RAIRO-Oper. Res. 52 (2018) 743–754
https://doi.org/10.1051/ro/2017001

RAIRO Operations Research
www.rairo-ro.org

A DEA MODEL TO EVALUATE BRAZILIAN CONTAINER TERMINALS

Eduardo Fagundes Costa[1,*], Lidia Angulo Meza[2] and Marcos Costa Roboredo[2]

Abstract. This study aims to evaluate the main Brazilian port terminals specialized in the operation of containers between the years 2010 and 2014. Therefore, it was applied Data Envelopment Analysis (DEA) and some of its complementary models, represented by the Cross Evaluation, in order to implement a peer-evaluation and improve the discrimination of the 100% efficient terminal; and a current model known as DEA-Game Cross Efficiency that combines DEA and Game Theory. This article proposes an adaptation to the original model, since it considers a radial output orientation, regarded as more compatible with the problem under analysis. DEA-Game was applied for the first time in port performance measurement and it was shown more suitable than the others, since the Decision Making Units (DMU) are seen from the perspective of a non-cooperative game and the results proved to be a Nash equilibrium.

Mathematics Subject Classification. 90C90, 90B30.

Received June 30, 2016. Accepted December 22, 2016.

1. Introduction

DEA has been used in several works that aims to get the efficiency of production units. One of its main advantages is the choice of multiple variables inherent to the object in question, so that they can get a more realistic overall assessment of the performance of each of these units according to the considered inputs and outputs, reflecting the characteristics and aspects of production you want to measure.

The first work relating DEA to the port sector [11] is a theoretical one. The first applied work regarding the use of DEA to assess ports that have container terminal operations [13], used actual data to evaluate 4 Australian and 12 other international ports in 1996.

Since then, a considerable amount of studies that apply this mathematical tool to the sector was held, which according [9] appears more appropriate for the evaluation of ports, not only for being a nonparametric method, but also because it doesnt require a priority relationship between inputs and outputs, keeping growing its use in work related to the port sector [15].

Additionally, it can be noted that, in Brazil, this segment is of crucial importance for the development of the country, in view of its 7408 km of border with the Atlantic Ocean (main entrance and exit of loads for the world), reflecting 95% of the country's trade by volume and 80% in value being drained by Brazilian ports.

Keywords. DEA-Game output oriented, data envelopment analysis, port efficiency.

[1] Post Graduation in Production Engineering, Fluminense Federal University, Passo da Pátria street 156, 24.210-240, Niterói/RJ, Brazil.

[2] Production Engineering Department, Fluminense Federal University, Passo da Pátria street 156, 24.210-240, Niterói/RJ, Brazil.

[*] Corresponding author: duds704@yahoo.com.br

Article published by EDP Sciences

Although the port sector presents different types of terminals with unique operating characteristics and that works with different loads, this study will be guided to the analysis of those whose main operation is container handling, considering that this type of load has a high added-value and uses standard equipments and operations, which preserve the principle of homogeneity between the selected production units.

Thus, this work aims to analyze Brazil's main container terminals from 2010 to 2014, using the DEA CCR method [2] and some of its complementary methods represented by the Cross-Evaluation [1] and DEA-Game Cross-Efficiency [6], where both allow to conduct a peer-evaluation and improve the discrimination of the 100% efficient terminal.

However, DEA-Game is a current model which considers a non-cooperative approach between the Decision Making Units (DMU) and will be applied to the port sector for the first time. This article will propose an adaptation to the original model, since it considers a radial output orientation, regarded as more compatible with the problem under analysis. Because of its characteristics, the use of DEA-Game may prove to be more suitable for this case study, as the Brazilian port sector has shown increasingly competitive, with disputes between the various terminals for new contracts with shipping companies and new leases.

The structure of the article is organized as follows: the next section presents the DEA models used and its adaptations; Section 3 presents the case study applied to 17 terminals of Brazilian containers; Section 4 makes some considerations on the results, followed by a conclusion in Section 5.

2. DEA model

2.1. CCR model

The CCR model, originally presented in [2] and transcribed below, is based on the construction of a linear surface in parts and nonparametric, which involves the data and considers constant scale returns, in other words, any variation of inputs results in a proportional variation of outputs. Its two classical forms are the Multipliers and the Envelopes models, where, in the first, the variables you want to get is the set of weights, while in the second, the decision variables allows the targets (benchmarks) for inefficient DMUs to be obtained as a results. Both models can be oriented by both input and output. In the Linear Programming Problem (LPP) (1), can be seen the CCR multipliers output oriented model, where v_i and u_j are respectively input i, $i = 1, \ldots, r$, and output j, $j = 1, \ldots, s$, weights; x_{ik} and y_{jk} are DMU_k, $k = 1, \ldots, n$ inputs i and outputs j; x_{i0} and y_{j0} are DMU_0 inputs i and outputs j.

$$(LPP)(1) \quad \min h_0 = \sum_{i=1}^{r} v_i x_{i0} \tag{2.1}$$

$$\text{subject to} \sum_{j=1}^{s} u_j y_{j0} = 1 \tag{2.2}$$

$$\sum_{j=1}^{s} u_j y_{jk} - \sum_{i=1}^{r} v_i x_{ik} \leq 0, \qquad \forall k = 1, \ldots, n. \tag{2.3}$$

$$v_i, u_j \geq 0, \qquad \forall i, j. \tag{2.4}$$

2.2. Cross-evaluation model

The Cross-Evaluation model was first developed by [12] and has as its basic premise the peer-evaluation, in other words, each DMU is evaluated according to the optimal weighting scheme from the others, allowing them to be evaluated not only for its judgment, but also from the "perspective" of all others. According [1], there are mainly two advantages of this method. It provides an ordering among DMUs, and it eliminates unrealistic weight schemes without requiring the elicitation of weight restrictions from application area experts.

