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Jaehun PARK
Daegu Haany University

Byung Kwon LEE
National University of Singapore

Joyce M. W. LOW
Singapore Management University, joycelow@smu.edu.sg

A two-stage parallel network DEA model for analyzing the operational capability of container terminals

Jaehun Park[a], Byung Kwon Leeb and Joyce M.W. Low[c*]

[a] Major in Industrial Quality Engineering, Division of Cosmetic Science and Technology, Daegu Haany University, Gyongsabuk-do, Republic of Korea; [b] Centre of Excellence in Modelling and Simulation for Next Generation Ports, National University of Singapore, Singapore, Singapore; [c] Lee Kong Chian School of Business, Singapore Management University, Singapore, Singapore

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Abstract: This study proposes a systematical approach to evaluate the operational capability of container terminals and discusses the effect of resource usages on operational performances. Two inter-dependent processes (i.e. the loading-discharging (L&D) and the delivery-receiving (D&R) operational processes) with shared/non-shared resources and common/separate productions are examined and characterized as a two-stage parallel network. An evaluation model is developed upon the principles of data envelopment analysis (DEA) to assess the operational capability of the terminals. Using the real-world dataset of 9 container terminals at Port of Busan, comparative performance results are obtained for 5 years spanning across 2014–2018. The proposed model demonstrates a much stronger discriminative power compared to the traditional CCR model in its estimations of performance in the decision-making units (DMUs). It can also be inferred from the results that efficiency in operations is a key qualifier for container volume while the market aggressiveness lends a competitive edge and reinforces a positive outcome on the performance of a container terminal. The study further examines the influence of management directive on a terminal performance and confirms that alignment of management directive with the operational capability of L&D and D&R processes is important in maximizing terminal throughout.

Keywords: Operational capability, resource sharing, parallel network structure, data envelopment analysis (DEA), container terminal, alignment of management directive

1. Introduction

Container terminal operations are complex and costly, of which, a significant proportion of the activities carried out in the terminal is related to container handling. Container-handling operations require huge investment in handling machines such as quay cranes, vehicles, yard cranes, and supporting machines (i.e. reach stackers, top handlers, fort lifts, etc.) on top of infrastructural facilities, such as wharf, travel lanes, storage space, refrigerator plugs, repair garages, etc. The service peripherals provided in the terminal is also dependent upon the workers operating the machines and their experiences so as to deploy the facilities to the best use. Hence, the container terminal will be expected to produce better operational performance in the form of larger transhipment and hinterland throughputs when terminal congestions and ship waiting times are reduced. In some ports, each container terminal may be independently operated by an operator. Port of Hong Kong and Port of Busan provide good examples. Meanwhile, in other ports like Port of Singapore, one operator may run multiple terminals. Be it at the port level or

[*] Corresponding author: Joyce M.W. Low, email: joycelow@smu.edu.sg

terminal level, efficient container-handling operations improve revenue and solidify the country's position as major transportation hub where the integration of logistics activities from different modes of transportation facilitates intercontinental logistics flows. According to Ha and Yang (2017), (2019)), the performances of a container terminal are measured along several dimensions encompassing the core and supporting activities (e.g. productivity and human and organization capitals), users' satisfaction (e.g. service reliability and costs), container logistics integration (e.g. intermodal transport and value-added services), and information-communication integration (e.g. information technology systems).

The ability to provide value-added services to carriers and shippers and generate container throughputs using the terminal resources (i.e. infrastructural facilities, handling machines, and service peripherals) is referred to as the operational capability of the terminal. Given that container terminal operators are mostly profit-driven, these operators will be concerned with the operational performances of their terminal(s) as higher levels of productivity increase the returns from their resources. This study aims to analyze the operational capability of a container terminal through a detailed characterization of its operational processes in container-handling operations and the resources involved. By and large, operational processes are often categorized into the sea-side operational processes (for container loading and discharging operations) and the hinterland operational processes (consisting of receiving and delivery operations). Together, the seaside and hinterland operational processes should be coordinated to allow seamless container flows through the terminals. To this end, the study relooks into the operational processes at a container terminal and develops parallel-network structure of DEA model to evaluate the process-specific and overall performances. In the proposed model, the shared and non-shared input variables are identified together with the common output variables. Based on the performance results in the seaside and hinterland processes, the study examines the influence of the management directive in guiding resource allocations on the operational capability of container terminals.

This study contributes to the understanding on how operational capability of a container terminal can be measured, as well as, extending the theoretical frontier in the developments of Data Envelopment Analysis[1] (DEA) models. In consideration of two inter-dependent processes that are run in parallel to produce the final output, a parallel-network DEA model that analyzes the operational capability of a container terminal as a decision-making unit (DMU) is developed in this study. Prior to this, DEA has been widely used in conducting performance evaluation in port operations. However, all these prior DEA studies on port operations represent each terminal as a 'black-box' DMU by only considering the initial inputs consumed and final outputs produced from it. Without looking into the details of the operational processes in the terminal, an implicit but oversimplifying assumption in these studies is that the operation processes are absolutely effective. In other words, an accurate analysis on the performance of container terminals is hindered due to the insufficient provision of the underlying diagnostic information that are critical in identifying inefficient container terminals as candidates for the performance improvement.

In addition, this study makes a practical contribution by conducting a comparative analysis among the container terminals managed under a single port authority. The parallel-network structure in the proposed model inspects the various types of operational processes in each of the container terminals as an individual DMU autonomously utilizing the necessary resources (i.e. infrastructural facilities, workforces, handling machines and service peripherals) and producing the container flows. On premise that the desired performance of a container terminal could be attained in container handling operations that are well-managed based on given resources, the proposed model allows the port authority or operator to benchmark the capability levels of terminal members and devises performance-based contract for each member.

The rest of this study is as follows: Section 2 reviews the extant literature on port performance measures and evaluations. Sections 3 and 4 explain the rationales for proposing a parallel-network structure, with Section 3 describing the container flows and operational processes and Section 4 that subsequently develops a suitable parallel-network DEA model for accurate performance assessments. Section 5 conducts numerical experiment using a real-world dataset. Section 6 draws insights from the experimental results and concludes the study.

2. Related work

While the subject on port performance has attracted much scholastic researches, the development and selection of performance measures presumably represent a fundamental step in the evaluation of port performances. By means of questionnaire surveys and comparative statistical analysis (e.g. t-test), Feng, Mangan, and Lalwani (2012) studied the differences in port performances between Humber Estuary of UK and Xiamen of China and sought to provide policy makers with comparative strategies. Ha and Yang (2017) described a systematic selection process of various port performance measures. Through an exploratory investigation, Ha and Yang aligned their study with the existing literatures including Ha and Yang (2017), (2019)) and surveyed practitioners to identify performance measures and their relative importance. The authors applied a DEMATEL (which stands for decision making trial and evaluation laboratory) to recognize the existence of significant independency among the performance measures. The intensity of independent relationships was further ascertained through an ANP (analytic network process) model and an AHP (analytic hierarchy process) model is applied to the performance measures that present insignificant interdependency. In another study, Ha et al. (2017) categorized various port performance measures into core activities, supporting activities, financial strength, users' satisfaction, terminal supply chain integration, and sustainable growth from multiple stakeholders, and proposed a framework that synthesizes the quantitative and qualitative measures via DEMATEL, ANP, FER (fuzzy evidential reasoning), and utility techniques aimed at conducting performance evaluation in a flexible manner. Ha, Yang, and Lam (2019) further improved the previous model via an importance-performance analysis (IPA) matrix to provide strategical guidance for decision of improving performance to port managers and policy makers in the context of container ports. Madeira et al. (2012) applied a multi-criteria decision-making approach, MACBETH (measuring attractiveness by a categorical-based evaluation technique), to evaluate the performance of container terminals in Brazilian ports from 2006 to 2009.

