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# Allocation models for DMUs with negative data

Ghasem Tohidi<sup>†</sup> and Maryam Khodadadi<sup>\*†</sup>

## Abstract

The formulas of cost and allocative efficiencies of decision making units (DMUs) with positive data cannot be used for DMUs with negative data. On the other hand, these formulas are needed to analyze the productivity and performance of DMUs with negative data. To this end, this study introduces the cost and allocative efficiencies of DMUs with negative data and demonstrates that the introduced cost efficiency is equal to the product of allocative and range directional measure efficiencies. The study then intends to extend the definition of the above efficiencies to DMUs with negative data and different unit costs. Finally, two numerical examples are given to illustrate the proposed methods.

**JEL classification:** C6, D2

**Keywords:** DEA, Cost efficiency, Negative data, Allocative efficiency, RDM

## Introduction

Data envelopment analysis (DEA) is a nonparametric method for computing and assessing the relative efficiency of homogeneous decision making units (DMUs) with multiple inputs and outputs. The traditional DEA models assume that all of the inputs and outputs are nonnegative, while in many situations and applications, the negative values in data might exist, which is a weakness of the traditional DEA models. To overcome the shortcoming, in recent years, different DEA models have been proposed in the literature about DMUs with negative data.

Portela et al. (2004) provided the range directional measure (RDM) approach to measure the efficiency of DMUs with negative data based on a directional distance function without the need to transform the data. The efficiency measurement of DMUs with negative data is also much debated. For example, in order to overcome the shortcomings of the slack-based measure model (Tone 2001) in dealing with negative inputs and outputs, Sharp et al. (2006) presented the modified slack-based measure model. Emrouznejad et al. (2010) proposed the semi-oriented radial measure model for dealing with negative inputs and outputs. Also, recently, a two-phase approach

model has been proposed by Kazemi Matin and Azizi (2011) based on a modified version of the additive model to achieve a target with nonnegative components for each DMU with negative inputs and outputs.

One of the most significant types of efficiency is cost efficiency. This type of efficiency is used to identify the different kinds of inefficiencies when information on costs is available. DMUs can achieve the best cost efficiency score with a combination of inputs which allow them to produce the desired outputs at minimum costs.

In many DEA literatures, the economic concepts of cost efficiency have been considered. The primary discussion of cost efficiency can be traced back to Farrell (1957) and Debreu (1951), from whom many of the ideas about DEA are derived. Farrell offered a measure of cost efficiency under fixed and known prices. His method extended to situations with different prices of inputs for DMUs (Tone 2002).

So far, all of the previous studies have explored cost efficiency of DMUs with nonnegative data, and there is no discussion concerning cost efficiency in the presence of negative data. However, in some cases, the inputs of DMUs have negative values with positive costs. This paper defines the cost and allocative efficiencies for DMUs with negative data, then demonstrates that the

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defined cost efficiency with negative data is equal to the product of allocative and RDM efficiencies, and then extends the definition of efficiencies to DMUs with negative data and different unit costs.

The rest of this paper is organized as follows: the Section 'Background models' explains the RDM efficiency and cost efficiency models. 'Cost efficiency in the presence of negative data' briefly introduces cost efficiency under common and different prices in the presence of negative data. The Section 'Illustrative examples' provides two numerical examples, and in the last section, the conclusion is given.

### Background models

In productive activities, we assume that there are  $n$  homogeneous DMUs. Each DMU produces  $s$  different outputs from  $m$  different inputs. Input and output vectors for the DMU which is under evaluation are denoted by  $x_o$  and  $y_o$ , and for DMU <sub>$j$</sub>  are denoted by  $x_j$  and  $y_j$ . The next section explains the RDM and cost efficiency models.

