Hybrid cross-efficiency approach based on Ideal and Anti-Ideal points and the CRITIC method for ranking decision-making units: A case study on ranking the methods of rice weevil disinfestation

Pariwat Nasawat[a], Sukangkana Talangkun[a*], Sirawadee Arunyanart[a] and Narong Wichapa[b]

[a]Department of Industrial Engineering, Faculty of Engineering, Khon Kaen University, Thailand
[b]Department of Industrial Engineering, Faculty of Engineering and Industrial Technology, Kalasin University, Thailand

CHRONICLE	ABSTRACT
	A new approach is applied in the process of measuring the efficiency of decision-making units (DMUs) through the cross-efficiency evaluation method. Ideal and Anti-Ideal models are generated to form a comprehensive method based on the cross-efficiency evaluation method. The two models are formulated and combined to the Data Envelopment Analysis using the CRITIC method. In a comparative analysis based on three numerical examples, the proposed approach can lead to achieving a more reliable result than one based on an individual method.

1. Introduction

Agriculture in Thailand, with more than 114,880 km^2 for rice cultivation and an output of about 32.63 million tons per year, is a diverse industry. One of the most important crops in Thailand is rice. In 2019, the production value of rice in Thailand reached almost 300 billion Thai baht. At the same time, the production volume of rice was forecast to be 28.36 million tons (Statista, 2019). However, there are insect pests, such as the Red flour beetle, Corn weevil and Rice weevil etc. that damage milled rice while it is in the warehouse awaiting export. Hence, entrepreneurs have discovered ways to protect rice from these insect pests. One of the most common methods for rice pest control is fumigation, which is easy and cheap. However, it uses substances toxic to the environment and humans. Furthermore, rice treated this way reduces consumer confidence, while rice exports do not comply with agricultural standards. A second method to protect rice is through vacuum seal packaging. This is a non-fumigant approach which complies with the agricultural standards appropriate for organic rice. However, it is expensive and has lower elimination efficiency. A new method to eliminate insect pests is using infrared. This method is environmentally friendly and it preserves the quality of the rice. There are various other methods for rice insect pest control. Each method has its own advantages and disadvantages. It is difficult to choose a best rice insect pest control method, because there are various criteria (both advantages and disadvantages) that we should consider. Therefore, it is not easy to rank the alternatives/decision making units (DMUs) for rice insect pest control, because there are several conflicting criteria (both inputs and outputs) such as cost, rice quality and production capacity. These factors should be taken into consideration simultaneously. Therefore, one important challenge to tackle in this complicated problem is to select an appropriate method to rank multiple DMUs with multiple factors (inputs and outputs).

* Corresponding author.
E-mail address: sukangkana@kku.ac.th (S. Talangkun)

The Data Envelopment Analysis (DEA) approach was first described by Farrel (1957), but a mathematical programming model was later developed by Charnes, Cooper and Rhodes (1979). A set of weights for each criterion (input or output) was not required (Davoodi & Rezai, 2012; Sun, Wu, & Guo, 2013). It is a non-parametric technique for evaluating the relative efficiencies of decision making units (DMUs) (Ruiz & Sirvent, 2012; Wichapa, Khokhajaikiat, & Chaiphet, 2021). In the framework of DEA, the weights of inputs and outputs are obtained by maximizing the ratio of the sum of weighted outputs to the sum of weighted inputs, constrained by DEA. Certainly, the ratio of each DMU cannot be greater than 1, and the maximum ratio is defined as the efficiency score (Ruiz & Sirvent, 2012; Wang, Chin, & Leung, 2009; Wichapa & Khokhajaikiat, 2019). A DMU can be defined as being efficient if its efficiency score is equal to 1; otherwise the DMU is non-efficient. Usually, non-efficient DMUs are considered to perform worse than efficient DMUs. Over the past four decades, this technique has been widely applied in performance evaluation and benchmarking in many industries, such as manufacturing, banking, hospitals and education (Kuah, Wong, & Behrouzi, 2010; Lesik et al., 2020; Liu, Lu, & Lu, 2016; Mardani, Zavadskas, Streimikiene, Jusoh, & Khoshnoudi, 2017). However, one of the main obstacles in DEA is that efficient DMUs cannot be fully discriminated from each other, because their efficiency scores are the same (Efficiency score =1).

To overcome this main drawback of DEA above, many scholars (Andersen & Petersen, 1993; Cook, Roll, & Kazakov, 1990; Li & Reeves, 1999; Sueyoshi, 1999) have suggested methods for ranking all DMUs. These ranking methods can be split into two groups as follows. The cross-efficiency approach (Group 1) can be employed to rank all DMUs using average values of the cross efficiency matrix evaluated for all DMUs (Ruiz & Sirvent, 2012) and the common weights approach (Group 2). However, one popular approach is the cross-efficiency evaluation approach, first proposed by Sexton et al. (1986), which is an extension of the DEA based on the cross-efficiency concept. The main idea of the cross-efficiency evaluation approach is to apply DEA with peer assessment, instead of self-assessment, so a set of weights can be obtained by averaging the best weights of all DMUs. Finally, each DMU can be ranked by its average score in the cross-efficiency matrix. However, there is still one drawback. The weights are not unique, so cannot provide clear results to help decision makers improve their performance (Si & Ma, 2019; J. Wu, Sun, Zha, & Liang, 2011). To solve the main drawback above, Sexton et al. (1986) first recommended using a secondary-goal model in the Cross-efficiency evaluation approach. Later, Doyle and Green (1994) proposed the aggressive and benevolent models, to deal with multiple DEA solutions. Even though aggressive and benevolent models are often suggested for ranking all DMUs, a question arises: which one is more suitable? It is usually possible that the DMU ratings obtained from aggressive and benevolent models may not be the same for solving the same ranking problem, because each of the models has a different view. Certainly, both of the above points should not be ignored. Hence, it is wise to try different models and combine the results of both models for ranking all DMUs. Recently, Wang, Chin, and Luo (2011) have proposed effective cross-efficiency models based on ideal and anti-ideal DMUs for ranking all DMUs. Hou, Wang, and Zhou (2018) have proposed an effective model based on Ideal and Anti-Ideal Points for ranking all DMUs. These Ideal and Anti-Ideal models were developed based on the concept of benevolent and aggressive models, which have the major advantages of being uncomplicated and simple, but are powerful for solving the ranking problem. Inspired by the above ideas, it is wise to try to combine the results of Ideal and Anti-Ideal models for ranking all DMUs, because neither view should be ignored. Criteria Importance Through Intercriteria Correlation (the CRITIC method) was originally developed by Diakoulaki et al. (1995), and is one of the most frequently used multi-criteria decision making (MCDM) methods to obtain the importance of criteria. It can be applied to combine the results of many cross-efficiency models for ranking all DMUs. There are various applications of the CRITIC method for determining criteria weights in decision making processes in the literature (Bellver, Cervelló, & García, 2011; Diakoulaki et al., 1995; Keshavarz Ghorabaee, Amiri, Zavadskas, & Antucheviciene, 2018; Vujicic, Papic, & Blagojević, 2017), which have proven that the CRITIC method is an effective method for determining the criteria weights in the decision matrix. The major advantage of the CRITIC method is that it is simple but effective for determining the weights of criteria. The above are the major reasons why the Ideal and Anti-Ideal models based on the CRITIC method are chosen as an appropriate approach for ranking all DMUs in this paper. To this end, this paper provides a new hybrid approach based on Ideal and Anti-Ideal points, with the CRITIC method, for ranking all decision-making units. The proposed model has been modified from the Ideal and Anti-Ideal points of Hou et al. (2018) in the following ways: (1) the Ideal and Anti-Ideal models generate the Ideal CEM and Anti-Ideal CEM respectively, and then the combined CEM is generated using a new formula, (2) the target DMUs and the DMUs in the combined CEM are viewed as criteria and alternatives respectively, and (3) the CRITIC method is used to generate the weights of each criterion (target DMUs) in combined CEM for calculating the final weights of all DMUs. The evaluation steps of this paper are as follows. Firstly, generate the Ideal CEM and Anti-Ideal CEM based on Ideal and Anti-Ideal models. Secondly, combine the Ideal CEM and Anti-Ideal CEM and then the CRITIC method to evaluate the weights of target DMUs/Criteria. Finally, evaluate the final weights of each DMU and rank all DMUs.

The rest of this research is organized as follows. Literature review, Methodology and Numerical examples are presented in Sections 2, 3 and 4 respectively. Finally, Section 5 is the Conclusion.

