NETWORK DATA ENVELOPMENT ANALYSIS OF CONTAINER SHIPPING LINES

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ABSTRACT
In this research a Network Data Envelopment Analysis (DEA) approach is proposed to assess the efficiency of a number of Container Shipping Lines (CSLs). Two stages are considered: one with labour, number of ships and fleet capacity as inputs, and container throughput handled as output and a second stage with the latter as input and turnover as output. A non-oriented Slacks-Based Measure of efficiency (SBM) metric is used. The approach is compared with the conventional single-process DEA. An increase in the discrimination power of the method is obtained by the use of the network DEA approach. In addition, the proposed approach not only computes an overall efficiency score for each CSL but also rates the relative efficiency of its two stages.

Keywords: Container shipping lines, Efficiency, Network DEA, SBM

1. INTRODUCTION

Data Envelopment Analysis (DEA) is a well-known non-parametric technique to assess the relative efficiency of different operating units, commonly referred to as Decision Making Units (DMUs) (Cooper et al. 2006). DEA has been applied in many sectors (education, health care, finance, sports, etc). In particular, there are many applications of DEA in transportation. Thus, DEA has been applied to railways (e.g. Hilmola 2007), airlines (e.g. Lozano and Gutiérrez 2011a), urban transit (e.g. Barros and Peypoch 2009), airports (e.g. Lozano and Gutiérrez 2011b), etc. DEA has also been extensively used to benchmark ports and container terminals (see, e.g., Tongzon 2001, Barros 2003, 2006, Park and De 2004, Lozano 2009, Cullinane and Wang 2010). Also, Managi (2007) applied DEA to estimate the productivity change of Japanese shipping firms. In spite of the importance of container traffic, which has become the fastest growing sector of maritime freight transport, (UNCTAD 2011) there are very few studies on the efficiency of Container Shipping Lines (CSLs). The interest of researchers on this topic is, however, increasing (Lun and Marlow 2011, Panayides et al. 2011).

In this research, DEA is applied to assess the efficiency of CSLs. In particular, a Network DEA approach is proposed. Conventional DEA considers a DMU as a single process assuming that this aggregate process consumes all the different inputs and produces all the different outputs. Network DEA, on the contrary, models the inner structure of the system. Different subprocesses or stages are considered and intermediate products produced and consumed within the system are identified (e.g. Färe and Grosskopf 2000, Färe et al 2007, Kao 2009, Lozano 2011). Network DEA has been applied to different transportation sector problems such as container terminals (Bichou 2011), bus routes (e.g. Sheth et al 2007), multi-mode bus transit (e.g. Yu 2008) railways (e.g. Yu and Lin 2008), airports (e.g. Yu 2010), air routes (e.g. Yu and Chen 2011) and airlines (e.g. Zhu 2011). To the best of our knowledge, no Network DEA approach to CSL operations has been previously proposed.

2. PROPOSED APPROACH

Consider the two-stage network structure shown in Figure 1. The first stage uses labour, number of ships and fleet capacity (in TEUs) as inputs, and container throughput handled as output while the second stage uses the latter as input and turnover as output. The first stage is related to the operative processes while the second is related to the commercial processes. The latter transforms the output of the physical operations (given by the container throughput) into revenue.

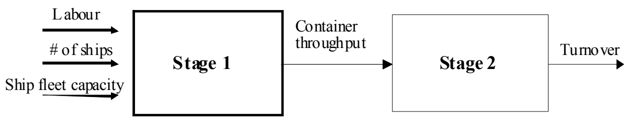

Figure 1: Two-stage network structure

A Slacks-Based Measure of efficiency (SBM) metric is used (Tone and Tsutsui 2009). Let

Stage 1 inputs

L_j Labour of CSL j

NS_j Number of ships of CSL j

FC_j	Fleet capacity of CSL j

Stage 1 output (intermediate product)

CT_j	Container throughput handled by CSL j

Stage 2 output (final product)