Cross-Evaluation is often calculated as a two-phase process. The first phase derives individual DMU weighting schemes through traditional DEA efficiency score calculations, obtained using LPP (1). Given the results of the first phase, we could use the weights used by the DMU for itself to calculate the peer-evaluation score for each of the other DMUs, where E_{kd} is cross efficiency of DMU_d using the DMU_k weighting scheme, as can be seen in equation (2.5).

$$E_{kd} = \frac{\sum_j u_{jk} y_{jd}}{\sum_i v_{ik} x_{id}} \tag{2.5}$$

After that, once all of the peer-evaluation scores are calculated, the crossefciency score E_d for a specic DMU_d is then simply the average of the self and peer evaluations obtained in LPP (1) and equation (2.5). However, the DEA classic models can have multiple solutions, a given set of optimal weights obtained by DMUs can make some favored and other disadvantaged while evaluated with this scheme, while the applying another set of weights can change this favoring ratio.

To mitigate this problem, in the second phase, [12] proposed two secondary objective functions to be used after DMU_k selects its set of weights. More specifically, after finding the self-rated efficiency score E_{kk} for each DMU_k by solving LPP (1), this value is fixed and a set of weights is selected in order to minimize (Aggressive Formulation) or maximize (Benevolent Formulation) the cross-efficiencies of the other DMUs.

The secondary objective functions were introduced by [5, 12] in two different ways, called B_k and C_k, respectively. An empirical analysis conducted by [5] showed that the results presented by these two formulations are similar. For this reason, in this work is used just the benevolent formulation objective function C_k oriented to output, which is described in (2.6) and adapted from [5].

$$\min C_k = \frac{\sum_i \left(v_{ik} \sum_{d \neq k} x_{id} \right)}{\sum_j \left(u_{jk} \sum_{d \neq k} y_{jd} \right)} \tag{2.6}$$

Because of their orientation being to output, occurs the reversal of the objective function, which the numerator is replaced by the sum of inputs. Thus, for the benevolent formulation remains the minimization of the function, since the goal is to minimize the weighted sum of inputs of the composed DMU divided by the weighted sum of outputs of the composed DMU.

The following formulation, LPP (2), is used as the second phase for the cross-evaluation of DMU_d, highlighting that the standard E_{kk} efficiency must be previously calculated for each DMU_k and $h_{kk} = \frac{1}{E_{kk}}$. Thus, we have:

$$(LPP)(2) \ \min C_k = \sum_{i=1}^{r} \left(v_{ik} \sum_{d \neq k} x_{id} \right) \tag{2.7}$$

$$\text{subject to} \ \sum_{j=1}^{s} \left(u_{jk} \sum_{d \neq k} y_{jd} \right) = 1 \tag{2.8}$$

$$- h_{kk} \sum_{j=1}^{s} u_{jk} y_{jk} + \sum_{i=1}^{r} v_{ik} x_{ik} = 0, \tag{2.9}$$

$$\sum_{j=1}^{s} u_{jk} y_{jd} - \sum_{i=1}^{r} v_{ik} x_{id} \leq 0, \qquad \forall d \neq k. \tag{2.10}$$

$$v_{ik}, u_{jk} \geq 0, \qquad \forall i, j. \tag{2.11}$$

In the first constraint (2.8), the C_k objective function is linearized equaling the denominator to 1. Constraint (2.9) is added to the model and ensures that the set of weights found will get the same value of the DMU_k standard efficiency (E_{kk}), relating his own outputs weighted with their weighted inputs, it is presented as a simple linearization of $h_{kk} = \frac{\sum_i v_{ik} x_{ik}}{\sum_j u_{jk} y_{jk}}$. Constraints (2.10) and (2.11) are standard classic DEA requirements. Note that the adjustments made in constraints (2.8) and (2.9) are due to the reversal of the objective function, characteristic of the output orientation. After the use of the model are obtained weights sets used for the calculation of cross-efficiencies according to equation (2.5) and then is constructed Cross-Efficiency Matrix of the DMU under analysis. Finally, the average cross-efficiency of each DMU is then calculated.

2.3. DEA-Game cross efficiency model

DEA-Game was developed and presented by [6] as a further extension of DEA models. This method has, as general definition, the concept that each DMU is seen as a player who aims to maximize its efficiency, on condition that the results of cross-evaluations of other DMUs do not deteriorate, being treated by the author as a general benevolent approach. Additionally, the method uses an iterative convergence algorithm for deriving average game crossefciency scores, making use of this tool to provide unique solutions and constitutes a Nash Equilibrium, making them more reliable and beneficial to DMUs in decision-making. In a few words, the Nash Equilibrium represents a non-cooperative game involving two or more players in which none of them has anything to gain by changing only his or her strategy.

Now are described all the steps associated to application of the DEA-Game cross efficiency algorithm oriented to input following [6]. This algorithm was applied by [16] to evaluate the performance of the countries in Olympic Games and by [8] applied the algorithm to evaluate Brazilian electrical distributors efficiency. In Section 2.3.1 is proposed an adaptation of the algorithm for output orientation.

