Container maritime transport on an international scale: data envelopment analysis for transhipment port

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Abstract

Port's performances depend on infrastructural and service characteristics. It is possible to adopt different evaluation methods to compare these performances. In this work a state of the art evaluation method to compare container ports is reported. Non-parametric methods are analysed and in particular applications of Data Envelopment Analysis (DEA) are reported. Prototypal results of DEA application for a set of Mediterranean container ports are presented.
Keywords: transhipment port, evaluation methods, DEA.

1 Introduction

Port characteristics and their possible evolutions are defined in relation to specific transportation planning dimensions [1, 2]. Respect to temporal dimension, three main commercial functions of a port can be defined: regional port, gateway, transhipment. Regional port competition regards only ports with similar external conditions. Gateway port competition regards ports with connection availability to high level of service quality railways and highways. Transhipment port competition regards ports with a hub and spoke function at intercontinental scale. Then for regional and gateway ports the competition is driven by external elements and the internal elements that define the specific port are sometime not important. The most important competition regards transhipment ports. Infrastructures and services influence competition between hub ports even if also non-material characteristics influence the challenge but in this case the weight is lower.

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Infrastructural characteristics influence port choice and often it constitutes constraints for some typologies of maritime traffic: for instance, quay depth influences transhipment traffic. Services characteristics supplied in a port, given the same infrastructural characteristics, are decisive factors in maritime travel choices.

At strategic scale evaluation concerns infrastructures investments, while at tactical scale, infrastructural characteristics can be considered constant, and then evaluation concerns principally services.

Investments evaluation is finalised to compare effects produced after implementation of infrastructures and services. Comparisons are carried out respect to one or more factors. The method generally adopted to evaluate infrastructural investments is Cost Benefit Analysis (CBA). One of limits of CBA concerns in the difficulty to consider non monetary effects. To overcome this limit, multicriteria methods can be adopted. These methods allow the comparison of effects that in some cases can be incommensurable. Most multicriteria methods require some information on preference of decision makers that are generally represented through weights. Specification of weight influences strongly results [3, 4] and in some case multicriteria is equivalent to CBA.

A different approach can be used for services. Services are modelled as a productive process characterised by a set of inputs that are combined to obtain a set of outputs. Investments, represented by means of a productive process are compared in terms of efficiency that is the capacity to transform a set of inputs into a set of outputs.

A possible method to analyse competition among ports is performance measurement that assume a relevant role in analysis of current situation and to support decision maker for possible future scenarios [5, 6].

A productive process is represented by means of a production function that is the relationship between quantity of inputs used and quantity of product resulting. A production frontier function is an extension of production function and it represents ideally maximum output obtainable with a given set of inputs [7].

Different methods to estimate efficiency are available in literature. A classification of these methods comprehends:

- parametric methods, based on the assumption that the production function of fully efficient firms is known [8]; a method is Stochastic Frontier Analysis (SFA) [9];
- non-parametric methods, based on the assumption that the production function of fully efficient firms is not known; some methods are Data Envelopment Analysis (DEA) [10] and Free Disposal Hull (FDH) [11, 12].

In this paper a DEA non-parametric method is proposed to evaluate in the same time infrastructures and services in a transhipment port. DEA was originally introduced to evaluate production efficiency in industrial systems, where inputs are labour, energy and capital resources and outputs are goods or services. Starting from Farrell’s definition of efficiency [13], the first formulation of DEA was introduced by Charnes et al. [10], it was indicated with the acronym CCR referring to author's names. This formulation was based on the hypothesis of *Constant Returns to Scale* (CRS). An extension of the CCR model, denoted with the acronym BCC, has been proposed by Banker et al. [14], in which the CRS hypothesis is removed and *Variable Returns to Scale* (VRS) (decreasing or increasing) are admitted.

DEA is based on technical efficiency concept that measures capacity of a decision unit (or in general Decision Making Unit – DMU) to realize a productive process that combines production factors (input) to obtain a product (output). Then, each DMU is represented by means of a set of one, or more, inputs and a set of one, or more, outputs.