2. Literature review

The CCR model by Charnes et al. (1979) is a classic DEA model for calculating the efficiency value of each DMU with multiple inputs and outputs. Many investigations have been carried out for various applications (Chandra, Cooper, Li, &

Rahman, 1998; Liang, Yang, Cook, & Zhu, 2006; Wei, Chen, Li, & Tsai, 2011), which prove that the CCR model is a valuable and capable approach for measuring performance of DMUs. It is well known that the main disadvantage of the classic DEA model is that efficient DMUs (Efficiency score of one) cannot be compared with each other on the basis of this criterion anymore. Therefore, it seems necessary to provide other models for further discrimination among these DMUs. Hence, many studies in the literature have proposed methods for ranking efficient DMUs. For example, Sexton et al. (1986) proposed the cross-efficiency evaluation to provide a full ranking for all DMUs. Later, applications of the cross-efficiency evaluation method have been widely applied in many fields. However, the main drawback of the cross-efficiency evaluation method is that the weights may be not unique, which clearly cannot provide results to help decision makers to improve their performance (Si & Ma, 2019; J. Wu et al., 2011). To overcome this problem, Sexton et al. (1986) and Doyle & Green (1994) have proposed benevolent and aggressive models for ranking all DMUs. Wang & Chin (2010) proposed a neutral DEA model for overcoming the difficulty of the choice between the aggressive and benevolent models, and also providing a full ranking for all the DMUs. All of the above models are based on the concept of the cross-efficiency method. Besides the above ranking methods, another way to solve the ranking problem is to combine the results of multiple ranking methods based on methodologies for determining criteria weights in calculating the rating of all the DMUs. Determining the weight of each criterion is one of the key factors of the decision-making process. Generally, most weighting methods can be divided into subjective and objective approaches. The subjective approach is based on determining the weight of each criterion using information from experts included in the decision-making process. On the other hand, the objective approach disregards the opinion of decision makers and is based on determining the weight of each criterion using data that is present in the initial decision matrix. The best known objective approaches include: Entropy (Shannon, 1948), CRITIC (Diakoulaki et al., 1995) and FANMA (Diakoulaki et al., 1995). The CRITIC method is one of the best known and most widely used in the literature (Abdel-Basset & Mohamed, 2020; H.-W. Wu, Zhen, & Zhang, 2020). For example, Rostamzadeh et al. (2018) proposed a framework for sustainable supply chain risk management using fuzzy TOPSIS based on the CRITIC method. Kazan and Ozdemir (2014) proposed the TOPSIS - CRITIC method for financial performance assessment of large scale conglomerates. Wang and Zhao (2016) proposed the CRITIC method and AHP for designing optimization of mechanical properties of ceramic tool materials. Wei et al. (2020) proposed the GRA based on the CRITIC method for location planning of electric vehicle charging stations. Zhao et al. (2020) proposed a combined prospect theory, the Copula-CRITIC method, to evaluate the construction schedule robustness. As shown in the above literature, the CRITIC method has been accepted as a powerful technique to generate criteria weights in decision-making problems. These are therefore the major reasons for choosing the CRITIC method to determine the weight of each criterion in this paper.

3. Methodology

There are many different ranking methods that have been proposed for solving the ranking problem in DEA. However, the results obtained for each model may produce different ranked decision-making units for similar ranking problems. Hence, it is wise to try effective methods that provide more reliable results in solving the ranking problems effectively. In this section, a new hybrid method is offered for solving the ranking problems. The framework for the proposed ranking method is shown in Fig. 1.
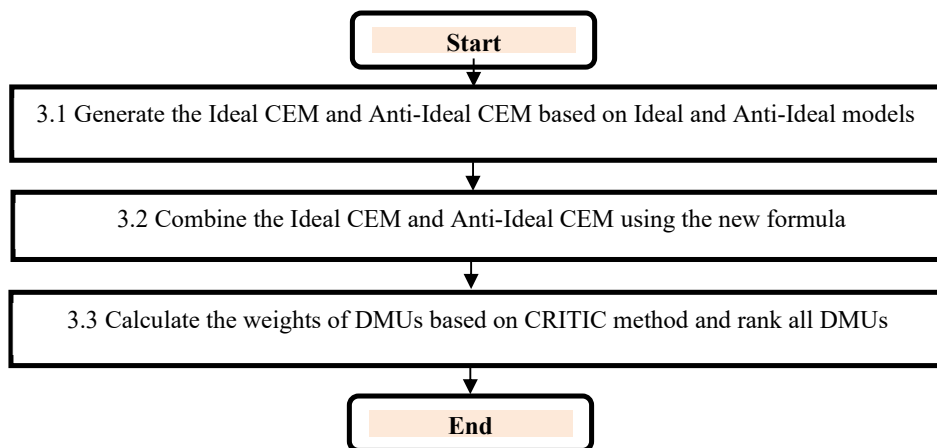
Fig.1. Framework for the proposed ranking approach

3.1 Generate the Ideal CEM and Anti-Ideal CEM based on Ideal and Anti-Ideal models

Assume that there be a set of n DMUs to be measured, where each DMU has m inputs to produces s outputs. We denote by x_{ij} ($i = 1,\ldots,m$) and y_{rj} ($r = 1,\ldots,s$) the values of inputs and outputs of DMU_j ($j = 1,\ldots,n$), which are all known and positive. An IDMU and an ADMU can be defined as follows:

Definition 1. An IDMU is a virtual DMU, which can use the least inputs to generate the most outputs. While an ADMU is a DMU, which consumes the most inputs only to produce the least outputs.

We denote by x^- and y^+ the Ideal input and Ideal output of the IDMU, and by x^+ and y^- the Anti-Ideal input and Anti-Ideal output of the ADMU, respectively. They are defined by the following formulae:

$$DMU_m^+ = \{min^+(x_{ij}), max^+(y_{rj}), j = 1, 2, ..., n\}.$$

Therein,

$$X^+ = \{min(x_{1j}), min(x_{2j}), min(x_{3j}), ..., min(x_{mj})\}$$
$$Y^+ = \{max(y_{1j}), max(y_{2j}), max(y_{3j}), ..., max(x_{sj})\}$$

Fictitious Decision Making Unit Based on the Anti-Ideal Point

$$DMU_m^- = \{max^-(x_{ij}), min^-(y_{rj}), j = 1, 2, ..., n\}.$$

Therein,

$$X^- = \{max(x_{1j}), max(x_{2j}), max(x_{3j}), ..., max(x_{mj})\}$$
$$Y^- = \{min(y_{1j}), min(y_{2j}), min(y_{3j}), ..., min(x_{sj})\}$$

or the concept of aggressive and benevolent cross-efficiency models, details are shown in the literature (Hou et al., 2018). Ideal and Anti-Ideal models can be determined as follows.

Let there be a set of n DMUs, where DMU_j ($j = 1, 2, ..., n$) uses m different inputs to produces s different outputs which can be denoted as $x_{ij} = (1, 2, ..., m)$ and $y_{rj} = (1, 2, ..., s)$ respectively. μ_{rd} and W_{id} are weights of outputs and weights of inputs respectively. For any evaluated DMU_d ($1 \leq d \leq n$), the efficiency score E_{dd} can be calculated by the CCR model as follows:

$$\max \quad \sum_{r=1}^{s} \mu_{rd} \cdot Y_{rd} = E_{dd}$$

subject to:

$$\sum_{r=1}^{s} \mu_{rd} \cdot Y_{rj} - \sum_{i=1}^{m} w_{id} \cdot X_{ij} \leq 0, \quad \forall j, \ j = 1, 2, ..., n$$

$$\sum_{i=1}^{m} w_{id} \cdot X_{ij} = 1 \tag{1}$$

$$w_{id} \geq 0, \quad \forall i, \quad i = 1, 2, ..., m$$

$$\mu_{rd} \geq 0, \quad \forall r, \quad r = 1, 2, ..., s$$

For each DMU_d ($d = 1, 2, ..., n$), the cross-efficiency of each decision making unit (E_{dj}) can be determined as follows.

$$E_{dj} = \frac{\sum_{r=1}^{s} \mu_{rd} \cdot Y_{rd}}{\sum_{i=1}^{m} w_{id} \cdot X_{id}}, \quad d, j = 1, 2, 3, ..., n \tag{2}$$

Then the average cross-efficiency (ACE) of each decision making unit is defined as follows.

$$\overline{E}_j = \frac{1}{n} \sum_{d=1}^{n} E_{dj}, \quad j = 1, 2, 3, ..., n, \quad d, j = 1, 2, 3, ..., n \tag{3}$$

According to the efficiency concept (Hou et al., 2018), the efficiency of Ideal and Anti-Ideal models can be defined as Eq. (4) and Eq. (5) respectively.