### RDM

The RDM model, introduced by Portela et al. (2004), can be used for comparing DMUs when some inputs and/or outputs are negative. Consider a point with maximum outputs and minimum inputs as an ideal point (i.e., the  $i$ th ( $i = 1, \dots, m$ ) input  $x_{iI}$  as  $\min_j \{x_{ij}\}$  and the  $r$ th ( $r = 1, \dots, s$ ) output  $y_{rI}$  as  $\max_j \{y_{rj}\}$ ). In RDM, a directional vector is considered as  $R_{ro}^+ = \max_j \{y_{rj}\} - y_{ro}; r = 1, \dots, s$  and  $R_{io}^- = x_{io} - \max_j \{x_{ij}\}; i = 1, \dots, m$ . The RDM model for DMU <sub>$o$</sub>  is as follows (Portela et al. 2004):

$$\begin{aligned} & \max \beta \\ \text{s.t. } & \sum_{j=1}^n \lambda_j x_{ij} \leq x_{io} - \beta R_{io}^-, \quad i = 1, \dots, m \\ & \sum_{j=1}^n \lambda_j y_{rj} \geq y_{ro} + \beta R_{ro}^+, \quad r = 1, \dots, s \\ & \sum_{j=1}^n \lambda_j = 1, \quad \lambda_j \geq 0, \quad j = 1, \dots, n. \end{aligned} \quad (1)$$

The optimal value of model (1),  $\beta^*$ , represents the inefficiency measurement for DMU <sub>$o$</sub> , while  $1 - \beta^*$  represents the efficiency measurement for DMU <sub>$o$</sub> . Unit invariance and translation invariance are the two important properties of the RDM model.

### Cost efficiency

For measuring the cost efficiency of the DMUs with multiple inputs and outputs under common unit

input prices, the following linear program is solved (Farrell 1957):

$$\begin{aligned} cx^* &= \min \sum_{i=1}^m c_i x_i \\ \text{s.t. } & \sum_{j=1}^n \lambda_j x_{ij} \leq x_i, \quad i = 1, \dots, m \\ & \sum_{j=1}^n \lambda_j y_{rj} \geq y_{ro}, \quad r = 1, \dots, s \\ & \sum_{j=1}^n \lambda_j = 1, \quad \lambda_j \geq 0, \quad j = 1, \dots, n. \end{aligned} \quad (2)$$

The cost efficiency is obtained as the following ratio:

$$CE = \frac{cx^*}{cx_o}, \quad (3)$$

where the nominator represents the minimum cost (i.e., the optimal value of model (2)) and the denominator shows the current cost at DMU <sub>$o$</sub> .

### Cost efficiency in the presence of negative data

In this section, we define cost and allocative efficiencies in the presence of negative data under common and different prices, and then it is shown that cost efficiency is the product of allocative and RDM efficiencies. Finally, the above subjects are extended to new cost, allocative, and RDM efficiencies.

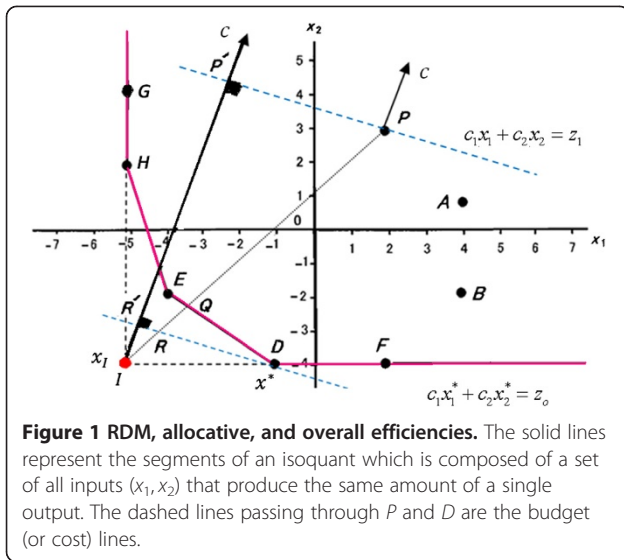
### Cost and allocative efficiencies with negative data under common unit prices

**Definition 1** Under common unit input prices, we define cost (overall) efficiency in the presence of negative data as follows:

$$CE = \frac{cx^* - cx_I}{cx_o - cx_I}. \quad (4)$$

In the above mentioned ratio, the nominator represents the difference between  $cx^*$  (the optimal value of model (2)) and the cost of the ideal point, i.e.,  $cx_I$ . In addition, the denominator depicts the difference between the observed cost of DMU <sub>$o$</sub> , i.e.,  $cx_o$  and  $cx_I$ . It is clear that the value of CE is equal to or less than 1. Cost efficiency might be less than 1 for one of the following two reasons: excessive input usage in production or production with a wrong input mix in light of input prices or both. In a particular case, when the ideal point is one of the observed DMUs, we define  $CE = 1$ .

