A two-stage supply chain DEA model for measuring container-terminal efficiency

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Abstract: Despite the growing amount of research into container-port operations and efficiency, much of the literature on the subject treats container ports and terminals as black box systems without examining the structure of their transformation and production processes. Research on the network and multi-stage structure of container-terminal operating systems is scarce and its applications in the context of port performance and benchmarking are even scarcer.

In this paper, we argue that the container terminal production would be best modelled as a network of interrelated sub-processes and operating sites and develop a supply chain DEA model aimed at capturing the transformational process within the container-terminal system and across its sub-systems. We start by modelling container terminal operations as a container-flow process and analyse their site-specific and combined efficiency before formalising a two-stage supply chain DEA model to measure the efficiencies of both individual and network container terminal operations. Although, due to the unavailability of detailed operational data, this study is limited to container export flows only, the results provide further insight on the network structure of container-terminal operating systems and confirm the existence of disproportionate performances and efficiency levels between container-terminal operating sites and sub-processes.

Keywords: container-terminals; terminal operating sites; data envelopment analysis; DEA; operational efficiency; network structure; supply chain DEA.

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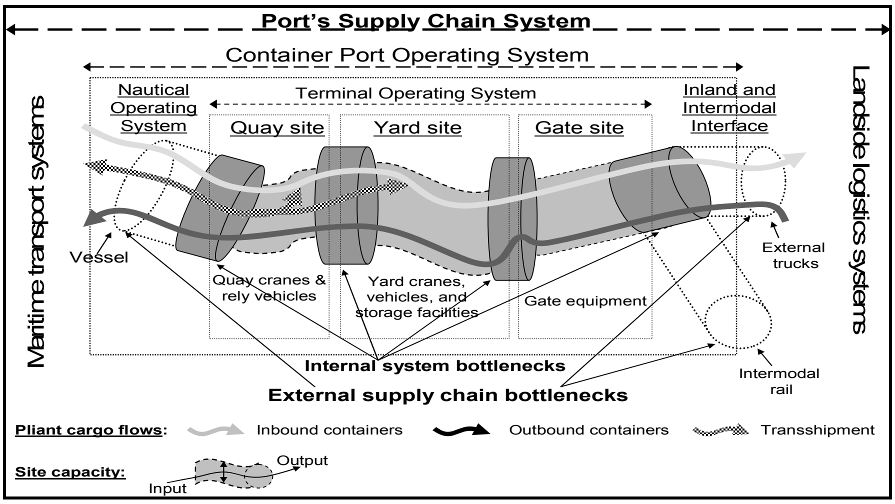
Biographical notes: Khalid Bichou is a Transport Logistics and Port Consultant and is the Co-Founder of PORTeC at Imperial College London. He has over 19 years of international experience in the industry including periods in senior positions and as consultant and advisor to public and private bodies. He has been involved in around 50 projects and advisory services in over 52 countries, and has also been active in professional training and capacity building. He has published three books and over 50 refereed academic papers and policy reports. He holds senior fellowship and visiting academic positions in several universities both in the UK and abroad.

1 Introduction

Much of the contemporary literature on container-port performance and efficiency involves the application of frontier methodologies notably the stochastic frontier analysis (SFA) and the data envelopment analysis (DEA). Both techniques attempt to construct an efficiency frontier from a set of best obtainable positions with the difference that the former relies on a stochastic specification of a distance function while the latter uses linear programming to determine the efficiency frontier. For a review of the theory and applications of the frontier methodology in container ports, see for instance Tovar et al. (2003), Wang et al. (2005), and Bichou (2009).

Nevertheless, the literature on the subject has mainly modelled port production as a black box in which inputs are transformed into outputs without examining the internal structure of the production process taking place within and across the container port system. As shown in Figure 1, modern container-terminal systems are designed and operated in terms of three main operating sites; the quay, the yard, and the gate, all of which must operate jointly for efficient cargo handling and transfer. Even though, no attempt has been made to date to model the internal structure of the container-port system in the context of performance benchmarking and we are not aware of any previous published work having developed a DEA or an SFA model aimed at capturing the transformation process within container terminals and across their sub-systems. The failure to integrate and link different terminal operating sites denotes a major gap in the container-port literature particularly for studies on performance measurement and benchmarking.

Figure 1 Illustration of operational bottlenecks in container terminal operating systems



DEA models that have attempted to model the internal structure of DMUs have been developed and applied successfully in fields other than container-port and terminal operations. Färe and Grosskopf (1996, 2000) have pioneered a line of research, coined network DEA, aimed at modelling general multi-stage processes with intermediate inputs and outputs. Their representation of the flow of products is consistent with the engineering and industrial economics literature on multi-stage systems where each internal stage's technology is modelled using a single stage DEA model. A more recent line of research has been initiated by Zhu and Seiford (2002) and Morita and Zhu (2003) and aims at developing DEA-based supply chain models to measure the aggregate efficiency of a supply chain and calculate the set of optimal values for intermediate performance measures that establish an efficient supply chain. Further literature on the specifications and applications of these models can be found in Liang et al. (2006) and Chen (2009).

This paper applies a two-stage supply chain DEA model aimed at capturing the internal structure of terminal operating processes in order to measure both the individual and aggregate performances of container terminal sites. The model presented in this paper relies on a generic representation of the network structure of container-terminal processes with a view of identifying the key performance indicators (KPIs) for variable (input and output) definition and selection. Because of the multi-directional structure of container terminal flows and the difficulty to obtain detailed and reliable operational data, the model described herein focuses on container export flows only.

The remainder of the paper is structured as follows. Section 2 provides a brief account of the DEA methodology and its applications in ports and highlights the limitations of the related port literature to understanding and incorporating the configuration technology and network structure of container-port operations. In Section 3, we formalise a two-stage supply chain DEA model for container export flows and specify the sampling frame and variables' selection. Section 4 presents the empirical results for both site-specific and supply chain efficiency estimates, while Section 5 concludes with a summary and suggestions for future research.

