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Procedia - Social and Behavioral Sciences 111 (2014) 770 – 779

Procedia
Social and Behavioral Sciences

EWGT2013 – 16th Meeting of the EURO Working Group on Transportation

Measuring transport systems efficiency under uncertainty by fuzzy sets theory based Data Envelopment Analysis

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Abstract

A crucial step in transportation planning process is the measure of systems efficiency. Many efforts have been made in this field in order to provide satisfactory answer to this problem. One of the most used methodologies is the Data Envelopment Analysis (DEA) that has been applied to a wide number of different situations where efficiency comparisons are required.
The DEA technique is a useful tool since the approach is non-parametric, and can handle many output and input at the same time.
In a lot of real applications, input and output data cannot be precisely measured. Imprecision (or approximation) may be originated from indirect measurements, model estimation, subjective interpretation, and expert judgment of available information. Therefore, methodologies that allow the analyst to explicitly deal with imprecise or approximate data are of great interest, especially in freight transport where available data as well as stakeholders' behavior often suffer from vagueness or ambiguity. This is particularly worrying when assessing efficiency with frontier-type models, such as Data Envelopment Analysis (DEA) models, since they are very sensitive to possible imprecision in the data set. The specification of the evaluation problem in the framework of the fuzzy set theory allows the analyst to extend the capability of the traditional "crisp" DEA to take into account and, thus, to represent the uncertainty embedded in real life problems. The existing fuzzy approaches are usually categorized in four categories: a) the tolerance approaches; b) the defuzzification approaches c) the α-level based approaches; d) the fuzzy ranking.
In this paper, we have explored the Fuzzy Theory-based DEA model, to assess efficiency measurement for transportation systems considering uncertainty in data, as well as in the evaluation result. In particular, the method is then applied to the evaluation of efficiency of container ports on the Mediterranean See with a sensitivity analysis in order to investigate the properties of the different approaches. The results are then compared with traditional DEA.

Keywords: container ports; DEA; fuzzy DEA; fuzzy linear programming; ports efficiency.

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doi:10.1016/j.sbspro.2014.01.111

1. Introduction

In order to support trade oriented economic development, port authorities have increasingly been under pressure to improve port efficiency by ensuring that port services are provided on an internationally competitive basis. Ports form a vital link in the overall trading chain and, consequently, port efficiency is an important contributor to a nation's international competitiveness. Thus, monitoring and comparing one's port with other ports in terms of overall efficiency has become an essential part of many countries' microeconomic reform programmes.

This study hopes to contribute to this important task by applying an innovative approach to port efficiency ratings covering a selected sample of ports based on DEA model applied in fuzzy environment.

Over the past three decades Data Envelopment Analysis (DEA) has emerged as a useful tool for business entities and organizations to evaluate their activities. Mathematically, DEA is a linear programming-based methodology for evaluating the relative efficiency of a set of decision making units (DMUs) with multi-inputs and multi-outputs. DEA evaluates the efficiency of each DMU relative to an estimated production possibility frontier determined by all DMUs. The advantage of using DEA is that it does not require any assumption on the shape of the frontier surface and it makes no assumptions concerning the internal operations of a DMU.

There are some limitations of DEA that have to be considered. Because DEA is a methodology focused on frontiers, small changes in data can change efficient frontiers significantly. Therefore, to successfully apply DEA, we have to have accurate measurement of both the inputs and outputs. However, the observed values of the input and output data in real-world problems are sometimes imprecise or vague. Imprecise evaluations may be the result of unquantifiable, incomplete or spot information.

In recent years, fuzzy set theory has been proven to be useful tool for imprecise data in DEA models. Some researchers have proposed various fuzzy methods for dealing with this impreciseness and ambiguity in DEA (Lertworasirikul, 2002). However, there is no universally accepted approach for solving the fuzzy DEA model. In this paper we used an original approach to solve DEA with imprecise data.

