A Fuzzy Mathematical Programming Approach to DEA Models

A. Azadeh, S.F.Ghaderi, Z. Javaheri and M. Saberi

1Department of Industrial Engineering and Center of Excellence for Intelligent Based Experimental Mechanics and Research Institute of Energy Management and Planning, College of Engineering, University of Tehran, P.O. Box 11365-4563, Iran

Abstract: Evaluating the performance of activities or organizations by traditional Data Envelopment Analysis (DEA) as efficiency frontier analysis models requires crisp input/output data. However, in real-world problems inputs and outputs are often imprecise. This study develops DEA models using imprecise data represented by fuzzy sets. An important outcome of assessing relative efficiencies within a group of Decision Making Units (DMUs) in fuzzy data envelopment analysis is to determine efficient DMUs. We find efficiency measures with fuzzy inputs and outputs via proposed model. An example using fuzzy data is presented for illustrative purposes. We apply this method in the application to the power generation sector of Iran.

Key words: Fuzzy logic, optimization, data envelopment analysis, power plant

INTRODUCTION

Efficiency frontier analysis has been an important approach of evaluating firms’ performance in private and public sectors. There have been many efficiency frontier analysis methods reported in the literature. However, the assumptions made for each of these methods are restrictive. Each of these methodologies has its strength as well as major limitations especially sensitivity of frontier models to data causes to use a fuzzy mathematical programming approach to the assessment of efficiency with DEA models developed. The first study on fuzzy DEA was written in 1992[24]. The author of study explored the use of fuzzy set theory in decision making[24]. In this study, three types of fuzzy models (fuzzy mathematical programming, fuzzy regression and fuzzy entropy) were presented to illustrate the types of decisions and solutions that were achievable.

Moreover, in other study ranking methods is used for determining the efficiency of DMUs in input-oriented CCR model with fuzzy inputs and fuzzy outputs[13]. Also the relationship between DEA and Regression Analysis (RA) is studied. The CCR model and RA were considered as two special cases of the following goal programming problem:

DEARA(combination of DEA and RA):

\[
\begin{align*}
\min \quad G &= \sum_{i=1}^{n} (a_i\beta_i + b_i\eta_i) \\
\text{s.t.} \quad v^T y_i - u^T x_i &= \rho_i - \eta_i \quad i = 1, \ldots, n \\
& \quad u^T x_0 = 1 \\
& \quad u, v \geq 0 \\
& \quad \rho_i, \eta_i \geq 0
\end{align*}
\]

The others develop some fuzzy versions of the classical DEA models by using some ranking methods based on the comparison of \( \alpha \)-cuts[26]. This makes an approach which is able to deal with inexact numbers or numbers in ranges, desirable. To deal quantitatively with imprecision in decision process, the notion of fuzziness is introduced[24]. In the conventional DEA approach, a set of weights which satisfies a set of constraints is selected to give the highest possible efficiency measure for each DMU. When some observations are fuzzy, the goal and constraints in the decision process become fuzzy as well. Since the DEA model is essentially a linear program, one straightforward idea is to apply the existing fuzzy Linear Programming (LP) techniques to the fuzzy DEA problems[15,13,16,18,19,26]. Unfortunately, most of the existing techniques only provide crisp solutions and others are only suitable for specific problems, although they are able to produce possibility distributions of the optimal objective values[15,4,13,16,18,19,26]. There are articles...
discussing efficiency measures when the observations are random, yet not fuzzy, in nature. A stochastic DEA model via specific membership functions to give a fuzzy programming interpretation is transformed\(^{[21,23,25]}\).

Two DEA models are formulated: one model that gives on upper limit (best case) efficiency and one model that gives lower limit (worse case) efficiency\(^{[18]}\). Then an interval-valued efficiency can be constructed from these two extreme efficiencies. For the upper limit case, their model is the same as the CCR model. However, only crisp efficiency measures are provided.

On the whole, there are the three procedures that have been discussed on solving fuzzy DEA problems. The first is the procedure that solves the fuzzy DEA by the tolerance approach. The next is, solving the fuzzy DEA by the ranking approach and the last is to solve the fuzzy DEA by the parametric programming.

In this study we develop a method which is able to provide fuzzy efficiency measures for DMUs with fuzzy observations. Restated, the membership functions, rather than crisp measures, of efficiencies will be derived. The basic idea is to apply the \( \alpha \)-cuts to transform the fuzzy DEA model to a series of conventional crisp DEA models. The conventional DEA models are then solved by the LP method.