Defining the space of input variables (R^r) and output variables (R^s), each DMU can be allocated in a point representative of his efficiency belonging to the space $R^{(r \cup s)}$.

Efficient DMUs belong to the frontier. The distance from this frontier is a measure of inefficiency of a DMU, that could be eliminated through a variation in quantity of inputs (*input-oriented*) or outputs (*output-oriented*) or both (*additive model*) [15]. Time variation of efficiency measures is considered according to different approaches. Common approaches presented in literature are: *contemporaneous approach*; *intertemporal approach*; *sequential approach*; *windows analysis* [16, 17]. These approaches differ on construction of observation set into different temporal periods.

DEA has subsequently been applied in many fields of economics and engineering [18]. The main works on transport planning regard evaluation performance of: urban transport systems [19, 20], air transport systems [21], transport system in emergency conditions [22, 23], railways systems [24, 25]. The general works regard the support decision making process in the phases of selection and ranking of alternative scenarios [26–29].

In this paper we propose to use the DEA approach to analyse the comparative effectiveness on a set of hub ports.

Each port is represented by means of a virtual productive process fed by a set of inputs that generate a set of outputs. Inputs comprehend a set of resources needed to realise infrastructures and/or services to perform functions of a transhipment port. Outputs of process comprehend two different time levels: the first level, defined properly output, comprehends products and services immediately available after investments (for instance a new higher depth quay or the cranes availability); the second level, defined outcome, comprehends effects produced by the terminal using infrastructures and services for instance annual container throughput in a port using depth quay and cranes. Starting from a set of alternative investments that can be made, DEA can be applied to compare investments represented in terms of inputs and the time level of results, output and outcome. It is possible to distinguish efficient and not efficient alternatives considering supply modification and effectiveness considering demand interception.

The paper is organized as follows. In section 2 DEA non-parametric methods are recalled, with a survey on the applications for maritime transport. In section 3 prototypal results of a DEA application for a set of container ports in

Mediterranean context are presented. In section 4 some final considerations are reported.

2 DEA in transportation planning

2.1 Definitions and notations

A transportation system is represented by means of a productive process characterised from a set of inputs that generates a set of outputs, adopting to DEA approach.

The analytic formulation of DEA is based on an efficiency measure (θ_j) of j^{th} process in terms of ratio between output (O_j) and input (I_j):

$$\theta_j = O_j / I_j \qquad (j = 1, ..., n) \tag{1}$$

The CCR form of efficiency measurement problem can be written as a set of n linear programming problems to obtain unknown weights assigned to inputs and outputs. If the goal is pursued for increasing values of output, it follows that objective function has to be maximized; otherwise, objective function has to be minimized.

In the maximizing form the j^{th} problem is expressed:

$$\underset{\mathbf{u}_j, \mathbf{v}_j}{\text{maximize}}\ \theta_j = O_j / I_j \qquad (j = 1, ..., n) \tag{2}$$

subject to:

$O_j / I_j \leq 1 \qquad (j = 1, ..., n)$

$\mathbf{u}_j \geq \mathbf{0}$

$\mathbf{v}_j \geq \mathbf{0}$

where

$O_j = \mathbf{u}_j^T \mathbf{o}_j$	is the measure of output for j^{th} process;
$I_j = \mathbf{v}_j^T \mathbf{i}_j$	is the measure of input for j^{th} process;
$\mathbf{o}_j \in R^s: (o_1, \ldots, o_s)^T$	vector of outputs;
$\mathbf{i}_j \in R^r: (i_1, \ldots, i_r)^T$	vector of inputs;
$\mathbf{u}_j \in R^s: (u_1, \ldots, u_s)^T$	vector of unknown weights for each component of outputs;
$\mathbf{v}_j \in R^r: (v_1, \ldots, v_r)^T$	vector of unknown weights for each component of inputs.

