

# DEA cross efficiency evaluation in presence of linear and nonlinear data

S. Sadeghi Gavvani<sup>\*</sup>, M. Zohrehbandian

**Received:** 19 November 2018 ;

**Accepted:** 5 March 2019

**Abstract** Cross-efficiency is an effective approach for evaluation of DMUs which can be performed with different secondary goals. DEA and cross-efficiency view all variables as behaving in a linear fashion and regardless of the amounts of a variable held by DMUs, DEA apply a same multiplier to those various amounts. But in certain situations, this linearity assumption is not appropriate, and the conventional models need to be altered to accommodate nonlinear representations. This paper proposed a modified cross efficiency structure of Liang et al. that captures certain form of nonlinear behavior. A numerical example is provided to illustrate the approach.

**Keyword:** Data Envelopment Analysis (DEA); Cross Efficiency; Nonlinear Value Function.

## 1 Introduction

Data envelopment analysis (DEA) developed by Charnes et al. [1] is a methodology for measuring the best relative efficiency of a group of decision making units (DMUs) that consume multiple inputs to produce multiple outputs. Since decades, DEA was obtained the dominant role of evaluating, and improving the performance of service operations and it has been extensively applied as a product-oriented analysis method through schools, hospitals, bank branches, production plants and etc., where the main goals are the evaluation; see [2-6]. DEA models were discussed for measuring efficiency score, but it wasn't enough for evaluating the performance of DMUs and as it mentioned in [7] and [8], this is because of the unrestricted weight flexibility problem in DEA. Therefore, for being the discrimination power of DEA more realistic, cross efficiency evaluation has been suggested by Sexton et al. [9], in DEA context. DMUs are mostly evaluated through cross efficiency evaluation considering both self and peer evaluation, whereas the peer evaluation requests each DMU to be evaluated with the weights determined by other DMUs. Finally, the overall efficiency of that DMU is the average of its self-evaluation efficiency and peer evaluation efficiencies and proves to have strong discrimination power and can usually provide a full ranking for the DMUs to be evaluated. That is the reason why efficiency evaluation is found a dominant application in various fields; see [10-18].

---

**Corresponding Author.** (✉)

**E-mail:** Sabasadeghi72@gmail.com Tel: +989144008413 Fax: +984143239696 (S.Sadeghi Gavvani)

**S.Sadeghi Gavvani**

Assistant Professor, Department of Mathematics, Sarab Branch, Islamic Azad University, Sarab, Iran.

**M.Zohrehbandian**

Assistant Professor, Department of Mathematics, Karaj Branch, Islamic Azad University, Karaj, Iran.

However, a problem which reduces the usefulness of cross efficiency evaluation method is that, cross efficiency scores may not be unique because of alternative optimal solutions to the DEA programs and it is due to this reason that some approaches have been suggested as a remedy for the issue of non-uniqueness of weights; See [19-39].

On the other hands, in DEA and cross efficiency formulations, often, the weights assigned to the outputs are considered as prices assigned by the DMU itself to the outputs. Thus the total virtual output of a unit can be considered as an overall value function of the outputs, which is additively separable with linear partial value functions. The interpretations of inputs are similar, too; see [40]. But, due to the fact that this linearity assumption might be unjustifiable, Cook and Zhu [41], Cook et al. [42] and Despotis et al. [40] relaxed the linearity assumption for input/output weights by using a piecewise linear representation of the value function.

In this paper, we propose a modified cross efficiency structure of Liang et al. [22] that captures certain forms of nonlinear behavior. The rest of the paper is organized as follows. In Section 2, we introduce cross efficiency concept and secondary goal formulation of Liang et al. [22]. In Section 3, we define nonlinear inputs/outputs and their conditions. In Section 4, we introduce cross efficiency for nonlinear data and in Section 5, we apply it for sample of maintenance patrol which introduced by Cook et al. [42], [43]. Finally, conclusion and suggestions are depicted in Section 6.

