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Efficiency in the environmental management of plastic wastes at Brazilian ports based on data envelopment analysis

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ABSTRACT

The aim of this study was to analyze different port areas (leased, nonleased and vessels) in terms of plastic segregation (scenario 1) and how much of this plastic is recycled (scenario 2). Data envelopment analysis was applied and the variables were total amount of solid waste and percentage of segregated plastic in relation to total solid waste (scenario 1) and amount of segregated plastics and percentage of recycled in relation to segregated plastics (scenario 2). Segregation efficiency was low (49%) in the nonleased area, but all the segregated material is recycled, suggesting that the management bottleneck in this case is waste segregation. Similar segregation results were obtained in the leased areas and vessels (36 and 35%, respectively), but recycling efficiency was greater in the former (92 and 24%, respectively).

1. Introduction

Data envelopment analysis (DEA), initially created to assess the efficiency of a teaching system, has developed rapidly through the use of increasingly accurate models (Mahdiloo et al., 2018; Kao, 2014). The technique is used to evaluate the relative efficiency of the environmental and sustainability sectors of comparable public and private industries, businesses and financial institutions (Macedo et al., 2009; Yeh et al., 2016; Haghighi et al., 2016; Zhou et al., 2016).

DEA is a comparative linear programming methodology that measures the performance and efficiency of multiple decision making units (DMUs) in a same sector, based on the ratio between inputs (available resources) and outputs (results obtained). Efficiency is determined on a scale from 0 to 1 (0 to 100%), whereby units that obtain an index of 1 are classified on the efficiency frontier (Guerreiro, 2006; Peixoto, 2013; Ehrgott et al., 2018).

A number of different models are used, all derived from the classic well-known CCR model developed by Charnes et al. (1978). It is also known as the constant returns to scale (CRS) model because it assumes constant returns to scale, whereby a change in resources (inputs) prompts a proportional change in the products (outputs) and is a measure of productive efficiency. The BCC model, also known as variable returns to scale or VRS (Sousa, 2010; Menegazzo, 2013; Peixoto, 2013), assumes variable returns to scale and disregards the proportionality between inputs and outputs, characterizing increasing, constant or decreasing returns to scale on the efficiency frontier. One of the advantages of DEA is that efficiency indices of the different DMUs can be compared, allowing individual observations to be made and optimizing the efficiency of one unit in relation to others. The production function of the most efficient DMUs is obtained to form an efficiency frontier and the efficiency of each DMU is determined based on its distance from the frontier.

The academic community has shown increasing interest in analyzing port efficiency using DEA (Table 1), largely due to its inherent methodological attributes, which are suited to the port environment (Menegazzo, 2013).

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Table 1
Studies published between 2001 and 2018 using data envelopment analysis in the port sector.