Data Envelopment Analysis (DEA) has been used intensively to evaluate performances of organizations in a variety of sectors including the port industry. For example, Low (2010) applied an integrated suite of DEA models including the CCR, BCC, SBM, congestion and measure-specific models to investigate the various sources of efficiency contributing to the overall efficiency of major ports in Asia and estimated the amount of savings a port can potentially achieve through intelligent capital investments that promote a lean and fully efficient operation. Cullinane and Wang (2010) calculated the container port efficiency comparatively using contemporaneous, intertemporal and window DEA panel data approaches to address dynamic changes in port efficiency over time using annual panel data. Wu and Goh (2010) studied on the efficiency of container ports at emerging and advanced markets using the DEA approaches such as CCR, BCC, and A&P (Andersen and Petersen) models by taking a port as a DMU. The authors used output-oriented models as they are more associated with planning and strategy formulation, in view that the input-oriented models are closely related to operational and managerial issues (Wang, Cullinane, and Song 2003). Similarly, Suárez-Alemán et al. (2016) estimated the drivers of productivity changes among developing regions and identified determinants of port efficiency via parametric (i.e. stochastic frontier analysis, SFA) and non-parametric (i.e. DEA) approaches on the explorative dataset. Through the SFA and DEA approaches, Wiegmans and Witte (2017) conducted the efficiency analysis studies on inland waterway container terminals, focusing on handling capacity and throughput for output variables. Bergantino, Musso, and Porcelli (2013) argued that contextual variables (i.e. gross domestic product, regional employment rate, population density, accessibility, and regulatory) are important considerations influencing port efficiency. The authors presented a three-stage approach in which stage 1 involves an input-oriented DEA model that evaluates port technical efficiency; stage 2 employs a SFA model that relooks the inputs netted of exogenous effects and statistical noise, considering the contextual variables; and stage 3 uses another DEA model to repeat the efficiency evaluation by replacing the observed inputs with adjusted inputs. de Oliveira and Cariou (2015) investigated the effect of inter-port competition on the port efficiency scores via a partial frontier approach (i.e. the order-α technique) to assess efficiency levels, as well as, a truncated bootstrapped regression to estimate the causes of inefficiency from a set of explanatory covariates representing the environment variables (e.g. Port city population, gateway or hub, liner shipping connectivity index, market share, etc.). Recent studies (Nguyen et al. 2016; Nwanosike, Tipi, and Warnock-Smith 2016; Cheon, Maltz, and Dooley 2017; Wanke, Obioma, and Chen 2018) have been proven that various DEA techniques could be applicable to real-world container ports to evaluate the port efficiency and productivity.

Common in all these studies, the performance or efficiency evaluation of a DMU as a port (or a container terminal) is based on the inputs used in the DMU and output that is produced. Taking an alternative perspective of DMUs, Luna et al. (2018) looked into the operational efficiency for containerships at a container terminal. The containerships, each representing an individual DMU, were grouped into two clusters in accordance with the homogeneity of their operational conditions. The authors computed the efficiency scores, which were then regressed against the operational variables such as number of containers to load, number of quay cranes, service time, etc. in each cluster. Strategies that would allow a container terminal to realize higher relative efficiency in the cargo-handling operations of a containership are identified through a decision tree.

Meanwhile, the port performance has been examined from the perspective of supply chain, which is referred to as the port-focal supply chain in Ng and Liu (2014). de Langen and Sharypov (2013) proposed a new performance measure that takes into account the degree of hinterland connectivity between a port (or a port group) and intermodal terminals as evidenced in European ports. Talley, Ng, and Marsillac (2014) proposed a concept of port service chain connecting the cargo, vessel and vehicle service providers, and emphasized that the cooperative port service will always result in a higher total profit for the port service providers than in the non-cooperative port service chain. Brooks and Schellinck (2013) identified discrepancies between performance effectiveness and user expectations and the degree of influence that a particular performance criterion has on the overall performance rating, and demonstrated the importance of port effectiveness for supply chain participants (i.e. beneficial cargo owners, shipping lines and supply chain partners). By means of a VRS-DEA model, Schøyena et al. (2018) examined container ports, in six Northern European countries, which acts mainly as gateways in global supply chains for shipping. The authors investigated the impact of logistics service delivery performance outcomes (i.e. logistics performance index, price, tracking & tracing, and timelines) and the existence of direct calls for deep-sea transcontinental container liners on the port efficiency.

On and all, it has been observed that most studies have applied the DEA models to score the port performance on efficiency. Each port (or terminal) was typically defined as an evaluation unit (i.e. a DMU). Similarly, the perspective of supply chains was also limited to the inter-port operations, even though the operational processes within a port (or terminal) could be addressed as a small-scale local supply chain. Therefore, this study fills the research gap by explicitly incorporating the operational processes within a port (terminal) into the design of DMUs when evaluating port performance.

3. Container flows and operational processes

While an actual container-handling process may vary according to the specifics of the operational activities (i.e. discharging, loading, receiving (gate-in) and delivery (gate-out)) and the types of handling machines deployed, it is generally made up of two operational process—the loading and dispatching (L&D) process and delivering and receiving (D&R) operational process.

The loading and dispatching (L&D) operational process performs the loading and unloading operations between the quay and yard sites. Upon arrival of a vessel, the quay cranes (QCs) discharge containers from the ship in accordance with the QC work schedule. These inbound containers are transported by vehicles to the storage yard, where the containers are accommodated until the next retrieval requests are arrived, and yard cranes (YCs) are deployed to pick up the containers and store them into the yard blocks. Outbound containers begin to load after the inbound containers are discharged from the ship. The loading operation works in the reverse sequence of the discharging operation. YCs retrieve containers from the yard blocks and release them onto vehicles so that the vehicles can transport the containers to QCs and eventually the containers are loaded onto the corresponding ships by the QCs.

The delivering and receiving (D&R) operational process performs the delivery and receiving operations between the yard and gate sites. Inbound containers may be laden onto another ship for transhipment or brought to the yard blocks for storage by the road trucks (RTs) via the terminal gate. In the delivery operations, YCs retrieve requested containers at yard blocks and place them into empty road trucks. After inspections, the road trucks will then deliver them to the consignees through the terminal gate.