$$\min \ \theta_+^* = \sum_{r=1}^{s} (\mu_{rd} \cdot Y^+)$$

subject to:

$$\sum_{i=1}^{m} (w_{id} \cdot X^+) = 1 \tag{4}$$

$$\sum_{r=1}^{s} \mu_{rd} \cdot Y_{rj} - E_{dd} \cdot \sum_{i=1}^{m} w_{id} \cdot X_{ij} = 0, \quad \forall j, j \neq d, \ j = 1, 2, 3, ..., n$$

$$\sum_{r=1}^{s} \mu_{rd} \cdot Y_{rj} - \sum_{i=1}^{m} w_{id} \cdot X_{ij} \leq 0, \quad \forall j, \ j \neq d, \ j = 1,2,3,...,n$$

$$w_{id} \geq 0, \quad \forall i, \quad i = 1,2,3,...,m$$

$$\mu_{rd} \geq 0, \quad \forall r, \quad r = 1,2,3,...,s \quad \text{and}$$

$$\max \theta_-^* = \sum_{r=1}^{s} (\mu_{rd} \cdot Y^-) \tag{5}$$

subject to:

$$\sum_{i=1}^{m} (w_{id} \cdot X^-) = 1 \text{ with others having the same constraints as in Model (4).}$$

According to the above models, two evaluation matrices can be obtained as follows:

Ideal Cross-Efficiency Matrix (Ideal CEM) is

$$\theta_+^* = \begin{bmatrix} \theta_{11}^{+*} & \theta_{12}^{+*} & \theta_{13}^{+*} & \cdots & \theta_{1n}^{+*} \\ \theta_{21}^{+*} & \theta_{22}^{+*} & \theta_{23}^{+*} & \cdots & \theta_{2n}^{+*} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \theta_{n1}^{+*} & \theta_{n2}^{+*} & \theta_{n3}^{+*} & \cdots & \theta_{nn}^{+*} \end{bmatrix}. \tag{6}$$

Anti-Ideal Cross-Efficiency Matrix (Anti-Ideal CEM) is

$$\theta_-^* = \begin{bmatrix} \theta_{11}^{-*} & \theta_{12}^{-*} & \theta_{13}^{-*} & \cdots & \theta_{1n}^{-*} \\ \theta_{21}^{-*} & \theta_{22}^{-*} & \theta_{23}^{-*} & \cdots & \theta_{2n}^{-*} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \theta_{n1}^{-*} & \theta_{n2}^{-*} & \theta_{n3}^{-*} & \cdots & \theta_{nn}^{-*} \end{bmatrix}. \tag{7}$$

3.2 Combine the Ideal CEM and Anti-Ideal CEM using the new formula

In calculating the weight of each criterion using the CRITIC method, there are three calculation steps as follows. The combined Cross-Efficiency Matrix (combined CEM) will be generated using the results of the Ideal CEM and Anti-Ideal CEM in Section 3.1. Details are shown in Table 1.

Table 1
The combined CEM (X) based on the Ideal and Anti-Ideal points

DMU	Target DMU				
	1	2	3	...	n
DMU1	θ_{11}^*	θ_{12}^*	θ_{13}^*	...	θ_{1n}^*
DMU2	θ_{21}^*	θ_{22}^*	θ_{23}^*	...	θ_{2n}^*
DMU3	θ_{31}^*	θ_{32}^*	θ_{33}^*	...	θ_{3n}^*
⋮	⋮	⋮	⋮	⋮	⋮
DMUn	θ_{n1}^*	θ_{n2}^*	θ_{n3}^*	...	θ_{nn}^*

In Table 1, consider a combined decision matrix (X), $X = \left[\theta_{ij}^* \right]_{n \times n}$, where θ_{ij}^* is the efficiency score of alternative i (DMUi) with respect to criterion j (target DMUj) and n is the number of DMUs respectively.

$$\theta_{ij}^* = \sqrt{(w_j^+ \cdot \theta_{ij}^{+*})(w_j^- \cdot \theta_{ij}^{-*})}, \ \forall i(i=1,2,3,...,n), \ \forall j(j=1,2,3,...,n) \tag{8}$$

where

$$w_j^+ = \frac{\sigma_{\theta_j^{+*}}}{\sigma_{\theta_j^{+*}} + \sigma_{\theta_j^{-*}}}, \quad \forall j \ (j = 1,2,3,...,n) \tag{9}$$

$$w_j^- = \frac{\sigma_{\theta_j^{-*}}}{\sigma_{\theta_j^{+*}} + \sigma_{\theta_j^{-*}}}, \quad \forall j \ (j = 1,2,3,...,n) \tag{10}$$

3.3 Calculate the weights of DMUs based on CRITIC method and rank all DMUs

3.3.1 Generate the normalized decision matrix

The normalized decision matrix can be generated using Eq. (11)

$$\chi_{ij} = \frac{\theta_{ij}^* - \theta_j^{\min}}{\theta_j^{\max} - \theta_j^{\min}} \tag{11}$$

where $\theta_j^{\max} = \max(\theta_{ij}^*, j = 1,2,3,...,n)$, and $\theta_j^{\min} = \min(\theta_{ij}^*, j = 1,2,3,...,n)$.

3.3.2 Calculate the weights of each criterion

While generating the weights of criterion j, the standard deviation of criterion j (σ_j) and correlation between the criterion i and criterion j (r_{ij}) can be calculated using Excel 2010. In this regard, the weight of the criterion j (w_j) is obtained as

$$w_j = \frac{C_j}{\sum\limits_{j=1}^{m} C_j} \tag{12}$$

where C_j is the quantity of information contained in criterion j determined as

$$C_j = \sigma_j \sum_{i=1}^{n} (1 - r_{ij}) \tag{13}$$

3.3.3 Calculate the weights of DMUs and rank all DMUs

The weight of each DMU_i is obtained by multiplying the CRITIC weight value by the corresponding decision matrix using Eq. (14).

$$\theta_i = \sum_{j=1}^{m} (w_j \cdot x_{ij}), \qquad \forall i, \ i = 1,2,3,...,n \tag{14}$$

where θ_i is the integrated weight of each DMU_i.

After calculating θ_i using Eq. (14), all DMUs can be ranked so that a higher value of θ_i means that the DMU's ranking is higher.

4. Numerical examples

This section uses the proposed ranking method to evaluate three numerical examples. The first is six nursing homes (Sexton et al., 1986), the second fourteen international passenger airlines (Tofallis, 1997a), and the third is a case study on choosing a suitable rice weevil disinfestation. Details of the calculation steps of the proposed methodology are shown in Sections 4.1, 4.2 and 4.3 respectively.

4.1. Efficiency evaluation of six nursing homes

In Table 2, the six nursing homes, proposed by Sexton et al. (1986), has two inputs (X_1 and X_2) and two outputs (Y_1 and Y_2).

X_1: staff hours per day, including nurses, physicians, etc.
X_2: supplies per day, measured in thousands of dollars.
Y_1: total Medicare-plus-Medicaid reimbursed patient days.
Y_2: total privately paid patient days.

Table 2
Data set of six nursing homes

DMUs	X_1	X_2	Y_1	Y_2	DEA-CCR
DMU1	1.50	0.20	1.40	0.35	**1.0000**
DMU2	4.00	0.70	1.40	2.10	**1.0000**
DMU3	3.20	1.20	4.20	1.05	**1.0000**
DMU4	5.20	2.00	2.80	4.20	**1.0000**
DMU5	3.50	1.20	1.90	2.50	**0.9775**
DMU6	3.20	0.70	1.40	1.50	**0.8675**

Step 1: Generate the Ideal CEM and Anti-Ideal CEM based on Ideal and Anti-Ideal models for six nursing homes

Consider a data set of six nursing homes, each DMU with two inputs and two outputs as in Table 2. The efficiency scores based on the CCR model (Equation (1)) must be evaluated first. After that, the Ideal model (Equation (4)) and Anti-Ideal

model (Equation (5)) were coded using LINGO software. The results (using LINGO) of all models are shown in Appendix A. As a result, the Ideal CEM and Anti-Ideal CEM can be obtained as listed in Table 3 and Table 4 respectively.

Table 3
Ideal CEM of six nursing homes

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	1.0000	0.5833	1.0000	0.4977	1.0000	1.0000
DMU2	1.0000	1.0000	0.8640	1.0000	1.0000	1.0000
DMU3	0.5000	0.2917	1.0000	0.4129	0.8295	0.8295
DMU4	0.7000	0.7000	1.0000	1.0000	1.0000	1.0000
DMU5	0.7083	0.6944	0.9676	0.9506	0.9775	0.9775
DMU6	0.7551	0.7143	0.8046	0.8027	0.8675	0.8675
$\sigma_{\theta_j^{+*}}$	**0.1936**	**0.2293**	**0.0844**	**0.2611**	**0.0768**	**0.0768**
w_j^+	**0.3833**	**0.7491**	**0.2323**	**0.6051**	**0.5000**	**0.5000**

Table 4
Anti-Ideal CEM of six nursing homes

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	1.0000	1.0000	0.7111	0.7111	1.0000	1.0000
DMU2	0.3505	1.0000	0.2667	0.6500	1.0000	1.0000
DMU3	1.0000	0.8295	1.0000	1.0000	0.8295	0.8295
DMU4	0.4056	1.0000	0.4103	1.0000	1.0000	1.0000
DMU5	0.4301	0.9775	0.4136	0.9205	0.9775	0.9775
DMU6	0.4099	0.8675	0.3333	0.6482	0.8675	0.8675
$\sigma_{\theta_j^{-*}}$	**0.3115**	**0.0768**	**0.2790**	**0.1704**	**0.0768**	**0.0768**
w_j^-	**0.6167**	**0.2509**	**0.7677**	**0.3949**	**0.5000**	**0.5000**

Step 2: Combine the Ideal CEM and Anti-Ideal CEM using the new formula for six nursing homes

After obtaining the Ideal and Anti-Ideal CEMs, the combined CEM can be generated using new formula (Eqs. (8-10) as listed in Table 5.