This formulation, for each j^{th} process, allows to find the set of weights, $\mathbf{u}_j$ and $\mathbf{v}_j$, that maximize the efficiency indicator, θ_j, assuming that the maximum value is equal to one.

The efficient frontier is obtained from envelopment of points representing efficient planning process. Points not belonging to the frontier represent non-efficient processes. Among the considered processes, there is at least one that is efficient. The distance from the frontier may be calculated for the inefficient points.

2.2 DEA for maritime transport system

In recent years several studies applying DEA, to evaluate efficiency of container ports have been developed in literature. These applications are referred to different set of ports at international scale, European and Mediterranean [30–33].

Input generally are: capital, for instance, in terms of number of quays for containers; labour, for instance, in terms of human resources dedicated to container traffics; port equipments, for instance, in terms of available cranes; land, for instance, in terms of surface dedicated to container terminal.

Outputs generally are: annual container throughput (TEU) or container throughput in a peak work hour; these measures represent indirectly a measure of quantity and quality of supplied services in a port.

Non-parametric methods generally applied are DEA and Free Disposal Hull (FDH). Proposed formulations are CCR, BCC input oriented, output oriented or additive model.

Classification of inputs (capital, labour, equipment and land), generally adopted in the applications of DEA to evaluate port's performances, can result not directly connected to temporal dimensions of transport planning. Using input classification, generally used in literature, a comparison of port performances in different temporal dimensions of transportation planning is complex; especially considering evolution of infrastructures and services characteristics.

A proposed classification referred to transportation planning activities comprehends: activities related to *material infrastructure* that include interventions to modify physical characteristics of transport system elements; activities related to *non-material* that include the consolidated research, learning and training, and other activities connected to telematics or Intelligent Transportation System; activities related to *equipment* that include interventions to provide operative tools that contribute to realise specific services; activities related to *management* that include interventions to manage transportation system; activities related to *governance* and *institutional* that include interventions to regulate transportation system.

Literature concerning DEA applications for container ports is classified according to the following criteria (Tab. 1):

- set of ports for which efficiency is calculated (*Set of DMU*);
- set of considered activities classified on, *material infrastructures*, non *materials*, *equipment, management*, *institutional* and *governance* (the last two are grouped in a only class), (*input*);
- set of considered output (*output*);
- DEA specification: Input Oriented (IO), Output Oriented (OO), Additive Model (AM) *(specification)*;
- DEA model CCR, BCC, FDH (*typology of model*).

3 DEA for Mediterranean container ports

In this paper an application of DEA to compare effectiveness of main transhipment container ports in the same area is presented. The application is

Table 1: Classification of literature concerning DEA applications.

Paper	Set of DMU	Input	Output	Spec.*	Typ. of model
Tongzon [34]	4 australian container ports 12 international container ports	*Material infrastructures* • Terminal area (m^2) • Number of container berths *Non – material infrastructures* • Number of stevedores *Management, institutional and governance* • Delay times *Equipment* • Number of cranes • Number of tugs	• Container throughput (TEU) • Throughput (tons)	AM	CCR
Valentine and Gray [35]	31 international container ports	*Material infrastructures* • Total quays length (m) • Container quay length (m)	• Container throughput (TEU) • Throughput (tons)		CCR
Cullinane et al. [36]	30 international container ports	*Material infrastructures* • Terminal area (m^2) • Total quays length (m) *Equipment* • Total number of cranes • Number of yard gantry • Number of straddle carriers	• Container throughput (TEU)	OO	CCR BCC
Cullinane et al. [37]	57 terminals of 28 international container ports	*Material infrastructures* • Terminal area (m^2) • Quay length (m) *Equipment* • Number of cranes • Number of yard gantry • Number of straddle carriers	• Container throughput (TEU)	IO	CCR BCC FDH
Cullinane et al. [38]	57 terminals of 28 international container ports	*Material infrastructures* • Total quays length (m) • Terminal surface (m^2) *Equipment* • Total number of cranes • Number of yard gantry • Number of straddle carriers	• Container throughput (TEU)	OO	CCR BCC
de Carvalho [39]	5 portuguese multipurpose ports	*Material infrastructures* • Investments expenses *Management, institutional and governance* • Managerial expenses	• General cargo (tons) • Ro-Ro (tons) • Container (tons) • Dry (tons) • Liquid (tons) • Number of passengers	IO	CCR BCC
Al-Eraqi et al. [40]	22 Middle East and East Africa ports	*Material infrastructures* • Distance from Hong Kong (nautical miles) • Terminal area (m^2) • Quay length (m)	• Throughput (tons) • Total ships	IO OO	CCR BCC
Ferrari and Basta ([41], [42])	8 italian container ports	*Material infrastructures* • Terminal area (m^2) • Quay length (m) • Quay depth (m)	• Container throughput (TEU)	OO	BCC