2 Introduction to DEA and its applications in port operations

DEA is a non-parametric approach that uses linear programming to determine (rather than estimate) the efficiency frontier. Primarily, DEA seeks to measure technical efficiency without using price and cost data or specifying a functional formulation. In an output orientation, we seek to find the maximum output that can be produced while holding the input at its current level. This is a maximisation problem, which can be solved with the following objective function:

$$
\begin{aligned}
& Max\phi_k && w.r.t && \lambda_1,\ldots,\lambda_n \\
& s.t.\sum_{j=1}^{n}\lambda_k x_{ij} - x_{ik} \le 0 && && i = 1,2,\ldots,m \\
& \phi y_{rk} - \sum_{j=1}^{n}\lambda_j y_{rj} \le 0 && && r = 1,2,\ldots,s \\
& \lambda_j \ge 0 && && j = 1,2,\ldots,n
\end{aligned}
\tag{1}
$$

where x_{ij} and y_{rj} are the respective amounts of ith input and rth output consumed and produced by decision making unit (DMU) j λj (j = 1, 2, …, n) are non-negative scalars representing input and output weights such that $\sum_{j=1}^{n}\lambda_j = 1$.

φ_k is the efficiency score to be determined for observation *k* (if $\varphi_k^* = 1$, then DMU$_k$ is a frontier point).

In equation 1 each firm or organisation, hereafter referred to as a (DMU), selects input and output weights that maximise its efficiency score and the problem is run *N* times to identify the relative efficiency scores of all DMUs. Input-oriented models can be formulated in the same way by minimising the input while holding the output constant as shown in equation (2).

$$\begin{aligned} & Min\theta_k \qquad w.r.t \qquad \lambda_1,\ldots,\lambda_n \\ & s.t.\ \ \theta x_{ik} - \sum_{j=1}^{n} \lambda_j x_{ij} \geq 0 \qquad i = 1,2,\ldots,m \\ & \quad -y_{rk} + \sum_{j=1}^{n} \lambda_j y_{rj} \geq 0 \qquad r = 1,2,\ldots,s \\ & \quad \lambda_j \geq 0 \qquad j = 1,\ldots,n \quad \text{(CCR)} \end{aligned} \tag{2}$$

The formulations in (1) and (2) are known as DEA-CCR (due to Charnes, Cooper, and Rhodes) for constant-returns to scale (CRS) but can also be expressed as a DEA-BCC model (due to Banker, Charnes and Cooper) to account for variable returns to scale (VRS) by adding the extra constraint $\sum_{j=1}^{n} \lambda_j = 1$.

DEA applications in ports are quite recent with the first attempt being attributed to Roll and Hayuth (1993). For a critical review of the use of DEA techniques in ports, see for instance Gonzalez and Trujillo (2009) and Panayides et al. (2009). The DEA literature in ports may be classified according to a-four categorisation criteria:

- between DEA-CCR models (Valentine and Gray, 2001; Tongzon, 2001) and DEA-BCC models (Martinez-Budria et al., 1999) although recent studies use both models
- between input-oriented models (Barros, 2003) and output oriented models (Wang and Cullinane, 2005)
- between applications looking at aggregate port operations (Barros and Athanassiou, 2004) and those focusing on a single port operation (Cullinane et al., 2004)
- between studies relying on DEA results solely and those complementing DEA with a second stage analysis such as regression or bootstrapping (Turner et al., 2004; Bonilla et al., 2002).

However, despite the growing amount of DEA applications to port efficiency, a review of the contemporary literature on the subject shows a great degree of discrepancy and inconsistent results across researchers and fields. This is typically the case when analysing the relationships between port's size and efficiency (Martinez-Budria et al., 1999 *versus* Coto-Millan et al., 2000), ownership structure and efficiency (Estache et al., 2004 *versus* Cullinane et al., 2002), and locational/logistical status and efficiency (Liu, 1995 *versus* Tongzon, 2001). What's more, much of the DEA applications on container-port efficiency seem to be incompatible with the operating environment of modern container ports and terminals, particularly with regard to ports' network structure, their handling systems and operating procedures. In the followings, we highlight some of the shortcomings of the contemporary DEA port literature with a view of understanding and incorporating the operating configurations and network structure of container ports and terminals:

- One of the main limitations of the DEA literature on container-port performance is that the variations in port operating configurations and technologies are hardly captured in variable's definition and selection. Take for instance the handling equipment and operating typologies for container-terminal operations. Most authors include the number of quay and yard cranes as standard variables in the input set, but only few of them have incorporated the variations in crane's performance and technology. As evidenced both in practice and through empirical research, different sea-to-shore (STS) cranes depict different performance and technology features. STS cranes' productivity varies greatly depending on the crane's type (single *vs.* dual cycles, twin *vs.* tandem lifts, etc.) and generation (panamax, post-panamax, super-post panamax, etc.) (see Table 1). Furthermore, several field studies show that STS cranes' productivity per hour varies greatly across different types of crane generations.
- In a similar vein, container yard configurations depict a variety of cargo handling and stacking typologies (the tractor chassis system, the straddle carrier direct system, the straddle carrier relay system, the rubber-tired gantry -RTG- system, the rail-mounted gantry -RMG- , etc.), each with a different performance and technology feature (see for instance Table 2).
- Even with similar quay and yard handling systems, port operators may design and implement different operating procedures. The latter include operating policies and work procedures such as opening and service hours (for quay, gate, and/or terminal operations), yard storage policies, strategies for segregation and retrieval, gate-in and gate-out arrangements, cut-off times for loading and late containers, procedures for container checking and inspection, and safety and security rules. Nevertheless, despite the significant impact of terminal procedures on port system's design and operations (Silberholz et al., 1991; Taleb-Ibrahimi et al., 1993), terminal procedures are largely overlooked by port researchers especially in studies on container-port efficiency and performance benchmarking.
- Last, but not least, and as shown in Figure 1 above, the production process of container-terminal operations may be decomposed into three generic sub-processes or operating sites; namely the quay (or the berth), the yard, and the gate; all of which must operate jointly for efficient cargo handling and transfer. Further examination of the transformational process of container terminal production reveals the existence of many critical processes or bottlenecks whereby the performance and capacity of one site is a binding constraint for the performance of another site, for instance when a specific site or sub-process is working fully while concurrent ones are underutilised or operated inefficiently.