Figure 1 illustrates the concepts dealing with allocative efficiency, RDM efficiency, and cost efficiency, using the units  $A, B, D, E, F, H, G$ , and  $P$  in the presence of



**Figure 1** RDM, allocative, and overall efficiencies. The solid lines represent the segments of an isoquant which is composed of a set of all inputs  $(x_1, x_2)$  that produce the same amount of a single output. The dashed lines passing through  $P$  and  $D$  are the budget (or cost) lines.

negative data. In Figure 1, the RDM inefficiency of  $DMU_P$  can be evaluated by

$$\beta = \frac{d(Q, P)}{d(I, P)}. \quad (5)$$

Hence,

$$1 - \beta = \frac{d(I, P) - d(Q, P)}{d(I, P)} = \frac{d(I, Q)}{d(I, P)} \quad (6)$$

Equation 6 represents the RDM efficiency of  $DMU_D$ , which is between 0 and 1.  $d(I, P)$  and  $d(I, Q)$  denote the distance from the ideal point  $I$  to  $P$  and the distance from the ideal point  $I$  to  $Q$ , respectively, and  $d(Q, P)$  is the distance from  $Q$  to  $P$ .

In order to illustrate allocative efficiency in Figure 1, we consider the budget (cost) line  $c_1x_1 + c_2x_2 = z_1$  passing through the point  $P$ . We move this cost line in parallel form until it crosses the isoquant at  $D$ .

By moving the budget line in parallel form, cost can be reduced. The lowest cost is associated with the budget (cost) line  $c_1x_1^* + c_2x_2^* = z_0$ , where  $z_0 < z_1$  and  $z_0$  can be obtained by substituting the coordinates of  $DMU_D$  in the budget (cost) line  $c_1x_1 + c_2x_2 = z_1$ . The best point  $D$  is achieved as the optimal solution  $x^*$  of the linear program (2) (Farrell 1957).

Now, we define  $\frac{d(I, R)}{d(I, Q)}$  as a measure of allocative efficiency, where  $d(I, R)$  and  $d(I, Q)$  denote the distance from the ideal point  $I$  to  $R$  and the distance from the ideal point  $I$  to  $Q$ , respectively. It shows that the minimum cost is not reached since we have failed to make the replacements which are involved in moving from point  $Q$  to  $D$  along the efficiency frontier.

According to Definition 1, we have

$$CE = \frac{cx^* - cx_I}{cx_o - cx_I}$$

$$CE = \frac{cx^* - cx_I}{cx_o - cx_I} = \frac{|c||x^* - x_I| \cos \theta}{|c||x_o - x_I| \cos \phi} = \frac{|x^* - x_I| \cos \theta}{|x_o - x_I| \cos \phi} \quad (7)$$

where  $|\cdot|$  in Equation 7 represents the norm function of a vector, and  $\theta$  and  $\phi$  are the angles between the vector  $c$  and vectors  $(x^* - x_I)$  and  $(x_o - x_I)$ , respectively. The numerator in Equation 7 represents the projection of vector  $(x^* - x_I)$  on vector  $c$  which is equal to  $d(I, R')$ , and the denominator in Equation 7 demonstrates the projection of vector  $(x_o - x_I)$  on vector  $c$  which is equal to  $d(I, P')$ . We can represent the defined cost efficiency in the presence of negative data by means of the following ratio:

$$CE = \frac{d(I, R')}{d(I, P')} \quad (8)$$

where  $d(I, R')$  and  $d(I, P')$  denote the distance from the ideal point  $I$  to  $R'$  and  $P'$ , respectively. According to Thales theorem, we have:

$$CE = \frac{d(I, R')}{d(I, P')} = \frac{d(I, R)}{d(I, P)}. \quad (9)$$

Therefore, the three above mentioned efficiencies in the presence of negative data have the following relationship:

$$\frac{d(I, R)}{d(I, Q)} \times \frac{d(I, Q)}{d(I, P)} = \frac{d(I, R)}{d(I, P)}. \quad (10)$$

That is, the product of allocative and RDM efficiencies is equal to cost efficiency.