**DEA AND FUZZY DEA**

Data Envelopment Analysis (DEA) is a methodology based on a Linear Programming (LP) model for evaluating relative efficiencies of Decision Making Units (DMUs) with common inputs and outputs. It is used to ranking and analysis of Decision-Making Units (DMUs), such as industries, universities, hospitals, cities, facilities layout, etc.\(^{[31]}\). The two basic DEA models are CCR and BCC with constant returns to scale and variable returns to scale, respectively\(^{\ref{3,6}}\). Each DMU \( k \) is assigned the highest possible efficiency score \(( h_k \leq 1)\) that the constraints allow from the available data, by choosing the optimal weights for the outputs and inputs. If DMU \( k \) receives the maximal value \( h_k = 1 \), then it is efficient, but if \( h_k < 1 \), it is inefficient, since with its optimal weights, another DMU receives the maximal efficiency Eq. (1). Basically, the model divides the DMUs into two groups, efficient \(( h_k = 1)\) and inefficient \(( h_k < 1)\), by identifying the efficient of the data. The original DEA model is not capable of ranking efficient units Therefore; the model is modified allowing for a ranking of the efficient units themselves.

The original fractional CCR model (1) evaluates the relative efficiencies of \( n \) DMUs \(( j = 1, \ldots, n)\), each with \( m \) inputs and \( s \) outputs denoted by \( x_{ij} \), \( x_{ij}^\prime \), \( x_{ij}^\prime \) and \( y_{ij} \), \( y_{ij}^\prime \), \( y_{ij}^\prime \) respectively, by maximizing the ratio of weighted sum of outputs to the weighted sum of inputs.

\[
\text{(CCR ratio model)}
\]

\[
\text{Max} \quad e_{j_0} = \frac{\sum_{r=1}^{s} u_r y_{rj_0}}{\sum_{i=1}^{m} v_i x_{ij_0}}
\]

s.t.

\[
\sum_{r=1}^{s} u_r y_{rj} \leq 1, \quad j = 1, \ldots, n.
\]

\[
\sum_{i=1}^{m} v_i x_{ij} 
\]

\[
u_r, v_i \geq 0, \quad r = 1, \ldots, s, \quad i = 1, \ldots, m.
\]

In order to computational convenience the fractional programming model (2) is re-expressed in LP form as follows:

\[
\text{(CCR-LP model)}
\]

\[
\text{Max} \quad e_{j_0} = \sum_{r=1}^{s} u_r y_{rj_0}
\]

s.t.

\[
\sum_{r=1}^{s} u_r y_{rj} = \sum_{i=1}^{m} v_i x_{ij}, \quad j = 1, \ldots, n.
\]

\[
\sum_{i=1}^{m} v_i x_{ij_0} = 1
\]

\[
u_r, v_i \geq 0, \quad r = 1, \ldots, s, \quad i = 1, \ldots, m.
\]

Suppose that there are \( n \) DMUs, each of which consumes the same type of inputs and produces the same type of outputs. Let \( m \) be the number of inputs and let \( r \) be the number of outputs. All inputs and outputs are assumed to be nonnegative, but at least one input and one output are positive. The following notation will be used throughout this study.

**NOTATIONS**

DMUi is the \( i \)th DMU, DMUo is target DMU,
$x_i \in \mathbb{R}^{m_i}$ is the column vector of inputs consumed by DMU $i$.

$x_o \in \mathbb{R}^{m_o}$ is the column vector of inputs of consumed by target DMU.

$x \in \mathbb{R}^{mn}$ is the matrix of inputs of all DMUs.

$y_i \in \mathbb{R}^{r_i}$ is the column vector of inputs of consumed by DMU $i$.

$y_o \in \mathbb{R}^{r_o}$ is the column vector of inputs of consumed by target DMU.

$y \in \mathbb{R}^{rn}$ is the matrix of outputs of all outputs.

$\lambda = (\lambda_i)_{n \times d}$, $\lambda \in \mathbb{R}^d$ is the column vector of a linear combination of $n$ DMUs.

$\theta$ is the objective value (efficiency) of the CCR model.

$u \in \mathbb{R}^{m_i}$ is the column vector of input weights.

$v \in \mathbb{R}^{r_i}$ is the column vector of output weights.