Table 1 Relationship between container-ship size and requirements for STS cranes

Container-ship's size and generation	*Panamax*	*Post panamax*	*Super-post panamax*	*Super-post panamax plus*	*Ultra-large container ships -ULCS-*	
					Suez max	*Malacca-max*
	3rd generation	*4th generation*	*5th generation*	*6th generation*	*On-order*	*Concept-design*
TEU capacity	3,000–4,000	4,000–6,000	6,000–8,000	8,000–12,000	13,000–15,000	16,000–20,000
Ship draft (m)	11–12	12–14	13.5–14.5	15–16	16–18	18–21
Ship beam (m)	30–32	33–40	40–45	43–50	50–60	55–60
Container rows	Up to 13	13–16	16–18	18–22	22–23	≥ 24
Corresponding requirements for container quay cranes (typical average values)						
Outreach (m)	35–42	44–47	50–55	55–65	70	Over 70
Gage (m)	15	30.5	30.5	30.5	30.5	30.5
Back-reach (m)	9.1	15.2	20	22	23	23
Capacity (LT)	30	40	50	60	65	65

Notes: Data compiled from the top six global quay crane manufacturers: ZPMC, SPMP, Liebherr, Paceco, Kalmar, and Noell

Source: Cargo Systems (2008a)

Table 2 Operational characteristics of major container yard handling systems

System features	*Tractor chassis systems (wheeled operations)*	*Straddle carrier (SC) systems*		*Yard gantry systems*	
		Direct	*Relay*	*RTG*	*Rail-Mounted Gantry (RMG)*
Equipment	Tractor-chassis sets throughout the terminal	Straddle carriers (quay transfer + yard operations + gate)	Tractor-trailer sets (quay transfer) + straddle carriers (yard) + combination at gate	Tractor-trailer sets (quay transfer) + RTG (yard) + lift truck at gate	Tractor-trailer or SC sets (quay transfer) + RMG (yard) + lift truck at gate. RMG may be used for rail gate operations
Average stacking height*	1	1 over 2 (up to 1 over 3)	1 over 2 (up to 1 over 3)	1 over 6 (up to 1 over 7)	1 over 6 (up to 1 over 7)
Average width (by number of container rows)	N/A	1 to 2 wide	1 to 2 wide	6 to 7 wide	9 to 11 wide
Practical storage capacity (TEU/hectare)	250	500 (based on 1 over 2) 750 (based on 1 over 3)	500 (based on 1 over 2) 750 (based on 1 over 3)	1,000 (based on 1 over 4)	1,100 (based on 1 over 4)
Land utilisation	Very low	High	High	Very high	Very high
Operating factor#	Good accessibility Low damage Labour intensive, but no requirement for skilled labour Scope for full automation possible	High flexibility Good stacking features Low labour usage Suits smaller or odd shaped terminal yards	High flexibility Good stacking features Low labour usage Less investment needed than direct system	Good flexibility – can move between stacks Low labour usage but requires highly skilled labour Scope for partial automation	Limited flexibility – cannot move between stacks Low labour usage but requires highly skilled labour Scope for partial automation
Terminal development costs	Very low	Medium	Medium	High	High
Equipment cost	Low	Medium	Low to medium	High	Very high

Notes: Data compiled from the top six global yard crane manufacturers: ZPMC, Kone cranes, Kalmar, Riggianne, FELS Crane, and Liebherr
*Excludes staking heights for empties, which can be up to one over eight depending on the equipment.
#Some modern RTG and RMG cranes offer tandem/twin lifting capabilities. They can also be automated, either partly or fully.

Source: Cargo Systems (2008b)

In this paper, container terminal production is first modelled as a network of interrelated sub-processes in order to test whether disproportionate efficiency levels exist between site-specific and overall terminal operations. We then formalise and apply a two-stage supply chain DEA model for container export flows with a view to measuring the efficiencies of both individual and network terminal operations.

3 Formalising the methodology

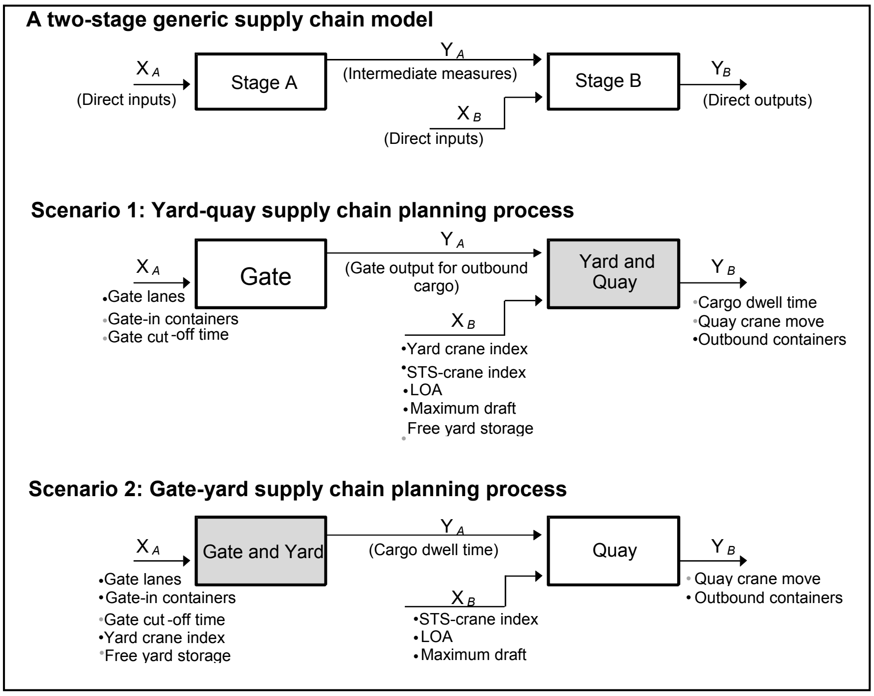
3.1 Supply chain DEA

Based on the above discussion, DEA applications into container-port efficiency must be conducted in terms that fit the network structure of container-terminal processes and integrate the differences in their operating configurations and handling systems. A container terminal would therefore be best modelled as a network of interrelated sub-processes. However, the complexity of the container-flow process and the unavailability of relevant data usually act against developing an applicable network DEA model capable of capturing the complex network structure of container terminals:

- The internal structure of container terminals depicts neither a serial multi-stage flow nor a hierarchical supply chain process through which the product passes forward, but is composed instead of several operating sites linked to each other by multi-directional and simultaneous container flows and processes.
- The linkages of inputs and outputs between the stages are not always evident to define, in particular when one subsystem's efficiency must be improved at the expense of efficiency deterioration in another subsystem.
- The typology of container terminal operations and procedures is not identical across world ports to allow a global benchmarking analysis based on network modelling. In particular, the planning, execution and coordination of work schedules across different terminal sites largely depend on the details of operational constraints, cargo mix, and planning strategy at the level of each container port or terminal.