Figure 1 shows that the L&D and D&R processes handling container flows from the quay to gate sites through the yards jointly contribute to the overall operational capability of a container terminal. Given the inter-dependency between the two processes, some resources may be shared between the L&D and D&R operations while other resources may be dedicated to either one of these processes. The representative shared resources are the yard and YCs while wharf, QCs, and vehicles are some examples of the dedicated resources to the L&D operational process. The notion of shared and dedicated resources presents important implications for resource allocations to the individual handling operations that optimize the resource usage in the terminal. When a terminal operator focuses on improving the throughput efficiency only, a straightforward way is to prioritize the L&D operational process over the D&R operational process. The reason is because throughput is measured as the amount of TEUs (twenty-foot equivalent units) handled by QCs for ships. However, since a class of resources has to be shared between the two operational processes, placing higher priority to manage the container flows for the L&D operational process will inevitably have an adverse impact on the ease in managing of the container flows in the D&R operational process. As a result, the performance improvement of one operational process (i.e. L&D operational process) would bring about deteriorations in performance of the other (i.e. D&R operational process). The trade-off between the performances of the two operational process will increase as capacity of the shared resources becomes increasingly limited. Simply put, the two operational processes need to be

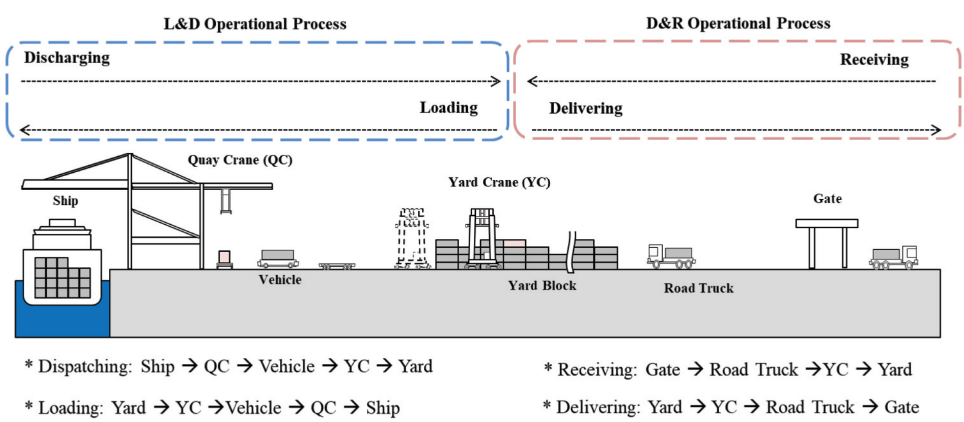

Figure 1. Container handling process at a container terminal.

managed concurrently within the container flows by taking into account the shared and non-shared resources to maximize the efficiency of the terminal.

4. Two-stage parallel network DEA model

This study develops a DEA model with a two-stage parallel network structure to evaluate the overall operational performance, taking into consideration of the interoperability of two operational processes that are running concurrently. The processes within the terminal consume inputs in the form of shared and dedicated (non-shared) resources to produce a common set of outputs.

4.1. DMUs and resource sharing

As described in Section 3, the container terminal conducts container-handling operations for outbound, inbound, and transhipment containers through two operational processes. In this DEA model, a DMU is defined as a container terminal carrying out both the L&D and D&R operational processes. The inputs and outputs for the evaluation of a DMU are the relevant resources required to perform the operational processes and the achievement results produced, respectively. Many resources are shared between the two operational processes given that the outbound containers should be eventually loaded onto a vessel, and the inbound containers will be delivered out to consignees via the gate.

Table 1 classifies the resources used in the operational processes into three categories—the infrastructural facilities, handling machines and services peripherals. Specifically, the 'facilities' variable consists of the wharf length measured in meters (denoted by x_{length}) which is a dedicated resource in the L&D process and two shared resources, namely, number of employees (denoted by x_{emp}) and yard area measured in square meters (denoted by x_{yard}). The 'machines' variable comprises a number of QCs (denoted by x_{qc}) used in the L&D process and a number of supporting machines such as reach stackers, top handlers, fork lifts, etc. (denoted by $x_{support}$) in the D&R processes. The two shared resources falling under the category of handling 'machines' are the number of vehicles transporting containers between the quay and the yard such as AGV, yard trucks, shuttle carriers, etc. (denoted by $x_{vehicle}$) and the number of YCs (denoted by x_{yc}). The 'service peripherals' variables are percentage of ships that have waited for more than 12 hours at the sea due to berth unavailability over the total number of ships served (denoted by $x_{service}$) in the L&D process, as well as, the level of market exposure characterized by the number of operating years (denoted as x_{market}) and planned throughput capacity (denoted by $x_{capacity}$) as shared resources between the two processes. The planned throughput capacity, $x_{capacity}$, is also typically referred to as the operational scale of handling containers at the terminal. Both x_{market} and $x_{capacity}$ represent the market presence and aggressiveness of the terminal to increase their market shares. The operational manageability of a container terminal, reflected in $x_{service}$, could also be enhanced by improving the management know-how in planning and controlling for container handling operations and introducing advanced information systems throughout the operational process.

The throughput is an aggregation of volume of transhipment containers, volume of hinterland (outbound and inbound) containers, and the percentage of intra-terminal transhipment rate. All are expressed in the number of TEUs handled per year. When conducting the performance

Table 1. Various resources and throughputs corresponding to operational processes.

	Facilities (DMU Inputs)	Handling Machines (DMU Inputs)	Services Peripherals (DMU Inputs)	Throughputs (DMU Outputs)
L&D process	x_{length}	$x_{qc} x_{vehicle}$	$x_{service}$	x_{trans}
Shared with both	$x_{emp} x_{yard}$	x_{yc}	$x_{market} x_{capacity}$	$x_{hinter} x_{itt}$
D&R process		$x_{support}$		

evaluation for the operational processes, the number of containers loaded/discharged on vessels (i.e. x_{trans}, $_{hinter}$, and x_{itt}) and received-in/delivered-out (i.e. x_{hinter} and x_{itt}) are explicitly considered as the outputs of the L&D and the D&R processes, respectively. The transhipment containers are doubly counted in the container throughput. The higher value of x_{itt}, the higher ability of container handling for transhipment operations.

4.2. Model development

Several network DEA models have been proposed to evaluate the performances of the DMUs in the fields of transportation (Yu 2010; Zhu 2011), banking (Fukuyama and Weber 2010; Fukuyama and Matousek 2011), utilities (Tone and Tsutsui 2009, 2010) and sports (Lewis, Lock, and Sexton 2009; Moreno and Lozano 2014). Network DEA models can be broadly classified into series-process models and parallel-process models, depending on how the sub-processes work together in a system. While network DEA studies that deal with series-of-processes system are well studied (Kao and Hwang 2008; Chen et al. 2009), similar studies on parallel-processes and general networks of processes are comparatively sparse (Kao 2009; Kao and Hwang 2010; Kao 2012). Among these, the relational network DEA model in Kao and Hwang (2008) is a suitable candidate for the performance evaluation of container terminals as the L&D and D&R processes intertwined each other through the use of shared resources and producing common outputs.

The L&D and D&R operational processes correspond to the two stages of the network that should be performed in parallel with shared resources to generate the container flows as shown in Figure 2. Suppose that there is a set of n container terminals represented by $DMU_j (j = 1, \ldots, n)$. Let x_i (i= {1, . . .,m}) be the i-th input and y_r (r ={1, . . ., s}) be the r-th outputs of the DMU_j and the input x_i consists of three types of input ($x_{i^1}, x_{i^2}, x_{i^3}$). x_{i^1} ($i^1 \in I_1$) and x_{i^2} ($i^2 \in I_2$) are used as inputs in the L&D and D&R operational processes, respectively. x_{i^3} ($i^3 \in I_3$) is the shared input between the two operational processes. Note that the sum of input sets of the L&D and D&R processes is equal to the i-th input of the DMU_j, where $I_1 \cup^{I_2} \cup^{I_3} = \{1, 2, \ldots, m\}$.