Table 5
Combined CEM of six nursing homes

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	0.4862	0.3311	0.3561	0.2908	0.5000	0.5000
DMU2	0.2878	0.4335	0.2027	0.3941	0.5000	0.5000
DMU3	0.3438	0.2132	0.4223	0.3141	0.4148	0.4148
DMU4	0.2591	0.3627	0.2705	0.4888	0.5000	0.5000
DMU5	0.2684	0.3572	0.2672	0.4573	0.4887	0.4887
DMU6	0.2705	0.3412	0.2187	0.3526	0.4337	0.4337
θ_j^{max}	**0.4862**	**0.4335**	**0.4223**	**0.4888**	**0.5000**	**0.5000**
θ_j^{min}	**0.2591**	**0.2132**	**0.2027**	**0.2908**	**0.4148**	**0.4148**

Step 3: Calculate the weights of DMUs based on CRITIC method and rank all DMUs for six nursing homes

Consider the combined CEM in Table 5, where each DMU is viewed as an alternative, and the target DMU is viewed as a criterion. After that, the combined CEM was normalized using Eq. (11). Then, σ_j was computed with Excel 2010. As a result, the normalized CEM can be obtained as listed in Table 6.

Table 6
Normalized CEM of six nursing homes

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	1.0000	0.5351	0.6986	0.0000	1.0000	1.0000
DMU2	0.1266	1.0000	0.0000	0.5216	1.0000	1.0000
DMU3	0.3730	0.0000	1.0000	0.1176	0.0000	0.0000
DMU4	0.0000	0.6785	0.3087	1.0000	1.0000	1.0000
DMU5	0.0410	0.6534	0.2935	0.8407	0.8680	0.8680
DMU6	0.0503	0.5811	0.0728	0.3120	0.2224	0.2224
σ_j	**0.3841**	**0.3255**	**0.3836**	**0.3977**	**0.4504**	**0.4504**

After obtaining the normalized CEM, the next step is to compute the correlation between target DMUi and target DMUj (r_{ij}) using Excel 2010. As a result, the correlation matrix can be obtained as listed in Table 7.

Table 7

Correlation matrix for six nursing homes

Target DMU	1	2	3	4	5	6
1	1.0000	-0.3145	0.6217	-0.7597	0.1026	0.1026
2	-0.3145	1.0000	-0.8757	0.5041	0.7630	0.7630
3	0.6217	-0.8757	1.0000	-0.5359	-0.3935	-0.3935
4	-0.7597	0.5041	-0.5359	1.0000	0.4660	0.4660
5	0.1026	0.7630	-0.3935	0.4660	1.0000	1.0000
6	0.1026	0.7630	-0.3935	0.4660	1.0000	1.0000

After obtaining the correlation matrix for six nursing homes, the weight of the target DMUj (w_j) was obtained using Eq. (12) and Eq. (13). C_j was evaluated using Eq. (14). For example, $C_1 = \sigma_1 \sum_{i=1}^{2}(1 - r_{i1}) = 0.3841(5.2473) = 2.0153$.

Likewise, the values of C_2 to C_6 were obtained from the same calculation as the C_1 value. Finally, $w_1, w_{2,...,}w_6$ are shown in Table 8.

Table 8

Criteria weights for six nursing homes using the CRITIC method

Target DMU	1	2	3	4	5	6
1	0.0000	1.3145	0.3783	1.7597	0.8974	0.8974
2	1.3145	0.0000	1.8757	0.4959	0.2370	0.2370
3	0.3783	1.8757	0.0000	1.5359	1.3935	1.3935
4	1.7597	0.4959	1.5359	0.0000	0.5340	0.5340
5	0.8974	0.2370	1.3935	0.5340	0.0000	0.0000
6	0.8974	0.2370	1.3935	0.5340	0.0000	0.0000
$\sum_{i=1}^{n}(1-r_{ij})$	5.2473	4.1601	6.5770	4.8594	3.0619	3.0619
C_j	2.0153	1.3541	2.5229	1.9327	1.3791	1.3791
w_j	**0.1904**	**0.1279**	**0.2384**	**0.1826**	**0.1303**	**0.1303**

After obtaining the w_j of each criterion, each DMU weight (θ_i) can be obtained using Equation (14). As a result, DMU$_s$ were ranked as listed in Table 9. Finally, Spearman's rank correlation was used for testing the correlation of each method (r_s). The details of each r_s value are shown in Table 10.

Table 9

The ranking of each DMU for six nursing homes

DMUs	Benevolent	Rank	Aggressive	Rank	Hou et al. (2018)	Rank	Proposed method	Rank
DMU1	1.0000	1	0.7639	1	0.8709	1	0.4033	1
DMU2	0.9773	3	0.7004	3	0.7934	4	0.3609	4
DMU3	0.8580	5	0.6428	5	0.7840	5	0.3589	5
DMU4	1.0000	1	0.7184	2	0.8169	2	0.3798	2
DMU5	0.9758	4	0.6956	4	0.8016	3	0.3714	3
DMU6	0.8570	6	0.6081	6	0.7074	6	0.3247	6

Table 10

Spearman's rank correlation test for six nursing homes

Correlation test	Benevolent	Aggressive	Hou et al. (2018)	Proposed model
Benevolent	1.000	0.986	0.928	0.928
Aggressive	0.986	1.000	0.943	0.943
Hou et al. (2018)	0.928	0.943	1.000	1.000
Proposed model	0.928	0.943	1.000	1.000

As seen in Table 9, the rating and ranking of all DMUs were obtained. The proposed method and Hou's model (Hou et al., 2018) assess that DMU$_1$> DMU$_4$ > DMU$_5$ > DMU$_2$ > DMU$_3$ > DMU$_6$. The aggressive model, Hou's model (Hou et al., 2018) and proposed method agree that the best DMU and the worst DMU are DMU$_1$ and DMU$_6$ respectively, but the benevolent model cannot discriminate between DMU$_1$ and DMU$_4$. As seen in Table 10, the correlation coefficients for the proposed method and benevolent efficiency and aggressive efficiency and Hou's efficiency values are evaluated as $r_s = 0.928, 0.943, 1.000$ respectively. This is a guarantee that the proposed method is more reliable.

4.2 Efficiency evaluation of fourteen international passenger airlines

In Table 9, the data set of fourteen international passenger airlines, proposed by Tofallis (Tofallis, 1997b), has three inputs (x_1, x_2 and x_3) and two outputs (y_1 and y_2).

X_1: aircraft capacity in ton kilometers,
X_2: operating cost,
X_3: non-flight assets such as reservation systems, facilities and current assets,
Y_1: passenger kilometers,
Y_2: non-passenger revenue.

Table 11
Data set of fourteen international passenger airlines

DMUs	X_1	X_2	X_3	Y_1	Y_2	CCR
1	5723	3239	2003	26677	697	**0.8684**
2	5895	4225	4557	3081	539	**0.3379**
3	24099	9560	6267	124055	1266	**0.9475**
4	13565	7499	3213	64734	1563	**0.9581**
5	5183	1880	783	23604	513	**1.0000**
6	19080	8032	3272	95011	572	**0.9766**
7	4603	3457	2360	22112	969	**1.0000**
8	12097	6779	6474	52363	2001	**0.8588**
9	6587	3341	3581	26504	1297	**0.9477**
10	5654	1878	1916	19277	972	**1.0000**
11	12559	8098	3310	41925	3398	**1.0000**
12	5728	2481	2254	27754	982	**1.0000**
13	4715	1792	2485	31332	543	**1.0000**
14	22793	9874	4145	122528	1404	**1.0000**

Step 1: Generate the Ideal CEM and Anti-Ideal CEM based on Ideal and Anti-Ideal models for fourteen international passenger airlines

Consider a data set of fourteen international passenger airlines; each DMU has three inputs and two outputs as shown in Table 11. The efficiency scores based on the CCR model (Eq. (1)) must be evaluated first. After that, the Ideal model (Eq. (4)) and Anti-Ideal model (Eq. (5)) were coded using LINGO software. The results (using LINGO) of all models are shown in Appendix B. As a result, the Ideal CEM and Anti-Ideal CEM can be obtained as listed in Table 12 and Table 13 respectively.