Nevertheless, while it is not practical to model the network structure of aggregate terminal operations, it is still possible to model the network technology for either import or export related processes subject to relevant data being available at both terminal and site levels. In our case, detailed operational export data was made available to us by ten container terminals (see next section). As shown in Figure 2, we present the container export flow in terms of a two-stage supply chain process with two supply chain planning scenarios: the first aggregates the gate and the yard as a single process while the second aggregates the yard and the quay as a single process. The use of a two-stage process instead of a three-stage process is dictated by the unavailability of relevant data at the level of each site. Port and terminal operators do not usually collect such detailed data or simply consider them too confidential to be shared with outside organisations. Furthermore, the aggregation in terms of gate and yard sites versus yard and quay sites is consistent with the industry's planning and operations practices for export containers. Under standard container-terminal operations, outbound containers passing through the gate are either indiscriminately assigned to available yard slots awaiting further information on ship's profile and loading list; or proceed directly to specific stacks which are pre-arranged by ship or trade destination.

Figure 2 Configuration of a two-stage supply chain model for the container export flow



Under a supply chain system, input and output measures are defined either as direct or intermediate measures. Direct measures are those associated with a specific stage while intermediate measures are those associated with two or more stages. In Figure 2, X_A and X_B are direct inputs and outputs while Y_A and Y_B are intermediate inputs and outputs, respectively. Because of the presence of intermediate measures, the performance of one stage or sub-process affects the efficiency of the other. Consequently, the values of intermediate measures must be determined through coordination between various stages or sub-processes. The two-stage supply-chain terminal process for DMU_0 can be expressed in DEA as the average efficiency of both stages:

$$
\begin{aligned}
& Max \frac{1}{2}\left[\frac{c_A^T y_{A_0}}{v_A^T x_{A_0}} + \frac{u^T y_{B_0}}{c_B^T y_{A_0} + v_B^T x_{B_0}}\right] \\
& \text{s.t.} \quad \frac{c_A^T y_{A_j}}{v_A^T x_{A_j}} \le 1 \qquad j = 1, 2, \ldots, n \,. \\
& \frac{u^T y_{B_j}}{c_B^T y_{A_j} + v_B^T x_{Bj}} \le 1 \qquad j = 1, 2, \ldots, n
\end{aligned}
\tag{3}
$$

Equation (3) above can be expressed in a primal form as shown below:

$$
\begin{aligned}
&\underset{c_A, u, v_A, v_B, c_B}{Max} \quad c_A^T y_{A_0} + u^T y_{B_0} \\
&\text{s.t. } v_A^T x_{A_0} = 1 \\
&c_A^T y_{A_0} + v_B^T x_{B_0} = 1 \\
&c_A^T y_{A_j} - v_A^T x_{A_j} \le 0 \qquad j = 1, 2, \ldots, n \\
&u^T y_{Bj} - c_B^T y_{A_j} - v_B^T x_{B_j} \le 0 \qquad j = 1, 2, \ldots, n
\end{aligned} \tag{4}
$$

where v and u are weights for direct inputs and outputs, and c is the weight for intermediate input /output. DMU_0 is defined supply chain efficient when it maximises both stage A and stage B efficiency.

The dual formulation of (4) can be specified as follows:

$$
\begin{aligned}
&\underset{\theta, \varphi, \eta, \mu}{Min} \quad \theta + \varphi \\
&\text{s.t. } -\theta x_{A_0} + \sum_j \eta_j x_{Aj} \le 0 \\
&y_{A_0} - \sum_j \eta_j x_{Aj} \le 0 \\
&-\varphi x_{B_0} + \sum_j \mu_j x_{Bj} \le 0 \\
&y_{B_0} - \sum_j \mu_j y_{Bj} \le 0 \\
&-\varphi y_{A_0} + \sum_j \mu_j y_{Aj} \le 0
\end{aligned} \tag{5}
$$

3.2 Dataset and variable selection

In this paper, we consider the container terminal, rather than the container port, as the homogenous unit or DMU. Both primary and secondary data sources are used to collect relevant data including information reported on the websites of global shipping lines particularly the data on gate cut-off time and free yard storage policy. Out of the 50 terminals in the original sample, only ten container terminals could provide us with detailed and complete data about outbound container flows. These terminals are Gamman Container Terminal (GCT), Jaseongdae Container Terminal (HBCT), Hanjing-Gamcheon Container Terminal (HGCT), Kingston Container Terminal (KCT), Jeddah Southern Container Terminal (JSCT), Santos Container Terminal 37 (ST37), South-Asia Gateway Terminal (SAGT), Salalah Port Container Terminal (SPCT), Tanjung-Pelepas Container Terminal (PTP), and Westport Container Terminal (WPCT). The data collected was over the seven-year period (2002–2008) resulting into a panel dataset of 70 terminal-years or terminal-DMUs. In a dynamic context, panel data prevail over times-series and cross-sectional data. On the one hand, because a DMU is observed only once either in the times-series or in the cross-sectional analysis, its efficiency estimate would be subjected to a higher degree of randomness and may therefore be misleading. On the other hand, the increase of the sample size under panel data analysis (from ten to 70) would reinforce analytical reliability and reduce statistical error.