T_j	Turnover of CSL j

Variables

$(\lambda_1, \lambda_2, ..., \lambda_N)$	Convex-linear-combination multipliers of Stage 1
$(\mu_1, \mu_2, ..., \mu_N)$	Convex-linear-combination multipliers of Stage 2
s_0^L	Potential reduction of input L for CSL 0
s_0^{NS}	Potential reduction of input NS for CSL 0
s_0^{FC}	Potential reduction of input FC for CSL 0
s_0^T	Potential increase of output T for CSL 0
ξ_0	SBM efficiency of CSL 0

Network DEA model for assessing efficiency of CSL 0

$$\text{Min} \quad \xi_0^{NDEA} = \frac{1 - \frac{1}{3} \cdot \left(\frac{s_0^L}{L_0} + \frac{s_0^{NS}}{NS_0} + \frac{s_0^{FC}}{FC_0} \right)}{1 + \frac{s_0^T}{T_0}} \tag{1}$$

subject to

$$\sum_j \lambda_j L_j = L_0 - s_0^L \tag{2}$$

$$\sum_j \lambda_j NS_j = NS_0 - s_0^{NS} \tag{3}$$

$$\sum_j \lambda_j FC_j = FC_0 - s_0^{FC} \tag{4}$$

$$\sum_j \lambda_j CT_j = \sum_j \mu_j CT_j \geq CT_0 \tag{5}$$

$$\sum_j \mu_j T_j = T_0 + s_0^T \tag{6}$$

$$\sum_j \lambda_j = 1 \tag{7}$$

$$\sum_j \mu_j = 1 \tag{8}$$

All variables non-negative

The above model aims at maximizing the ratio of the output relative increase to the average input relative reduction. Thus, the numerator of the objective function (1) decreases with the increase in the input reductions (a.k.a. input slacks). Since some inputs may experience more reductions than others the average relative reduction is computed. The denominator of (1) is analogous in the sense that it increases as the output slack increase. In this case, since there is only one output, there is no need to use the average value (of the relative output increase).

The efficiency score computed by the proposed approach is directly related to the objective function used and therefore a CSL is assessed efficient if the model cannot find a feasible operation point with equal or less input and equal or less output. On the contrary, if the model is able to find a feasible operation point that consumes equal or less inputs and produces equal or more output than the CSL being assessed then an efficiency score less than unity is given.

The constraints limit the feasible target values for the inputs and outputs to those that lie within the corresponding Variable Returns to Scale (VRS) Production Possibility Set of each process. This is a distinct feature of Network DEA models, i.e. each process/stage has its own set of linear-combination multipliers. Constraints (5) impose, on one hand, the balance between the amounts of the intermediate product produced and consumed, which, on the other hand, should be at least equal to the observed value CT_0.

The above model is non-linear but can be linearised introducing the following variables

$$\begin{aligned} &\tau_0 > 0 \\ &\hat{\lambda}_j = \tau_0 \lambda_j \quad \forall j \\ &\hat{\mu}_j = \tau_0 \mu_j \quad \forall j \\ &\hat{s}_0^X = \tau_0 s_0^X \quad \forall X = L, NS, FC, T \end{aligned} \tag{9}$$

The resulting Linear Programming model is

$$\text{Min} \quad \xi_0^{NDEA} = 1 - \frac{1}{3} \cdot \left(\frac{\hat{s}_0^L}{L_0} + \frac{\hat{s}_0^{NS}}{NS_0} + \frac{\hat{s}_0^{FC}}{FC_0} \right) \tag{10}$$

subject to

$$\tau_0 + \frac{\hat{s}_0^T}{T_0} = 1 \tag{11}$$

$$\sum_j \hat{\lambda}_j L_j = \tau_0 L_0 - \hat{s}_0^L \tag{12}$$

$$\sum_j \hat{\lambda}_j NS_j = \tau_0 NS_0 - \hat{s}_0^{NS} \tag{13}$$

$$\sum_j \hat{\lambda}_j FC_j = \tau_0 FC_0 - \hat{s}_0^{FC} \tag{14}$$

$$\sum_j \hat{\lambda}_j CT_j = \sum_j \hat{\mu}_j CT_j \geq \tau_0 CT_0 \tag{15}$$