Title	Inputs	Outputs	Reference
The measurement of port efficiency using data envelopment analysis	Berth size; Investment	No. of containers; Throughput in metric tons	Valentine and Gray (2001)
Efficiency changes at major container ports in Japan: a window application of DEA	Terminal Area; No. of employees; No. of berths; No. of cranes	Cargo throughput (TEU[a])[a]	Itoh (2002)
Analisis de la eficiencia de los servicios de infraestructura em Espana: una application al trafico de contenedores	Berth size; Terminal area; No. of cranes	Cargo throughput (TEU[a]); Throughput in metric tons	Serrano and Castellano (2003)
North American container port productivity: 1984–1997	Berth size; Terminal area; No. of cranes	Cargo throughput (TEU[a])	Turner et al. (2004)
An application of DEA windows analysis to container port production efficiency	Berth size; Terminal area; No. of quay cranes; No. of straddle carriers; No. of yard cranes	Cargo throughput (TEU[a])	Cullinane et al. (2004)
Analyzing the relative efficiency of container terminals of Mercosul using DEA	No. of cranes; No. of berths; Terminal area; No. of employees; Amount of equipment	Cargo throughput (TEU[a]); Average no. of containers per hour	Rios and Maçada (2006)
Avaliação da eficiência portuária através de uma modelagem DEA	Quay length	Total number of vessels; Cargo throughput	Fontes and Mello (2006)
Uma Aplicação do Método de Data Envelopment Analysis - DEA para Medir a Eficiência Operacional dos Terminais de Contêineres	Quay length; Total area; Amount of berthing and transfer equipment	Cargo throughput (TEU[a])	Costa (2007)
Análise da eficiência dos portos da região Nordeste do Brasil baseada em Análise Envoltória de Dados	Quay length; Maximum draft	Cargo throughput (in metric tons or no. of containers)	Sousa et al. (2008)
Análise da eficiência de portos de carregamento de minério de ferro	Berth depth; Quay length; Berth width	Cargo throughput	Pires et al. (2009)
Benchmark optimization and attribute identification for improvement of container terminals	Quay length; Terminal area; Number of quay cranes; Number of transfer cranes; Number of reach stackers; Number of straddle carriers	Container throughput (TEU[a])	Sharma and Yu (2010)
Benchmarking the operating efficiency of Asia container ports	Terminal area; Number of ship-shore container gantry cranes; Number of container berths; Terminal length	Container throughput (TEUs)	Hung et al. (2010)
Analyzing port efficiency in the ASEAN and the V.I.S.T.A. by Data Envelopment Analysis (DEA) Technique	Terminal area; Length of terminal; Number of gantry crane; Number of yard crane; Number of straddle carrier	Container throughput (TEUs)	Lirn and Guo (2011)
Análise de Eficiência dos Portos Marítimos do Brasil: uma abordagem utilizando a análise envoltória de dados (DEA)	Average waiting time to berth (h); Quay length; Minimum depth of access channels	Cargo throughput; Average productivity (t/h); No. of berths	Menegazzo (2013)
Avaliação da eficiência dos portos utilizando análise envoltória de dados: estudo de caso dos portos da região nordeste do Brasil	Draft; Berth length; Static capacity (TEU[a])	No. of vessels; Cargo throughput (TEU[a]); Throughput per hour (un/h)	Sousa et al. (2013)
Environmental efficiency of ports: A Data Envelopment Analysis approach	No. of employees; Quay length; Terminal area; Energy consumed	No. of vessels; Cargo throughput; CO2 emissions	Chang (2013)
An application of centralized data envelopment analysis in resource allocation in container terminal operations	Number of quay gantry cranes; Marshalling yards; Labour; Number of hauling equipment	Container throughput (TEU)	Chang et al. (2015)
Measuring port efficiency using bootstrapped DEA: the case of Vietnamese ports	Berth length; Terminal areas; Warehouse capacity; Cargo handling equipment	Cargo throughput	Nguyen et al. (2016)
Relative Efficiencies of ASEAN Container Ports based on Data Envelopment Analysis	Max depth at berth; Size of the container yard; Length of the quays; Number of quay cranes; Number of yard cranes; Number of trucks	Annual container throughput (TEUs)	Kutin et al. (2017)

(continued on next page)

Table 1 (*continued*)

Title	Inputs	Outputs	Reference
Analysis of the Efficiency of Port Container Terminals with the Use of the Data Envelopment Analysis Method of Relative Productivity Evaluation	Quay length; Ship's draught; Number of ship-to-shore gantry cranes; Number of container yard gantry cranes; Container yard capacity (TEU)	Annual throughput of the terminal	Wiśnicki et al. (2017)
Performance evaluation of Chinese port enterprises under significant environmental concerns: An extended DEA-based analysis	Staff number; Operational costs; Fixed assets	Net profit; Cargo throughput; NOx emissions	Sun et al. (2017)
Análise da eficiência na geração de resíduos nos terminais portuários de carga geral utilizando DEA	Cargo throughput No. of berths	Amount of waste generated (metric tons)	Garcia et al. (2017)
Efficiency in Nigerian ports: handling imprecise data with a two-stage fuzzy approach	Number of employees; Number of berths; Port area; Quay length	Port traffic (ships visiting/year); Gross tonnage (tons/year); General cargo (tons/year); Dry bulk cargo (tons/year); Liquid cargo (m^3/year)	Wanke et al. (2018)
Efficiency Analysis of Mediterranean Container Ports	Total quay length; Terminal area; Number of quay gantry cranes; Number of yard gantry cranes	Container throughput (TEU[a])	Gökçek and Şenol (2018)
Evaluation of Investment Impact on Port Efficiency: Berthing Time Difference as a Performance Indicator	Number of berths; Berth length; Draft; Number of tugs; Number of quay cranes; Storage area; Labor	Berthing Time Difference (BTD[b])	Sağlam et al. (2018)
A Study on the Influence Mechanism of Port Environmental Carrying Capacity	Number of berths; Length of berths; Sewage treatment rate; Pollutant emissions; Number of environmental management practitioners	Passenger throughput; Container throughput; Per capita GDP	Li et al. (2018)
Benchmarking environmental efficiency of ports using data mining and RDEA: the case of a U.S. container ports	Number of quay cranes; Acres, berth and depth	Number of calls; Throughput and deadweight tonnage; CO_2 emissions	Park et al. (2018)
Sustainability and interactivity between cities and ports: a two-stage data envelopment analysis (DEA) approach[c]	Terminal area; Berth length; Number of quay crane	Annual container throughput	Chen and Lam (2018)