Similarly, the outputs from each internal process y_{r^1} ($r^1 \in R_1$) and y_{r^2} ($r^2 \in R_2$) and shared output for the two operational processes y_{r^3} ($r^3 \in R_3$) are aggregated into a single output measure (Y_r) in any DMU_j, where $R_1 \cup^{R_2} \cup^{R_3} = \{1, 2, \ldots, s\}$. Since inputs $i^3 \in I_3$ are shared by the two operational processes, the shared inputs x_{i^3j} will be arbitrarily split between the two operational processes with $\alpha_{i^3j}x_{i^3j}$ and (1-α_{i^3j}) x_{i^3j} ($0 \le \alpha_{i^3j} \le 1$) allocated to the L&D and D&R processes, respectively. In the same way, all shared outputs y_{r^3j} are divided into $\beta_{r^3j}y_{r^3j}$ for the L&D and (1-β_{r^3j}) y_{r^3j} ($0 \le \beta_{r^3j} \le 1$) for the D&R processes. All α will be required to be within certain intervals, namely $L^1_{i^3j} \le \alpha_{i^3j} \le L^2_{i^3j}$. Referring to the parallel network DEA model in Kao and Hwang (2008), the performance of the k-th container terminal (DMU k), P_k, taking into

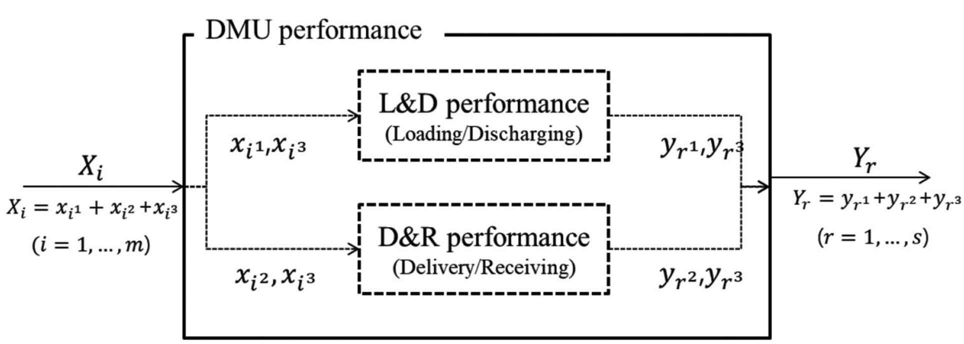

Figure 2. Inputs and outputs of a DMU with parallel network structure.

considerations of the two operational processes running in parallel is calculated in the following relational model.

$$P_k = Max \sum_{r=1}^{s} u_r Y_{rk} \tag{1.0}$$

$$s.t. \sum_{i=1}^{m} v_i X_{ik} = 1 \tag{1.1}$$

$$\sum_{r=1}^{s} u_r Y_{rk} - \sum_{i=1}^{m} v_i X_{ik} + s_k = 0 \tag{1.2}$$

$$\left(\sum_{r^1 \in R_1} u_r y_{r^1k} + \sum_{r^3 \in R_3} u_r \left(1 - \beta_{r^3k}\right) y_{r^3k}\right) - \left(\sum_{i^1 \in I_1} v_i x_{i^1k} + \sum_{i^3 \in I_3} v_i \alpha_{i^3k} x_{i^3k}\right) + s_k^1 = 0 \tag{1.3}$$

$$\left(\sum_{r^2 \in R_2} u_r y_{r^2k} + \sum_{r^3 \in R_3} u_r \beta_{r^3k} y_{r^3k}\right) - \left(\sum_{i^2 \in I_2} v_i x_{i^2k} + \sum_{i^3 \in I_3} v_i (1 - \alpha_{i^3k}) x_{i^3k}\right) + s_k^2 = 0 \tag{1.4}$$

$$\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \leq 0, j = 1, \ldots, n, j \neq k \tag{1.5}$$

$$\left(\sum_{r^1 \in R_1} u_r y_{r^1j} + \sum_{r^3 \in R_3} u_r \left(1 - \beta_{r^3j}\right) y_{r^3j}\right) - \left(\sum_{i^1 \in I_1} v_i x_{i^1j} + \sum_{i^3 \in I_3} v_i \alpha_{i^3j} x_{i^3j}\right) \leq 0, j = 1, .., n, j \neq k \tag{1.6}$$

$$\left(\sum_{r^2 \in R_2} u_r y_{r^2j} + \sum_{r^3 \in R_3} u_r \beta_{r^3j} y_{r^3j}\right) - \left(\sum_{i^2 \in I_2} v_i x_{i^2j} + \sum_{i^3 \in I_3} v_i \left(1 - \alpha_{i^3j}\right) x_{i^3j}\right) \leq 0, j = 1, \ldots, n, j \neq k \tag{1.7}$$

$u_r, v_i, s_k, s_k^1, s_k^2 \geq \varepsilon,\ r^1 \in R_1, r^2 \in R_2, i^1 \in I_1, i^2 \in I_2, i^3 \in I_3$

$$r = 1, \ldots, s, i = 1, \ldots, m$$

In this model, Constraint (1.5) represents performance of the overall operational process. Constraints (1.6) and (1.7) describe performance of the D&R and L&D processes, respectively. Constraint (1.2), (1.3) and (1.4) are the constraints for the evaluation of DMU k specially while Constraints of (1.5), (1.6) and (1.7) pertain to the rest of DMUs. Based on the definition of the relational network DEA, a container terminal (i.e. DMU) is efficient overall if and only if L&D and D&R operational processes are both efficient. Conversely, the performance can be also measured by the degree of inefficiency since the objective of maximizing efficiency is equivalent to minimizing inefficiency. Since the collective inputs (outputs) in the L&D and D&R operational processes is equal to the inputs (outputs) of the DMU, it follows that the inefficiency slack of the DMU is equal to the sum of the inefficiency slacks of the L&D and D&R processes given as $s_k = s_k^1 + s_k^2$. The integration of constraints for L&D and D&R operational processes (i.e. Constraints (1.3) and (1.4)) is equivalent to the constraint for the overall operational process (i.e. Constraint (1.2)) with the condition $s_k = s_k^1 + s_k^2$. Likewise, the integration of Constraints (1.6) and (1.7) is equivalent to Constraint (1.5) under the same condition. It means that Constraint (1.2) (or the Constraint (1.5)) and Constraints (1.3) and (1.4) (or Constraints (1.6) and (1.7)) are redundant and can be omitted if estimating s_k^1 and s_k^2 is of little concerned. As characterized by Kao (2012, 2017), the multiplier associated with the same inputs or outputs is the same for all sub-processes. Let E_k^{DR} and E_k^{LD} be the performance of D&R and L&D processes, respectively. Denote the optimal solution (marked with *) for the overall operational process for DMU k, based on Constraints (1.2), (1.3) and (1.4), are

$$P_k = \sum_{r=1}^{s} u_r^* Y_{rk} / \sum_{i=1}^{m} v_i^* X_{ik} = 1 - s_k^* \tag{2.1}$$

$$\begin{aligned} E_k^{LD} &= \left(\sum_{r^1 \in R_1} u_r^* y_{r^1 k} + \sum_{r^3 \in R_3} u_r^* (1 - \beta_{r^3 k}) y_{r^3 k} \right) / \left(\sum_{i^1 \in I_1} v_i^* x_{i^1 k} + \sum_{i^3 \in I_3} v_i^* \alpha_{i^3 k} x_{i^3 k} \right) \\ &= 1 - s_k^{1*} / \left(\sum_{i^1 \in I_1} v_i^* x_{i^1 k} + \sum_{i^3 \in I_3} v_i^* \alpha_{i^3 k} x_{i^3 k} \right) \end{aligned} \tag{2.2}$$

$$\begin{aligned} E_k^{DR} &= \left(\sum_{r^2 \in R_2} u_r y_{r^2 k} + \sum_{r^3 \in R_3} u_r \beta_{r^3 k} y_{r^3 k} \right) / \left(\sum_{i^2 \in I_2} v_i x_{i^2 k} + \sum_{i^3 \in I_3} v_i (1 - \alpha_{i^3 k}) x_{i^3 k} \right) \\ &= 1 - s_k^{2*} / \left(\sum_{i^2 \in I_2} v_i x_{i^2 k} + \sum_{i^3 \in I_3} v_i (1 - \alpha_{i^3 k}) x_{i^3 k} \right) \end{aligned} \tag{2.3}$$