We measure efficiency of sixteen international container ports considering six inputs (number of cranes, number of container berths, number of tugs, terminal area, delay time and labor units) and four outputs (TEUs handled, shipcalls, shiprate, crane prod.). Delay time is fuzzy input in developed model. Membership functions are of triangular shape. Applying this new approach we solve a Fuzzy Theory-based DEA model by FUZZY LOGIC TOOLBOX (collection of functions built on the MATLAB numeric computing environment to create and edit fuzzy inference systems and models).

The rest of the paper is organized as follows. Section 2 gives a brief review of related studies which have used DEA and Fuzzy DEA techniques. Section 3 introduces DEA model and develops the Fuzzy Theory-based DEA model built using MATLAB. Section 4 presents the results of empirical study conducted on 16 international container ports. Conclusions are reported in the final section.

2. Literature review on DEA and Fuzzy DEA

Many application of DEA can be found in literature. This method has been used in several contexts including education systems, health care units, agricultural production, and military logistics. DEA has also been applied in various transport systems. A briefly literature review on studies that have applied DEA method to analyze transport systems efficiency is proposed, with particular attention to port efficiency.

Chu et al. (1992) use DEA to measure efficiency of selected bus transit systems in the United States. Roll and Hayuth (1993) first tried to use DEA model in analyzing the efficiency of container ports. They evaluated the efficiency of 20 virtual ports through DEA with 3 inputs and 4 outputs. Martinez-Budria et al. (1999) classified 26 container ports in Spain into three groups according to the level of complexity based on data from 1993 to 1997 and then evaluated the efficiency of those ports through DEA-BCC model with 3 inputs and 1 outputs.

Tongzon (2001) uses DEA to measure efficiency of four Australian and twelve international ports. Valentine and Gray (2001) also applied the DEA model with 2 inputs and 2 outputs to examine the efficiency of 31 container ports out of the world's top 100 container ports in 1998. Boile (2001) extends previous work by considering variable returns to scale. She uses DEA to measure efficiency of 23 bus transit systems. Park and De (2004) evaluated the efficiency of 11 Korean container ports with 2 inputs and 4 outputs. Park (2005) performed DEA/Window analysis on 11 Korean container terminals during the five years from 1999 to 2002. Song and Sin (2005) also evaluated the efficiency of 53 international major container ports using DEA based on data from 1995 and 2001. Cullinane and Wang (2006) use DEA for measuring the efficiency of 69 container terminals in Europe. Pjevcevic and Vukadinovic (2010) measured efficiency of bulk cargo handling at river port.

The observed values in real-world problems are often imprecise or vague. Imprecise or vague data may be the result of unquantifiable, incomplete and non obtainable information. Imprecise or vague data is often expressed with bounded intervals, ordinal (rank order) data or fuzzy numbers. In recent years, many researchers have formulated fuzzy DEA models to deal with situations where some of the input and output data are imprecise or vague. There are a relative large number of papers in the fuzzy DEA literature. Fuzzy sets theory has been used widely to model uncertainty in DEA. The applications of fuzzy sets theory in DEA are usually categorized into four groups (Lertworasirikul 2002, Lertworasirikul et al. 2003, Karsak 2008): the tolerance approach, the α-level based approach, the fuzzy ranking approach and the possibility approach. While most of these approaches are powerful, they usually have some theoretical and/or computational limitations and sometimes applicable to a very specific situation (e.g., Soleimani-damaneh et al. (2006)). The tolerance approach was one of the first fuzzy DEA models that was developed by Sengupta (1992a) and further improved by Kahraman and Tolga (1998). In this approach the main idea is to incorporate uncertainty into the DEA models by defining tolerance levels on constraint violations. The α-level approach is perhaps the most popular fuzzy DEA model. This is evident by the number of α-level based papers published in the fuzzy DEA literature. In this approach the main idea is to convert the fuzzy CCR model into a pair of parametric programs in order to find the lower and upper bounds of the α-level of the membership functions of the efficiency scores. The fuzzy ranking approach is also another popular technique that has attracted a great deal of attention in the fuzzy DEA literature. In this approach the main idea is to find the fuzzy efficiency scores of the DMUs using fuzzy linear programs which require ranking fuzzy sets. In this section, we also review a related method, called "defuzzification approach", proposed by Lertworasirikul (2002). In this approach, which is essentially a fuzzy ranking method, fuzzy inputs and fuzzy outputs are first defuzzified into crisp values. These crisp values are then used in a conventional crisp DEA model which can be solved by an LP solver. The fundamental principles of the possibility theory are entrenched in Zadeh's (1978) fuzzy set theory. In fuzzy LP models, fuzzy coefficients can be viewed as fuzzy variables and constraint can be considered to be fuzzy events. Hence, the possibilities of fuzzy events (i.e., fuzzy constraints) can be determined using possibility theory. Dubois and Prade (1988) provide a comprehensive overview of the possibility theory. Lertworasirikul (2002) have proposed two approaches for solving the ranking problem in fuzzy DEA models called the "possibility approach" and the "credibility approach."