* AM: Additive Model; IO: Input Oriented; OO: Output Oriented

finalised to obtain frontier efficiency starting from available data relative to the period 2006-2008. We can use the term efficiency but, recalling the specifications before introduced, the current should be effectiveness.

Database is obtained from results of a two-year research project financed by the Italian Ministry of University and Research, whose general objective is to define guidelines for the competitiveness of the Italian transhipment ports of Gioia Tauro, Cagliari and Taranto in the euro-Mediterranean context. Other specific lines of research concern the development, and the application to the Mediterranean area, of aggregate procedures [43] and models [44] to estimate the demand variables of container maritime transport, of choice models of maritime container services and ports [45], of methods to evaluate the efficiency of container transhipment ports. During the project development, a homogeneous database, related to the main container ports in Mediterranean sea, realised. Database collects information about: infrastructural supply that comprehends available infrastructures relative to land and sea sides; services supply for container traffic, in terms of lines and frequencies that reach ports; container transport demand, expressed in terms of throughput in analysed ports (TEU).

In this paper, starting from the full database, that comprehends all ports for which homogeneous information is available, three different port subsets are considered:

- subset of container ports in which annual container throughput is more than 500.000 TEU and less than 1.000.000 TEU and that have, respect to annual container throughput, a transhipment incidence greater than 80%: Cagliari, Damietta and Taranto (Mediterranean medium transhipment ports);
- subset of container ports in which annual container throughput is more than 1.000.000 TEU and that have, respect to annual container throughput, a transhipment incidence more than 80%: Algeciras, Gioia Tauro, Marsaxlokk and Port Said (Mediterranean large transhipment ports);
- subset of container ports that have, respect to annual container throughput, a transhipment incidence more than 80%: Cagliari, Damietta and Taranto, Algeciras, Gioia Tauro, Marsaxlokk and Port Said (Mediterranean transhipment ports).

DEA exercise is applied for each port subset.

In order to represent productive process of each port, the following data are selected:

- two inputs,
  - length of quay dedicated to container traffic with depth more than 14 meters (quay length);
  - number of cranes dedicated to container traffic (cranes number);
- one output, annual quantity of TEU relative to each port (TEU/year).

DEA methods applied are relative to CCR and BCC formulations; in all cases input oriented specification is adopted.

Results are presented in aggregate form, considering the following classes:

- efficient ports with an index equal to 1 (efficient ports synthetically indicated with “E”);

- inefficient ports with an index included in the range between 0,9 and 1 (inefficient ports synthetically indicated with the symbol "***");
- inefficient ports with an efficiency index included in the range between 0,6 and 0,9 (inefficient ports synthetically indicated with the symbol "**");
- inefficient ports with an efficiency index included in the range between 0 and 0,6 (inefficient ports synthetically indicated with the symbol "*").