The slack variables s_k^*, s_k^{1*}, and s_k^{2*} give the differences between the aggregated input and the aggregated output of the overall process, the L&D process, and the D&R process, respectively. As noted in Kao (2012, 2017), the slack variable of the overall process, s_k^*, is equal to the sum of the stacks for L&D and D&R operational processes, $s_k^{1*}+s_k^{2*}$. In Kao (2012, 2017) showed that the performance proportion between system and sub-processes. The Eq. (3) and (4) relates to the contributions of the L&D and D&R processes to the terminal overall performances. Let w_k^{LD} and w_k^{DR} be the proportions of relative importance corresponding to the performances of L&D and D&R processes, respectively. Hence,

$$w_k^{LD} = \left(\sum_{i^1 \in I_1} v_i x_{i^1 k} + \sum_{i^3 \in I_3} v_i \alpha_{i^3 k} x_{i^3 k} \right) / \sum_{i=1}^{m} v_i X_{ik} \tag{3.1}$$

$$w_k^{DR} = \left(\sum_{i^2 \in I_2} v_i x_{i^2 k} + \sum_{i^3 \in I_3} v_i (1 - \alpha_{i^3 k}) x_{i^3 k} \right) / \sum_{i=1}^{m} v_i X_{ik} \tag{3.2}$$

The average performance of the L&D and D&R processes, weighted by w^{DL} and w^{DR}, gives performance of the overall operational process of DMU k (Kao 2012, 2017). It follows that the overall performance is expected to produce the same result to P_k of (2.1) such as

$$w_k^{LD} \times E_k^{LD} + w_k^{DR} \times E_k^{DR} = \sum_{r=1}^{s} u_r Y_{rk} / \sum_{i=1}^{m} v_i X_{ik} \tag{4}$$

This relationship conforms that the L&D and D&R processes exert the influences over the performance of the operational process of DMU k that are weighted by their relative contributions.

5. Experimental analysis

The proposed network DEA model is run using the real-world data. From the performance scores generated by the model, the relative positioning of terminals and their dynamics will be explored to understand how management directive may influence the operational capability of container terminals.

5.1. Sample, variables and data

The sample consists of 9 container terminals—4 terminals at Northern Port District and 5 terminals at New Port District (Table 2). The experiment uses the most recent five years dataset between 2014 and 2018 (both years inclusive) published on the Busan Port Authority (BPA) website (https://www.busanpa.com/). Despite the fact that there are some changes in the operators, the consistency of data on the container terminals is maintained as the database is managed independently by BPA.

Table 3 presents the sample data of year 2018 in BPA dataset. The variables are divided into input and output variables. Within the group of input variables, the infrastructural 'facilities' (i.e., x_{length}, x_{emp}, x_{yard}) estimate the system size, the handling 'machine' (x_{qc}, $x_{vehicle}$, x_{yc}, $x_{support}$) counts the number of handling equipment performing the container-handling activities, and the service peripherals ($x_{service}$, x_{market}, $x_{capacity}$) represents the market attractiveness to shippers and shipping lines. As 'service peripherals' is presented in the form of aggregated data on the BPA website, the values of $x_{service}$ for the container terminals at New Port District are estimated by distributing the $x_{service}$ value of New Port District to the individual container terminals in accordance with $x_{hinter} + x_{trans}$. In addition, the proposed parallel network-DEA model uses $Exp(100x_{service})$ instead of $x_{service}$ because the DEA model discourages input values less than 1. For shared resources, the x values are split equally between the two operational processes (i.e. $\alpha_{i^3j} = 0.5$ and $\beta_{r^3j} = 0.5$ for all j).

The output is measured by the volume of throughput consisting of outbound, inbound and transshipment containers (x_{trans}, x_{hinter}). The outbound and inbound containers typically represent the operational achievement over time while the intra-terminal transshipment (x_{itt}) indicates the level of self-sufficiency on container handling capacity for transshipment operations without inter-terminal transportation.

5.2. Comparative analysis on operational capabilities

In the set of experiments that follows, each DMU in the dataset is identified by the name of the container terminal and the year in which the performance scores are computed from. To illustrate, the Jaseongdae container terminal in 2016 and 2017 are treated as the two different DMUs. This setting allows efficiency outcomes to be compared across terminals, as well as, across years.

Figure 3–5 compare the experiment results obtained from the proposed parallel-network DEA model against the conventional CCR model without the network structure (Cooper, Seiford, and Tone 2007). According to Odeck (2007), conventional DEA models are noted for their tendency to

Table 2. Container terminals and their operators over years at Port of Busan.

Districts	Piers (Container Terminals)	Operators		Operators' full names
		2014–2015	2016–2018	
Northern Port District	Jaseongdae Pier	HBCT	HBCT	Hutchison Busan Container Terminal
	Shinseondae Pier	CJKBCT	BPT	CJ Korea Express Busan Container Terminal Busan Port Terminal
	Gamman Pier	BIT	BPT	Busan International Terminal
	Shingamman Pier	DPCT	DPCT	Dongbu Pusan Container Terminal
New Port District	New Pier 1	PNIT	PNIT	Pusan Newport International Terminal
	New Pier 2	PNC	PNC	Pusan Newport Container Terminal
	New Pier 3	HJNC	HJNC	Hanjin Busan Newport Terminal
	New Pier 4	HPNT	PSA-HPNT	Hyundai Pusan New-port Terminal
	New Pier 5	BNCT	BNCT	Busan Newport Container Terminal

Table 3. Input and output variables of BPA container terminals in 2018.

	Jaseongdae	Shinseondae	Gamman	Shingamman	New Pier 1	New Pier 2	New Pier 3	New Pier 4	New Pier 5
x_{length}	1,447	1,500	1,400	826	1,200	2,000	1,100	1,150	1,400
x_{emp}	342	608	315	315	565	897	398	620	492
x_{yard}	335,000	804,000	384,000	153,000	294,400	525,000	373,000	213,000	154,000
x_{qc}	14	15	11	7	12	22	12	12	11
$x_{vehicle}$	90	82	54	39	80	154	96	85	33
x_{yc}	31	42	30	19	39	73	42	38	42
$x_{support}$	29	19	10	3	20	41	12	15	12
$x_{service}$	969.7	12,023.9	12.1	2.3	1.0	1.0	1.0	1.0	1.0
x_{market}	40.3	27.5	20.7	16.7	8.8	12.9	9.8	8.8	6.9
$x_{capacity}$	1,720,000	2,230,000	1,600,000	820,000	2,090,000	3,670,000	2,310,000	1,930,000	2,440,000
x_{trans}	930,251	1,099,907	445,931	211,153	1,510,628	3,097,587	1,695,662	924,188	1,313,429
x_{hinter}	995,932	1,390,296	841,979	759,352	967,156	1,840,860	1,074,873	1,136,943	956,253
x_{itt}	0.49	0.51	0.27	0.36	0.66	0.80	0.77	0.56	0.76

produce higher efficiency estimates. Therefore, from the efficiency scores generated in conventional DEA model, the performance differentials among the DMUs appear to be insignificant. In order to increase the discriminative power of DEA, the proposed parallel-network structure suppresses the over-estimation of efficiency performance by introducing concurrent operational processes in DMUs.