Regarding the input/output variable selection, we relied on our expert analysis in order to prescribe and analyse operational workflows and business processes in container terminals with a view to utilising available and reliable data and ensuring homogeneity between observation units. We have also taken into consideration the differences in the configurations and operating typologies of container terminals, for instance by using indices that account for the variations of technological performance for STS and yard-staking cranes.

STS Crane Index = Number of quay cranes*Lifting capability

Yard crane Index = Yard staking crane*Ground storage capacity*Stacking height

where the lifting capability index (in TEU) is calculated as follows:

Conventional STS 20' = 1, Twin 20' = 2, Tandem 40' = 2, Two tandem = 4, Triple 40' = 6

Table 3 Input and output variables for supply chain DEA model

	Gate		*Yard and quay*		*Terminal*	
	Input	*Output*	*Input*	*Output*	*Input*	*Output*
Scenario 2: yard and quay as a single process	Gate lanes	*Gate outbound TEUs*	*Gate outbound TEUs*	Export TEUs	Gate inputs	Export TEUs
	Cut-off time		Yard staking index	Yard dwell time	Yard and quay inputs	Yard dwell time
			Free yard storage	STS crane move/hour	*Gate outbound TEUs*	STS crane move/hour
			STS crane index			
			LOA* max draft			
	Gate and yard		*Quay*		*Terminal*	
	Input	*Output*	*Input*	*Output*	*Input*	*Output*
Scenario 1: gate and yard as a single process	Gate lanes	Gate outbound TEUs	*Yard dwell time*	Export TEUs	Gate and yard inputs	Export TEUs
	Cut-off time		STS crane index	STS crane move/hour		STS crane move/hour
	Yard stacking index	*Yard dwell time*	LOA* max draft		Quay site inputs	
	Free yard storage				*Yard dwell time*	

Note: *LOA: length overall

Table 3 depicts the input and output variables relative to the dataset used. Note that because of the unavailability of data on port labour, researchers usually avoid the inclusion of labour data in port benchmarking studies under the assumption that the amount of labour required in a container terminal is proportional to the number of the cranes deployed or equipment used (Tongzon, 1995; Notteboom et al., 2000). In the context of this paper, the main thrust of benchmarking container-port operational efficiency in terms of generic operating typologies (for both quay and yard operating sites) is that each configuration incorporates a corresponding set of capital and labour mix, and thus no cost or labour data is required.

In order to ensure the validity and reliability of the dataset in the context of DEA, we ran a number of tests particularly with regard to homogeneity, positivity, data scaling, and isotonicity. Because of the time frame of this study and since output levels in the short-run tend to be exogenously determined by the volume of demand and other locational factors, we mainly use the DEA input oriented specification. We also focus on DEA-BCC models given that container terminals generally depict a variable returns to scale technology, although some results are expressed in both DEA-CCR and DEA-BCC models.

4 Results and interpretation

4.1 Analysis of site-specific efficiency

Earlier in this paper, we described the configuration of container terminal systems and the relationship between different operating sites. In particular, we emphasised the existence of disproportionate performance and capacity constraints at the level of each terminal site and the need to integrate the operations of these sites with a view of achieving overall terminal productivity. To test the assumption of whether disproportionate performance levels exists or not between terminal sub-processes, efficiency estimates for various operating sites (the quay, the yard, and the gate) are compared with the efficiency of the overall terminal system. Table 4 depicts the datasets and analytical models used for estimating the efficiency scores for the quay and the yard sites, respectively. We could not however estimate the technical efficiency for the gate site because of prevalent data unavailability on gate inputs and outputs.

Appendix 1 depicts the results of efficiency scores for quay/berth, yard, and terminal sites, respectively. The results show that berth operations clearly exhibit the highest average performance levels while yard operations generally exhibit lower performance levels (see Table 4). Note that none of the DMUs under study has achieved a 100% efficiency score for yard operations, in other words the yard system could achieve more input savings by rationalising the use of yard equipment and resources. Further analysis reveals a low positive correlation coefficient ($r = 0.1$) between the efficiency estimates yielded from the various sites. In particular, the berth output, measured here as the STS-crane move per hour, does not seem to be causally linked to the terminal output (throughput in TEUs). This may be due to the fact that most port operators do not usually record non-working and idle-time crane hours as part of STS productivity.

Table 4 Site-specific datasets and their corresponding analytical models

Site	*Data nature*	*DMUs*	*Variables*	*Estimation model*
Quay site	Panel	70	*Inputs*	CCR-I/BCC-I
			Quay site inputs (maximum draft, LOA, STS crane index), terminal area, internal trucks and vehicles	Measure-specific DEA
			Output	
			STS crane move/hour	
Yard site	Panel	70	*Inputs*	CCR-I/BCC-I
			Yard site input (yard stacking index, yard free storage time), terminal area, internal trucks and vehicles	Measure-specific DEA
			Output	
			Cargo dwell time	
Terminal	Panel	70	*Inputs*	CCR-I/BCC-I
			Combined quay and yard site inputs (from above)	Measure-specific DEA
			Output	
			Terminal throughput in TEUs	

Table 5 Variation of average efficiency by operating site

DMU/site	*GCT*	*HBCT*	*HGCT*	*WPCT*	*PTP*	*JSCT*	*SAGT*	*T37*	*SPCT*	*KCT*
Yard	0.740	0.552	0.771	0.507	0.730	0.508	0.721	0.764	0.683	0.718
Quay	0.815	0.721	0.952	0.586	0.742	0.645	0.871	0.929	0.640	0.774
Terminal	0.952	0.761	0.718	0.734	0.827	0.434	0.729	0.885	0.714	0.809

We also ran a sensitivity analysis by applying proportionally similar increments in berth and yard efficiencies, e.g., a 10% increase in quay crane move versus a 10% decrease in yard dwell time. The analysis shows positive but different incremental increases in terminal efficiency, with the bigger increments being the results of shorter cargo dwell times. These results imply that although terminal operators often advocate greater performance through higher achievements in berth productivity, the latter does not necessarily translate into similar levels of productive efficiency for the overall terminal system. These findings are consistent with recent empirical studies showing that operational bottlenecks in port operations often occur in the yard (Kim et al., 2006; Nang and Hadjiconstantnou, 2008) and that more focus must be placed on yard and land-interface operations (Bichou, 2005).