Before showing the LPP related to DEA-Game, some explanations are necessary. In a competitive scenario, a player defined as DMU_d has a value of α_d average cross-efficiency. So, another player, defined as DMU_k, attempts to maximize its own efficiency on the condition that $_d$ is not reduced. That said, the cross efficiency game definition of DMU_k on DMU_d is in equation (2.12).

$$\alpha_{dk} = \frac{\sum_{j=1}^{s} u_{jk}^d y_{jk}}{\sum_{i=1}^{r} v_{ik}^d x_{ik}}, \tag{2.12}$$

where u_{jk}^d and v_{ik}^d are the optimal weights that will be presented at LPP (3). The dk subscript indicates that DMU_k can only choose the weights which do not adversely affect the present value of the estimated average cross-efficiency for DMU_d. The main difference between the equation (2.12) and that shown in (2.5) is that the weights in (2.12) are not necessarily an optimal, but rather are a feasible solution to the CCR model. This setting allows DMUs to choose (negotiate) a set of weights (hence a form of cross-efciency scores), that are best for all of the DMUs, making an approach to a non-cooperative game to be adopted.

To calculate the d-game cross efficiency oriented to input, defined in equation (2.12) and presented in [6], is applied to each DMU_k the LPP below:

$$(LPP)(3)\ \max \sum_{j=1}^{s} u_{jk}^d y_{jk} \tag{2.13}$$

$$\text{subject to} \sum_{i=1}^{r} v_{ik}^d x_{ik} = 1 \tag{2.14}$$

$$\alpha_d \sum_{i=1}^{r} v_{ik}^d x_{id} - \sum_{j=1}^{s} u_{jk}^d y_{jd} \leq 0, \qquad \forall d \tag{2.15}$$

$$\sum_{i=1}^{r} v_{ik}^d x_{ik} - \sum_{j=1}^{s} u_{jk}^d y_{jk} \geq 0, \qquad \forall k \tag{2.16}$$

$$v_{ik}^d, u_{jk}^d \geq 0, \qquad \forall i, j. \tag{2.17}$$

The first constraint (2.14) corresponds to the linearization of the objective function (2.12), equaling the denominator to 1. Constraint (2.15) is added to the model and seeks to maximize the efficiency of DMU_k under the condition that the efficiency of DMU_d given by $\frac{\sum_{j=1}^{s} u_{jk}^{d} y_{jd}}{\sum_{i=1}^{r} v_{ik}^{d} x_{id}}$ is not less than α_d.

α_d is as a parameter whose the value is less than 1 and its initial value is the classical average cross-efficiencies DMU_d presented in Section 2.2. As the algorithm converges, the value of α_d becomes the best average game-cross efficiency, which led the authors to define the model as DEA Game d-cross-efficiency.

Constraint (2.16) is the linearization of the equation (2.12), ensuring that all efficiencies are less than or equal to 1 and constraint (2.17) ensures that the weights are positive. For each DMU_k the LPP (3) is executed n times, one for each $d = 1, \ldots, n$. Therefore, for each DMU_k, the optimum objective function value obtained from the LPP (3) is a game-cross efficiency compared to DMU_d (d-game cross efficiency), generating the optimal solution $u_{jk}^{d^*}(\alpha_d)$. Those values are used to obtain, for each DMU_k, a new value for α_k through the equation $\alpha_k = \frac{1}{n}(\sum_{d=1}^{n}\sum_{j=1}^{s} u_{jk}^{d^*}(\alpha_d)\, y_{jk})$, which is an average of the game cross-efficiency for that DMU. It should be noted that this average does not represent the values obtained in the Cross-Evaluation and the procedure to get the best value for this average is performed through convergent iterative algorithm that is discussed and detailed in [6]. All the steps necessary to adapt the DEA game cross efficiency algorithm to output orientation is described by the first time in this paper in Section 2.3.1.

2.3.1. Output oriented DEA-Game Cross Efficiency Model and solving algorithm

The contribution of this paper is the proposal of the output oriented DEA game cross efficiency algorithm. For that orientation, the LPP (3) is replaced by LPP (4) presented below:

$$(LPP)(4)\ \min \sum_{i=1}^{r} v_{ik}^{d} x_{ik} \tag{2.18}$$

$$\text{subject to } \sum_{j=1}^{s} u_{jk}^{d} y_{jk} = 1 \tag{2.19}$$

$$\sum_{i=1}^{r} v_{ik}^{d} x_{id} - \gamma_d \sum_{j=1}^{s} u_{jk}^{d} y_{jd} \leq 0, \qquad \forall d \tag{2.20}$$

$$\sum_{i=1}^{r} v_{ik}^{d} x_{ik} - \sum_{j=1}^{s} u_{jk}^{d} y_{jk} \geq 0, \qquad \forall k \tag{2.21}$$

$$v_{ik}^{d}, u_{jk}^{d} \geq 0, \qquad \forall i, j. \tag{2.22}$$

The first constraint (2.19) corresponds to the linearization of the objective function $\frac{\sum_{i=1}^{r} v_{ik}^{d} x_{ik}}{\sum_{j=1}^{s} u_{jk}^{d} y_{jk}}$, equaling the denominator to 1. Constraint (2.20) has the same purpose of its equivalent in LPP (3) and it is presented as a simple linearization of $\frac{\sum_{i=1}^{r} v_{ik}^{d} x_{id}}{\sum_{j=1}^{s} u_{jk}^{d} y_{jd}} \leq \gamma_d$, where $\gamma_d \geq 1$ indicates the inverse of the current DEA game cross efficiency of the DMU_d. Existing modifications are due to the LPP (4) is output oriented. Constraints (2.21) and (2.22) are the same shown in LPP (3).