## 2. Cross efficiency evaluation

Consider  $n$  DMUs to be evaluated with  $m$  inputs and  $s$  outputs. Denote by  $x_{ij}$  and  $y_{ij}$  the input/output values of DMU <sub>$j$</sub> , whose self-efficiency can usually be measured by the CCR fractional model (1), where  $\theta_{oo}^*$  is called CCR-efficiency score of DMU <sub>$o$</sub> . DMU <sub>$o$</sub>  is considered to be efficient if and only if it is equal to one. Moreover, this model can be transformed to the LP model (2).

$$\begin{aligned} \text{Max } \theta_{oo} &= \frac{\sum_{r=1}^s u_{r0} y_{r0}}{\sum_{i=1}^m v_{i0} x_{i0}} \\ \text{s.t.} & \end{aligned} \tag{1}$$

$$\begin{aligned} \frac{\sum_{r=1}^s u_{r0} y_{rj}}{\sum_{i=1}^m v_{i0} x_{ij}} &\leq 1 \quad j = 1, \dots, n, \\ u_{r0} &\geq 0 \quad r = 1, \dots, s, v_{i0} \geq 0 \quad i = 1, \dots, m. \end{aligned}$$

$$\begin{aligned} \text{Max } \theta_{oo} &= \sum_{r=1}^s u_{ro} y_{ro} \\ \text{s.t.} & \end{aligned} \tag{2}$$

$$\begin{aligned} \sum_{i=1}^m v_{io} x_{io} &= 1, \\ \sum_{r=1}^s u_{ro} y_{rj} - \sum_{i=1}^m v_{io} x_{ij} &\leq 0 \quad j = 1, \dots, n, \\ v_{io} &\geq 0 \quad i = 1, \dots, m, u_{ro} \geq 0 \quad r = 1, \dots, s. \end{aligned}$$

As it is mentioned, the self-evaluation allows each DMU to be evaluated with its most favorable input/output weights so that  $\theta_{oo}^*$  is referred as the optimistic efficiency can be achieved for each DMU<sub>o</sub>, whereas the peer evaluation requests each DMU to be evaluated with the weights determined by other DMUs. In other words, peer evaluation of DMU<sub>j</sub> using the most favorable weights of DMU<sub>o</sub> is calculated based on the formula (3):

$$\theta_{jo} = \frac{\sum_{r=1}^s u_{ro}^* y_{rj}}{\sum_{i=1}^m v_{io}^* x_{ij}} \quad j=1, \dots, n \quad (3)$$

And finally formula (4) is referred as the cross efficiency score for DMU<sub>j</sub>, which is simply the mean of the self and peer evaluations.

$$E_j = \frac{\sum_{k=1}^n \theta_{jk}}{n} \quad (4)$$

However, optimal weights obtained from model (2) are usually not unique. As a result, the cross efficiency score is arbitrarily generated depending on optimal solution arising from the particular software in use. Hence, this non-uniqueness of input/output weights would damage the use of cross efficiency evaluation.

To resolve this problem, one remedy suggested by sexton et al. [9] and was later investigated by Doyle and Green [44] is to introduce a secondary goal which optimizes the input/output weights while keeping unchanged the CCR efficiency score. They were the first who developed aggressive and benevolent formulations of cross efficiency to deal with the non-uniqueness issue. For example, in the benevolent approach, which is more appropriate from the standpoint of the DEA evaluation framework, an attempt is made to identify the optimal weights that maximize the average cross efficiency of other DMUs while keeping unchanged the CCR efficiency score of a particular DMU under evaluation.

Similar thoughts also appeared in the article of Lim [45], since it seeks the optimal weights that minimize (or maximize) the cross efficiency of the best (or worst) performing DMU by incorporating a minimax or a maximin objective into cross efficiency evaluation. A different idea can be found in Wu et al. [46]. They proposed a weight balanced model to solve the non-uniqueness of the optimal weights in DEA models where each DMU makes its own choice of weights without considering the effects on the other DMUs.

In an effort to extend the model of Doyle and Green [44], Liang et al. [22] presented slightly different secondary objective functions by showing that the CCR model can also be expressed equivalently in the deviation variable form (5),

$$\begin{aligned} & \text{Min} \quad \alpha_o \\ & \text{s.t.} \\ & \sum_{i=1}^m v_{io} x_{io} = 1 \\ & \sum_{r=1}^s u_{ro} y_{rj} - \sum_{i=1}^m v_{io} x_{ij} + \alpha_j = 0 \quad j=1, \dots, n, \\ & \alpha_j \geq 0 \quad j=1, \dots, n, \quad u_{ro} \geq 0 \quad r=1, \dots, s, \quad v_{io} \geq 0 \quad i=1, \dots, m. \end{aligned} \quad (5)$$