4.2 Analysis of terminal (supply chain) efficiency

The models and tests used in the previous section examined individual efficiencies of site-specific operations and provided evidence of the existence of disproportionate performance levels between various terminal sites. However, they stop short at analysing the efficiency of the network structure resulting from the interplay between various terminal sites and their operational sub-processes.

Appendix 2 lists the efficiency estimates for individual and networked terminal processes under the two supply chain planning scenarios. The results show that while many observations on site-specific operations are efficient, only 9 DMUs are efficient when the network structure is analysed. These DMUs are GCT-2005, HGCT-2002, HGCT-2004, HGCT-2005, PTP-2004, PTP-2008, and T37-2004 for the combined gate-yard terminal planning process; and HGCT-2008 and PTP-2003 for the combined yard-quay terminal planning process. Note that none of the DMUs under study is efficient in both gate-yard and yard-quay planning processes.

Table 6 provides a comparative analysis of average efficiency scores for terminal DMUs by network type of planning process. The results show that for all DMUs under study, the average network efficiency is lower than the average efficiency relative to specific or combined operating sites. On the other hand, inefficient DMUs seem to achieve higher productivity in site-specific operations against low efficiency scores in the overall network operations. This implies that the overall (multi-stage) terminal system could achieve higher productivity (input savings or output increases) by adjusting the levels of input resources and output productions in each operating site or sub-process. The scope and extent of such savings/increases depend on the efficiency scores of both site-specific and aggregate terminal operations, and on how these can be improved collaboratively to achieve best practice.

Table 6 Comparative results of average supply chain (network) efficiency scores

		2002	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*
Gate and yard network	Gate and yard	0.872	0.877	0.867	0.842	0.835	0.86	0.888
	Quay	0.873	0.874	0.902	0.908	0.719	0.763	0.833
	Network	0.818	0.838	0.853	0.85	0.678	0.73	0.807
Yard and quay network	Gate	0.847	0.924	0.903	0.871	0.729	0.767	0.857
	Yard and quay	0.826	0.837	0.89	0.908	0.916	0.91	0.956
	Network	0.749	0.81	0.854	0.811	0.73	0.739	0.831

Table 7 HGCT supply chain (network) efficiency for outbound container flow

	1st scenario port supply chain planning				*2nd scenario port supply chain planning*			
	Gate and yard	*Quay*	*Network efficiency*	*Average efficiency*	*Gate*	*Yard and quay*	*Network efficiency*	*Average efficiency*
HGCT-2002	1.00	1.00	1.00	0.92	1.00	0.84	0.90	1.00
HGCT-2003	0.95	1.00	0.92	0.88	1.00	0.76	0.83	0.98
HGCT-2004	1.00	1.00	1.00	0.97	0.98	0.96	0.92	1.00
HGCT-2005	1.00	1.00	1.00	0.77	0.72	0.81	0.64	1.00
HGCT-2006	0.89	0.67	0.6	0.76	0.69	0.82	0.66	0.78
HGCT-2007	0.87	0.76	0.7	0.79	0.75	0.82	0.72	0.81
HGCT-2008	1.00	0.92	0.88	1.00	1.00	1.00	1.00	0.96

Consider for instance the productive efficiency for HGCT, which are reported in Table 7. The table shows that the DMU HGCT-2008 achieves optimum efficiency for the combined gate-yard supply chain process (scenario 1) while DMUs HGCT-2002, HGCT-2004 and HGCT-2005 achieve an equally efficient rating for the combined yard-quay supply chain process (scenario 2). The results for DMUs HGCT-2002, HGCT-2003 and HGCT-2008 also show that inefficient network operations also occur when one process is efficient while another is operating inefficiently. In all such cases, operational adjustments may be undertaken to counterbalance disproportionate performances between sites. For instance, in order to achieve optimal efficiency for HGCT-2002 and HGCT-2003 under the yard-quay planning configuration, the terminal operator may decide either to improve the efficiency of the combined yard-quay system, for instance through quicker container yard dwell time, so that it levels up with that of gate operations; or to slowdown the gate-in rate for export containers, for instance by imposing minimum queuing headways for inbound trucks, so that it matches the production level of the combined yard-quay operations. In a similar vein, DMU HGCT-2008 can achieve optimal efficiency under the gate-yard planning configuration by improving the efficiency of the quay site, for instance through quicker vessel turn-around time and higher rates of STS crane productivity, or by adjusting the efficiency for the combined gate-yard system through for reducing the number of interchange vehicles between the yard and the quay. Similar adjustments may be taken when either site is inefficient by selecting the appropriate input/output operating mix that achieves optimal network efficiency.

5 Conclusions

Although container-port operating systems and planning processes exhibit a supply-chain network structure, much of the DEA literature on the subject applies a black-box approach that examines container port or terminal operations as an aggregate single-process. This paper models the container-terminal system as a two-stage supply chain process and applies a relevant DEA model to measure and analyse the performances of both individual and combined terminal sub-processes and operating sites.

The analysis of site-specific efficiency shows that quay-site operations tend to exhibit higher performance levels than aggregate terminal operations. Conversely, yard operations tend to yield lower efficiency ratings than either yard or terminal operations. Even though, there was a low correlation between the berth/quay efficiency and the overall terminal efficiency. The analysis also shows that the yard site exhibits the lower performance level and is therefore the most critical process in container terminal efficiency.

The analysis of network efficiency confirms the above findings in that container terminals exhibit disproportionate performance levels between terminal sites and sub-processes. The analysis in terms of DEA supply chain efficiency has shown that managing terminals as integrated operating sites is the key to achieving aggregate best-practice performance. For instance, in order to counterbalance disproportionate performance levels between terminal sites, appropriate adjustments can be taken by either accelerating or decelerating the rates of handling, staking and transfer at the relevant site, hence requiring a high degree of flexibility in allocating and shifting resources and equipment between terminal operating sites. In adopting a supply chain approach to container terminal operations, operators may choose to operate their terminal sites with varying degrees of utilisation and service levels in order to improve the overall terminal efficiency.