Table 12
Ideal CEM of fourteen international passenger airlines

DMU	Target DMU						
	1	2	3	4	5	6	7
DMU1	0.8684	0.4501	0.6225	0.8684	0.4418	0.4726	0.8108
DMU2	0.1719	0.3379	0.0472	0.1719	0.0224	0.0247	0.2479
DMU3	0.8826	0.1942	0.9475	0.8826	0.6566	0.6898	0.7232
DMU4	0.9581	0.4259	0.7034	0.9581	0.6683	0.6973	0.8228
DMU5	0.9653	0.3658	1.0000	0.9653	1.0000	1.0000	0.7704
DMU6	0.8818	0.1108	0.9563	0.8818	0.9632	0.9766	0.6615
DMU7	0.9211	0.7781	0.4773	0.9211	0.3108	0.3382	1.0000
DMU8	0.7813	0.6114	0.5162	0.7813	0.2683	0.2924	0.8458
DMU9	0.7855	0.7278	0.5075	0.7855	0.2455	0.2677	0.8782
DMU10	0.7821	0.6354	0.6520	0.7821	0.3337	0.3564	0.7780
DMU11	1.0000	1.0000	0.4287	1.0000	0.4202	0.4418	1.0000
DMU12	0.9462	0.6336	0.7500	0.9462	0.4085	0.4395	0.9362
DMU13	1.0000	0.4256	1.0000	1.0000	0.4183	0.4555	1.0000
DMU14	1.0000	0.2277	1.0000	1.0000	0.9806	1.0000	0.7795
$\sigma_{\theta_j^{+*}}$	**0.2117**	**0.2487**	**0.2808**	**0.2117**	**0.3015**	**0.2996**	**0.1919**
w_j^+	**0.5000**	**0.5000**	**0.5000**	**0.5000**	**0.5927**	**0.5000**	**0.4986**

DMU	Target DMU						
	8	9	10	11	12	13	14
DMU1	0.7881	0.7031	0.6603	0.4870	0.7480	0.4711	0.4726
DMU2	0.2724	0.2808	0.1641	0.1024	0.2021	0.0417	0.0247
DMU3	0.6833	0.6225	0.7894	0.4805	0.7930	0.7422	0.6898
DMU4	0.7850	0.6991	0.7109	0.7058	0.8055	0.4937	0.6973
DMU5	0.7359	0.7778	1.0000	1.0000	1.0000	0.7181	1.0000
DMU6	0.6084	0.5099	0.7125	0.6111	0.7242	0.6766	0.9766
DMU7	1.0000	0.8395	0.6340	0.4705	0.7714	0.3658	0.3382
DMU8	0.8588	0.8208	0.6645	0.3712	0.7512	0.4418	0.2924
DMU9	0.9072	0.9477	0.7504	0.4009	0.8349	0.4537	0.2677
DMU10	0.7944	1.0000	1.0000	0.5565	1.0000	0.5871	0.3564
DMU11	1.0000	1.0000	0.7970	1.0000	0.9763	0.2961	0.4418
DMU12	0.9395	0.9998	0.9399	0.5382	1.0000	0.6398	0.4395
DMU13	1.0000	1.0000	1.0000	0.3754	1.0000	1.0000	0.4555
DMU14	0.7275	0.6478	0.8286	0.7462	0.8604	0.7097	1.0000

DMU	Target DMU						
	1	2	3	4	5	6	7
$\sigma_{\theta_j^{+*}}$	0.1946	0.2154	0.2161	0.2434	0.2076	0.2330	0.2996
w_j^+	0.5000	0.5000	0.4413	0.4946	0.4915	0.5449	0.5862

Table 13
Anti-Ideal CEM of fourteen international passenger airlines

DMU	Target DMU						
	1	2	3	4	5	6	7
DMU1	0.8684	0.4501	0.6225	0.8684	0.7512	0.4726	0.7679
DMU2	0.1719	0.3379	0.0472	0.1719	0.2058	0.0247	0.2770
DMU3	0.8826	0.1942	0.9475	0.8826	0.7846	0.6898	0.6468
DMU4	0.9581	0.4259	0.7034	0.9581	0.8112	0.6973	0.7629
DMU5	0.9653	0.3658	1.0000	0.9653	1.0000	1.0000	0.7011
DMU6	0.8818	0.1108	0.9563	0.8818	0.7176	0.9766	0.5745
DMU7	0.9211	0.7781	0.4773	0.9211	0.7808	0.3382	1.0000
DMU8	0.7813	0.6114	0.5162	0.7813	0.7532	0.2924	0.8415
DMU9	0.7855	0.7278	0.5075	0.7855	0.8375	0.2677	0.8881
DMU10	0.7821	0.6354	0.6520	0.7821	1.0000	0.3564	0.7650
DMU11	1.0000	1.0000	0.4287	1.0000	1.0000	0.4418	1.0000
DMU12	0.9462	0.6336	0.7500	0.9462	1.0000	0.4395	0.9082
DMU13	1.0000	0.4256	1.0000	1.0000	0.9843	0.4555	0.9511
DMU14	1.0000	0.2277	1.0000	1.0000	0.8569	1.0000	0.6919
$\sigma_{\theta_j^*}$	0.2117	0.2487	0.2808	0.2117	0.2072	0.2996	0.1930
w_j^-	0.5000	0.5000	0.5000	0.5000	0.4073	0.5000	0.5014

DMU	Target DMU						
	8	9	10	11	12	13	14
DMU1	0.7881	0.7031	0.4957	0.4501	0.7043	0.7881	0.8492
DMU2	0.2724	0.2808	0.3118	0.3379	0.2789	0.2724	0.1735
DMU3	0.6833	0.6225	0.2732	0.1942	0.6261	0.6833	0.8844
DMU4	0.7850	0.6991	0.4770	0.4259	0.7016	0.7850	0.9413
DMU5	0.7359	0.7778	0.5452	0.3658	0.7819	0.7359	1.0000
DMU6	0.6084	0.5099	0.1499	0.1108	0.5141	0.6084	0.8780
DMU7	1.0000	0.8395	0.6923	0.7781	0.8383	1.0000	0.8795
DMU8	0.8588	0.8208	0.6781	0.6114	0.8194	0.8588	0.7702
DMU9	0.9072	0.9477	0.8668	0.7278	0.9452	0.9072	0.7889
DMU10	0.7944	1.0000	1.0000	0.6354	1.0000	0.7944	0.8250
DMU11	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
DMU12	0.9395	0.9998	0.8413	0.6336	1.0000	0.9395	0.9602
DMU13	1.0000	1.0000	0.6158	0.4256	1.0000	1.0000	1.0000
DMU14	0.7275	0.6478	0.3022	0.2277	0.6521	0.7275	1.0000
$\sigma_{\theta_j^*}$	0.1946	0.2154	0.2735	0.2487	0.2147	0.1946	0.2115
w_j^-	0.5000	0.5000	0.5587	0.5054	0.5085	0.4551	0.4138

Step 2: Combine the Ideal CEM and Anti-Ideal CEM using the new formula for fourteen international passenger airlines

After obtaining the Ideal and Anti-Ideal CEMs, using Equations 8 to 10, the combined CEM can be obtained as listed in Table 14.

Table 14
Combined CEM of fourteen international passenger airlines

DMU	Target DMU						
	1	2	3	4	5	6	7
DMU1	0.4342	0.2251	0.3113	0.4342	0.2830	0.2363	0.3945
DMU2	0.0859	0.1690	0.0236	0.0859	0.0334	0.0124	0.1310
DMU3	0.4413	0.0971	0.4738	0.4413	0.3527	0.3449	0.3420
DMU4	0.4790	0.2129	0.3517	0.4790	0.3618	0.3487	0.3961
DMU5	0.4826	0.1829	0.5000	0.4826	0.4913	0.5000	0.3675
DMU6	0.4409	0.0554	0.4781	0.4409	0.4085	0.4883	0.3082
DMU7	0.4605	0.3890	0.2386	0.4605	0.2420	0.1691	0.5000
DMU8	0.3907	0.3057	0.2581	0.3907	0.2209	0.1462	0.4218
DMU9	0.3927	0.3639	0.2538	0.3927	0.2228	0.1338	0.4416
DMU10	0.3911	0.3177	0.3260	0.3911	0.2838	0.1782	0.3857
DMU11	0.5000	0.5000	0.2143	0.5000	0.3185	0.2209	0.5000
DMU12	0.4731	0.3168	0.3750	0.4731	0.3140	0.2198	0.4611
DMU13	0.5000	0.2128	0.5000	0.5000	0.3152	0.2278	0.4876
DMU14	0.5000	0.1138	0.5000	0.5000	0.4504	0.5000	0.3672
θ_j^{max}	0.5000	0.5000	0.5000	0.5000	0.4913	0.5000	0.5000