[a] TEU: Twenty Foot Equivalent Unit, the standard unit of measurement for a ship's cargo carrying capacity based on 20-foot long containers. Container throughput is the total number of containers loaded and unloaded in 20 foot equivalent units (TEUs).
[b] BTD: difference between the actual berthing time and that requested by the vessel.
[c] The variables cited in the table for this study are those related to ports. Sustainability-related variables were only used for the cities approach.

As shown in Table 1, the most widely used variables in the port sector are related to the physical (such as the number and/or length of berths, depth and/or width of access channels and terminal area) and technical infrastructure (such as the amount of equipment) as well as the amount of cargo handled (throughput). This is because most of the studies share a common objective of assessing the operational efficiency of cargo handling in the ports.

Only a small number of studies used DEA to evaluate the environmental efficiency of the ports (Chang, 2013; Sun et al., 2017; Park et al., 2018), and even fewer applied the technique specifically for waste management in port settings (Garcia et al., 2017). Garcia et al. (2017) quantified the amount of solid waste generated at ports as a function of cargo throughput and number of berths.

As such, we opted to test the methodology in question in a case study on plastic waste. This study is relevant due to the international trend of ports and countries to adopt environmental best practices and environmental certification to provide a competitive advantage, evident in the existence of the Marine Environment Protection Committee (MEPC), a branch of the International Maritime Organization (IMO) that addresses environmental issues, and international reports such as “Environmental Best Practice for Port Development: An analysis of International Approaches” (GHD, 2013).

Thus, the present study aimed to use data envelopment analysis (DEA) to comparatively assess different areas of Brazilian ports in terms of their environmental efficiency (waste sorting and recycling) in managing plastic waste and complying with the concepts and guidelines of the Circular Economy, which focuses on reintroducing waste into the supply chain (Pacheco et al., 2012; Kirchherr et al., 2017; Pomponi and Moncaster, 2017).

2. Methodology

2.1. Selecting the ports and data sources

The present study and our previous article (Gobbi et al., 2017) are part of a project supported by the Brazilian government in partnership with the Federal University of Rio de Janeiro, entitled “Conformity Program for Managing Solid Waste and Liquid Effluents at Brazilian Maritime Ports”. This project was organized in conjunction with the Special Secretariat of Ports (Ministry of Transportation, Ports and Civil Aviation), and the Federal University of Rio de Janeiro, through its International Virtual Institute on Global Change (IVIG) (Freitas et al., 2014). As such, both the ports selected and the quantitative information on the generation and disposal of plastic waste were extracted from these previous studies, along with the data collection period (2011 to 2013).

2.2. Data organization

In this study, we considered only nonhazardous plastic waste, which

Table 2
Input and output values for the nonleased area of the ports and the results obtained by SIAD software.