Where  $\alpha_o$  is the deviation variable for DMU<sub>o</sub>,  $\alpha_j$  is the deviation variable for DMU<sub>j</sub> ( $j=1, \dots, n$ ), and if DMU<sub>o</sub> is inefficient then its efficiency score is  $1 - \alpha_o^*$ . Hence,

$$\text{DMU}_o \text{ is efficient if and only if } \alpha_o^* = 0 \quad (6)$$

Based on this model, a reasonable secondary objective function is to treat  $\alpha_j$  as goal achievement variable to minimize total deviation from the ideal point. In this manner, for each DMU<sub>o</sub>, Liang et al. [22] derived a multiplier set which with the efficiency score same as to the CCR efficiency score, minimizes the sum of  $\alpha_j$  variables as model (7):

$$\begin{aligned}
 & \text{Min} \quad \sum_{j=1}^n \alpha'_j \\
 & \text{s.t.} \\
 & \sum_{i=1}^m v_{io} x_{io} = 1 \\
 & \sum_{r=1}^s u_{ro} y_{rj} - \sum_{i=1}^m v_{io} x_{ij} + \alpha'_j = 0 \quad j=1, \dots, n, \\
 & \sum_{r=1}^s u_{ro} y_{ro} = 1 - \alpha_o^* \\
 & u_{ro} \geq 0 \quad r=1, \dots, s, v_{io} \geq 0 \quad i=1, \dots, m, \alpha'_j \geq 0 \quad j=1, \dots, n.
 \end{aligned} \tag{7}$$

### 3 Nonlinear inputs and outputs

Cook et al. [42] and Despotis et al. [40] presented a DEA approach for measuring the relative efficiencies of a set of maintenance patrols with nonlinear inputs and outputs. Efficiency evaluation has considerable benefit for highway departments and maintenance units and, from the perspective of top management.

One way of expressing the nonlinear inputs/outputs is to replace the single linear expression by the nonlinear function. A piecewise linear function proposed by Despotis et al. [40], by relaxing the linearity assumption overall value of the input vector  $X_j = (x_{1j}, \dots, x_{mj})$  of unit  $j$ , can be given by the following additive function  $V(X_j) = v_1 x_{1j} + \dots + v_m x_{mj}$  where  $v_1, \dots, v_m$  are assumed nonlinear partial value function. Then, to deal the nonlinear function  $V(X_j)$ , the partial value functions  $v_i, i = 1, \dots, m$  in a piecewise linear fashion suggested as follows:

Let  $[l_i, h_i]$  be the range of input  $i$  over the entire set of DMUs, where

$$l_i = \min_j \{x_{ij}\}, \quad h_i = \max_j \{x_{ij}\} \tag{8}$$

Segmenting the interval  $[l_i, h_i]$  by considering the  $p_i$  break points

$$l_i = L_i^1, \dots, L_i^k, \dots, L_i^{p_i} = h_i \tag{9}$$

Then for each  $x_{ij} > l_i$  there is one interval, such that  $x_{ij} \in (L_i^{k_j}, L_i^{k_j+1}]$  and then

$$x_{ij} = L_i^1 + (L_i^2 - L_i^1) + \dots + (L_i^{k_j} - L_i^{k_j-1}) + (x_{ij} - L_i^{k_j}) \tag{10}$$

$$\alpha_{i1}^j = L_i^1, \alpha_{i2}^j = L_i^2 - L_i^1, \dots, \alpha_{ik_j+1}^j = x_{ij} - L_i^{k_j}, \alpha_{ik_j+2}^j = 0, \dots, \alpha_{ip_i}^j = 0 \tag{11}$$

Without loss of generality, assume that the inputs  $i = 1, \dots, t$  have linear property and nonlinear assumption is applicable only for particular inputs like  $i = t + 1, \dots, m$ . Then we have:

$$V(X_j) = \sum_{i=1}^t x_{ij} v_{io} + \sum_{i=t+1}^m (\alpha_{i1}^j + \alpha_{i2}^j) v_{io}^1 + \sum_{k=3}^{p_i} \alpha_{ik}^j v_{io}^{k-1} \quad (12)$$

Furthermore, we can use this manner for nonlinear outputs where we assume that linear outputs are  $r = 1, \dots, d$  and nonlinear outputs are  $r = d + 1, \dots, s$ .