DMU	Target DMU						
	1	2	3	4	5	6	7
θ_j^{min}	0.0859	0.0554	0.0236	0.0859	0.0334	0.0124	0.1310

Table 14
(Continued)

DMU	Target DMU						
	8	9	10	11	12	13	14
DMU1	0.3941	0.3515	0.2841	0.2341	0.3629	0.3034	0.3120
DMU2	0.1362	0.1404	0.1123	0.0930	0.1187	0.0531	0.0322
DMU3	0.3417	0.3113	0.2306	0.1527	0.3523	0.3546	0.3847
DMU4	0.3925	0.3496	0.2892	0.2741	0.3758	0.3100	0.3990
DMU5	0.3680	0.3889	0.3666	0.3024	0.4421	0.3620	0.4925
DMU6	0.3042	0.2550	0.1623	0.1301	0.3050	0.3195	0.4561
DMU7	0.5000	0.4197	0.3289	0.3025	0.4020	0.3012	0.2686
DMU8	0.4294	0.4104	0.3333	0.2382	0.3922	0.3067	0.2337
DMU9	0.4536	0.4739	0.4005	0.2701	0.4441	0.3195	0.2263
DMU10	0.3972	0.5000	0.4965	0.2973	0.4999	0.3401	0.2671
DMU11	0.5000	0.5000	0.4433	0.5000	0.4940	0.2710	0.3274
DMU12	0.4698	0.4999	0.4415	0.2920	0.4999	0.3861	0.3200
DMU13	0.5000	0.5000	0.3896	0.1999	0.4999	0.4980	0.3324
DMU14	0.3638	0.3239	0.2485	0.2061	0.3744	0.3578	0.4925
θ_j^{max}	0.5000	0.5000	0.4965	0.5000	0.4999	0.4980	0.4925
θ_j^{min}	0.1362	0.1404	0.1123	0.0930	0.1187	0.0531	0.0322

Step 3: Calculate the weights of DMUs based on CRITIC method and rank all DMUs

Considering the combined CEM of fourteen international passenger airlines in Table 14, the evaluation steps are the same as Step 2 of Section 4.1. As a result, the normalized decision matrix was generated as shown in Table 15.

Table 15
Normalized CEM of fourteen international passenger airlines

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	0.8410	0.3816	0.6038	0.8410	0.5452	0.4592
DMU2	0.0000	0.2554	0.0000	0.0000	0.0000	0.0000
DMU3	0.8582	0.0937	0.9449	0.8582	0.6972	0.6819
DMU4	0.9494	0.3543	0.6887	0.9494	0.7171	0.6896
DMU5	0.9581	0.2868	1.0000	0.9581	1.0000	1.0000
DMU6	0.8573	0.0000	0.9541	0.8573	0.8191	0.9760
DMU7	0.9047	0.7504	0.4514	0.9047	0.4556	0.3214
DMU8	0.7359	0.5629	0.4923	0.7359	0.4094	0.2744
DMU9	0.7409	0.6938	0.4832	0.7409	0.4136	0.2491
DMU10	0.7369	0.5900	0.6348	0.7369	0.5469	0.3401
DMU11	1.0000	1.0000	0.4004	1.0000	0.6226	0.4276
DMU12	0.9350	0.5880	0.7376	0.9350	0.6128	0.4253
DMU13	1.0000	0.3541	1.0000	1.0000	0.6155	0.4417
DMU14	1.0000	0.1314	1.0000	1.0000	0.9106	1.0000
σ_j	0.2556	0.2797	0.2948	0.2556	0.2459	0.3072

DMU	Target DMU						
	8	9	10	11	12	13	14
DMU1	0.7088	0.5871	0.4470	0.3467	0.6405	0.5627	0.6078
DMU2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DMU3	0.5647	0.4751	0.3078	0.1467	0.6127	0.6778	0.7657
DMU4	0.7045	0.5817	0.4602	0.4450	0.6745	0.5775	0.7969
DMU5	0.6370	0.6910	0.6619	0.5145	0.8483	0.6944	1.0000
DMU6	0.4617	0.3185	0.1301	0.0912	0.4888	0.5988	0.9208
DMU7	1.0000	0.7768	0.5638	0.5148	0.7432	0.5577	0.5135
DMU8	0.8059	0.7509	0.5752	0.3567	0.7175	0.5701	0.4377
DMU9	0.8724	0.9273	0.7500	0.4351	0.8536	0.5988	0.4217
DMU10	0.7174	1.0000	1.0000	0.5020	1.0000	0.6451	0.5102
DMU11	1.0000	1.0000	0.8614	1.0000	0.9844	0.4898	0.6412
DMU12	0.9169	0.9998	0.8569	0.4889	1.0000	0.7485	0.6251
DMU13	1.0000	1.0000	0.7218	0.2626	1.0000	1.0000	0.6521
DMU14	0.6255	0.5103	0.3544	0.2778	0.6709	0.6850	1.0000
σ_j	0.2674	0.2996	0.2870	0.2422	0.2678	0.2118	0.2647

After obtaining the normalized CEM, the next step is to compute the correlation between target DMUi and target DMUj (r_{ij}) using Excel 2010. As a result, the correlation matrix can be obtained as listed in Table 16.

Table 16
Correlation matrix for fourteen international passenger airlines

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	1.0000	0.1278	0.7242	1.0000	0.8082	0.6089
DMU2	0.1278	1.0000	-0.5209	0.1278	-0.3286	-0.5728
DMU3	0.7242	-0.5209	1.0000	0.7242	0.8844	0.8352
DMU4	1.0000	0.1278	0.7242	1.0000	0.8082	0.6089
DMU5	0.8082	-0.3286	0.8844	0.8082	1.0000	0.9397
DMU6	0.6089	-0.5728	0.8352	0.6089	0.9397	1.0000
DMU7	0.7833	0.6446	0.2452	0.7833	0.2964	0.0031
DMU8	0.7568	0.6594	0.2280	0.7568	0.2626	-0.0370
DMU9	0.6032	0.7063	0.1726	0.6032	0.1881	-0.1486
DMU10	0.4831	0.7259	0.0845	0.4831	0.1517	-0.1825
DMU11	0.4990	0.8294	-0.1250	0.4990	0.2009	-0.0616
DMU12	0.7609	0.5394	0.4076	0.7609	0.4411	0.1152
DMU13	0.8301	-0.0476	0.8247	0.8301	0.6590	0.4509
DMU14	0.8067	-0.3833	0.8850	0.8067	0.9904	0.9584

DMU	Target DMU						
	8	9	10	11	12	13	14
DMU1	0.7568	0.6032	0.4831	0.4990	0.7609	0.8301	0.8067
DMU2	0.6594	0.7063	0.7259	0.8294	0.5394	-0.0476	-0.3833
DMU3	0.2280	0.1726	0.0845	-0.1250	0.4076	0.8247	0.8850
DMU4	0.7568	0.6032	0.4831	0.4990	0.7609	0.8301	0.8067
DMU5	0.2626	0.1881	0.1517	0.2009	0.4411	0.6590	0.9904
DMU6	-0.0370	-0.1486	-0.1825	-0.0616	0.1152	0.4509	0.9584
DMU7	0.9981	0.8873	0.7629	0.7072	0.8751	0.6781	0.2748
DMU8	1.0000	0.9075	0.7865	0.6990	0.8856	0.6803	0.2364
DMU9	0.9075	1.0000	0.9641	0.7267	0.9628	0.6462	0.1128
DMU10	0.7865	0.9641	1.0000	0.7668	0.9254	0.5190	0.0523
DMU11	0.6990	0.7267	0.7668	1.0000	0.7032	0.1729	0.1362
DMU12	0.8856	0.9628	0.9254	0.7032	1.0000	0.7755	0.3675
DMU13	0.6803	0.6462	0.5190	0.1729	0.7755	1.0000	0.6369
DMU14	0.2364	0.1128	0.0523	0.1362	0.3675	0.6369	1.0000

After obtaining the correlation matrix for the fourteen international airlines, the weight of the target DMUj (w_j) was obtained using Eq. (12) and Eq. (13). C_j was evaluated using Eq. (14). Likewise, the values of C_1 to C_{14} were obtained from the same calculation as Step 2 of Section 4.1. Finally, $w_1, w_2,..., w_{14}$ are shown in Table 17.