Port/year (DMU)	Nonleased area					
	Scenario 1		Scenario 2		Result Scenario 1	Result Scenario 2
	Input (t)	Output (%)	Input (t)	Output (%)		
Itaqui/2012	272.8	4.0	9.8	100.0	1.00	1.00
Itaqui/2013	572.7	1.0	5.4	100.0	0.25	1.00
Suape/2012	157.5	0.2	0.3	100.0	0.10	1.00
Suape/2013	118.0	1.1	1.3	100.0	1.00	1.00
Vitória/2011	994.7	0.4	4.4	100.0	0.11	1.00
		Mean			0.49	1.00

does not require special treatment before reuse or disposal (contains no chemical substances or oil). The different types of plastic waste generally produced at ports include barrels and similar containers; cups, bottles and jars (from staff canteens); equipment housings; packaging materials and films (wrappers and sacks) (Gobbi et al., 2017).

The plastic waste studied here was divided into three categories according to its origin within the port (waste-generating source). The nonleased area is the total area of the port not leased by a private company (for example, administrative offices, workshops, restaurant, first-aid station), the leased area is the total area controlled by private companies and used for their activities, also referred to as leased terminals, and the vessel source is the total number of vessels that berthed at the port and disposed of plastic waste.

2.3. Application of data envelopment analysis

DEA application involved the following three stages:

1) Defining and selecting the decision making units (DMUs);
2) Selecting the variables (inputs and outputs)
3) Software application.

Each DMU represents a port, considering the year in which data collection occurred. Given the small number of DMUs and the fact that too many variables would preclude modeling the samples via DEA (Nanci et al., 2004), a limited number of variables were used (Guerreiro, 2006).

DEA was applied to analyze port efficiency in plastic waste management using SIAD (Integrated System for Decision Support) software, version 3.0, developed by Angulo Meza et al. (2005), and available at www.uff.br/decisao.

An output-oriented BCC model was used to assess the results obtained. The input and output values were fed into the SIAD program, which automatically calculated efficiency. The resulting amounts varied from zero to one, with one representing absolute efficiency and zero absolute inefficiency. For the purposes of this study, only basic DEA modeling was used without including advanced level alternatives (weight restrictions, cross-efficiency evaluation or variable selection).

Assessments were made for each waste-generating source, considering two aspects: the efficiency of plastic waste sorting, and appropriate disposal (recycling). To that end, each port and its respective one-year data period were considered one DMU.

Two scenarios were established for each waste-generating source according to the two aspects assessed, with the following variables:

Scenario 1
Input – Total amount of solid waste (metric tons)
Output – Percentage of segregated plastics in relation to total solid waste (%)
Scenario 2
Input – Amount of plastic waste segregated (metric tons)
Output – Percentage of plastics recycled in relation to segregated plastics (%)

The goal of scenario 1 was to determine the performance and efficiency of each port in sorting and selectively collecting plastic waste, and in scenario 2, their efficiency in designating this waste for recycling.

DEA was applied to the different DMUs of the waste-generating sources for which there was sufficient or adequate data to analyze. Several ports did not have plastic waste data for the three generating sources (leased and nonleased areas and vessels) over the three-year collection period, characterizing a lack of information and precluding using these ports in the study. As a result, 5 DMUs were established for the nonleased areas (Itaqui/2012, Itaqui/2013, Suape/2012, Suape/2013, Vitória/2011); 10 for leased areas (Fortaleza/2012, Salvador/2012, Rio de Janeiro/2011, Rio de Janeiro/2012, Rio de Janeiro/2013, Itaguaí/2011, Itaguaí/2012, Santos/2012, Santos/2013, Rio Grande/2012); and 9 for vessels (Itaqui/2011, Itaqui/2012, Itaqui/2013; Natal/2012, Cabedelo/2011, Recife/2011, Salvador/2011, Rio de Janeiro/2011, Rio de Janeiro/2012).

3. Results and discussion

The data compiled were submitted to data envelopment analysis (DEA), combining the number of decision-making units (DMUs) with the variables (input and output) to assess port performance and efficiency in plastic waste management.

3.1. Nonleased area

Table 2 shows the total amount of solid waste (input) and percentage of segregated plastics in relation to total solid waste for scenario 1 and the amount of segregated plastics (input) and percentage recycled in relation to segregated plastics (output) for scenario 2 in the nonleased areas of the Itaqui (2012), Itaqui (2013), Suape (2012), Suape (2013), and Vitória (2011) ports, as well as the results obtained by SIAD software regarding their efficiency in plastic sorting (scenario 1) and designating this waste for recycling (scenario 2).