#### Cost efficiency with negative data under different prices

In some situations, the unit prices of input are not the same among DMUs. Therefore, the above definitions of cost and allocative efficiencies have shortcomings, and they are not applicable to these cases (Farrell 1957). In this case, we define new cost and allocative efficiencies, which are extensions of the prior definitions and are applicable to situations in which the input prices are not the same among DMUs.

In order to discuss cost efficiency in the presence of different unit input costs, we consider the cost-based production possibility set,  $P_C$ , as follows (Tone 2002):

$$P_C = \left\{ \begin{aligned} &(\bar{x}, y) \mid \bar{x} \geq \sum_{j=1}^n \lambda_j \bar{x}_j, \\ &y \leq \sum_{j=1}^n \lambda_j y_j, \sum_{j=1}^n \lambda_j = 1, \lambda_j \geq 0, j = 1, \dots, n \end{aligned} \right\} \quad (11)$$

where  $\bar{x}_j = (\bar{x}_{1j}, \dots, \bar{x}_{mj})^T = (c_{1j}x_{1j}, \dots, c_{mj}x_{mj})^T$ , in which  $c_j = (c_{1j}, \dots, c_{mj})^T$  is the positive cost vector of DMU<sub>j</sub>.

**Definition 2** The ideal point, by using the new production possibility set, is a point with maximum outputs and minimum inputs, i.e.,  $\bar{x}_I = (\bar{x}_{1I}, \dots, \bar{x}_{mI})^T$  where  $\bar{x}_{iI} = \min_j \bar{x}_{ij}$ ,  $i = 1, \dots, m$ , and  $y_I = (y_{1I}, \dots, y_{sI})^T$  where  $y_{rI} = \max_j y_{rj}$ ,  $r = 1, \dots, s$ . In the new production possibility set,  $P_C$ , the new RDM inefficiency,  $\bar{\beta}^*$ , is obtained by solving the following linear program:

$$\begin{aligned} \text{[NRDM]} \quad &\bar{\beta}^* = \max \bar{\beta} \\ \text{s.t.} \quad &\sum_{j=1}^n \lambda_j \bar{x}_{ij} \leq \bar{x}_{i0} - \bar{\beta} \bar{R}_{i0}^-, \quad i = 1, \dots, m \\ &\sum_{j=1}^n \lambda_j y_{rj} \geq y_{r0} + \bar{\beta} R_{r0}^+, \quad r = 1, \dots, s \\ &\sum_{j=1}^n \lambda_j = 1, \quad \lambda_j \geq 0, \quad j = 1, \dots, n, \end{aligned} \quad (12)$$

where  $\bar{R}_{i0}^- = \bar{x}_{i0} - \min_j \{\bar{x}_{ij}\}$ ;  $i = 1, \dots, m$  and  $R_{r0}^+ = \max_j \{y_{rj}\} - y_{r0}$ ;  $r = 1, \dots, s$ . To interpret  $\bar{\beta}^*$  (the optimal value of model (12)) and  $1 - \bar{\beta}^*$ , it can be said that  $\bar{\beta}^*$  demonstrates the new RDM inefficiency, and  $1 - \bar{\beta}^*$  demonstrates the new RDM efficiency of DMU<sub>0</sub>.

**Definition 3** The new cost efficiency in the presence of negative data under different unit prices is defined as follows:

$$\bar{CE} = \frac{e\bar{x}^* - e\bar{x}_I}{e\bar{x}_0 - e\bar{x}_I} \quad (13)$$

where  $e$  is a vector in  $R_m$  with each component equal to 1, and  $\bar{x}^*$  is an optimal solution of the following model (Tone 2002):

$$\begin{aligned} \text{[NCost]} \quad &e\bar{x}^* = \min e\bar{x} \\ \text{s.t.} \quad &\sum_{j=1}^n \lambda_j \bar{x}_j \leq \bar{x} \\ &\sum_{j=1}^n \lambda_j y_j \geq y_0 \\ &\sum_{j=1}^n \lambda_j = 1, \\ &\lambda_j \geq 0, \quad j = 1, \dots, n. \end{aligned} \quad (14)$$

It is obvious that  $0 \leq \bar{CE} \leq 1$ . The following theorem states a relationship between new RDM efficiency and new cost efficiency scores.