The possibility approach deals with the uncertainty in fuzzy objectives and fuzzy constraints through the use of possibility measures. By using the possibility approach, fuzzy DEA models are transformed into well-defined possibility DEA models. The approach can avoid the problem with fuzzy ranking, and provides the flexibility to decision makers to set their own possibility levels in comparing DMUs.By using the credibility approach, fuzzy DEA models are transformed into credibility programming-DEA (CP-DEA) models. In the CP-DEA model fuzzy variables are replaced by "expected credits", which are derived by using credibility measures. The credibility approach provides an efficiency value for each DMU as a representative of its possible range. Mugera (2011) applied fuzzy DEA to compute the technical efficiency scores of 34 DMUs using the α-cut level approach. Nedeljkovic and Drenovac (2008) used fuzzy DEA, credibility approach, to measure efficiency of Serbian post offices. Nedeljković and Drenovac (2012) used fuzzy DEA, possibility approach, to measure efficiency of five Serbian post offices.

3. Formulation of the proposed methodology

In this section we investigate the DEA model, the fuzzy number and the Fuzzy Theory-based DEA model that we have developed in MATLAB for the study of port efficiencies.

DEA is a linear programming (LP) based deterministic and non-parametric method for measuring the relative efficiency of DMUs (Decision Making Units) with multiple inputs and outputs. The DEA models most widely used in practice are the CCR. The CCR model assumes constant returns to scale (CRS). DEA models can be distinguished according to whether they are input-oriented or output-oriented (i.e. either minimizing inputs for a given level of output, or maximizing output for a given level of input).

Charnes, Cooper and Rhodes(1978) extended Farrell's(1957) work in the measurement of technical efficiency and first introduced the term data envelopment analysis, known as the CCR model. Here we give a brief introduction to the model. More formally, assume that there are n DMUs to be evaluated. Each DMU consumes varying amounts of m different inputs to produce s different outputs. Specifically, DMU_j consumes amounts $X_j = [x_{ij}]$of inputs (i = 1; . . . ;m) and produces amounts $Y_j = [y_{rj}]$of outputs (r = 1; . . . ; s). The s x n matrix of output measures is denoted by Y, and the m x n matrix of input measures is denoted by X. Also, assume that $x_{ij} > 0$ and $y_{rj} > 0$. Consider the problem of evaluating the relative efficiency for any one of the n DMUs, which will be identified as DMU_0. Relative efficiency for DMU_0 is calculated by forming the ratio of a weighted sum of outputs to a weighted sum of inputs, subject to the constraint that no DMU can have a relative efficiency score greater than unity. Symbolically:

Input-oriented CCR model

$$max_{u,v} \frac{\sum_r u_r y_{r0}}{\sum_i v_i x_{i0}}$$

Subject to

$$\frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \leq 1$$

$$u_r, v_i \geq 0$$

For $j = 1,2,\ldots,n;\ u_r, v_i \geq 0\ \ for\ \ r = 1,2,\ldots,s\ and\ i = 1,2,\ldots,n$