Based on the above discussion, the CCR model (15) obtained with a nonlinear input matrix (13) and a nonlinear output matrix (14).

$$\hat{X} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & & \\ x_{t1} & \cdots & x_{tn} \\ (\alpha_{t+1,1}^1 + \alpha_{t+1,2}^1) & \cdots & (\alpha_{t+1,1}^n + \alpha_{t+1,2}^n) \\ \vdots & & \\ \alpha_{t+1,p_{t+1}-1}^1 & \cdots & \alpha_{t+1,p_{t+1}-1}^n \\ \vdots & & \\ (\alpha_{m1}^1 + \alpha_{m2}^1) & \cdots & (\alpha_{m1}^n + \alpha_{m2}^n) \\ \vdots & & \\ \alpha_{m,p_m-1}^1 & \cdots & \alpha_{m,p_m-1}^n \end{bmatrix} \quad (13)$$

$$\hat{Y} = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & & \\ y_{d1} & \cdots & y_{dn} \\ (\beta_{d+1,1}^1 + \beta_{d+1,2}^1) & \cdots & (\beta_{d+1,1}^n + \beta_{d+1,2}^n) \\ \vdots & & \\ \beta_{d+1,p_{d+1}-1}^1 & \cdots & \beta_{d+1,p_{d+1}-1}^n \\ \vdots & & \\ (\beta_{s1}^1 + \beta_{s2}^1) & \cdots & (\beta_{s1}^n + \beta_{s2}^n) \\ \vdots & & \\ \beta_{s,p_s-1}^1 & \cdots & \beta_{s,p_s-1}^n \end{bmatrix} \quad (14)$$

$$\text{Max } \hat{u}_o \hat{y}_o$$

s.t.

$$\hat{v}_o \hat{x}_o = 1, \quad (15)$$

$$\hat{u}_o \hat{Y} - \hat{v}_o \hat{X} \leq 0,$$

$$\hat{u}_o \geq 0, \quad \hat{v}_o \geq 0.$$

#### 4. Cross efficiency with linear and nonlinear data

The conventional DEA models are made on the assumption that input/output data are linear. Dispotis et al. [40] addressed the some cases that inputs/outputs must be nonlinear and if the DEA model doesn't have nonlinear supposition, it can't reflect the correct efficiency for

DMUs. Similar is the interpretation of cross efficiency model which doesn't have nonlinear supposition. Then, along the same line of thought, we present an approach that actually accords with that by Liang et al. [22] and Despotis et al. [40], in the sense that we propose a modified cross efficiency structure of Liang et al. [22] that captures certain forms of nonlinear behavior of Despotis et al. [40]. Here and by incorporating secondary goal introduced in model (5) to nonlinear inputs/outputs concept of model (15), we obtain model (16).

$$\begin{aligned}
 & \text{Min } 1\hat{\alpha}' \\
 & \text{s.t.} \\
 & \hat{v}_o \hat{x}_o = 1, \\
 & \hat{u}_o \hat{Y} - \hat{v}_o \hat{X} + I\hat{\alpha}' = 0, \\
 & \hat{u}_o \hat{y}_o = 1 - \alpha_o^*, \\
 & \hat{u}_o \geq 0, \quad \hat{v}_o \geq 0, \quad \hat{\alpha}' \geq 0.
 \end{aligned} \tag{16}$$

$\hat{X}$  and  $\hat{Y}$  obtain from same rule discussed in Section 3. Moreover, for diminishing marginal value concept proposed by Cook et al. [42], the multipliers which are assign nonlinear inputs should form a non-increasing sequence. Then, we impose assurance region restriction of Thomson et al. [47]  $v_{io} \leq \gamma_o$ ,  $\gamma_o < 1$ , and derive following weight restriction for nonlinear inputs.

$$\frac{v_{io+1}}{v_{io}} \leq \gamma_o \Rightarrow v_{io+1} - \gamma_o v_{io} \leq 0 \tag{17}$$

In addition we choose  $\gamma_o$  as follows, where  $D_o$  is the width of subinterval O.

$$\gamma_o < \frac{D_o}{D_{o+1}} \tag{18}$$

We can define weight restriction for nonlinear outputs in the form of a non-decreasing sequence, too. Then, model (19) with weight restriction obtains as a secondary goal to resolve the problem of non-uniqueness of inputs/outputs weights. By solving it, we can derive a multiplier set for cross efficiency evaluation of linear and nonlinear input/output data which with a same efficiency score as later efficiency score, minimizes the sum of deviation variables.