The CCR model with fuzzy data can be written as:

$$\begin{align*}
\text{Max } e_{j_o} &= \sum_{i=1}^{s} u_r y_{j_o}^i - \frac{1}{m} \sum_{i=1}^{s} v_i x_{j_o}^i \\
\text{s.t. } &\sum_{r=1}^{s} u_r y_{j_o}^i - \frac{1}{m} \sum_{i=1}^{s} v_i x_{j_o}^i \leq 0, \quad j = 1,...,n, \\
&\frac{1}{m} \sum_{i=1}^{s} v_i x_{j_o}^i = 1 \\
u_r, v_i \geq 0, \quad r = 1,...,s, \quad i = 1,...,m.
\end{align*}$$

(5)

where, \-', \-' indicate the fuzziness.

There are different types of fuzzy numbers, but triangular fuzzy numbers are more useful so that we consider the inputs and outputs of DMUs as triangular fuzzy numbers.

Therefore, (3) can be written as follows:

$$\begin{align*}
\tilde{x}_j &= (x_{j_1}^m, x_{j_2}^l, x_{j_3}^u) \text{ and } \tilde{y}_j &= (y_{j_1}^m, y_{j_2}^l, y_{j_3}^u)
\end{align*}$$

Let

$$\begin{align*}
\text{Max } e_{j_o} &= \sum_{i=1}^{s} u_r (y_{j_o}^m, y_{j_o}^l, y_{j_o}^u) \\
\text{s.t. } &\sum_{r=1}^{s} u_r y_{j_o}^i - \frac{1}{m} \sum_{i=1}^{s} v_i x_{j_o}^i \leq 0, \\
&\frac{1}{m} \sum_{i=1}^{s} v_i x_{j_o}^i = 1 \\
u_r, v_i \geq 0, \quad r = 1,...,s, \quad i = 1,...,m.
\end{align*}$$

(6)

Model (5) is a nonlinear programming. There are various methods to solve it. In most of these methods for solving is to convert the possibilistic programming problem using $\alpha$-cut, the intervals in both sides of the constraints are compared with each other. There are many methods for comparing the intervals; hence many methods may be suggested for solving interval-programming problem.

### THE PROPOSED MODEL

The basic idea is to transform the fuzzy CCR model into a crisp linear programming problem by applying an alternative $\alpha$-cut approach. Thereby, the problem is converted to an interval programming. Different methodologies have been suggested for the comparison of the intervals in this study based on Tang Cheng Method is worked.

At first, we use $\alpha$-cut to convert fuzzy DEA into interval programming as follows:

$$\begin{align*}
\text{Max } e_{j_o} &= \sum_{i=1}^{s} u_r (\alpha y_{j_o}^m, (1 - \alpha) y_{j_o}^l, \alpha y_{j_o}^u) \\
\text{s.t. } &\sum_{r=1}^{s} u_r (\alpha y_{j_o}^m, (1 - \alpha) y_{j_o}^l, \alpha y_{j_o}^u) \geq \sum_{r=1}^{s} u_r (\alpha y_{j_o}^m, (1 - \alpha) y_{j_o}^l) \\
&\sum_{i=1}^{s} v_i (\alpha x_{j_o}^m, (1 - \alpha) x_{j_o}^l, \alpha x_{j_o}^u) = 1 \\
u_r, v_i \geq 0, \quad r = 1,...,s, \quad i = 1,...,m
\end{align*}$$

(7)

With considering our method model change into as follows this model gives upper bound of efficiency and next model gives lower bound of efficiency.

$$\begin{align*}
\text{Max } e_{j_n} &= \sum_{i=1}^{s} u_r (\alpha y_{j_n}^m, (1 - \alpha) y_{j_n}^l) \\
\text{s.t. } &\sum_{i=1}^{s} v_i (\alpha x_{j_n}^m, (1 - \alpha) x_{j_n}^l) \geq \sum_{i=1}^{s} u_r (\alpha y_{j_n}^m, (1 - \alpha) y_{j_n}^l) \\
&\sum_{i=1}^{s} v_i (\alpha x_{j_n}^m, (1 - \alpha) x_{j_n}^l) = 1
\end{align*}$$