Where u_r and v_i are weights assigned to output r and input i, respectively. This fractional programming problem can be easily transformed into the following equivalent linear programming problem:

$$max_{\ u,v} \sum_r u_r y_{r0}$$

Subject to

$$\sum_i v_i x_{i0} = 1$$

$$\sum_r u_r y_{rj} - \sum_i v_i x_{ij} \leq 0 \qquad (1)$$

$$u_r, v_i \geq 0$$

Similarly, the output-oriented CCR model can be written as follows:

$min_{u,v} \sum_i v_i x_{i0}$

Subject to

$$\sum_r u_r y_{r0} = 1 \tag{2}$$

$-\sum_i v_i x_{ij} + \sum_r u_r y_{rj} \leq 0$
$u_r, v_i \geq 0$

Input-oriented efficiency scores range between 0 and 1.0, and whereas output-oriented efficiency scores range from 1.0 to infinity, in both cases 1.0 is efficient. For the output-oriented model, we define the efficiency score as the inverse of the estimated score. The DEA model can only deal with accurate measurement of both the inputs and outputs. The observed values of the input and output data in real-world problems are sometimes imprecise or vague. Imprecise evaluations may be the result of unquantifiable, incomplete and non obtainable information. In our model we propose to specify these uncertain data as a fuzzy set (Zadeh, 1965). The concept of fuzzy set theory can incorporate the DEA model, so we can represent input or output data as fuzzy symmetrical triangular number. In fuzzy logic a crisp number belongs to a set (fuzzy set) with a certain degree of membership, named also satisfaction h. The degree of membership is defined by a ''membership function''. If there is no additional specific information, a triangular membership function can be assumed to specify the fuzzy constraint which is analytically defined by the fuzzy set depicted in Fig. 1. In fuzzy set theory, the closer to one the degree of membership is, the more the corresponding abscissa value belongs to the respective linguistic variable (fuzzy set). If the membership functions are triangular then all the fuzzy constraints considered can be expressed as inequalities and depend on the satisfaction h (Zimmermann, 1996).

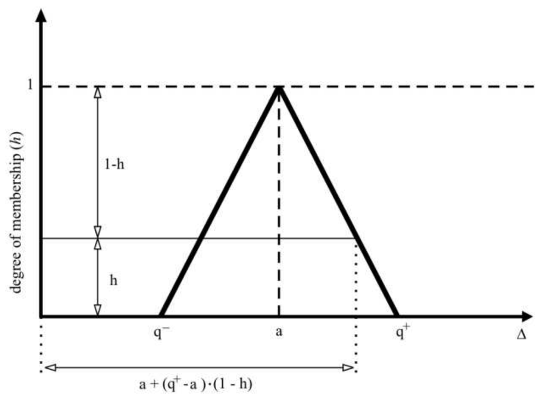

Fig. 1. Fuzzy set $\Delta \cong a$

Where Δ represents the fuzzy input (x_{ij}) or the fuzzy output (y_{rj}) that we are considering. Inequalities representing the fuzzy constraints are:

$\Delta \leq a + [(q_+ - a)(1 - h)]$

$\Delta \geq a - [(a - q_-)(1 - h)]$

The closer to one the satisfaction is, the more the constraints are fulfilled. Therefore, in order to find the optimal solution to problems (1) and (2), it is necessary to maximize the satisfaction h of the fuzzy constraints.
In fuzzy optimization, problem (1) and (2) are equivalent to the problems in Eq. (2) and (3), where the objective function to be maximized are the satisfactions h (Fig. 2-).