**Theorem 1**  $\bar{CE} \leq 1 - \bar{\beta}^*$ .

*Proof* Let  $(\bar{\beta}^*, \lambda^*)$  be an optimal solution of model (12); then  $(\bar{x}_0 - \bar{\beta}^* \bar{R}_0^-, \lambda^*)$  is a feasible solution for model (14). This shows that  $e\bar{x}^* \leq e\bar{x}_0 - e\bar{\beta}^* \bar{R}_0^-$ . Using Equation 13 we have:

$$\begin{aligned} \bar{CE} &= \frac{e\bar{x}^* - e\bar{x}_I}{e\bar{x}_0 - e\bar{x}_I} \leq \frac{e\bar{x}_0 - e\bar{\beta}^* \bar{R}_0^- - e\bar{x}_I}{e\bar{x}_0 - e\bar{x}_I} \leq \frac{e\bar{x}_0 - e\bar{\beta}^* (\bar{x}_0 - \bar{x}_I) - e\bar{x}_I}{e\bar{x}_0 - e\bar{x}_I} \\ &= \frac{e\bar{x}_0 (1 - \bar{\beta}^*) - e\bar{x}_I (1 - \bar{\beta}^*)}{e\bar{x}_0 - e\bar{x}_I} = (1 - \bar{\beta}^*). \end{aligned} \quad (15)$$

This fact completes the proof.

**Definition 4** The new allocative efficiency under the different unit prices in the presence of negative data is defined as follows:

$$\bar{AE} = \frac{\bar{CE}}{1 - \bar{\beta}^*}. \quad (16)$$

It is obvious that  $0 \leq \bar{AE} \leq 1$ .

### Illustrative examples

In this section, two numerical examples are used to illustrate the concepts of what was mentioned earlier.

**Table 1 The inputs, outputs, and costs for eight DMUs**

DMUs	$x_1$	$c_1$	$x_2$	$c_2$	$y$
A	4	1	1	2	1
B	4	1	-2	2	1
D	-1	1	-4	2	1
E	-4	1	-2	2	1
F	2	1	-4	2	1
G	-5	1	4	2	1
H	-5	1	2	2	1
P	2	1	3	2	1

**Table 2 RDM, cost, and allocative efficiencies**

DMUs	$\beta^*$	$1 - \beta^*$	$c\bar{x}^*$	$c\bar{x}_o$	$c\bar{x}_l$	CE	AL
A	0.76	0.24	-9	6	-13	0.21	0.87
B	0.67	0.33	-9	0	-13	0.30	0.90
D	0	1	-9	-9	-13	1	1
E	0	1	-9	-8	-13	0.8	0.8
F	0.43	0.57	-9	-6	-13	0.57	1
G	0.25	0.75	-9	3	-13	0.25	0.33
H	0	1	-9	-1	-13	0.33	0.33
P	0.77	0.23	-9	8	-13	0.19	0.82

*Example 1* In Table 1, we have eight DMUs with two inputs and one output. Figure 1 depicts the production possibility set composed of these input and output data. The values of  $x_1$  and  $x_2$  and their relative unit costs are exhibited in the columns of Table 1.

Table 2 reports the obtained results for the data of Table 1. To compare the results of Table 2 with Equations 5, 6, 9, and 10 as an example, we select DMU<sub>P</sub>. As it can be seen in Figure 1, the coordinates of Q are  $(-\frac{17}{5}, -\frac{12}{5})$ , which are obtained from the intersection of the line passing through E and D and the line passing through I and P.

The RDM efficiency for P is obtained as follows:

$$1 - \beta^* = \frac{d(I, Q)}{d(I, P)} = \frac{\sqrt{(-5 + \frac{17}{5})^2 + (-4 + \frac{12}{5})^2}}{\sqrt{(-5 - 2)^2 + (-4 - 3)^2}} = \frac{8}{35} \approx 0.23$$

where  $(-5, -4)$  are the coordinates of the ideal point. The coordinates of R are  $(-\frac{11}{3}, -\frac{8}{3})$ , which were achieved from the intersection of the line passing through D and R' and the line passing through I and P. Hence, the cost and the allocative efficiencies of DMU<sub>P</sub> are obtained as follows:

**Table 3 Data for eight DMUs**

DMUs	$x_1$	$c_1$	$x_2$	$c_2$	y
A	4	3	1	2	1
B	4	1	-2	2	1
D	-1	2	-4	2	1
E	-4	1	-2	3	1
F	2	3	-4	1	1
G	-5	4	4	5	1
H	-5	3	2	4	1
P	2	3	3	2	1

**Table 4 New data set**

DMUs	$\bar{x}_1$	$\bar{x}_2$	y
A	12	2	1
B	4	-4	1
D	-2	-8	1
E	-4	-6	1
F	6	-4	1
G	-20	20	1
H	-15	8	1
P	6	6	1
Ideal	-20	-8	1

$$CE = \frac{d(I, R)}{d(I, P)} = \frac{\sqrt{(-5 + \frac{11}{3})^2 + (-4 + \frac{8}{3})^2}}{\sqrt{(-5 - 2)^2 + (-4 - 3)^2}} = \frac{4}{21} \approx 0.19$$

$$AL = \frac{d(I, R)}{d(I, Q)} = \frac{\sqrt{(-5 + \frac{11}{3})^2 + (-4 + \frac{8}{3})^2}}{\sqrt{(-5 + \frac{17}{5})^2 + (-4 + \frac{12}{5})^2}} = \frac{5}{6} \approx 0.82.$$

Hence,

$$\frac{d(I, R)}{d(I, Q)} \times \frac{d(I, Q)}{d(I, P)} = \frac{d(I, R)}{d(I, P)}.$$

The above results are the same as the results which are exhibited in Table 2.

*Example 2* Table 3 represents the data set of Table 1 under the different unit costs. The coordinates of inputs and output in the PPS  $P_C$  and the ideal point are represented in Table 4. These data were obtained by multiplying the relevant unit costs of  $x_1$  and  $x_2$  by the values of  $x_1$  and  $x_2$ .

Table 5 shows the new RDM inefficiency, new RDM, cost, and allocative efficiencies under the different unit prices in the presence of the negative data of Table 4. The results of Table 5 indicate that the DMUs D and E have

**Table 5 New RDM, new cost, and new allocative efficiencies**

DMU	$\beta^*$	$1 - \beta^*$	$e\bar{x}^*$	$e\bar{x}_o$	$e\bar{x}_l$	$\bar{C}E$	$\bar{A}L$
A	0.56	0.44	-10	14	-13	0.11	0.25
B	0.35	0.65	-10	0	-13	0.23	0.35
D	0	1	-10	-10	-13	1	1
E	0	1	-10	-10	-13	1	1
F	0.45	0.55	-10	2	-13	0.2	0.36
G	0	1	-10	0	-13	0.23	0.23
H	0	1	-10	-7	-13	0.5	0.5
P	0.53	0.47	-10	12	-13	0.12	0.25

the best performance. The DMUs  $G$  and  $H$  are new RDM efficient, in spite of the fact that these DMUs fell short in their new cost and new allocative efficiency scores.

## Conclusions

This paper introduced cost and allocative efficiencies under common and different unit prices in the presence of negative data. It was shown that under common and different unit prices, the defined cost efficiency is the product of allocative efficiency and RDM efficiency. Finally, to illustrate the mentioned concepts, two numerical examples were used.

## Competing interests

Both authors declare that they have no competing interests.

## Authors' contributions

GT proposed the definition of cost efficiency of DMUs in the presence of negative data. Then MKH and GT extended this definition to DMUs with negative data and different unit costs and then demonstrated that the introduced cost efficiency is equal to the product of allocative and range directional measure efficiencies. Both authors read and approved the final manuscript.

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GT is currently an assistant professor in the Department of Mathematics of Islamic Azad University, Central Tehran Branch. His research interests include data envelopment analysis (DEA) and fuzzy and multi objective programming (MOP). He has published many articles in a number of peer-reviewed academic journals and conferences. MKH is a doctoral student in applied mathematics (operational research) at Islamic Azad University, Central Tehran Branch in Iran. She holds a M.Sc. and B.Sc. in Applied Mathematics from Kharazmi University and Urmia University in Iran. Her research interests include applied mathematics, operation research, and data envelopment analysis.

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