3.1.1 Mediterranean medium transhipment ports

Concerning the subset Mediterranean medium transhipment ports (Tab. 2):

- considering a productive process characterised by one input (cranes number) and one output (TEU/year) result that:
  - in the CCR case, Algeciras is efficient; other considered ports are inefficient;
  - in the BCC case, Algeciras and Cagliari are efficient; other considered ports are inefficient;
- considering a productive process characterised by two input (cranes number and quay length) and one output (TEU/year) result that:
  - in the CCR case, Algeciras and East Port Said are efficient; other considered ports are inefficient;
  - in the BCC Algeciras, East Port Said, Cagliari and Damietta are efficient; other considered ports are inefficient.

3.1.2 Mediterranean large transhipment ports

Concerning the subset Mediterranean large transhipment ports (Tab. 2):

- considering a productive process characterised by one input (cranes number) and one output (TEU/years) result that:
  - in the CCR case, the only one efficient port is Cagliari; other considered ports are inefficient;
  - in the BCC case, all considered ports are efficient (Cagliari, Damietta and Taranto);
- considering a productive process characterised by two input (cranes number and quay length) and one output (TEU/years) result that:
  - in the CCR case, Cagliari and Damietta are efficient; other considered ports are inefficient;
  - in the BCC case, all considered ports are efficient (Cagliari, Damietta and Taranto).

3.1.3 Mediterranean transhipment ports

Concerning the subset Mediterranean transhipment ports (Tab. 2):

- considering a productive process characterised by one input (cranes number) and one output (TEU/years) result that:
  - in the CCR case, the only one efficient port is Algeciras; other considered ports are inefficient;
  - in the BCC case, Algeciras, Gioia Tauro and East Port Said are efficient; Marsaxlokk is inefficient;

- considering a productive process characterised by two input (cranes number and quay length) and one output (TEU/years) result that:
  - in the CCR case, Algeciras and East Port Said are efficient; other considered ports are inefficient;
  - in the BCC case, Algeciras, Gioia Tauro and East Port Said are efficient; Marsaxlokk is inefficient.

Table 2: Summary of results from DEA applications.

Port	Mediterranean medium transhipment ports				Mediterranean large transhipment ports				Mediterranean transhipment ports			
	1i_1o CCR	1i_1o BCC	2i_1o CCR	2i_1o BCC	1i_1o CCR	1i_1o BCC	2i_1o CCR	2i_1o BCC	1i_1o CCR	1i_1o BCC	2i_1o CCR	2i_1o BCC
Cagliari	E	E	E	E					**	E	**	E
Damietta	**	E	E	E					*	**	**	E
Taranto	*	E	**	E					*	*	*	**
Algeciras					E	E	E	E	E	E	E	E
Gioia Tauro					***	E	***	E	***	***	***	***
Marsaxlokk					*	***	*	***	*	*	*	**
East Port Said					**	E	E	E	**	**	E	E

1i_1o: 1 input (cranes number), 1 output (TEU/year)
2i_1o: 2 inputs (cranes number, quay length), 1 output (TEU/year)
E: efficient port
***: efficiency index included in the range [0,9; 1)
**: efficiency index included in the range [0,6; 0,9)
*: efficiency index included in the range [0; 0,6)

4 Final considerations

Non-parametric methods measure efficiency of a port respect to a frontier production function that depends on the set of ports considered. This means that if set changes, then measure of efficiency can be different.

Prototypal results of DEA applications presented in this paper show that efficiency of transhipment ports varies with of DEA method, formulation and the subset of considered data. In all DEA specification analysed: considering competition among all and Mediterranean large transhipment ports, Algeciras port results efficient; in the competition among Mediterranean medium transhipment ports, Cagliari results efficient; Marsaxlokk in all set of transhipment ports results inefficient; Egyptian ports (Damietta and East Port Said) and the other Italian ports (Taranto and Gioia Tauro) have high index of efficiency considering BCC specifications. At medium term, activation of Tanger Med port in Morocco could modify relative efficiency of Mediterranean transhipment ports. At strategic scale, activation of Enfidha port in Tunisia could introduce a new element of congestion among Mediterranean ports.

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