(8)

$$\begin{align*}
\text{Max } e_{j_n} &= \sum_{i=1}^{s} u_r (\alpha y_{j_n}^m, (1 - \alpha) y_{j_n}^l) \\
\text{s.t. } &\sum_{i=1}^{s} v_i (\alpha x_{j_n}^m, (1 - \alpha) x_{j_n}^l) \geq \sum_{i=1}^{s} u_r (\alpha y_{j_n}^m, (1 - \alpha) y_{j_n}^l) \\
&\sum_{i=1}^{s} v_i (\alpha x_{j_n}^m, (1 - \alpha) x_{j_n}^l) = 1
\end{align*}$$

(9)
The above model is equivalent to a the fuzzy linear programming problem with $\alpha \in [0, 1]$. It is noted that for each $\alpha$, we have an optimal solution.

| Power plant product $\alpha = 0$ | $\alpha = 0.25$ | $\alpha = 0.5$ | $\alpha = 0.75$ | $\alpha = 1$ |
|----------------------------------|----------------|----------------|----------------|-----------|
| Montazer                         | 0              | 0.92           | 0.93           | 0.89      |
| Besat                            | 0.87           | 0.75           | 0.82           | 1         |
| Firozi                           | 0.71           | 0.63           | 0.67           | 1         |
| Salimi                           | 0              | 1              | 1              | 1         |
| Shazand                          | 0              | 1              | 1              | 1         |
| Rajaie                           | 0              | 1              | 1              | 1         |
| Beheshti                         | 0              | 0.92           | 0.95           | 0.93      |
| Tabriz                           | 0              | 0.86           | 0.91           | 0.9       |
| Mofateh                          | 0              | 0.94           | 0.95           | 0.91      |
| Biston                           | 0              | 0.91           | 1              | 1         |
| Ramin                            | 0              | 1              | 1              | 1         |
| Medhaj                           | 0              | 0.91           | 0.91           | 0.92      |
| Bandar                           | 0.99           | 0.85           | 0.89           | 0.87      |
| Zarand                           | 0.79           | 0.69           | 0.76           | 1         |
| Esfehan                          | 0              | 1              | 1              | 1         |
| Montazeri                        | 0              | 0.94           | 1              | 1         |
| Tos                              | 0              | 0.9            | 0.95           | 0.95      |
| Mashhad                          | 0.82           | 0.71           | 0.77           | 0.86      |
| Iranshahr                        | 0              | 1              | 1              | 1         |

Thus, we can provide the decision maker a solution table with different $\alpha$ in $[0, 1)$.

**THE CASE STUDY**

Evaluation of conventional thermal steam-electric performance may be described conveniently within an engineering framework. In this framework, pertinent inputs are the fuel quantity consumed and installed power, which is the maximum nominal power the plants are initially designed. On the other hand labor inputs contribute to production through control and maintenance services, which also require some capital. The output is, of course, electrical energy production. But by notice of studies about efficiency measurement of thermal power generations in Iran which indicate that labor isn’t an effective factor in our study, electric power (in megawatt hour) generated from thermal power plants in each DMU (P) is used as the output variable, while capital (C), fuel (F) and internal power (Ic) are three inputs used for power generation. Capital is measured in terms of installed thermal generating capacity in megawatt (MW) Various natural elements have been used as fuel in the production of electric power in various steam plants in Iran (natural gas, gas oil and mazute). The choice of fuel depends on many factors such as availability, cost and environmental concerns and each fuel has its limitations. Our figures measure fuel consumption in terms of Tera Joule (TJ). In other words, our figures have already adjusted for the quality of fuel used in different plants. Internal power is the amount of energy consumed (in megawatt hour) within the site (for electrically powered equipment etc.). We purpose a method to evaluate the performance of power plants and find their efficiencies. Lower bound is is expressed in Table 1. Also, upper bound is is expressed in Table 2.

Then in order to validate this approach we compare these results on $\alpha = 1$ with results ordinary DEA model. With regard to objective function of proposed model is maximizing so that we consider upper bound of values. We can see Table 3 of comparing two methods.