Subject to the availability of detailed and reliable operational data, future research can apply similar supply chain DEA models in order to shed further insight on the network structure of terminal operating systems and on how to manage them efficiently. The same approach can be adopted to analyse individual and combined efficiencies of the wider port supply chain network involving port operators, ocean carriers, 3PLs, shippers, and other supply chain stakeholders.

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Appendix 1

Table A1 DEA efficiency scores for quay, yard, and aggregate terminal operations

Terminal-year	*Quay-site efficiency*		*Yard-site efficiency*		*Terminal efficiency*	
	BCC-I	*CCR-I*	*BCC-I*	*CCR-I*	*BCC-I*	*CCR-I*
GCT-2002	0.79	0.738	0.812	0.661	0.992	0.763
GCT-2003	0.728	0.615	0.803	0.608	0.85	0.822
GCT-2004	1	1	0.882	0.8	1	0.966
GCT-2005	0.819	0.758	0.833	0.741	1	1
GCT-2006	0.836	0.781	0.94	0.78	0.965	0.908
GCT-2007	0.843	0.79	0.963	0.8	1	0.941
GCT-2007	0.896	0.865	0.955	0.79	0.907	0.787
HBCT-2002	0.847	0.646	0.9	0.444	0.636	0.532
HBCT-2003	0.847	0.655	0.668	0.434	0.564	0.472
HBCT-2004	0.848	0.655	0.75	0.458	0.681	0.569
HBCT-2005	0.848	0.712	0.882	0.49	0.703	0.588
HBCT-2006	0.867	0.777	0.916	0.598	0.793	0.613
HBCT-2007	0.851	0.832	0.9	0.72	0.817	0.714
HBCT-2008	0.808	0.78	0.843	0.719	0.85	0.683
HGCT-2002	1	0.858	0.94	0.686	0.755	0.403
HGCT-2003	1	0.885	0.966	0.708	0.845	0.451
HGCT-2004	1	1	1	0.8	0.988	0.527
HGCT-2005	1	0.957	1	0.8	1	0.533
HGCT-2006	1	0.965	1	0.8	1	0.545
HGCT-2007	1	1	1	0.8	0.908	0.49
HGCT-2008	1	1	1	0.8	0.92	0.496
WPCT-2002	0.8	0.534	0.868	0.386	0.328	0.325
WPCT-2003	0.8	0.584	0.776	0.424	0.465	0.461
WPCT-2004	0.8	0.628	0.758	0.49	0.655	0.648
WPCT-2005	0.8	0.671	0.7221	0.536	0.735	0.727
WPCT-2006	0.8	0.693	0.668	0.574	0.817	0.808
WPCT-2007	0.8	0.726	0.625	0.536	0.817	0.817
WPCT-2008	0.8	0.747	0.839	0.603	1	1
PTP-2002	0.8	0.696	0.867	0.576	0.479	0.479
PTP-2003	0.8	0.743	0.88	0.654	0.587	0.587
PTP-2004	0.8	0.743	0.91	0.703	0.762	0.762
PTP-2005	0.8	0.789	0.982	0.8	1	1
PTP-2006	0.8	0.794	0.792	0.776	0.962	0.962
PTP-2007	0.82	0.816	0.966	0.8	1	1
PTP-2008	0.807	0.806	0.966	0.8	1	1

Table A1 DEA efficiency scores for quay, yard, and aggregate terminal operations (continued)

Terminal-year	*Quay-site efficiency*		*Yard-site efficiency*		*Terminal efficiency*	
	BCC-I	*CCR-I*	*BCC-I*	*CCR-I*	*BCC-I*	*CCR-I*
T37-2002	0.995	0.965	0.981	0.772	0.789	0.446
T37-2003	0.987	0.904	0.968	0.739	0.947	0.536
T37-2004	1	1	0.9	0.8	1	0.566
T37-2005	1	1	0.9	0.8	1	0.598
T37-2006	0.852	0.85	0.877	0.734	0.76	0.671
T37-2007	1	0.974	0.925	0.8	0.783	0.691
T37-2008	0.83	0.744	0.866	0.706	0.801	0.707
JSCT-2002	0.774	0.369	0.79	0.579	0.359	0.352
JSCT-2003	0.773	0.365	0.79	0.552	0.355	0.348
JSCT-2004	0.769	0.342	0.853	0.452	0.332	0.326
JSCT-2005	0.712	0.337	0.814	0.48	0.345	0.343
JSCT-2006	0.731	0.392	0.822	0.488	0.401	0.398
JSCT-2007	0.74	0.419	0.828	0.501	0.429	0.426
JSCT-2008	0.733	0.398	0.825	0.501	0.407	0.404
SAGT-2002	1	0.929	0.895	0.743	0.912	0.507
SAGT-2003	1	1	0.966	0.8	1	0.556
SAGT-2004	0.847	0.846	0.934	0.767	0.887	0.791
SAGT-2005	0.751	0.725	0.826	0.683	0.728	0.687
SAGT-2006	0.732	0.673	0.803	0.624	0.673	0.673
SAGT-2007	0.736	0.694	0.811	0.645	0.698	0.698
SAGT-2008	0.75	0.738	0.792	0.784	1	1
SPCT-2002	0.675	0.521	0.85	0.554	0.4	0.4
SPCT-2003	0.675	0.521	0.86	0.559	0.475	0.475
SPCT-2004	0.675	0.54	0.891	0.577	0.484	0.484
SPCT-2005	0.682	0.579	0.82	0.724	0.8	0.8
SPCT-2006	0.686	0.598	0.835	0.768	0.88	0.88
SPCT-2007	0.682	0.579	0.955	0.8	1	1
SPCT-2008	0.69	0.617	0.965	0.8	0.96	0.96
KCT-2002	0.812	0.499	0.855	0.74	1	0.411
KCT-2003	0.81	0.502	0.97	0.8	0.748	0.5
KCT-2004	0.81	0.522	0.94	0.866	0.68	0.483
KCT-2005	0.81	0.531	0.672	0.49	1	0.827
KCT-2006	0.81	0.503	0.877	0.602	0.877	0.819
KCT-2007	0.753	0.461	0.827	0.727	0.859	0.853
KCT-2008	0.753	0.434	0.88	0.8	1	1