$$\begin{aligned}
 & \text{Min } 1\hat{\alpha}' \\
 & \text{s.t.} \\
 & \hat{v}_o \hat{x}_o = 1, \\
 & \hat{u}_o \hat{Y} - \hat{v}_o \hat{X} + I\hat{\alpha}' = 0, \\
 & \hat{u}_o \hat{y}_o = 1 - \alpha_o^*, \\
 & \hat{v}_o P \leq 0, \quad *
 \end{aligned} \tag{19}$$

$$\hat{u}_o Q \leq 0, \quad **$$

$$\hat{u}_o \geq 0, \quad \hat{v}_o \geq 0, \quad \hat{\alpha}' \geq 0.$$

Where \* and \*\* are weight restriction Constraints. Efficiency scores obtain from inserting optimal solution of model (19) in (3) and (4). Advantage of our method in comparison with the other methods is using nonlinear supposition for inputs/outputs to introduce both peer and self-evaluation in order to compute the efficiency score, which is more realistic than the CCR efficiency score in some situations. Moreover, the new efficiency score provides complete ranking for all DMUs and based on its results, we can select the most efficient DMU, which is an important task in decision sciences.

## 5. Illustrative example

To measure the relative efficiencies of highway maintenance patrols, which introduced by Cook et al. [42], we compute cross efficiency scores for that system which has linear and nonlinear inputs.

**Table 1** Data for highway maintenance patrols

Crew no	Input1(MEX)	Input2(CEX)	Input3(CLF)	Input4(PCR)	Output1(ASF)	Output2(ATS)	Output3(RCF)
1	585	284	715	60	404	267	184
2	610	245	525	65	551	324	175
3	485	425	680	65	506	284	193
4	345	380	660	70	335	255	180
5	288	325	665	75	455	325	190
6	396	322	604	78	565	350	205
7	336	388	712	70	400	235	177
8	367	413	668	60	433	325	202
9	356	325	678	77	457	202	177
10	535	312	677	63	335	256	248
11	599	248	715	68	421	277	194
12	612	275	525	80	554	364	185
13	465	425	690	83	556	294	173
14	325	390	670	68	317	265	190
15	308	305	665	89	485	345	178
16	366	342	604	92	516	369	200
17	346	378	722	83	423	325	197
18	327	433	678	88	413	235	196
19	236	365	688	85	487	302	197
20	545	322	678	74	385	276	238

The outputs are: Size of the system (ASF), Average traffic serviced (ATS) and Accidents (ACC), and the inputs are: Maintenance expenditure (MEX), Capital expenditure (CEX), Climatic factor (CLF) and Pavement condition rating (PCR); See Table 1.

The scale of maintenance and rehabilitation expenditures as inputs greatly depend upon the road condition prevailing at the time work is being done. Then, maintenance and capital expenditures as behaving in a linear fashion, such is likely not true of the PCR. For this

reason we replace this input with piecewise linear function and we assume the PCR in a few subintervals with different values. Moreover, the factor PCR, as an input, should be valued in a diminishing marginal value sense. We assumed the PCR range [0,100] is split into three subintervals [0,60] , [60,80] , [80,100]. Thus,  $L_4^1 = 0$ ,  $L_4^2 = 60$ ,  $L_4^3 = 80$ ,  $L_4^4 = 100$ . First PCR, second PCR and third PCR are shown in three last column of the input matrix (20).

$$\hat{X} = \begin{bmatrix} 585 & 610 & 485 & 345 & 288 & 396 & 336 & 367 & 356 & 535 & 599 & 612 & 465 & 325 & 308 & 366 & 346 & 327 & 236 & 545 \\ 284 & 245 & 425 & 380 & 325 & 322 & 388 & 413 & 325 & 312 & 248 & 275 & 425 & 390 & 305 & 342 & 378 & 433 & 365 & 322 \\ 715 & 525 & 680 & 660 & 665 & 604 & 712 & 668 & 678 & 677 & 715 & 525 & 690 & 670 & 665 & 604 & 722 & 678 & 688 & 678 \\ 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 & 60 \\ 0 & 5 & 5 & 10 & 15 & 18 & 10 & 0 & 17 & 3 & 8 & 20 & 20 & 8 & 20 & 20 & 20 & 20 & 20 & 14 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 9 & 12 & 3 & 8 & 5 & 0 \end{bmatrix} \quad (20)$$

**Table 2** Efficiency scores and ranking

Crew no	CCR efficiency	Cross efficiency	Rank
1	0.9313	0.871	12
2	1	0.911	3
3	1	0.915	2
4	0.87	0.838	18
5	1	0.901	8
6	1	0.905	6
7	0.8693	0.881	11
8	1	0.909	4
9	0.8801	0.858	14
10	1	0.896	9
11	1	0.849	16
12	1	0.903	7
13	0.9841	0.791	19
14	0.944	0.843	17
15	1	0.777	20
16	1	0.923	1
17	0.9655	0.907	5
18	0.9291	0.852	15
19	1	0.862	13
20	0.9979	0.891	10