Scenario 1 indicated 100% efficiency for Itaqui port in 2012 and Suape in 2013. In 2012, Itaqui obtained a higher plastic sorting percentage when compared to the other ports studied. Itaqui (2013), Suape (2012) and Vitória (2011) were less efficient in plastic waste sorting, with 25%, 10% and 11%, respectively. This result demonstrates that Itaqui and Suape have potential to segregate all the plastic waste produced, which was not observed at the Vitória port. For scenario 1, plastic sorting efficiency increased at Suape between 2012 and 2013, but declined at Itaqui in the same period (Table 2).

The arithmetic mean of the efficiency results for all the ports and respective years in scenario 1 (plastic sorting efficiency) reached 49%, indicating the need for improvement in this management phase for nonleased areas.

In scenario 2, 100% efficiency was recorded for all the DMUs analyzed. Despite the need for improvement in plastic sorting in the

Table 3
Input and output values for the leased area of the ports and the results obtained by SIAD software.

Port/year (DMU)	Leased area					
	Scenario 1		Scenario 2		Result scenario 1	Result scenario 2
	Input (t)	Output (%)	Input (t)	Output (%)		
Fortaleza/2012	488.0	0.1	0.3	100.0	0.01	1.00
Salvador/2012	50.1	4.0	2.0	100.0	1.00	1.00
Rio de Janeiro/2011	587.0	2.0	79.0	99.7	0.45	0.99
Rio de Janeiro/2012	12,263.5	1.0	47.7	75.0	0.07	0.75
Rio de Janeiro/2013	3757.2	3.0	111.2	87.0	0.43	0.87
Itaguaí/2011	3211.0	1.0	26.4	100.0	0.15	1.00
Itaguaí/2012	4544.1	2.0	85.2	90.0	0.26	0.90
Santos/2012	11,013.9	2.0	165.7	93.0	0.16	0.93
Santos/2013	16,558.9	1.0	190.2	86.7	0.06	0.86
Rio Grande/2012	15,543.4	16.0	2528.0	93.0	1.00	0.93
		Mean			0.36	0.92

nonleased areas of the ports studied, all the segregated plastics were designated for recycling.

3.2. Leased area

Table 3 shows the amount of total solid waste (input) and percentage of segregated plastics in relation to total solid waste (output) for scenario 1, and the amount of plastic waste segregated (input) and the percentage of plastics recycled in relation to segregated plastics (output) for scenario 2 in the leased areas of the Fortaleza (2012), Salvador (2012), Rio de Janeiro (2011), Rio de Janeiro (2012), Rio de Janeiro (2013), Itaguaí (2011), Itaguaí (2012), Santos (2012), Santos (2013), and Rio Grande (2012) ports, as well as the results obtained by SIAD software.

Of the ten ports studied, the most efficient in terms of plastic sorting were Salvador (2012) and Rio Grande (2012). The highest plastic sorting percentage was recorded at Rio Grande and the lowest total solid waste generation at Salvador. Efficiency at the other eight ports varied from 1 to 45%, Fortaleza (2012) and Rio de Janeiro (2011) being the least and most efficient, respectively.

Although a comparison of the individual years in the three-year data collection period showed a significant decline (7%) in plastic sorting efficiency (scenario 1) in 2012 when compared to 2011 (45%), it increased in 2013 to almost the same percentage as 2011 (43%). This varying efficiency may be related to flawed practices and control procedures as well as inaccurate information on the waste generated and disposed of by each port.

In scenario 1, efficiency increased from 15% in 2011 to 26% in 2012 at Itaguaí port, but declined from 16% in 2012 to 6% in 2013 at Santos for the same scenario.

The arithmetic mean of the efficiency results for all the ports and respective years in scenario 1 (plastic sorting efficiency) reached 36%, indicating the need for improvement in this management phase for nonleased areas.