Fuzzy CCR model input-oriented

$Max\ h$
Subject to:

$$\begin{aligned}
&\textstyle\sum_r u_r y_{r0} \leq 1 + z(1-h) \\
&\textstyle\sum_i v_i x_{i0} = 1 \\
&\textstyle\sum_r u_r y_{rj} - \sum_i v_i x_{ij} \leq 0 \\
&u_r, v_i \geq 0 \\
&for\ i = 1, \dots m \\
&for\ r = 1, \dots s
\end{aligned} \tag{3}$$

$$\begin{cases} \sum_r u_r y_{rj} \leq a + [(q_+ - b)(1-h)] \\ \sum_r u_r y_{rj} \geq a - [(a - q_-)(1-h)] \end{cases}$$

Similarly, the fuzzy CCR model output-oriented can be written as follows:

$Max\ h$

$$\begin{aligned}
&\textstyle\sum_i v_i x_{i0} \geq h \\
&\textstyle\sum_r u_r y_{r0} = 1 \\
&-\textstyle\sum_i v_i x_{ij} + \sum_r u_r y_{rj} \leq 0 \\
&u_r, v_i \geq 0 \\
&for\ i = 1, \dots m \\
&for\ r = 1, \dots s
\end{aligned} \tag{4}$$

$$\begin{cases} \sum_r u_r y_{rj} \leq a + [(q_+ - b)(1-h)] \\ \sum_r u_r y_{rj} \geq a - [(a - q_-)(1-h)] \end{cases}$$

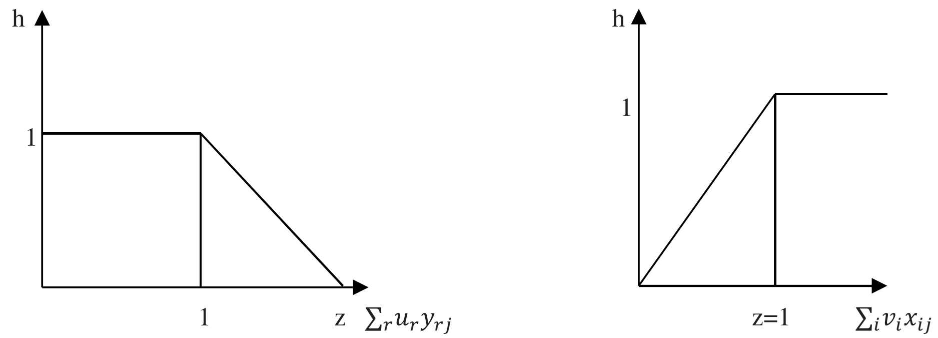

Fig. 2. Fuzzy set representing the expression ‘‘satisfactory maximization” (fuzzy CCR in. and out. oriented)

4. Numerical application

As said previously, this study examines efficiency with respect to containerized cargoes across ports recognized for their high level performance (in terms of throughput) in Asia and Europe for which data are available. Data availability is particularly important since many of the ports surveyed for data via questionnaires refused to reveal information on some aspects of their port operations due to confidentiality. Thus, apart from the data obtained from the survey, the study has to depend on secondary sources. The following are the secondary sources of data for this study: the Australian Bureau of Transport and Communications Economics (1996) survey data on four Australian ports and selected Asian and European ports for data on reliability and speed; Containerisation International Yearbook (1998) and Lloyd's Ports of the World (1998) for data on port infrastructure. The Australian Bureau of Transport and Communications Economics data on reliability and speed should be quite reliable and unbiased since these were obtained from the same shipping lines calling at the selected ports, rather than from their various port authorities or terminal operators. In this numerical application is applied the fuzzy DEA (CCR input oriented) empirical analysis for four Australian and twelve other international container ports. The outputs measures used are four: TEUs handled (the number of twenty foot container equivalent units handled), *shipcalls* (number of ship visits), *shiprate* (ship working rate which measures the number of containers moved per working hour), crane prod. (crane productivity which measures the number of containers moved per crane per working hour);. The input measures used are: *nocranes* (number of cranes), *noberths* (number of container berths), *notugs* (number of tugs), *termiarea* (terminal area), *delaytime* (delay time) and labor (proxied by the number of port authority employees).To illustrate the application of the fuzzy DEA, uncertainty is introduced in the data by representing one input (delay time) as symmetric triangular fuzzy number for five ports. The data are listed in Table 1.