As depicted in Figure 3 (left), the container terminals located at the New Port District generally outperform the terminals of Northern Port District. In particular, New Pier 2 reports outstanding performances with an efficiency score as high as 0.99, followed by New Pier 5 with a comparative good average score of 0.94 over the five years. A closer scrutiny of the data reveals that the piers of New Port District handle hinterland (transhipment) throughput volumes which are 13.5%, 16.1%, 17.1%, 18.5%, and 19.9% higher than that those at the Northern Port District across the years spanning from 2014 to 2018. Correspondingly, the volumes of transhipment throughputs are also 1.29, 1.58, 1.54, 1.38 and 1.54 times higher. The larger throughput volumes stimulate a virtuous cycle where large volumes allow more intensive utilizations of the resources leading to high-efficiency scores for terminals, which in turn, attract a larger container traffic. The volume of transhipment also reflects contributions of a terminal in the value chain. Statistics reveal that the average volume of transhipment handled by the terminals in New Port District is 61.4% higher than that in Northern Port District over the study period. This could possibly suggest a regional network effect.

New Pier 2 triumphs all its competitors in the hinterland and transhipment throughput volumes and the intra-terminal transhipment rates throughout the study period. The terminal has many merits in the eyes of the shipping liners and consignees as it is equipped with extensive facilities and machines and offer supporting services. While the performance scores of terminals in New Port District are generally outstanding in 2014, their performance scores dipped in 2015. The drop in scores is attributed to the BPA's planned expansion to the capacity to the terminals in New Port District, which averages about a 35.8% increase. In comparison, the terminals in Northern Port District experienced relatively minor adjustments with a mere 2.9% increase.

The performance scores of other terminals shed light on dynamics of operating landscape at Busan port. Unlike New Pier 2 and New Pier 5, these terminals produce efficiency scores that fluctuate over the study period. For instance, New Pier 3 has achieved a full efficiency score of 1 in the operating year 2014. Despite the impressive increase in hinterland throughput of 11.6%, New Pier 3 has obtained a lower efficiency score of 0.86 in 2015. The spectacular improvement of service peripherals by 22.6%, the additional provision of 18.1% labour to its workforce and a 2.3% reduction in transhipment throughput are possible explanatory factors for the weaker performance. In an attempt to alleviate the problem of congestions, the terminal engaged in aggressive expansion

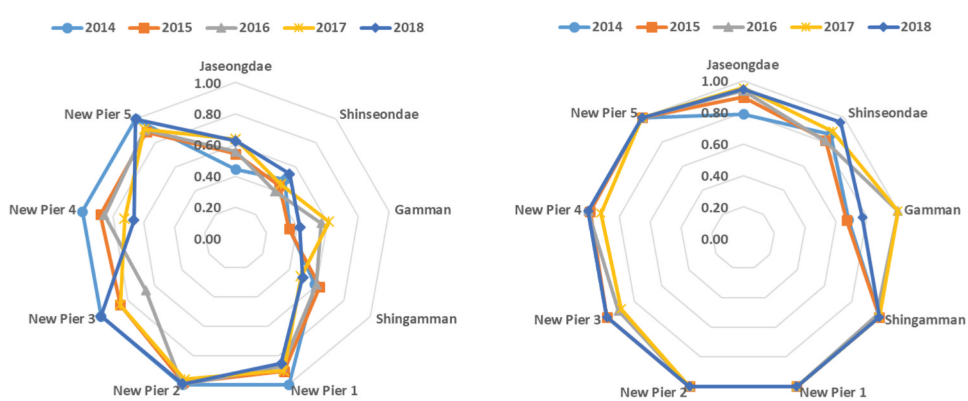

Figure 3. Performance results for both L&D and D&R processes measured by the parallel-network model (left) and the conventional model (right).

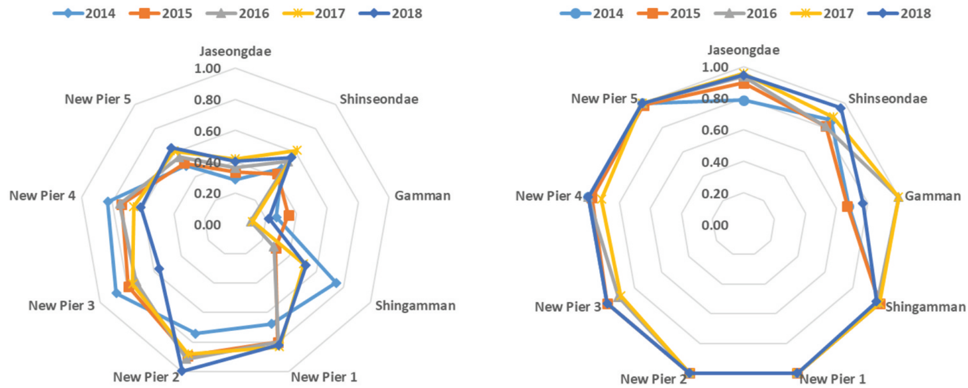

Figure 4. Partial performance results for L&D process measured by the parallel-network model (left) and the conventional model (right).

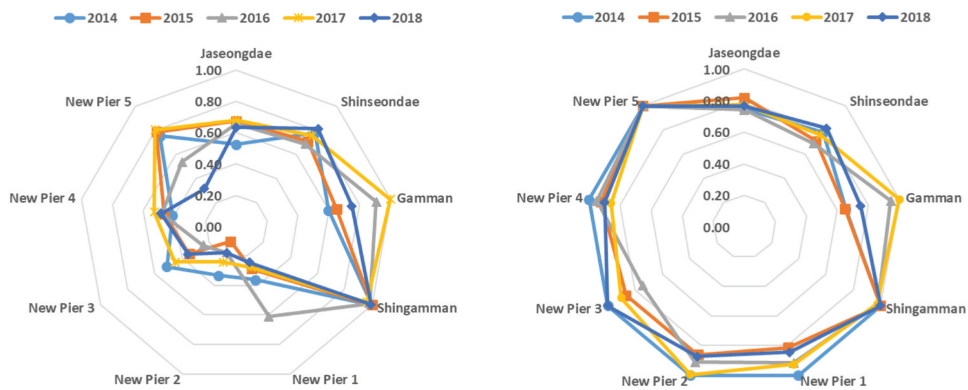

Figure 5. Partial performance results for D&R process measured by the parallel-network model (left) and the conventional model (right).

on its hardware and software leading to the under-utilization of its resources. Recognizing that capacity surplus is costly and reduces the terminal competitiveness, the terminal lowers its service peripherals by 1.6 times in 2016. However, the terminal performance continues to deteriorate to 0.67 as both hinterland and transhipment throughputs are reduced by 23.5% and 25.6%, respectively, at the same time. Subsequently, New Pier 3 reduces its workforces by 47.2% and further diminishes its service peripherals by 2.08 times in 2017. Together with a 1.02% increase in hinterland and 27.4% increase in transhipment throughputs, the terminal reverses the trend of declining performance and the efficiency score improves to 0.85. This performance improvement continues into 2018 when the service peripherals significantly increases by 99.1%, together with a 19.4% and 28.7% respective growth in hinterland and transhipment throughputs. In 2018, New Pier 3 achieved full efficiency. It can be inferred that lean operations drive efficiency and, when complemented with service peripherals, attract traffic and enhance terminal performances. Simply put, efficient operations are qualifiers for container traffic while service peripherals strengthen the competitive edge.