There was a slight decrease in efficiency in scenario 2 at the Rio de Janeiro (99% in 2011 to 87% in 2013), Santos (93% in 2012 to 86% in 2013) and Itaguaí ports (100% in 2011 to 90% in 2012), signaling the need for more careful management in this phase. Mean efficiency in scenario 2 was 92% for the 10 ports assessed, indicating more efficient management of segregated plastic disposal in the leased areas.

3.3. Vessels

Table 4 shows the amount of total solid waste (input) and percentage of segregated plastics in relation to total solid waste (output) for scenario 1, and the amount of plastic waste segregated (input) and percentage of plastics recycled in relation to segregated plastics (output) for scenario 2 on the vessels at Itaqui (2011), Itaqui (2012), Itaqui (2013), Natal (2012), Cabedelo (2011), Recife (2011), Salvador (2011), Rio de Janeiro (2011), and Rio de Janeiro (2012) ports, as well as the results obtained by SIAD software.

Itaqui (2011) was the most efficient (100%) in relation to the other ports and respective years. Among the other eight ports, Itaqui/2012 and Rio de Janeiro/2012 were the most efficient at plastic sorting, with 70 and 62%, respectively. Efficiency at the remaining ports varied from 0 to 25%. There was a significant increase in plastic sorting efficiency at Rio de Janeiro between 2011 and 2012 (38 to 62%) and a decline from 100 to 25% at Itaqui for 2011 and 2013, respectively.

The arithmetic mean of the efficiency results for all the ports in scenario 1 (plastic sorting efficiency) reached 35%, indicating the need for improvement in this management phase for vessels.

In scenario 2, Natal (2012) was evaluated as 100% efficient when compared to the other ports. Itaqui (2011) was 78% efficient in this management phase, followed by Itaqui (2012), with the other six ports exhibiting efficiency between 0 and 2%. Thus, the average efficiency in this management phase for the nine ports analyzed was 24%, the lowest among all the waste-generating sources. This indicates a significant need for improved procedures and the proper disposal of plastic waste from vessels.

Data envelopment analysis was found to be suitable for application in an environmental context to assess waste management efficiency, since the results obtained corroborate those from a previous study (Gobbi et al., 2017), which demonstrated a high level of segregated plastic recycling (even in small amounts) in leased and non-leased areas and low recycling efficiency for vessels.

4. Conclusions

Data envelopment analysis (DEA) made it possible to evaluate plastic waste management in different years for different areas of several Brazilian ports. In general, there was a substantial variation in efficiency between the years, suggesting that waste management was not maintained from year to year during the study period. This may be due to flawed practices and control procedures as well as inaccurate information on the waste generated and disposed of by each port.

According to DEA, efficiency in the plastic segregation phase was low (49%) in the non-leased area, but high in terms of designation for recycling (100%), suggesting that the segregation phase is a bottleneck in waste management. The same method showed similar efficiency indices for plastic segregation in the leased areas and vessels (36 and 35%, respectively), with far higher recycling efficiency in the leased area (92%) when compared to the vessels (24%). The lowest efficiency in the disposal (recycling) stage was recorded for vessels, whose waste is largely disposed of in sanitary landfills.

Table 4
Input and output values for the vessels and results obtained by SIAD software.

Port/year (DMU)	Vessels					
	Scenario 1		Scenario 2		Result scenario 1	Result scenario 2
	Input (t)	Output (%)	Input (t)	Output (%)		
Itaqui/2011	73.2	31.0	22.6	78.0	1.00	0.78
Itaqui/2012	84.2	22.0	18.5	38.0	0.70	0.38
Itaqui/2013	365.2	8.0	27.6	1.0	0.25	0.01
Natal/2012	93.9	1.0	1.0	100.0	0.03	1.00
Cabedelo/2011	263.9	5.0	11.8	0.0	0.16	0.00
Recife/2011	456.5	1.0	4.6	0.0	0.03	0.00
Salvador/2011	5482.0	0.0	1.6	0.0	0.00	0.00
Rio de Janeiro/2011	286.2	12.0	34.5	2.6	0.38	0.02
Rio de Janeiro/2012	1622.8	19.4	315.5	1.0	0.62	0.01
		Média			0.35	0.24

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