For example,  $PCR = 88$  for  $DMU_{18}$  in Table 1. Then,  $PCR_1 = 60$  in  $[0, 60]$ ,  $PCR_2 = 20$  in  $[60, 80]$  and  $PCR_3 = 8$  in  $[80, 100]$ , and we have the subinterval widths as  $D_1 = 60, D_2 = 20, D_3 = 20$ . For each subinterval different values or weights are attached and

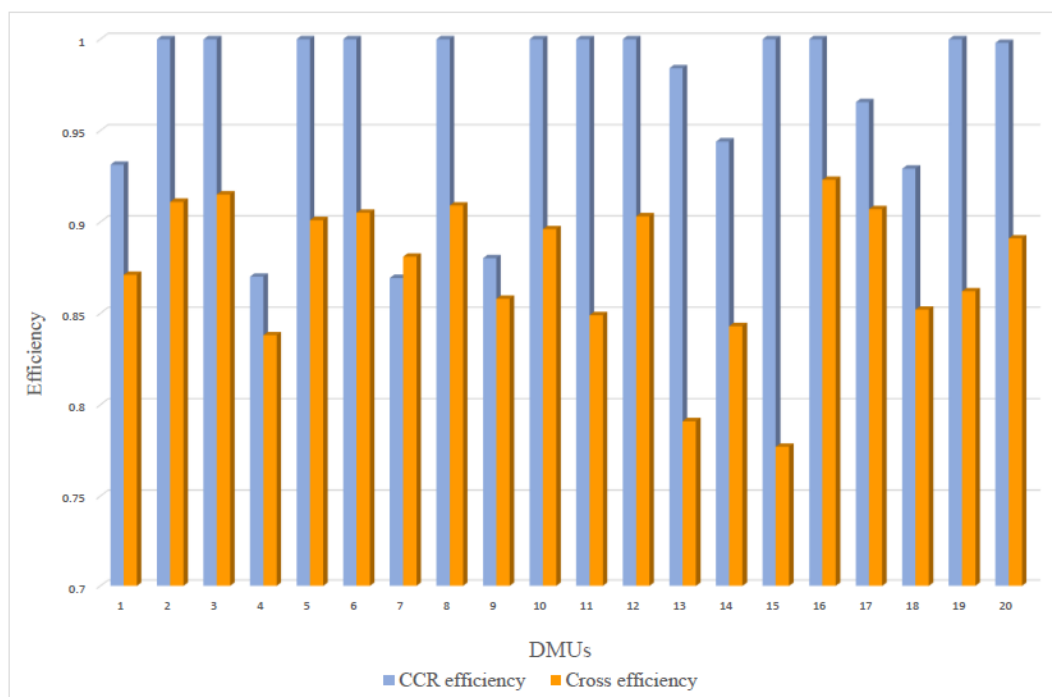
$$\frac{v_{ik+1}}{v_{ik}} \leq \gamma_k, \gamma_1 = 0.75, \gamma_2 = 0.5$$

Table 2 and Figure 1 show the efficiency scores from model (16) and cross efficiency scores from model (19). Moreover, rank values of DMUs by cross efficiency scores are given in the third column of Table 2.

As shown in Figure 1, most of DMUs are efficient with Despotis et al.’s model [40] (blue bar). For this reason, that model is not suitable for ranking. Then, we introduced model (19)



as a secondary goal of cross efficiency evaluation (orange bar). Various scores obtained for nonlinear data using the new model and it seems that new scores are better than previous one. Note that, for example  $DMU_{17}$  is CCR inefficient, but it has cross efficiency score better than some CCR efficient DMUs. Moreover,  $DMU_{16}$  is the most efficient unit. Indeed, the purpose of Despotis et al.'s model [40] is only computing the efficiency scores, but our model is an extension of their model.



**Fig. 1** Efficiency scores

## 6. Conclusion

Cross efficiency evaluation has been considered to be a powerful extension of DEA, and it can be used for various purposes, e.g. ranking efficient units. The DEA and cross efficiency models traditionally rely on the linearity assumption for the virtual inputs and outputs (i.e. the weights coupled with the ratio scales of the inputs and outputs imply linear value functions). In this paper, we present a general modeling approach for dealing with nonlinear virtual inputs/outputs in cross efficiency concept, which traditional models generally lack this feature. This investigation is an extension of the model introduced by Despotis et al. [40] for nonlinear inputs/outputs, to the cross efficiency method proposed by Liang et al. [22].