Figures 4 and 5 (left) show the partial performance scores of the 9 terminals on the L&D and D&R processes, respectively. A key highlight is New Pier 2, which has consistently placed more priority on container flows of the L&D process, resulting in better performance throughout the study horizon. Table 3 shows that the average number of vehicles facilitating container flows of L&D process in New Pier 2 is 1.6, 1.7, 1.7, 1.5 and 1.7 times higher than that in overall New Port District between 2014 and 2018. The number of vehicles in the New Port District is also found to be

1.7, 1.9, 1.9, 1.7 and 1.9 times higher than the average figures in the entire port of Busan during the same period. Similarly, the number of quay cranes is found to be 1.5 and 1.6 times larger than those at New Port District and at the port, respectively, on average over the 5 years undertaken in study. On the other hand, Shingamman pier concentrated its effort most highly on the facilitation of container flows in the D&R process among all the terminals in the port. Shingamman pier is the smallest terminals in the North Port District. Its hinterland throughputs are seen to be 1.95, 2.05, 2.16, 3.57 and 3.60 times higher than its transhipment throughputs. These figures sharply contrast against those of New Pier 2 where hinterland throughputs are recorded to be 0.75, 0.54, 0.59, 0.68 and 0.59 times lower compared to the transhipment throughputs. The resulting gap in the overall efficiency scores between New Pier 2 and Shingamman port further points to the importance of having a strong transhipment market in addition to a captive hinterland. Despite a seemingly similar geographical location, ports in the New Port district enjoy more transhipment traffic than their counterparts in the Northern Port district. A large part of this can be attributed to the state-of-the-art facilities at new port and good ship services, which attract big ships to use the terminals. Meanwhile, the proximity to the industrial parks offer huge hinterland volumes to ports in the Northern port district.

Within the Northern Port District, Shinseondae pier is the largest terminal. This terminal is 1.8 times larger than Shingamman pier in terms of the quay length and handles hinterland and transhipment throughputs that are about 1.7 and 3.3 times higher than Shingamman pier. Contrary to intuition, Shingamman pier is found to consistently outperform Shinseondae pier over the years, producing a performance score that is about 22.6% higher on average. The outstanding performance in D&R process in Shingamman pier is the main driver for the high overall performance score in the small terminal. The subsequent subsection explores the role of management directive in enabling a terminal, and the port, to achieve higher efficiency via a resource allocation strategy that is aligned with the terminal's size and operational capability.

5.3. The relationship between container-handling efficiency and management directive

Container terminals can potentially handle a larger volume of throughputs by better leveraging on the capability of their existing infrastructure facilities, machines and services and achieve higher efficiency scores. To this end, container terminals need to have the right management directive that will optimize the resource allocations between the two operational processes and produce a smooth flow of containers through the terminal.

Figure 6–8 show the partial performances of the container terminals plotted onto a 4-quadrant graph, in which the two axes correspond to the L&D and D&R processes. The DMUs numbered from 1 to 45 according to the performance scores (P_k) in descending order in Table 4. The centre point of the quadrant graph, representing the gravitational convergent, is determined by the average partial performance scores for L&D and D&R processes among DMUs.

Terminals that have shown outstanding performances in both L&D and D&R processes fall into the upper-right quadrant which clearly represents most ideal situation (Figure 6). At the opposite end, the lower-left quadrant houses terminals that could neither facilitate container flows for the L&D nor D&R processes efficiently, leading unambiguously to a poor performance outcome.

Most of the DMUs are positioned at either the upper-left or the lower-right quadrants of the graph, indicating the trade-off in efficiency that is likely to occur between the L&D and D&R processes. Terminals, which are positioned on the upper-left quadrant, achieve higher operational efficiencies in the L&D process relative to the D&R process. These terminals engage in container-handling activities of the L&D processes more intensively, handling large volume of transhipment containers. Among them, New Pier 2 occupies very remarkable positions at the upper-left quadrant and the terminal is seen to maintain these positions consistently over the years (i.e. DMUs 6, 15, 24, 33, and 42). The performances of New Pier 1 are also commendable for its efficiencies on the L&D process as evidenced from the positions of DMUs 5, 14, 32 and 41 at

Table 4. Experiment results ranked by performance scores (P_k).

Observations										
Years	Terminals	DMUs	P_k	E_k^{LD}	E_k^{DR}	w_k^{LD}	w_k^{DR}	Conv*-P_k	Conv*-E_k^{LD}	Conv*-E_k^{DR}
2014	New Pier 1	5	1.000	0.678	0.361	1.044	0.809	1.000	1.000	1.000
2014	New Pier 2	6	1.000	0.741	0.331	1.146	0.456	1.000	1.000	1.000
2014	New Pier 3	7	1.000	0.882	0.510	0.807	0.565	1.000	1.000	1.000
2014	New Pier 4	8	1.000	0.830	0.412	0.900	0.615	1.000	1.000	1.000
2014	New Pier 5	9	1.000	0.490	0.755	1.163	0.569	1.000	1.000	1.000
2016	New Pier 2	24	1.000	0.915	0.176	0.958	0.700	1.000	1.000	0.911
2018	New Pier 3	43	1.000	0.563	0.354	1.679	0.152	1.000	1.000	1.000
2018	New Pier 5	45	1.000	0.638	0.315	1.493	0.152	1.000	1.000	1.000
2018	New Pier 2	42	0.994	0.998	0.177	0.904	0.519	1.000	1.000	0.872
2015	New Pier 2	15	0.985	0.893	0.102	1.019	0.739	1.000	1.000	0.862
2017	New Pier 2	33	0.964	0.881	0.242	0.990	0.380	1.000	1.000	0.995
2017	New Pier 5	36	0.914	0.611	0.805	0.908	0.448	1.000	1.000	1.000
2015	New Pier 1	14	0.909	0.800	0.285	0.839	0.836	1.000	1.000	0.815
2016	New Pier 5	27	0.907	0.561	0.537	0.940	0.710	1.000	1.000	1.000
2017	New Pier 1	32	0.904	0.831	0.276	0.844	0.732	1.000	1.000	0.926
2015	New Pier 5	18	0.890	0.510	0.789	1.001	0.480	1.000	0.987	1.000
2015	New Pier 4	17	0.882	0.740	0.466	0.843	0.554	0.988	0.977	0.922
2016	New Pier 1	23	0.876	0.801	0.612	0.788	0.400	1.000	1.000	0.916
2018	New Pier 1	41	0.856	0.819	0.243	0.847	0.664	1.000	1.000	0.846
2015	New Pier 3	16	0.855	0.792	0.347	0.723	0.816	1.000	1.000	0.868
2016	New Pier 4	26	0.855	0.751	0.482	0.801	0.526	1.000	1.000	0.950
2017	New Pier 3	34	0.855	0.760	0.452	0.797	0.553	0.895	0.900	0.900
2017	New Pier 4	35	0.723	0.661	0.530	0.761	0.416	0.918	0.916	0.857
2016	New Pier 3	25	0.666	0.733	0.241	0.596	0.953	0.917	0.917	0.744
2018	New Pier 4	44	0.664	0.616	0.487	0.787	0.370	1.000	1.000	0.900
2017	Jaseongdae	28	0.637	0.419	0.678	1.395	0.079	0.957	0.957	0.773
2018	Jaseongdae	37	0.626	0.401	0.634	1.437	0.079	0.947	0.947	0.765
2015	Shingamman	13	0.623	0.300	1.000	1.446	0.189	1.000	1.000	1.000
2017	Gamman	30	0.608	0.112	1.000	3.528	0.214	1.000	1.000	1.000
2016	Shingamman	22	0.598	0.286	0.981	1.447	0.189	0.981	0.981	0.981
2014	Shingamman	4	0.587	0.748	1.000	0.509	0.207	1.000	1.000	1.000
2016	Gamman	21	0.560	0.102	0.907	3.548	0.219	1.000	1.000	0.945
2016	Jaseongdae	19	0.556	0.362	0.657	1.394	0.079	0.938	0.938	0.742
2015	Jaseongdae	10	0.543	0.333	0.674	1.486	0.072	0.898	0.896	0.817
2018	Shinseondae	38	0.538	0.558	0.815	0.840	0.085	0.962	0.962	0.815
2018	Shingamman	40	0.499	0.523	0.993	0.517	0.230	1.000	0.976	1.000
2014	Shinseondae	2	0.493	0.464	0.780	0.927	0.081	0.865	0.865	0.780
2017	Shingamman	31	0.486	0.507	0.963	0.519	0.231	1.000	1.000	0.975
2017	Shinseondae	29	0.453	0.616	0.758	0.523	0.173	0.889	0.889	0.758
2014	Jaseongdae	1	0.443	0.286	0.526	1.404	0.078	0.790	0.788	0.747
2015	Shinseondae	11	0.439	0.420	0.710	0.904	0.083	0.813	0.813	0.710
2018	Gamman	39	0.419	0.219	0.750	1.287	0.183	0.770	0.770	0.750
2016	Shinseondae	20	0.393	0.526	0.687	0.522	0.173	0.811	0.811	0.688
2014	Gamman	3	0.355	0.269	0.597	0.804	0.233	0.680	0.679	0.655
2015	Gamman	12	0.349	0.346	0.650	0.666	0.183	0.669	0.669	0.650