$$\sum_j \hat{\mu}_j T_j = \tau_0 T_0 + \hat{s}_0^T \tag{16}$$

$$\sum_j \hat{\lambda}_j = \tau_0 \tag{17}$$

$$\sum_j \hat{\mu}_j = \tau_0 \quad (18)$$

All variables non-negative

The optimal solution of the proposed Network DEA model does not only provide the estimated efficiency score of each DMU but also efficiency scores of each of its two stages as per

$$\xi_0^{Stage1} = 1 - \frac{1}{3} \cdot \left(\frac{s_0^L}{L_0} + \frac{s_0^{NS}}{NS_0} + \frac{s_0^{FC}}{FC_0} \right) \quad (19)$$

$$\xi_0^{Stage2} = \frac{1}{1 + \frac{s_0^T}{T_0}} \quad (20)$$

Moreover, the overall efficiency is the product of the efficiency of the two stages:

$$\xi_0^{NDEA} = \xi_0^{Stage1} \cdot \xi_0^{Stage2} \quad (21)$$

In order to compare the proposed approach with the conventional single-process DEA approach the corresponding linearised model is shown below. Note that a single set of convex-linear-combination multipliers is used. Note also that, in the conventional DEA approach, the CT variable is considered an output and therefore its potential relative increase is also included in the objective function.

Single-Process DEA model for CSL 0

$$\text{Min} \quad \xi_0^{SP} = 1 - \frac{1}{3} \cdot \left(\frac{\hat{s}_0^L}{L_0} + \frac{\hat{s}_0^{NS}}{NS_0} + \frac{\hat{s}_0^{FC}}{FC_0} \right) \quad (22)$$

subject to

$$\tau_0 + \frac{1}{2} \cdot \left(\frac{\hat{s}_0^T}{T_0} + \frac{\hat{s}_0^{CT}}{CT_0} \right) = 1 \quad (23)$$

$$\sum_j \hat{\omega}_j \, L_j = \tau_0 L_0 - \hat{s}_0^L \quad (24)$$

$$\sum_j \hat{\omega}_j \, NS_j = \tau_0 NS_0 - \hat{s}_0^{NS} \quad (25)$$

$$\sum_j \hat{\omega}_j \, FC_j = \tau_0 FC_0 - \hat{s}_0^{FC} \quad (26)$$

$$\sum_j \hat{\omega}_j \, T_j = \tau_0 T_0 + \hat{s}_0^T \quad (27)$$

$$\sum_j \hat{\omega}_j \, CT_j = \tau_0 CT_0 + \hat{s}_0^T \quad (28)$$

$$\sum_j \hat{\omega}_j = \tau_0 \quad (29)$$

All variables non-negative

3. RESULTS AND DISCUSSION

In this section, the results of the proposed Network DEA approach are presented and compared with those of the conventional DEA approach. The dataset used involves 15 international major CSLs with a throughput of over 10,000 TEUs and corresponds to year 2009. The research data can be found at Containerisation International (2011). The 2009 annual reports of the selected CSLs were also used. Turnover figures correspond to million US$. Table 1 shows the dataset together with some summary statistics.

