Hwang's approach. They yield the almost identical ranking.

TABLE 1 .DATA SET

DMU	Operation expenses(x_1)	Insurance expenses(x_2)	Direct written premiums(z_1)	Reinsurance premiums(z_2)	Underwriting profit(y_1)	Investment profit(y_2)
1 Taiwan Fire	1,178,744	673,512	7,451,757	856,735	984,143	681,687
2 Chung Kuo	1,381,822	1,352,755	10,020,274	1,812,894	1,228,502	834,754
3 Tai Ping	1,177,494	592,790	4,776,548	560,244	293,613	658,428
4 China Mariners	601,320	594,259	3,174,851	371,863	248,709	177,331
5 Fubon	6,627,707	3,531,614	37,392,862	1,753,794	7,851,229	3,925,272
6 Zurich	2,627,707	668,363	9,747,908	952,326	1,713,598	415,058
7 Taian	1,942,833	1,443,100	10,685,457	643,412	2,239,593	439,039
8 Ming Tai	3,789,001	1,873,530	17,267,266	1,134,600	3,899,530	622,868
9 Central	1,567,746	950,432	11,473,162	546,337	1,043,778	264,098
10 The First	1,303,249	1,298,470	8,210,389	504,528	1,697,941	554,806
11 Kuo Hua	1,962,448	672,414	7,222,378	643,178	1,486,014	18,259
12 Union	2,592,790	650,952	9,434,406	1,118,489	1,574,191	909,295
13 Shingkong	2,609,941	1,368,802	13,921,464	811,343	3,609,236	223,047
14 South China	1,396,002	988,888	7,396,396	465,509	1,401,200	332,283
15 Cathay Century	2,184,944	651,063	10,422,297	749,893	3,355,197	555,482
16 Allianz president	211,716	415,071	5,606,013	402,881	854,054	197,947
17 Newa	1,453,797	1,085,019	7,695,461	342,489	3,144,484	371,984
18 AIU	757,515	547,997	3,631,484	995,620	692,731	163,927
19 North America	159,422	182,338	1,141,950	483,291	519,121	46,857
20 Federal	145,442	53,518	316,829	131,920	355,624	26,537
21 Royal Sunalliance	84,171	26,224	225,888	40,542	51,950	6491
22 Asia	15,993	10,502	52,063	14,574	82,141	4181
23 AXA	54,693	28,408	245,910	49,864	0.1	18,980
24 Mitsui Sumitomo	163,297	235,094	476,419	644,816	142,370	16,976

TABLE 2. EFFICIENCY SCORES

DMU	ρ_1^*	ρ_2^*	$\rho_{overall}^*$
1 Taiwan Fire	0.990	0.613	0.679
2 Chung Kuo	0.907	0.499	0.545
3 Tai Ping	0.669	1.000	0.669
4 China Mariners	0.621	0.372	0.264
5 Fubon	0.820	1.000	0.742
6 Zurich	0.902	0.388	0.350
7 Taian	0.692	0.536	0.273
8 Ming Tai	0.710	0.508	0.263
9 Central	1.000	0.291	0.216
10 The First	0.702	0.672	0.410
11 Kuo Hua	0.740	0.270	0.124
12 Union	1.000	0.641	0.687
13 Shingkong	0.797	0.490	0.187
14 South China	0.684	0.518	0.284
15 Cathay Century	1.000	0.695	0.559
16 Allianz president	0.907	0.383	0.305
17 Newa	0.655	1.000	0.353
18 AIU	0.760	0.292	0.256
19 North America	1.000	0.320	0.361
20 Federal	0.620	0.715	0.464
21 Royal Sunalliance	0.650	0.270	0.179
22 Asia	0.548	1.000	0.548
23 AXA	0.806	0.442	0.408
24 Mitsui Sumitomo	1.000	0.193	0.106

The Spearman Rank Correlation coefficient for the rankings in Table 3 corresponds to 0.994, which shows that the correlation between our approach and Kao and Hwang's approach is very high. Thus this approach is suitable for measuring the efficiency of the whole system.

TABLE 3. RANKING OF EFFICIENCY SCORES

DMU	Our ranking	Kao and Hwang's results	
		Ranking	*Overall efficiency*
1	3	3	0.699
2	7	5	0.625
3	4	4	0.690
4	17	15	0.304
5	1	1	0.767
6	13	12	0.390
7	16	17	0.277
8	18	18	0.275
9	20	20	0.223
10	9	9	0.466
11	23	23	0.164
12	2	2	0.760
13	21	21	0.208
14	15	16	0.289
15	5	6	0.614
16	14	14	0.320
17	12	13	0.360
18	19	19	0.259
19	11	11	0.411
20	8	8	0.547
21	22	22	0.201
22	6	7	0.590
23	10	10	0.420
24	24	24	0.135

Finally, if we obtain the projection DMUs for all the 24 inefficient DMUs, we can see that the overall efficiency scores, calculated by the input-oriented of model (7), for all new DMUs are equal to one.

VI. CONCLUSIONS

This paper applies an enhanced Russell Measure (ERM) for measuring the performance of two stage production processes. The proposed model evaluates overall efficiency of DMUs, by taking into account the series relationship between two-stages. This approach enables us to determine the frontier points for the inefficient DMUs within the structure of two-stage DEA. The non-life insurance case depicted in Kao and Hwang [6] is used to compare our approach with their approach. Results show that our approach is equivalent to Kao and Hwang's approach in determining the overall efficiency score of the two-stage process. Unlike the Kao and Hwang's approach the presented model can be applied under both constant and variable returns to scale assumptions. There are manufacturing processes which are composed of more than two sub-processes (e.g., Amado [12]). Therefore our approach can be extended easily to systems of multiple stages connected in series.

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