As previously mentioned, an iterative procedure is applied to derive the average of the results obtained with cross-game efficiency, which they prove to be convergent (see [6]). For this procedure to be understood better, in Algorithm 1 will be presented their step-by-step development for the output oriented model.

As stated in "Step 1", the value used as γ_d^1 in the LPP (4) is that one obtained by averaging the Cross-Evaluations. Although already know these values are not unique, the proof of convergence of the algorithm shown in [6] concluded that any initial value obtained for γ_d will converge to unique and stable values in the game-cross efficiency, which makes the results and decisions based on DEA-game more reliable.

Algorithm 1. Output oriented DEA-Game Cross Efficiency algorithm.

Require: ϵ

Step 1: Set $t = 1$. For each DMU_d, obtain the classical cross-evaluation E_d and set $\gamma_d^t = \frac{1}{E_d}$.

Step 2: For each DMU_k and each DMU_d, solve LPP (4). Next, find for γ^{t+1} as following: $\frac{1}{\gamma_k^{t+1}} = \frac{1}{n}\left(\sum_{d=1}^{n} \frac{1}{\sum_{i=1}^{r} v_{ik}^{d^*}(\gamma_d^t) x_{ik}}\right)$, where $v_{ik}^{d^*}\left(\gamma_d^t\right)$ is the optimal value of v_{ik}^d in the LPP (4) when $\gamma_d = \gamma_d^t$. Go to step 3.

Step 3: if $\left|\frac{1}{\gamma_k^{t+1}} - \frac{1}{\gamma_k^t}\right| \geq \epsilon$ for some k, where ϵ is a small positive and predetermined value, so $\gamma_d = \gamma_d^{t+1}$ and step 2. is performed again. If $\left|\frac{1}{\gamma_k^{t+1}} - \frac{1}{\gamma_k^t}\right| < \epsilon$, for all k, then the algorithm stops and γ_k^{t+1} is the inverse of the best average game-cross efficiency of DMU_k.

3. Case study

The Brazilian port sector, despite all the attempts to adopt new policies and administrative changes over time, still did not have a consistency. In order to change this situation, it was enacted Law 12,815/2013. Its basic objective is reshaping the sector, due to the significant increase in demand for infrastructure in the country's ports and one of its fundamental guide-lines is to allow the private sector to make investments, explore and improve port facilities and, consequently, the system as a whole.

In order to analyze the initial changes obtained with the new Ports Law, were selected 17 terminals operated by the private sector in the period 2010-2014, which has as main operation the cargo handling in containers, considering that this type of load has a high added value and uses standard equipments and operations. Thus, the principle of homogeneity was preserved and compared only those DMUs that have similar production functions [4, 14].

According to the classification presented in [10], port area executives classify large container terminals as those that move up 250 thousand TEU (Twenty-foot Equivalent Unit). Therefore, each terminal in one year of operation was taken into account as a separate DMU, being considered for analysis only those operated in large scale, being dropped from the analysis year that may have fallen below this movement range, obtaining a total of 54 DMUs. Thus, the terminals considered are those of most importance for national trade and which operated on the same scale factor, reinforcing the use of the CCR model, which will be applied to the study. Of the 17 terminals, 15 are located along the Brazilian coast and two in Rio Amazonas (Manaus), as seen in Figure 1.

As for the selection of variables, were chosen three input (the terminal area, the pier length and the amount of equipment) and one output (number of containers handled in TEU), which reflect the characteristics of a port terminal, represented by the amount of moved containers with the available resources. Other variables related to human resources, financial resources, natural and artificial resources could also be used, but the difficulty of obtaining quality and accurate data on these aspects could jeopardize the reliability of the results (see [4]).

As for the orientation of the model, given the characteristics of the national container terminal sector and the nature of the study in question, where the inputs denote the infrastructure of port units and the output indicates the amount of cargo handled, the use of input orientation would not be appropriate, since it would not make much sense to reduce any of the inputs used. Thus, it was necessary to formulate the DEA model and its variations, oriented to outputs.

With regard to models used in Section 4, was applied the DEA CCR-O (LPP 1) to make a benchmark analysis and to identify those terminals that are reference for the others. The Cross-Evaluation (LPP 2) was also carried out in order to realize a peer-evaluation of all the 54 DMUs and to allow greater discrimination between the analyzed units, particularly with regard to those considered 100% efficient. This second model was already applied in other papers in the port sector [3, 7, 17]. The results of the models above were compared and the cases with greater variations between the rankings obtained on both were highlighted.

FIGURE 1. Geographical location of terminals.