Table 1: Dataset used

CSL	L	NS	FC	CT	T
MAERSK	24,500	430	1,753,996	13,800,000	19,962
CMA CGM SA	17,000	284	944,514	7,882,000	10,600
HAPAG LLOYD	6,670	112	460,241	4,637,000	6,194
COSCON	71,584	142	490,836	5,200,000	4,307
EVERGREEN LINE	4,141	167	593,443	5,815,000	2,704
APL	19,500	129	528,515	4,930,000	5,485
CSCL	4,311	121	457,648	6,700,000	3,090
OOCL	7,748	64	297,367	4,159,000	4,350
CSAV	6,972	65	194,010	1,790,500	3,028
HAMBURG SUD	4,791	90	288,297	2,300,000	4,463
KLINE	7,119	92	334,741	3,081,000	10,983
YML	4,197	82	325,828	2,780,000	2,934
HMM	2,038	52	255,643	2,510,000	5,256
WAN HAI	769	63	122,069	2,685,166	1,595
DELMAS	727	63	90,978	692,000	1,766
Mean	12,138	130.4	475,975	4,597,444	5,781
Standard dev.	17,867	101.6	412,429	3,207,943	4,810
Minimum	727	52	90,978	692,000	1,595
Maximum	71,584	430	1,753,996	13,800,000	19,962
Sum	182,067	1,956	7,138,126	68,961,666	86,718

Table 2 shows the efficiency scores computed by conventional DEA and Network DEA. For the latter, the efficiency scores of the two stages are also shown. Note that Single-Process DEA has less discriminant power overestimating efficiency and assessing almost half of the CSLs as relative efficient. On the contrary, Network DEA is more demanding: a DMU is efficient if and only if all its stages are efficient. That only happens in the case of two CSLs, namely MAERSK and DELMAS. However, it is not by chance that these two CSLs are the largest and the smallest DMUs in the sample. It is common, when VRS are assumed, that this happens. Note also that there are some CSLs with an efficiency score of unity for one of the two stages. In general, the efficiency of the stage 1 is higher than that of the second stage.

Table 2: Efficiency scores

CSL	ξ_0^{SP}	ξ_0^{NDEA}	ξ_0^{Stage1}	ξ_0^{Stage2}
MAERSK	1.000	1.000	1.000	1.000
CMA CGM SA	0.761	0.417	0.591	0.706
HAPAG LLOYD	0.797	0.304	0.602	0.504
COSCON	0.521	0.160	0.473	0.338
EVERGREEN LINE	0.639	0.146	0.716	0.204
APL	0.550	0.214	0.489	0.438
CSCL	1.000	0.221	1.000	0.221
OOCL	1.000	0.366	1.000	0.366
CSAV	0.530	0.182	0.570	0.320
HAMBURG SUD	0.555	0.202	0.428	0.472
KLINE	1.000	0.456	0.456	1.000
YML	0.494	0.138	0.462	0.299
HMM	1.000	0.599	1.000	0.599
WAN HAI	1.000	0.169	1.000	0.169
DELMAS	1.000	1.000	1.000	1.000

Figure 2 shows the cumulative frequency of the efficiency scores of the CSLs computed by the two methods. It can be readily noted that the relative efficiency scores computed by Single-Process DEA are more generous than those estimated by Network DEA. Our claim is that the latter are more valid since they have been computed using a more fine-grained approach that instead of considering a DMU as a black box distinguishes different stages.

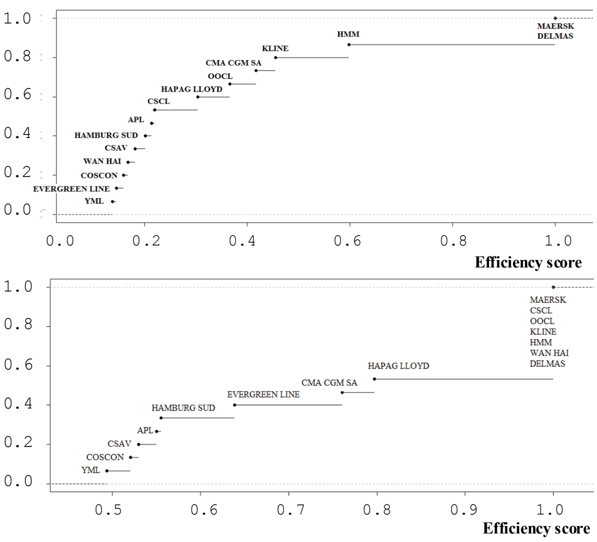

Figure 2: Cumulative distribution of efficiency scores

Table 3 shows, for the proposed Network DEA approach, the slacks (i.e. potential improvements) of the different variables as well as the sum of all of them in absolute and in relative terms. Table 4 shows the corresponding values for the Single-Process DEA. It can be noted that Network DEA is able to find more inefficiencies than conventional DEA, especially in the Turnover variable.