Appendix 2

Table A2 Supply chain DEA efficiency scores for export operations

DMU	*1st scenario supply chain planning*			*2nd scenario supply chain planning*		
	Gate and yard	*Quay*	*Network*	*Gate*	*Yard and quay*	*Network*
GCT-2002	0.780	1.000	0.697	0.850	0.850	0.850
GCT-2003	0.879	0.987	0.846	0.987	0.850	0.821
GCT-2004	0.825	0.990	0.841	0.990	0.831	0.788
GCT-2005	1.000	1.000	1.000	1.000	0.850	0.833
GCT-2006	0.904	0.754	0.666	0.754	0.840	0.816
GCT-2007	0.897	0.812	0.703	0.812	0.850	0.846
GCT-2008	0.911	0.900	0.796	0.900	0.850	0.851
HBCT-2002	0.911	1.000	0.904	1.000	0.740	0.682
HBCT-2003	0.928	0.980	0.905	0.980	0.830	0.639
HBCT-2004	0.777	0.955	0.720	0.955	0.819	0.868
HBCT-2005	0.725	0.974	0.759	0.974	0.850	0.822
HBCT-2006	0.818	0.670	0.555	0.670	0.850	0.686
HBCT-2007	0.870	0.866	0.752	0.866	0.730	0.778
HBCT-2008	0.910	0.937	0.914	0.937	0.839	0.884
HGCT-2002	1.000	1.000	1.000	1.000	0.844	0.902
HGCT-2003	0.949	1.000	0.922	1.000	0.761	0.828
HGCT-2004	1.000	1.000	1.000	0.977	0.964	0.917
HGCT-2005	1.000	1.000	1.000	0.722	0.815	0.645
HGCT-2006	0.893	0.674	0.590	0.690	0.820	0.665
HGCT-2007	0.867	0.760	0.698	0.754	0.820	0.719
HGCT-2008	1.000	0.921	0.885	1.000	1.000	1.000
WPCT-2002	0.867	0.842	0.780	0.836	0.778	0.748
WPCT-2003	0.872	0.776	0.762	0.847	0.787	0.727
WPCT-2004	0.898	0.822	0.892	0.900	0.866	0.832
WPCT-2005	0.746	0.884	0.784	0.917	0.900	0.897
WPCT-2006	0.825	0.727	0.689	0.683	0.915	0.657
WPCT-2007	0.887	0.695	0.662	0.672	0.928	0.601
WPCT-2008	0.945	0.715	0.694	0.705	0.941	0.618
PTP-2002	1.000	0.989	0.966	0.817	1.000	0.796
PTP-2003	1.000	0.945	0.921	1.000	1.000	1.000
PTP-2004	1.000	1.000	1.000	1.000	0.996	0.921
PTP-2005	0.969	1.000	0.936	0.985	1.000	0.944
PTP-2006	0.945	1.000	0.933	0.887	1.000	0.851
PTP-2007	0.994	1.000	0.977	0.912	0.988	0.814
PTP-2008	1.000	1.000	1.000	0.966	1.000	0.953

Table A2 Supply chain DEA efficiency scores for export operations (continued)

DMU	*1st scenario supply chain planning*			*2nd scenario supply chain planning*		
	Gate and yard	*Quay*	*Network*	*Gate*	*Yard and quay*	*Network*
JSCT-2002	0.752	0.783	0.767	0.833	0.950	0.801
JSCT-2003	0.765	0.794	0.775	0.941	0.889	0.880
JSCT-2004	0.815	0.851	0.822	0.818	0.941	0.876
JSCT-2005	0.697	0.776	0.721	0.881	1.000	0.833
JSCT-2006	0.723	0.740	0.735	0.950	1.000	0.928
JSCT-2007	0.713	0.727	0.719	0.894	0.968	0.890
JSCT-2008	0.722	0.792	0.738	0.916	1.000	0.885
SAGT-2002	0.786	0.560	0.623	0.550	0.689	0.522
SAGT-2003	0.686	0.576	0.631	0.634	0.650	0.641
SAGT-2004	0.614	0.673	0.620	0.624	0.667	0.655
SAGT-2005	0.627	0.722	0.678	0.600	0.740	0.604
SAGT-2006	0.729	0.421	0.566	0.429	0.768	0.526
SAGT-2007	0.773	0.675	0.714	0.498	0.850	0.507
SAGT-2008	0.771	0.800	0.766	0.755	0.929	0.734
T37-2002	0.873	0.922	0.855	0.907	0.529	0.502
T37-2003	0.928	0.989	0.977	0.979	0.788	0.766
T37-2004	1.000	1.000	1.000	1.000	0.941	0.920
T37-2005	0.964	1.000	0.942	0.785	0.954	0.733
T37-2006	0.839	0.677	0.644	0.729	1.000	0.753
T37-2007	0.891	0.626	0.657	0.794	1.000	0.823
T37-2008	0.900	0.675	0.773	0.828	1.000	0.858
SPCT-2002	1.000	0.847	0.823	0.847	0.928	0.885
SPCT-2003	1.000	0.897	0.871	0.930	0.924	0.917
SPCT-2004	0.927	0.879	0.812	0.945	0.934	0.925
SPCT-2005	0.997	0.945	0.960	0.965	0.967	0.954
SPCT-2006	0.956	0.788	0.668	0.553	0.965	0.498
SPCT-2007	1.000	0.747	0.698	0.580	1.000	0.544
SPCT-2008	1.000	0.800	0.765	0.652	1.000	0.637
KCT-2002	0.752	0.783	0.767	0.833	0.950	0.801
KCT-2003	0.765	0.794	0.775	0.941	0.889	0.880
KCT-2004	0.815	0.851	0.822	0.818	0.941	0.836
KCT-2005	0.697	0.776	0.721	0.881	1.000	0.850
KCT-2006	0.723	0.740	0.735	0.950	1.000	0.928
KCT-2007	0.713	0.727	0.719	0.889	0.968	0.870
KCT-2008	0.722	0.792	0.738	0.916	1.000	0.885