Finally, DEA-Game (LPP 4) was applied for the first time to the port sector, where each terminal aims to maximize its efficiency, under condition that the results of cross-evaluations of the other terminals do not deteriorate, in other words, does neither favor nor harm the units under review. Thus, their application to Brazilian container terminals makes itself interesting, given that it is an increasingly competitive market, where the competition for new contracts with navigation companies and new leases is increasingly growing. Another aspect that is worth mentioning is the fact that, in DEA-game, the problem is analyzed in a more individual way than in Cross-Evaluation because each unit interacts in a particular way with the others. For these reasons, DEA-Game is shown a more appropriate model to be applied to the port sector, presenting different set of weights and, consequently, different results from those obtained with the Cross-Evaluation.

4. RESULTS

Table 1 shows the terminals in each year of operation in column (1). Columns (2) and (3) show the results and the rankings obtained with the DEA-Game model oriented to output using (LPP 4), that it is being used as a basis for sort the table. After that, columns (4) and (5) show the results and the rankings obtained with DEA CCR model oriented to output with Cross-Evaluation in benevolent C_k formulation (LPP 2). It is also informed the rankings and benchmarks of inefficient terminals in the CCR-Model (LPP 1), as can be seen in columns (6) and (7). Finally, the difference positions and results from the rankings of the first two models mentioned are shown in columns (8) and (9).

In the application of DEA$-$Game was adopted $\epsilon = 0.0001$, which is a positive value that establishes the time that contain the model iterations, as explained in topic 2.3.1. In this way, if any terminal presents a greater difference than or equal to 0.0001 between its value in current efficiency and that obtained in the previous

Table 1. Ranking of large terminals.

Terminal (1)	DEA-Game (2)	Ranking DEA-Game (3)	Cross-Evaluation (CE) (4)	Ranking CE (5)	Ranking CCR-O (6)	Benchmarks (7)	Diff. DEA-Game x CE (8)	Diff. DEA-Game × CE (9)
Itapoá 2014 (1)	1.000000	1	0.983786	1	1	–	0	0.01621
Itapoá 2013	0.999266	2	0.983063	2	5	1	0	0.01620
TECON SP 2013 (4)	0.992862	3	0.976579	3	1	–	0	0.01628
Super Terminais 2011 (2)	0.992019	4	0.967914	4	1	–	0	0.02411
PortoNave 2014	0.915637	5	0.893615	5	8	1, 4	0	0.02202
TCP 2012	0.911929	6	0.890921	6	7	1, 4	0	0.02101
PortoNave 2013	0.910852	7	0.888945	7	10	1, 4	0	0.02191
TCP 2013	0.903816	8	0.882994	8	9	1, 4	0	0.02082
Libra SP 2011 (3)	0.891861	9	0.785244	14	1	–	−5	0.10662
TCP 2014	0.869219	10	0.850924	10	11	1, 4	0	0.01829
TECON SP 2012	0.866009	11	0.851806	9	12	4	2	0.01420
Libra SP 2010	0.848962	12	0.747474	17	6	3	−5	0.10149
PortoNave 2012	0.836828	13	0.816702	11	15	1, 4	2	0.02013
TCP 2011	0.832180	14	0.813008	12	13	1, 4	2	0.01917
APMT 2011	0.824175	15	0.756238	16	16	1	−1	0.06794
TECON SP 2011	0.802324	16	0.789166	13	17	4	3	0.01316
PortoNave 2011	0.786842	17	0.767918	15	18	1, 4	2	0.01892
Libra SP 2012	0.767339	18	0.675608	23	14	3	−5	0.09173
APMT 2013	0.755634	19	0.693347	22	21	1	−3	0.06229
TECON SP 2014	0.753787	20	0.741425	18	25	4	2	0.01236
Embraport 2014	0.746643	21	0.712655	19	23	2, 3, 4	2	0.03399
APMT 2012	0.723570	22	0.663927	24	27	1	−2	0.05964
APMT 2010	0.723110	23	0.663504	25	28	1	−2	0.05961
BTP 2014	0.722572	24	0.697040	21	22	1, 4	3	0.02553
TECON SP 2010	0.721588	25	0.709754	20	30	4	5	0.01183
APMT 2014	0.697578	26	0.640077	28	33	1	−2	0.05750
Libra SP 2013	0.692599	27	0.609803	31	20	3	−4	0.08280
TECON RS 2014	0.690393	28	0.658324	26	19	1, 4	2	0.03207
TVV 2011	0.685929	29	0.646172	27	32	1, 2, 3	2	0.03976
TVV 2012	0.668690	30	0.629932	29	34	1, 2, 3	1	0.03876
TECON RS 2010	0.651972	31	0.621687	30	24	1, 4	1	0.03028
TECON RS 2013	0.636454	32	0.606890	32	26	1, 4	0	0.02956
TECON RS 2011	0.628405	33	0.599216	33	29	1, 4	0	0.02919
TECON RS 2012	0.621453	34	0.592586	34	31	1, 4	0	0.02887
TCP 2010	0.591520	35	0.577893	35	38	1, 4	0	0.01363
Libra SP 2014	0.583329	36	0.513596	40	36	3	−4	0.06973
Itapoá 2012	0.580707	37	0.571291	36	41	1	1	0.00942
TECON BA 2014	0.575207	38	0.527616	38	37	1, 3	0	0.04759
PortoNave 2010	0.574042	39	0.560235	37	40	1, 4	2	0.01381
TECON BA 2013	0.560566	40	0.514187	39	39	1, 3	1	0.04638
Chibatão 2014	0.551354	41	0.463174	41	35	3, 4	0	0.08818
TECON PE 2014	0.470338	42	0.454319	42	43	1, 4	0	0.01602
TECON RJ 2013	0.460659	43	0.444093	43	44	1, 4	0	0.01657
T2 − MultiRio 2012	0.439004	44	0.420936	44	46	2, 3, 4	0	0.01807
Chibatão 2013	0.430001	45	0.361229	48	42	3, 4	−3	0.06877
TECON RJ 2012	0.427796	46	0.412412	45	45	1, 4	1	0.01538
T2 − MultiRio 2013	0.424346	47	0.406881	46	49	2, 3, 4	1	0.01746
TECON PE 2011	0.415447	48	0.401298	47	48	1, 4	1	0.01415
EcoPorto 2010	0.386386	49	0.333129	51	47	1, 3	−2	0.05326
TECON PE 2010	0.369565	50	0.356978	49	52	1, 4	1	0.01259
TECON PE 2012	0.356219	51	0.344087	50	53	1, 4	1	0.01213
EcoPorto 2011	0.345571	52	0.297939	53	51	1, 3	−1	0.04763
TECON PE 2013	0.335168	53	0.323753	52	54	1, 4	1	0.01141
Chibatão 2012	0.322439	54	0.270870	54	50	3, 4	0	0.05157