Table 17
Criteria weights for fourteen international passenger airlines using the CRITIC method

Target DMU	1	2	3	4	5	6	7
1	0.0000	0.8722	0.2758	0.0000	0.1918	0.3911	0.2167
2	0.8722	0.0000	1.5209	0.8722	1.3286	1.5728	0.3554
3	0.2758	1.5209	0.0000	0.2758	0.1156	0.1648	0.7548
4	0.0000	0.8722	0.2758	0.0000	0.1918	0.3911	0.2167
5	0.1918	1.3286	0.1156	0.1918	0.0000	0.0603	0.7036
6	0.3911	1.5728	0.1648	0.3911	0.0603	0.0000	0.9969
7	0.2167	0.3554	0.7548	0.2167	0.7036	0.9969	0.0000
8	0.2432	0.3406	0.7720	0.2432	0.7374	1.0370	0.0019
9	0.3968	0.2937	0.8274	0.3968	0.8119	1.1486	0.1127
10	0.5169	0.2741	0.9155	0.5169	0.8483	1.1825	0.2371
11	0.5010	0.1706	1.1250	0.5010	0.7991	1.0616	0.2928
12	0.2391	0.4606	0.5924	0.2391	0.5589	0.8848	0.1249
13	0.1699	1.0476	0.1753	0.1699	0.3410	0.5491	0.3219

Target DMU	1	2	3	4	5	6	7
14	0.1933	1.3833	0.1150	0.1933	0.0096	0.0416	0.7252
$\sum\limits_{i=1}^{n}(1-r_{ij})$	4.2079	10.4927	7.6303	4.2079	6.6980	9.4822	5.0605
C_j	1.0755	2.9352	2.2491	1.0755	1.6472	2.9130	1.3148
w_j	0.0446	0.1217	0.0932	0.0446	0.0683	0.1208	0.0545

Table 17

(Continued)

Target DMU	8	9	10	11	12	13	14
1	0.2432	0.3968	0.5169	0.5010	0.2391	0.1699	0.1933
2	0.3406	0.2937	0.2741	0.1706	0.4606	1.0476	1.3833
3	0.7720	0.8274	0.9155	1.1250	0.5924	0.1753	0.1150
4	0.2432	0.3968	0.5169	0.5010	0.2391	0.1699	0.1933
5	0.7374	0.8119	0.8483	0.7991	0.5589	0.3410	0.0096
6	1.0370	1.1486	1.1825	1.0616	0.8848	0.5491	0.0416
7	0.0019	0.1127	0.2371	0.2928	0.1249	0.3219	0.7252
8	0.0000	0.0925	0.2135	0.3010	0.1144	0.3197	0.7636
9	0.0925	0.0000	0.0359	0.2733	0.0372	0.3538	0.8872
10	0.2135	0.0359	0.0000	0.2332	0.0746	0.4810	0.9477
11	0.3010	0.2733	0.2332	0.0000	0.2968	0.8271	0.8638
12	0.1144	0.0372	0.0746	0.2968	0.0000	0.2245	0.6325
13	0.3197	0.3538	0.4810	0.8271	0.2245	0.0000	0.3631
14	0.7636	0.8872	0.9477	0.8638	0.6325	0.3631	0.0000
$\sum\limits_{i=1}^{n}(1-r_{ij})$	5.1799	5.6678	6.4770	7.2464	4.4798	5.3440	7.1192
C_j	1.3852	1.6978	1.8589	1.7550	1.1997	1.1317	1.8842
w_j	0.0574	0.0704	0.0771	0.0728	0.0497	0.0469	0.0781

After obtaining the w_j of each criterion, each DMU weight (θ_i) can be obtained using Equation (14). As a result, DMU_s were ranked as listed in Table 18. Finally, Spearman's rank correlation was used for testing the correlation of each method (r_s). The details of each r_s value are shown in Table 19.

Table 18

The ranking of each DMU for fourteen international passenger airlines

DMU	Benevolent	Rank	Aggressive	Rank	Hou et al. (2018)	Rank	Proposed approach	Rank
1	0.7543	12	0.5990	12	0.6496	10	0.3074	12
2	0.1894	14	0.1652	14	0.1697	14	0.0854	14
3	0.7678	9	0.6226	11	0.6360	12	0.3143	11
4	0.8222	6	0.6734	7	0.7120	8	0.3436	7
5	0.8912	3	0.7983	1	0.8103	2	0.4021	1
6	0.7554	11	0.6385	9	0.6106	13	0.3175	10
7	0.8214	7	0.6478	8	0.7148	7	0.3356	8
8	0.7242	13	0.5855	13	0.6422	11	0.3005	13
9	0.7590	10	0.6309	10	0.6865	9	0.3231	9
10	0.7803	8	0.6813	6	0.7254	6	0.3454	6
11	0.9193	1	0.7742	2	0.8302	1	0.3984	2
12	0.8850	4	0.7314	5	0.7936	4	0.3742	4
13	0.9190	2	0.7503	3	0.7998	3	0.3754	3
14	0.8659	5	0.7316	4	0.7319	5	0.3679	5

Table 19

Spearman's rank correlation test for fourteen international passenger airlines

Ranking model	Benevolent	Aggressive	Hou et al. (2018)	Proposed approach
Benevolent	1.000	0.952	0.930	0.960
Aggressive	0.952	1.000	0.930	0.991
Hou et al. (2018)	0.930	0.930	1.000	0.952
Proposed approach	0.960	0.991	0.952	1.000

As seen in Table 18, we use the proposed approach to calculate the efficiency rating and ranking of all DMUs. The proposed approach and aggressive model agree that DMU_5 is the best DMU, but the benevolent model and Hou's method (Hou et al., 2018) indicate that DMU_{11} is the best DMU. All of the methods agree that DMU_2 is the worst DMU.

As seen in Table 19, after the Spearman correlation test, the Spearman's rank correlation coefficients for the proposed method and the CCR efficiency value, benevolent efficiency value, aggressive efficiency and Hou's efficiency values are calculated as $r_s = 0.960, 0.991$ and 0.952 respectively. This is a guarantee that the proposed method is highly reliable.

4.3 Application to rank the methods of rice weevil disinfestations

Thailand is an agricultural country in Southeast Asia having a large amount of rice, which is an important economic crop for Thailand. However, in the harvesting season, there are many problems with various rice insect pests during warehouse storage while awaiting export that reduce the quality of milled rice, such as the Red flour beetle, Corn weevil and Rice weevil etc. Hence, various machines have been developed to prevent rice weevil disinfestations in Thailand. These machines should be evaluated and ranked in order to guide the development of more appropriate machines for rice weevil disinfestation. However, the selection of suitable machines for rice weevil disinfestation must consider various factors (inputs or outputs) and many alternatives (DMUs) at the same time. This is one multi-criteria decision-making problem that is difficult to evaluate. There are many tools for solving multi-criteria decision-making problems. However, the DEA cross-efficiency evaluation is one approach that is effective for evaluating and ranking DMUs. Hence, this paper has applied this tool for solving this problem. Fig.1 shows an example of the machine developed by the research team.

Fig.1 An example of the machine developed by the research team

In this case, six machines for rice weevil disinfestations are evaluated and ranked using the DEA approach. As seen in Table 20, the six machines selected have three inputs (x_1, x_2 and x_3) and two outputs (y_1 and y_2).

X_1 : Cost of equipment (Million baht).
X_2 : Production cost (Baht/kg).
X_3 : Environmental risk (The risk scale is between 1 and 5).
Y_1 : Capacity (Ton/day).
Y_2 : Rice quality (The rice quality is between 1 and 5).

Table 20
Data set of the method of rice weevil disinfestations

DMU	X_1	X_2	X_3	Y_1	Y_2	CCR
1	0.3000	1.6500	3.0000	0.5000	4.000	**1.0000**
2	0.9500	1.5000	3.0000	1.0000	4.000	**0.8235**
3	1.6500	0.5000	2.0000	3.0000	4.000	**1.0000**
4	0.7500	1.5000	2.0000	1.0000	4.500	**1.0000**
5	2.0000	1.5000	3.0000	1.0000	4.000	**0.6275**
6	3.0000	1.4500	3.0000	1.5000	4.000	**0.6299**
Ideal point		0.3000			4.5000	
Anti-Ideal point		3.0000			0.5000	

Step 1: Generate the Ideal CEM and Anti-Ideal CEM based on Ideal and Anti-Ideal models for the methods of rice weevil disinfestation
Consider a data set of the method of rice weevil disinfestations; each DMU with three inputs and two outputs as in Table 20. The efficiency scores based on the CCR model (Equation (1)) must be evaluated first. After that, the Ideal model (Equation (4)) and Anti-Ideal model (Equation (5)) were coded using LINGO software. The results (using LINGO) of all models are shown in Appendix C. As a result, the Ideal CEM and Anti-Ideal CEM can be obtained as listed in Table 21 and Table 22 respectively.