Table 3: Potential improvements (Network DEA)

CSL	L	NS	FC	CT	T
MAERSK	0	0	0	0	0
CMA CGM SA	9,328	112	271,052	0	4,404
HAPAG LLOYD	4,179	21	175,028	0	6,092
COSCON	68,596	43	158,565	0	8,451
EVERGREEN LINE	611	59	209,768	0	10,569
APL	16,751	34	218,812	0	7,047
CSCL	0	0	0	0	10,924
OOCL	0	0	0	0	7,536
CSAV	6,203	2	71,941	894,666	6,428
HAMBURG SUD	4,022	27	166,228	385,166	4,992
KLINE	6,001	23	179,586	0	0
YML	3,344	18	195,832	0	6,888
HMM	0	0	0	0	3,524
WAN HAI	0	0	0	0	7,861
DELMAS	0	0	0	0	0
Total	119,035	337	1,646,812	1,279,834	84,716
	65.4%	17.2%	23.1%	1.9%	97.7%

Table 4: Potential improvements (Single-Process DEA)

CSL	L	NS	FC	CT	T
MAERSK	0	0	0	0	0
CMA CGM SA	5,594	75	117,726	0	0
HAPAG LLOYD	758	8	72,656	0	1,395
COSCON	7,712	13	0	0	4,635
EVERGREEN LINE	0	59	175,110	0	1,235
APL	13,816	22	130,979	0	1,466
CSCL	0	0	0	0	0
OOCL	0	0	0	0	0
CSAV	5,520	8	0	800,324	539
HAMBURG SUD	2,753	38	32,654	210,000	793
KLINE	0	0	0	0	0
YML	2,013	26	57,168	0	2,183
HMM	0	0	0	0	0
WAN HAI	0	0	0	0	0
DELMAS	0	0	0	0	0
Total	38,165	248	586,293	1,010,324	12,244
	30.4%	12.7%	8.2%	1.5%	14.1%

4. CONCLUSIONS AND FURTHER RESEARCH

In this paper the relative efficiency of major international CSLs has been analyzed. To that end, a new Network DEA approach has been used, which is able to carry out a finer performance assessment. The proposed approach distinguishes two stages which correspond to the operations and commercial subsystems, respectively. It has been found that almost all CSLs are inefficient in one or another (or both) stages. Only two (MAERSK and DELMAS) are overall efficient. Significant capacity slacks have been found in the payroll and fleet size (both in terms of number of ships and TEU capacity). Although in some cases an increase in container throughput has also been estimated, the largest inefficiency lies in the commercial subsystem where, extending the best practices to all CSLs, a substantial (of almost 100% in average) increase in turnover would be attainable.

A limitation of this study is that it draws a static analysis of the situation, and precisely in a rather special year, in the midst of the current economic crisis. Extending the study to a longer period would allow a more complete analysis, including productivity changes. Enlarging the dataset would also help to better gauge efficiency although, as it happens often, the size of the dataset is severely restricted by data availability issues. Also, should data on additional variables (e.g. operating costs, work accidents, etc) be available a more detailed DEA model could be used.

Finally, although our claim is that the efficiency scores computed by Network DEA are more valid than those obtained by the conventional single-process DEA, such superiority cannot be proved neither on theoretical nor on empirical grounds. The claim is based on two ideas. One is that Network DEA uses more information and therefore its analysis is more fine-grained. The second idea is that Network DEA has more discriminant power than single-process DEA. Further research on this topic is warranted.

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