### Tables

**Table 1: Lower bound result**

| Power plant product $\alpha = 0$ | $\alpha = 0.25$ | $\alpha = 0.5$ | $\alpha = 0.75$ | $\alpha = 1$ |
|----------------------------------|----------------|----------------|----------------|-----------|
| Montazer                         | 0              | 0.92           | 0.93           | 0.89      |
| Besat                            | 0.87           | 0.75           | 0.82           | 1         |
| Firozi                           | 0.71           | 0.63           | 0.67           | 1         |
| Salimi                           | 0              | 1              | 1              | 1         |
| Shazand                          | 0              | 1              | 1              | 1         |
| Rajaie                           | 0              | 1              | 1              | 1         |
| Beheshti                         | 0              | 0.92           | 0.95           | 0.93      |
| Tabriz                           | 0              | 0.86           | 0.91           | 0.9       |
| Mofateh                          | 0              | 0.94           | 0.95           | 0.91      |
| Biston                           | 0              | 0.91           | 1              | 1         |
| Ramin                            | 0              | 1              | 1              | 1         |
| Medhaj                           | 0              | 0.91           | 0.91           | 0.92      |
| Bandar                           | 0.99           | 0.85           | 0.89           | 0.87      |
| Zarand                           | 0.79           | 0.69           | 0.76           | 1         |
| Esfehan                          | 0              | 1              | 1              | 1         |
| Montazeri                        | 0              | 0.94           | 1              | 1         |
| Tos                              | 0              | 0.9            | 0.95           | 0.95      |
| Mashhad                          | 0.82           | 0.71           | 0.77           | 0.86      |
| Iranshahr                        | 0              | 1              | 1              | 1         |

**Table 2: Upper bound result**

| Power plant product $\alpha = 0$ | $\alpha = 0.25$ | $\alpha = 0.5$ | $\alpha = 0.75$ | $\alpha = 1$ |
|----------------------------------|----------------|----------------|----------------|-----------|
| Montazer                         | 2.17           | 1.24           | 0.97           | 0.89      |
| Besat                            | 2.08           | 1.37           | 1.02           | 1         |
| Firozi                           | 1.06           | 0.58           | 2.3            | 1         |
| Salimi                           | 2.38           | 1.34           | 1.07           | 1         |
| Shazand                          | 2.49           | 1.48           | 1.1            | 1         |
| Rajaie                           | 2.45           | 1.4            | 1.1            | 1         |
| Beheshti                         | 2.36           | 1.33           | 1.03           | 0.93      |
| Tabriz                           | 2.22           | 1.26           | 0.98           | 0.9       |
| Mofateh                          | 2.2            | 1.26           | 0.99           | 0.91      |
| Biston                           | 2.47           | 1.42           | 1.12           | 1         |
| Ramin                            | 2.39           | 1.38           | 1.08           | 1         |
| Medhaj                           | 2.55           | 1.54           | 1.03           | 0.92      |
| Bandar                           | 2.09           | 1.2            | 0.94           | 0.87      |
| Zarand                           | 4.49           | 5.36           | 1.57           | 1         |
| Esfehan                          | 2.36           | 1.37           | 1.08           | 1         |
| Montazeri                        | 2.5            | 1.4            | 1.09           | 1         |
| Tos                              | 2.29           | 1.31           | 1.03           | 0.95      |
| Mashhad                          | 2.62           | 1.15           | 0.89           | 0.86      |
| Iranshahr                        | 2.15           | 1.24           | 0.97           | 1         |

**Table 3: Result of two method**

| Power plants | Ordinary method | Proposed method |
|--------------|-----------------|-----------------|
| Montazer     | 0.89            | 0.89            |
| Besat        | 0.88            | 1               |
| Firozi       | 0.66            | 1               |
| Salimi       | 1               | 1               |
| Shazand      | 1               | 1               |
| Rajaie       | 1               | 1               |
| Beheshti     | 0.93            | 0.93            |
| Tabriz       | 0.9             | 0.9             |
| Mofateh      | 0.91            | 0.91            |
| Biston       | 0.99            | 1               |
| Ramin        | 1               | 1               |
| Medhaj       | 0.92            | 0.92            |
| Bandar       | 0.87            | 0.87            |
| Zarand       | 0.83            | 1               |
| Esfehan      | 0.88            | 1               |
| Montazeri    | 1               | 1               |
| Tos          | 0.95            | 0.95            |
| Mashhad      | 0.81            | 0.86            |
| Iranshahr    | 0.87            | 1               |
CONCLUSION

We transformed the fuzzy CCR model into a crisp linear programming problem by applying an alternative \( \alpha \)-cut approach. Thereby, the problem was converted to an interval programming. Different methodologies have been suggested for the comparison of the intervals in this study based on Tang Cheng Method is worked. We used \( \alpha \)-cut to convert fuzzy DEA into interval programming. In proposed model, two linear programming problems were solved to obtain the efficiency of a given DMU with symmetrical triangular fuzzy number. This model is an application of fuzzy set theory in DEA.

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