## References

1. Charnes A., Cooper W.W., Rhodes E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2, 429-444.
2. Banker R. (1984). Estimating most productive scale size using data envelopment analysis. *European Journal of Operational Research*, 17, 35-44.

3. Miliotis P.A. (1992). Data envelopment analysis applied to electricity distribution districts. *Journal of Operational Research Society*, 43, 549-555.
4. Carrico C.S., Hogan S.M., Dyson R.G., Athanassopoulos A. (1997). Data envelopment analysis and university selection. *Journal of Operational Research Society*, 48, 1163-1177.
5. Ali A., Nakosteen R. (2005). Ranking industry performance in the US. *Socio Economics Planning Science*, 39, 11-24.
6. Lozano S., Villa G., Canca D. (2011). Application of centralized DEA approach to capital budgeting in Spanish ports. *Computers & Industrial Engineering*, 60(3), 455-465.
7. Dyson R.G., Thannassoulis E. (1988). Reducing weight flexibility in data envelopment analysis. *Journal of Operational Research Society*, 39, 563-576.
8. Wong Y.H.B., Beasley J.E. (1990). Restricting weight flexibility in data envelopment analysis. *Journal of Operational Research Society*, 41(9), 829-835.
9. Sexton T.R. Silkman R.H., Hogan A.J. (1986) Data envelopment analysis: Critique and extensions. In R.H. Silkman (Ed.) *Measuring efficiency: An assessment of data envelopment analysis* (Vol. 32, pp. 73-105). San Francisco: Jossey-Bass.
10. Doyle J., Green R., Cook W.D. (1996). Preference voting and project ranking using DEA and cross-evolution. *European Journal of Operational Research*, 90, 461-472.
11. Banker R., Talluri S. (1997). A closer look at the use of data envelopment analysis for technology selection. *Computers & Industrial Engineering*, 32(1), 101-108.
12. Chen T.Y. (2002). An assessment of technical efficiency and cross efficiency in Taiwan's electricity distribution sector. *European Journal of Operational Research*, 137, 421-433.
13. Sun S. (2002). Assessing computer numerical control machines using data envelopment analysis. *International Journal of Production Research*, 40, 2011-2039.
14. Wu J. Liang L., Wu D., Yang F. (2008). Olympics ranking and benchmarking based on cross efficiency evaluation method and cluster analysis: The case of Sydney 2000. *International Journal of Enterprise Network Management*, 2, 377-392.
15. Wu J., Liang L, Chen Y. (2009a). DEA game cross-efficiency approach to Olympic rankings. *Omega*, 37, 909-918.
16. Wu J., Liang L, Yang F. (2009b). Achievement and benchmarking of countries at the Summer Olympics using cross-efficiency evaluation method. *European Journal of Operational Research*, 197, 722-730.
17. Wang Y.M., Luo Y., Xu Y.S. (2013). Cross-weight evaluation for pairwise comparison matrices. *Group Decision and Negotiation*, 22(3), 483-497.
18. Sadeghi Gavgani S., Zohrehbandian M., Sadeghi N. (2017). Selecting dispatching rule in manufacturing systems via DEA cross efficiency, 9(2),168-178.
19. Anderson T.R., Hollingsworth K.B., Inman L.B. (2002). The fixed weighting nature of a cross-evaluation model. *Journal of Productivity Analysis*, 18, 249-255.
20. Sun S., Lu W.M. (2005). A cross-efficiency profiling for increasing discrimination in Data Envelopment Analysis. *INFOR*, 43, 51-60.
21. Bao C.P., Chen T.H., Chang S.Y. (2008). Slack based ranking method: An interpretation to the cross efficiency method in DEA. *Journal of the Operational Research Society*, 59, 860-862.
22. Liang L., Wu J., Cook W.D., Zhu J. (2008a). Alternative secondary goal in DEA cross efficiency evaluation. *International Journal of Production Economics*, 113, 1025-1030.
23. Liang L., Wu J., Cook W.D., Zhu J. (2008b). The DEA game cross-efficiency model and its Nash equilibrium. *Operations Research*, 56, 1278-1288.
24. Wu J., Liang L, Yang F. (2009c). Determination of the weights for the ultimate cross efficiency using shapely value in cooperative game. *Expert Systems with Applications*, 36, 872-876.
25. Wu J., Liang L., Zha Y., Yang F. (2009d). Determination of cross efficiency under the principle of rank priority in cross evaluation. *Expert Systems with Applications*, 36, 4826-4829.
26. Lam K.F. (2010). In the determination of weight sets to compute cross-efficiency ratios in DEA. *Journal of the Operational Research Society*, 61, 134-143.
27. Jahanshahloo G.R., Hosseinzadeh Lotfi F., Jafari Y., Maddahi R. (2011). Selecting symmetric weights as secondary goal in DEA cross efficiency evaluation. *Applied Mathematical Modeling*, 35, 544-549.
28. Ramon N, Ruiz J.L., Sirvent I. (2010). On the choice of weights profiles in cross-efficiency evaluations. *European Journal of Operational Research*, 207, 1564-1572
29. Ramon N, Ruiz J.L., Sirvent I. (2011). Reducing differences between profiles of weights: A 'peer-restricted' cross-efficiency evaluation. *Omega* 39, 634-641.
30. Wang Y., Chin K.S. (2010). A neutral DEA model for cross efficiency evaluation and its extension. *Expert System with Applications*, 37, 3666-3675.