* The numbers in parentheses identify the terminals shown in the column "Benchmarks".

iteration, the model must continue to be applied. For example, if a terminal in the fourth iteration was 0.87670 and 0.87650, in the fifth, the observed difference is 0.0002, then the algorithm is not interrupted. However, if the smaller difference observed in efficiency values of a terminal between the ninth and tenth iteration is: 0.87678 (9th iteration) − 0.87674 (10th iteration) = 0.00004, the algorithm is interrupted. In the case study, it was held 12 iterations.

After being observed the results in Table 1, there were some considerations regarding the terminals based on the ranking obtained with DEA−Game, highlighting the improvements or deteriorations in positions over the years, in order to identify possible external factors that were not considered in the variables used, which may have contributed to this change in their performances:

- With the start of operations of the BTP and Embraport terminals in the port of Santos, in mid−August 2013, there was a redistribution of container movements, decreasing other terminals operations already in 2014, as the case of TECON SP, Libra SP. Ecoporto terminal was not set between the large terminals in the same year;
- These terminals above, which began recently operations, along with the terminal Port of Itapoá, which began operating in July 2012, had a significant growth in a short time. In 2014, the Port of Itapoá, Embraport and BTP terminals occupied the 1st, 21th and 24th place, respectively. The reasons that led to these results were the big investment capacitsy and experience in the sector of its leaseholders, the availability of modern equipment with greater handling capacity of containers and their favored location;
- The Portonave terminal has shown a significant improvement over the years, rising from 39th (2010) to the 5th (2014) placement, resulting in a constant process of company productivity improvement and its team, with investment in equipment, training and qualification of its employees. The result: in 2014, the port broke the South American record productivity, reaching the mark of 270.4 movements per hour in container handling ship MSC Agrigento;
- The TCP terminal had a considerable improvement in the ranking, leaving the 35th in 2010 to 10th in 2014. Its growth over the years is due to the fact that TCP is gaining new customers from other ports, offering some attractive such as the expansion of the railways, now responsible for 100% of shipping containers by rail, reducing up to 15% of transport costs and thus attracting exporters in other States. On the other hand, the MultiRio terminal suffers from access infrastructure problems, cooperating with its negative results (44th in 2012 and 47th in 2013). Rail access is difficult, due to urban occupations that prevent their expansion or cause traffic to be restricted to 10 km/h; have road access, lack of investment and restructuring, considering that the terminals are located in the city center in an area of constant car and bus congestion.
- The TVV terminal, in the years when operated within the large scale terminals, remained in intermediate positions, occupying 29th and 30th position in 2011 and 2012 respectively. However, in 2013 it showed a considerable decline, moving less than 250 thousand containers (in TEU) in the following years. This decrease is due to the international ship owners scales rearrangement, in addition to the heavy rains that hit the region and the shutdowns of employees.

Then, to look specifically at the four terminals that were efficient using the CCR−O classic model (LPP 1) and, thus served as a benchmark for others, it may be noted that:

- The Port of Itapoá (2014) was the DMU which was the benchmark more times (on 36 occasions), getting the 1st place in the Cross−Evaluation and DEA−Game, where it was obtained 100% efficiency. Empirically, it can be seen that there is a consistency in the results, since the terminal which was more often reference to the others, got the first place in the two peer−evaluation (Cross−Evaluation and DEA−Game);
- TECON SP (2013) was benchmark for 33 DMUs and got the 3rd place in the two peer−evaluation;
- The Super Terminais (2011) remained in 4th place in both rankings, with benchmark in just five occasions;
- The Libra SP terminal (2011) rose from 14th in the Cross−Evaluation for 9th place in DEA−game and was on benchmark 16 occasions. As can be seen, Libra SP was the only terminal among those bechmarks in CCR−O classic model, which had a more pronounced drop in other modeling.

TABLE 2. Efficiency matrix extract and set of weights Cross−Evaluation.