Table 1. 1996 Port data

Ports	TEUs	Shipcalls	Shiprate	Crane prod	Number of cranes	Number of container berths	Number of tugs	Terminal area (m^2)	Labor (UNITS)	Delay time (h)	Spread Delay time
Melbourne	904618	823	20,8	14,8	16	12	6	1184100	829	8	30%
Hong kong	13460343	12880	45	45	64	18	24	2198300	800	5	CRISP
Hamburg	3054320	4178	37,2	19,6	52	14	25	3030000	1168	0,2	CRISP
Rotterdam	4935616	5544	32	16	66	18	15	4158000	981	1,7	CRISP
Felixstowe	2042423	2677	56,4	23,5	29	13	3	1432000	1824	0,6	CRISP
Yokohama	3911927	11908	47	47	41	20	34	1823250	472	6	CRISP
Singapore	12943900	24015	40	39,3	95	17	12	2979211	978	2,3	40%
Keelung	2320397	3144	24	24	23	14	9	339000	690	13	20%
Sydney	695312	759	22,8	13,4	14	11	3	1124500	635	9,5	CRISP
Fremantle	202680	692	13,3	12,9	5	7	5	273000	498	9	CRISP
Brisbane	249439	556	21	12,5	6	3	5	474000	200	5,5	CRISP
Tilbury	394772	347	32,8	18,2	11	4	2	519000	750	4,5	CRISP
Zeebrugge	553175	1608	36,7	26,2	16	9	5	2311100	21	1	20%
La Spezia	871100	1045	23,9	17,1	8	7	8	270000	177	3,7	CRISP
Tanjung Priok	1421693	3239	18	18	10	6	11	310000	1513	50	CRISP
Osaka	987948	2375	32	32	24	13	10	1154000	1070	4	30%

The efficiencies of ports obtained by the proposed method are reported in Table 2.

Table 2. Relative efficiency measures using the fuzzy DEA (CCR input oriented)

Ports	Efficiecy Fuzzy DEA
Melbourne	0.6003
Hong Kong	1
Hamburg	0.5114
Rotterdam	0.6795
Felixstowe	1
Yokohama	1
Singapore	1
Keelung	1
Sydney	0.6823
Fremantle	1
Brisbane	1
Tilbury	1
Zeebrugge	1
La Spezia	1
Tanjung Priok	1
Osaka	1

From Table 2, Hong Kong, Felixstowe, Yokohama, Singapore, Keelung, Fremantle, Brisbane, Tilbury, Zeebrugge, La Spezia, Tanjung Priok and Osaka are efficient while Melbourne, Hamburg, Rotterdam and Sydney are inefficient.

5. Conclusions

This study is an attempt to provide a satisfactory answer to the problem of making efficiency comparisons across ports by applying the fuzzy DEA analysis to a sample of Australian and other international ports for which relevant data are available. Fuzzy DEA has recently been successfully applied to a number of different economic efficiency measurement situations. The technique offers a significant alternative to classical econometric approaches to extracting efficiency information from sample observations, such as the use of stochastic frontier production functions. Important features of fuzzy DEA are that the technique is non-parametric and that more than one output measure can be specified. In the case of port efficiency, the ability to handle more than one output is particularly appealing because a number of different measures of port output are available, depending on which features of port operation are being evaluated. Although this study has shown the suitability of fuzzy DEA for port efficiency evaluation and produced useful findings for certain ports, there is still more scope for future investigation. The lack of access to stevedoring employment data for most of the sampled ports has constrained the fuzzy DEA analysis. It will be interesting to see how port efficiency can be attributed to stevedoring labor once complete data for this particular variable are available and this variable is incorporated into the analysis. With availability of more port data and inclusion of more ports, applying the fuzzy DEA analysis to similar ports based on a larger sample size is another interesting area for future research. Ports can be classified into various clusters in terms of size, facilities and function (i.e., whether hub or feeder ports), and only ports belonging to the same clusters are included in the port efficiency analysis (Tongzon and Ganesalingam, 1994).

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