Table 21
Ideal CEM of the methods of rice weevil disinfestations

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	1.0000	0.9969	0.3030	1.0000	0.6202	0.6202
DMU2	0.3158	0.8235	0.3333	0.6486	0.6275	0.6275
DMU3	0.1818	1.0000	1.0000	0.5333	1.0000	1.0000
DMU4	0.4500	1.0000	0.3750	1.0000	1.0000	1.0000
DMU5	0.1500	0.5942	0.3333	0.4138	0.6275	0.6275
DMU6	0.1000	0.4755	0.3448	0.3077	0.6299	0.6299
$\sigma_{\theta_{ij}^+}$	**0.3355**	**0.2305**	**0.2713**	**0.2938**	**0.1930**	**0.1930**
w_j^+	**0.5074**	**0.5000**	**0.4592**	**0.4903**	**0.5000**	**0.5000**

Table 22
Anti-Ideal CEM of the methods of rice weevil disinfestations

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	1.0000	0.9969	0.1111	1.0000	0.6202	0.6202
DMU2	0.6000	0.8235	0.2222	0.7056	0.6275	0.6275
DMU3	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
DMU4	0.7650	1.0000	0.3333	1.0000	1.0000	1.0000
DMU5	0.2850	0.5942	0.2222	0.4020	0.6275	0.6275
DMU6	0.2800	0.4755	0.3333	0.3551	0.6299	0.6299
$\sigma_{\theta_{ij}^-}$	**0.3258**	**0.2305**	**0.3195**	**0.3054**	**0.1930**	**0.1930**
w_j^-	**0.4926**	**0.5000**	**0.5408**	**0.5097**	**0.5000**	**0.5000**

Step 2: Combine the Ideal CEM and Anti-Ideal CEM using the new formula

After obtaining Ideal and Anti-Ideal CEMs, using Equations 8 to 10, the combined CEM can be obtained as listed in Table 23.

Table 23
Combined CEM of the methods of rice weevil disinfestations

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	0.4999	0.4984	0.0914	0.4999	0.3101	0.3101
DMU2	0.2176	0.4118	0.1356	0.3382	0.3137	0.3137
DMU3	0.2132	0.5000	0.4983	0.3651	0.5000	0.5000
DMU4	0.2933	0.5000	0.1762	0.4999	0.5000	0.5000
DMU5	0.1034	0.2971	0.1356	0.2039	0.3137	0.3137
DMU6	0.0837	0.2377	0.1690	0.1653	0.3150	0.3150
θ_j^{max}	**0.4999**	**0.5000**	**0.4983**	**0.4999**	**0.5000**	**0.5000**
θ_j^{min}	**0.0837**	**0.2377**	**0.0914**	**0.1653**	**0.3101**	**0.3101**

Step 3: Calculate the weights of DMUs based on CRITIC method and rank all DMUs

Consider the combined CEM in Table 23 in which each DMU is viewed as an alternative, and the target DMU is viewed as a criterion. After that, the combined CEM was normalized using Equation (11). Then, σ_j was computed by Excel 2010. As a result, the normalized CEM can be obtained as listed in Table 24.

Table 24
Normalized CEM of the methods of rice weevil disinfestations

DMU	Target DMU					
	1	2	3	4	5	6
DMU1	1.0000	0.9941	0.0000	1.0000	0.0000	0.0000
DMU2	0.3218	0.6636	0.1086	0.5168	0.0192	0.0192
DMU3	0.3111	1.0000	1.0000	0.5971	1.0000	1.0000
DMU4	0.5037	1.0000	0.2083	1.0000	1.0000	1.0000
DMU5	0.0474	0.2263	0.1086	0.1155	0.0192	0.0192
DMU6	0.0000	0.0000	0.1905	0.0000	0.0257	0.0257
σ_j	**0.3637**	**0.4394**	**0.3655**	**0.4240**	**0.5082**	**0.5082**

After obtaining the normalized CEM, the next step is to compute the correlation between target DMUi and target DMUj (r_{ij}) using Excel 2010. As a result, the correlation matrix can be obtained as listed in Table 25.

Table 25
Correlation matrix for the methods of rice weevil disinfestations

Target DMU	1	2	3	4	5	6
1	1.0000	0.7751	-0.1987	0.8895	0.0764	0.0764
2	0.7751	1.0000	0.3223	0.9337	0.6098	0.6098
3	-0.1987	0.3223	1.0000	0.0055	0.7121	0.7121
4	0.8895	0.9337	0.0055	1.0000	0.4625	0.4625
5	0.0764	0.6098	0.7121	0.4625	1.0000	1.0000
6	0.0764	0.6098	0.7121	0.4625	1.0000	1.0000

After obtaining the correlation matrix for the methods of rice weevil disinfestations, the weight of the target DMUj (w_j) was obtained using Equation (12) and Equation (13). C_j was evaluated using Equation (14), For example,

$$C_1 = \sigma_1 \sum_{i=1}^{2}(1-r_{i1}) = 0.3841(5.2473) = 2.0153$$. Likewise, the values of C_2 to C_6 were obtained from the same

calculation as the C_1 value. Finally, w_1, $w_{2...}w_6$ are as shown in Table 26.

Table 26
Criteria weights for the methods of rice weevil disinfestations using the CRITIC method

Target DMU	1	2	3	4	5	6
1	0.0000	0.2249	1.1987	0.1105	0.9236	0.9236
2	0.2249	0.0000	0.6777	0.0663	0.3902	0.3902
3	1.1987	0.6777	0.0000	0.9945	0.2879	0.2879
4	0.1105	0.0663	0.9945	0.0000	0.5375	0.5375
5	0.9236	0.3902	0.2879	0.5375	0.0000	0.0000
6	0.9236	0.3902	0.2879	0.5375	0.0000	0.0000
$\sum_{i=1}^{n}(1-r_{ij})$	3.381	1.749	3.447	2.246	2.139	2.139
C_j	**1.2298**	**0.7687**	**1.2598**	**0.9524**	**1.0871**	**1.0871**
w_j	**0.1926**	**0.1204**	**0.1973**	**0.1492**	**0.1703**	**0.1703**

After obtaining the w_j of each criterion, each DMU weight (θ_i) can be obtained using Equation (14). As a result, DMUs were ranked as listed in Table 27. Finally, Spearman's rank correlation was used for testing the correlation of each method (r_s). The details of each r_s value are shown in Table 28.

Table 27
The ranking of each DMU for the methods of rice weevil disinfestations

DMUs	Benevolent	Rank	Aggressive	Rank	Hou et al. (2018)	Rank	Proposed method	Rank
DMU1	0.8718	3	0.7146	3	0.6632	3	0.3545	3
DMU2	0.7580	4	0.5257	4	0.5606	4	0.2755	4
DMU3	1.0000	1	0.7859	1	0.9066	1	0.4243	1
DMU4	1.0000	1	0.7602	2	0.7997	2	0.3963	2
DMU5	0.6045	5	0.4207	5	0.4397	5	0.2197	5
DMU6	0.5263	6	0.3859	6	0.4229	6	0.2100	6

Table 28
Spearman's rank correlation test for the methods of rice weevil disinfestations

Correlation test	Benevolent	Aggressive	Hou et al. (2018)	Proposed model
Benevolent	1.000	0.986	0.986	0.986
Aggressive	0.986	1.000	1.000	1.000
Hou et al. (2018)	0.986	1.000	1.000	1.000
Proposed model	0.986	1.000	1.000	1.000

As seen in Table 27, the rating and ranking of all DMUs were obtained. The proposed method and Hou's method (Hou et al., 2018) assess that DMU$_3$> DMU$_4$ > DMU$_1$ > DMU$_2$ > DMU$_5$ > DMU$_6$. The aggressive model and proposed approach agree that the best DMU and the worst DMU are DMU$_3$ and DMU$_6$ respectively, but the benevolent model cannot discriminate between DMU$_3$ and DMU$_4$.

As seen in Table 28, the correlation coefficients for the proposed method and benevolent efficiency, aggressive efficiency and Hou's efficiency values are evaluated as $r_s = 0.986$, 1.000 and 1.000 respectively. This is a guarantee that the proposed method is more reliable.

5. Conclusions

This paper presents a novel hybrid approach to tackle ranking problems with multiple inputs, multiple outputs and multiple DMUs. The proposed approach was tested with three numerical examples. We first utilized Ideal and Anti-Ideal models to calculate the efficiency rating of decision making units. The results of both models were used to generate an Ideal Cross-Efficiency Matrix (Ideal CEM) and Anti-Ideal Cross-Efficiency Matrix (Anti-Ideal CEM). In each Ideal Cross-Efficiency Matrix, the target DMUs of Ideal and Anti-Ideal models were viewed as criteria and DMUs were viewed as alternatives. Secondly, the combined CEM was generated using the new formula for combining Ideal and Anti-Ideal CEMs. After that, the criteria weights were generated by the CRITIC method. Finally, decision making units were ranked. The proposed hybrid approach showed potential in ranking decision making units, which differ from other models in the literature. We believe that the proposed ranking method can be employed to solve other real-world ranking problems.

For future research, in order to enhance the validity of the research output further, application of the proposed hybrid approach should be tested with more cases.

Acknowledgement

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Appendix:

Appendix A, Appendix B and Appendix C:

https://sites.google.com/view/relevantinformation/%E0%B8%AB%E0%B8%99%E0%B8%B2%E0%B9%81%E0%B8%A3%E0%B8%81