	Matrix "Libra SP 11"(1)	Weights "Equipment" (2)	Weights "Terminal Area" (3)	Weights "Pier Extension" (4)	Weights "Moving Containers" (5)
APMT 10	0.62276	0.070805	0.000000	0.000000	0.058599
APMT 11	0.62276	0.070931	0.000000	0.000000	0.058704
APMT 12	0.62276	0.070806	0.000000	0.000000	0.058599
APMT 13	0.62276	0.070846	0.000000	0.000000	0.058633
APMT 14	0.62276	0.070773	0.000000	0.000000	0.058573
Chibatão 12	1.00000	0.000000	0.062728	0.018699	0.058388
Chibatão 13	1.00000	0.000000	0.062920	0.018756	0.058566
Chibatão 14	1.00000	0.000000	0.063137	0.018821	0.058768
TECON RJ 12	0.69068	0.052247	0.000000	0.008769	0.058497
TECON RJ 13	0.69068	0.052291	0.000000	0.008776	0.058546
Libra SP 11	1.00000	0.024220	0.043753	0.005289	0.059420

Table 2 partially shows the Cross−Efficiency Matrix, highlighting the Libra SP 2011, APMT, Chibatão and TECON RJ terminals cross−evaluation. Column (1) shows the cross−evaluation values of Libra SP 2011 by these terminals cited, including the self−evaluation of Libra SP 2011. In columns (2), (3), (4) and (5) is informed the weighting scheme of the variables "Equipment", "Terminal Area", "Pier Extension" and "Moving Containers" obtained in the cross−evaluation model (LLP 4).

It could be observed in Table 2 that the Libra SP 2011 terminal assessments by other DMUs not had a regular, ranging from some results with maximum efficiency (Chibatão); other regular results, with evaluation around 0.7 given by TECON RJ and other seven terminals, omitted in Table 2; and its lower performance (0.62276), to be assessed by APMT terminal. In the last case, when analyzing the assigned weights, also disclosed in Table 2, it is observed that the AMPT assigns zero weight to inputs "Area" and "Pier Extension", giving weight only "Equipment"; while Libra SP considers the three input variables, but assign greater importance to the "Area". It should be noted that the APMT has a smaller quantities of equipment, while Libra SP is one of the smaller areas of all the terminals.

Thus, the fact that Libra SP terminal (2011) is efficient in the classic DEA−CCR model (LPP 1), but show a considerable drop in the benevolent model C_k (LPP 2), can be understood by the fact that this terminal has different operating practices of some of the other evaluated terminals.

- It should be noted that the two terminals that were benchmark more often were those who obtained the best placements in DEA−Game. However, the Port of Itapoá (2013), which was in 2nd place in the Cross−Evaluation and DEA−Game, has not reached the efficiency frontier in CCR classic model and therefore not served as a benchmark for any DMU. In this analysis (CCR−O), it has ranked just behind the efficient DMUs, with 0.999266 and its benchmark was the terminal itself, only in 2014. So, it was evident that this fact was the reason it has not reached the efficiency frontier, because the Port of Itapoá (2014) showed increased movement of containers with the same amount of inputs.

Finally, there were some comparative observations on terminal behavior when applying DEA-Game and Cross-Evaluation, highlighting the following:

- In DEA-Game, all DMUs had an increase in their efficiency when compared to the results of the Cross-Evaluation. These additions represented approximately a gain of 1 to 10 percentage points in the final results of efficiency and have no type of relationship with the classification of terminals;
- Regarding the classification of the DMUs at the Cross-Evaluation and the DEA-Game, there were no significant position changes, ranging from five to none, with improvements and falls in two rankings;
- The terminal that had greater variation in the rankings was the Libra SP, which varied five positions, rising from 17th in the Cross-Evaluation for 12th in DEA-Game in 2010; from 14th to 9th in 2011; and the 23th

to the 18th in 2012. On the other hand, the TECON SP (2010) also had a range of five positions, but in this case, with a decrease from 20th place in the Cross-Evaluation to the 25th in DEA-Game;

- When analyzing the behavior of positions changes in these two rankings, from the 54 DMUs, 13 improved their position on DEA-Game (24%), 22 fell in the ranking (41%) and 19 had no change (35%). Of these 19 DMUs that did not change their positions, nine are among the top 10 in the rankings, which corresponds to approximately 47% of DMUs. Thus, it is clear that the terminals that showed the best performance in both models had a minor influence on their comparative results.

5. Conclusions

In this work, Brazilian port terminals of containers were assessed using DEA methodology. In addition, were considered for analysis only those terminals operating on large scales, which are of greater relevance to national and international trade. Thus, we tried to get a group of port terminals as homogeneous as possible, which will drive standardized loads, systematically and within a predefined range, enabling to obtain more consistent results.

DEA CCR-O was applied to have a benchmark analysis. The Cross Evaluation was also used to allow greater discrimination among the evaluated units and an analysis of the pairs was performed, in other words, all units being evaluated from the point of view of the others. The results of the above two models were compared, analyzed and highlighted in greater detail in which way the cases were greater variations between the rankings obtained on both, as in case of Libra SP terminal (2011). Empirically, it was noticed that Porto de Itapoá (2014), that was benchmark more times, was also the 1st place terminal in the Cross-Evaluation, showing a consistency in the results.

Some terminals have been successful in the CCR-classical modeling, but showed a drop in performance in the peer review. This shows that good individual performance does not translate into good ratings by other terminals, which may have different operating practices of some of the evaluated terminals.