31. Wang Y., Chin K.S. (2011a). The use of OWA operator weights for cross-efficiency aggregation. *Omega* 39, 493–503.
32. Wang Y., Chin K.S., Jiang P. (2011b). Weight determination in the cross efficiency evaluation. *Computers & Industrial Engineering*, 61(3), 497-502.
33. Wang Y., Chin K.S., Lou Y. (2011c). Cross efficiency evaluation based on ideal and anti-ideal decision making units. *Expert System with Applications*, 38, 10312-10319.
34. Orkcu H.H., Bal H. (2011). Goal programming approaches for data envelopment analysis cross efficiency evaluation. *Applied Mathematics and Computation*, 218, 346-356.
35. Ruiz J.L., Sirvent I. (2012). On the DEA total weight flexibility and the aggregation in cross-efficiency evaluations. *European Journal of Operational Research*, 223, 732–738.
36. Yang F., Ang S., Xia Q., Yang C. (2012). Ranking DMUs by using interval DEA cross efficiency matrix with acceptability analysis. *European Journal of Operational Research*, 223, 483–488.
37. Sadeghi Gavgani S., Zohrehbandian M.(2014). A Cross-Efficiency Based Ranking Method for Finding the Most Efficient DMU, *Mathematical Problems in Engineering*, 2014, 6 pages.
38. Sadeghi Gavgani S., Zohrehbandian M.(2017) A New Goal Programming Approach for Cross Efficiency Evaluation. *International Journal of Applied Operational Research*, 7, 87-94.
39. Hou Q., Wang M., Zhou X. (2018). Improved DEA Cross Efficiency Evaluation Method Based on Ideal and Anti-Ideal Points. *Discrete Dynamics in Nature and Society*, 2018, 6 pages.
40. Despotis D.K., Stamati L.V., Smirlis Y.G. (2009). Data envelopment analysis with nonlinear virtual inputs and outputs. *European Journal of Operational Research*, 202, 604-613.
41. Cook W.D., Zhu J. (2009). Piecewise linear output measures in DEA. *European Journal of Operational Research*, 197, 312-319.
42. Cook W.D., Yang F., Zhu J. (2009). Nonlinear inputs and diminishing marginal value in DEA. *Journal of Operational Research Society*, 60, 1567-1574.
43. Cook W.D., Roll Y., Kazakov A. (1990) "A DEA model for measuring the relative efficiency of highway maintenance patrols," *INFOR*, 28, 113-124.
44. Doyle J.R., Green R. (1994). Efficiency and cross-efficiency in data envelopment analysis: Derivatives meaning and uses. *Journal of the Operational Research Society*, 45(5), 567-578.
45. Lim S. (2012). Minimax and maximin formulations of cross-efficiency in DEA. *Computers & Industrial Engineering* 62, 726–731.
46. Wu J., Sun J., Liang L. (2012). Crosse efficiency evaluation method based on weight-balanced data envelopment analysis model. *Computers & Industrial Engineering*, 63,513–519.
47. Thompson R., Langemeier L., Lee C., Lee L., Thrall R. (1990). The role of multiplier bounds in efficiency analysis with application to Kansas farming. *Journal of Econometrics*, 46, 93-108.