DEA-Game methodology, introduced by [6], was used for the first time in the port sector. The article proposed an adaptation to the original model, since it considers a radial output orientation, regarded as more compatible with the problem under analysis. This method considers a non-cooperative game among terminals under analysis and the results proved to be a Nash equilibrium. So, it has shown more suitable for this case study because, nowadays, Brazilian port sector has shown increasingly competitive, with regional dispute among various terminals that are increasingly fighting for new contracts with navigation companies and new leases.

In the comparison of the Cross-Evaluation and DEA-Game models, presented in LPP (2) and LPP (4), respectively, there is an increase in efficiency values to be applied to the latter when compared to the results obtained with the first model; on the classification of the DMUs, significant changes in position were observed, ranging from improvements and declines in both rankings.

Based on the analysis of ports that showed the worst results, it was possible to identify some cases where the inefficiency of these units is characterized by demand, as the shortage of cargo as opposed to a scenario with a large supply terminals in the same region (as the case of the Embraport, BTP, TECON SP, Libra SP and EcoPorto); the limited use of the available infrastructure, coupled with low productivity levels offered, as the case of old equipment and have a low hourly rate of movement; difficulty of accessing the terminals; and other external factors, such as the case of natural disasters and labor issues.

However, it may be noted that the performance of the terminal that started operations recently (as the case of the Port of Itapoá, Embraport and BTP), in general, has been translated into good results in the rankings, influenced by the most modern equipment used in its dock operations and patio, which allow a greater amount of container handling.

Finally, as a proposal for future work, a new assessment can be carried out, because of several awards (TUP and leases) already authorized and those that are still under review by Secretariat of Ports. They can also be added to study international reference ports, allowing highlight the level of relative efficiency of national ports with international. They can add new relevant variables that characterize the sector, related both to aspects of infrastructure as superstructure of the port unit; and perform comparative studies with other methods, in order to compare the results with DEA, the differences identifying and evaluating advantages and disadvantages of each.

Acknowledgements. We acknowledge the financial support of CNPq (Brazilian Ministry of Science and Technology).

References

[1] T.R. Anderson, K. Hollingsworth and L. Inman, The fixed weighting nature of a cross-evaluation model. *J. Produc. Anal.* **17** (2002) 249–255.

[2] A. Charnes, W.W. Cooper and E. Rhodes, Measuring the efficiency of decision making units. *Europ. J. Oper. Res.* **2** (1978) 429–444.

[3] L.C.S. Cortez, L.R.d. Oliveira, E.F. Martins, I.R.D.d. Jesus and J.C.C.B. Soares de Mello, Análise de eficiência na gestão de portos públicos brasileiros em relação ao papel das autoridades portuárias. *J. Transport Literature* **7** (2012) 78–96.

[4] M.De Koster, B. Balk and W. Van Nus, On using dea for benchmarking container terminals. *Inter. J. Oper. Production Manag.* **29** (2009) 1140–1155.

[5] J. Doyle and R. Green, Efficiency and cross-efficiency in dea: Derivations, meanings and uses. *J. Operat. Res. Soc.* **45** (1994) 567–578.

[6] L. Liang, J. Wu, W.D. Cook and J. Zhu, The dea game cross-efficiency model and its nash equilibrium. *Operat. Res.* **56** (2008) 1278–1288.

[7] T.-C. Lirn and J. Guo, Analyzing ports efficiency in the asean and the vista by data envelopment analysis (dea) technique. *J. Eastern Asia Society for Transportation Studies* **9** (2011) 2129–2144.

[8] L.G. Machado, J.C C.B. Soares de Mello and M.C. Roboredo, Efficiency evaluation of brazilian electrical distributors using dea game and cluster analysis. *IEEE Latin Amer. Trans.* **14** (2016) 4499–4505.

[9] R.K. Pillania, Y.-C. Jim Wu and C.-W. Lin, National port competitiveness: implications for india. *Manag. Decision* **46** (2008) 1482–1507.

[10] L.R. Rios and A.C.G. Maçada, Analysing the relative efficiency of container terminals of mercosur using dea. *Maritime Economics and Logistics* **8** (2006) 331–346.

[11] Y. Roll and Y. Hayuth, Port performance comparison applying data envelopment analysis (dea). *Maritime Policy Manage.* **20** (1993) 153–161.

[12] T.R. Sexton, R.H. Silkman and A.J. Hogan, Data envelopment analysis: Critique and extensions. *New Directions Program Eval.* **1986** (1986) 73–105.

[13] J. Tongzon, Efficiency measurement of selected australian and other international ports using data envelopment analysis. *Transportation Research Part A: Policy and Practice* **35** (2001) 107–122.

[14] T.-F. Wang, D.-W. Song and K. Cullinane, The applicability of data envelopment analysis to efficiency measurement of container ports. In *Proc. of the International Association of Maritime Economists Conference* (2002) 13–15.

[15] P.F. Wanke, R.G. Barbastefano and M.F. Hijjar, Determinants of efficiency at major brazilian port terminals. *Trans. Rev.* **31** (2011) 653–677.

[16] J. Wu, L. Liang and Y. Chen, Dea game cross-efficiency approach to olympic rankings. *Omega* **37** (2009) 909–918.

[17] C.-H. Yeh, K. Lin, K.-K. Chen, T.-S. Cho, H.-S. Lee and M.-T. Chou, Evaluating the operating efficiency of international ports in asia: the dea/topsis approach. *J. Eastern Asia Soc. Trans. Studies* **7** (2007) 2999–3014.