*Conv indicates the results applied by the conventional DEA model without network.

upper-left quadrant. In 2016, New Pier 1 moved into the upper-right quadrant (i.e. DMU 23). The deficiency in D&R process efficiency of 0.4, however, has dragged the terminal overall performance down to 0.88. Apart from New Pier 1 and New Pier 2, New Pier 3 is another terminal that largely sits in the upper-left quadrant except the year 2018 when its L&D's efficiency score falls below the port average (as exemplified in DMU 43). Notably, New Pier 4 takes positions near to the vertical axis at the upper-left quadrant. Although the terminal has attained good performance on the L&D process in general, it does not appear to be sufficient to compensate its inferior performance in its D&R process (as seen from the positions of DMU 8, 17, 26, 35, 44). Compared to other terminals in the New Port District, the aggregate efficiency levels of New Pier 4 are second-rated. This may probably suggest that a stronger concentration on the L&D process will be helpful.

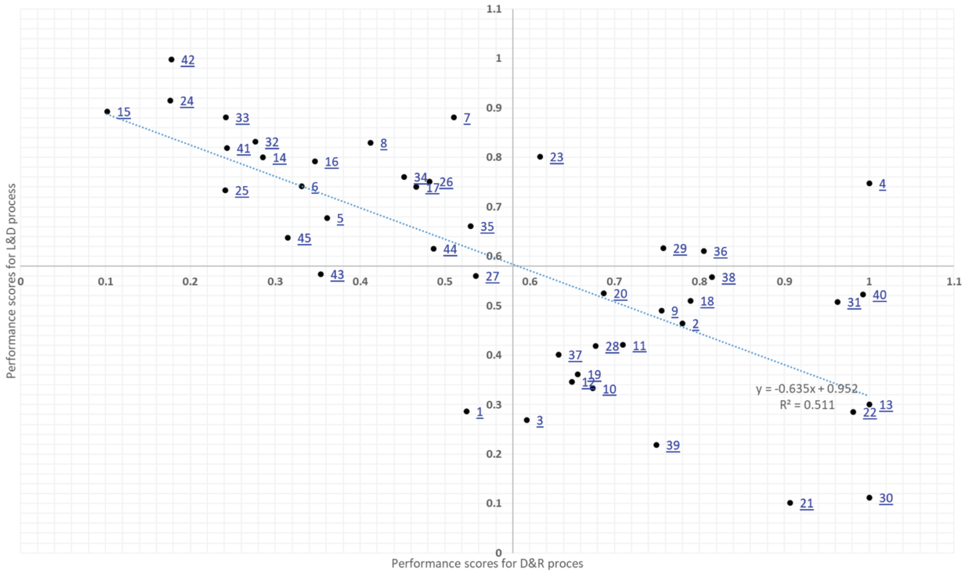

Figure 6. Partial efficiency scores in the L&D and D&R processes in Parallel-network DEA model.

Conversely, terminals in the lower-right quadrant focus more on D&R operations process. Most of Jaseongdae terminals lie at lower-right quadrant, achieving improved performance outcome on the D&R process at the expense of the L&D process (i.e. DMU 1, 10, 19, 28 and 37). The same is observed in the Shinseondae pier (i.e. DMU 2, 11, 20, 29 and 38) where high D&R's efficiency scores are accompanied by low-efficiency scores on the L&R counterpart. Notably, Gamman pier performs considerably much better on its D&R process. DMUs 3, 12, 21, 30 and 39 have exhibited D&R efficiency scores of 0.6, 0.65, 0.91, 1 and 0.75 over the period 2014–2018. Overall, the efficiency scores of the Shinseondae and Gamman piers averaged around 0.46 while Jaseongdae attains an average efficiency score of 0.56.

Meanwhile, some terminals exhibit significant variations in efficiency performances on one or both of their operational processes. For example, the efficiency scores of the D&R process in New Pier 5 improve from 0.76 in 2014 (i.e. DMU 9) to 0.79 in 2015 (i.e. DMU 18) to 0.81 in 2016 (i.e. DMU 36). However, the terminal D&R performance drops to 0.31 in 2018 with DMU 45 moving into the upper left quadrant (when its D&R process efficiency falls below the average of 0.58). Amidst dynamics, the terminal has been maintaining average efficiency levels in the L&D process and in the overall performance of the terminal. It can be inferred that, through the D&R process, the operator in New Pier 5 adjusts its container operations to offer a consistent service to the shippers at the terminal level. On the contrary, Shingamman pier sustains high D&R's efficiency consistently while allowing the efficiency levels of its L&D process to fluctuate from good (i.e. DMU 4) to average (i.e. DMU 31 and 40) to poor (i.e. DMU 13, 22). In this respect, the operator of Shingamman terminal has appeared to have taken a contrasting stance in relation to the New Pier 2. At the aggregate industry level, as represented in our sample of ports, a negative association is found between the performance in the L&D process and the D&R process with a correlation of 51.1%.

The priorities that management place on the L&D and the D&R processes are reflected by the resource allocations between the two processes competing for the common pool of shared resources in Table 3. Figure 7 categorizes the DMUs into the four regions based on the contributions of the L&D and D&R processes to the aggregate terminal performances. The DMUs which are recommended to allocate substantially more resources to its L&D process than the D&R process, in comparison to the sample of terminals in the port, are grouped

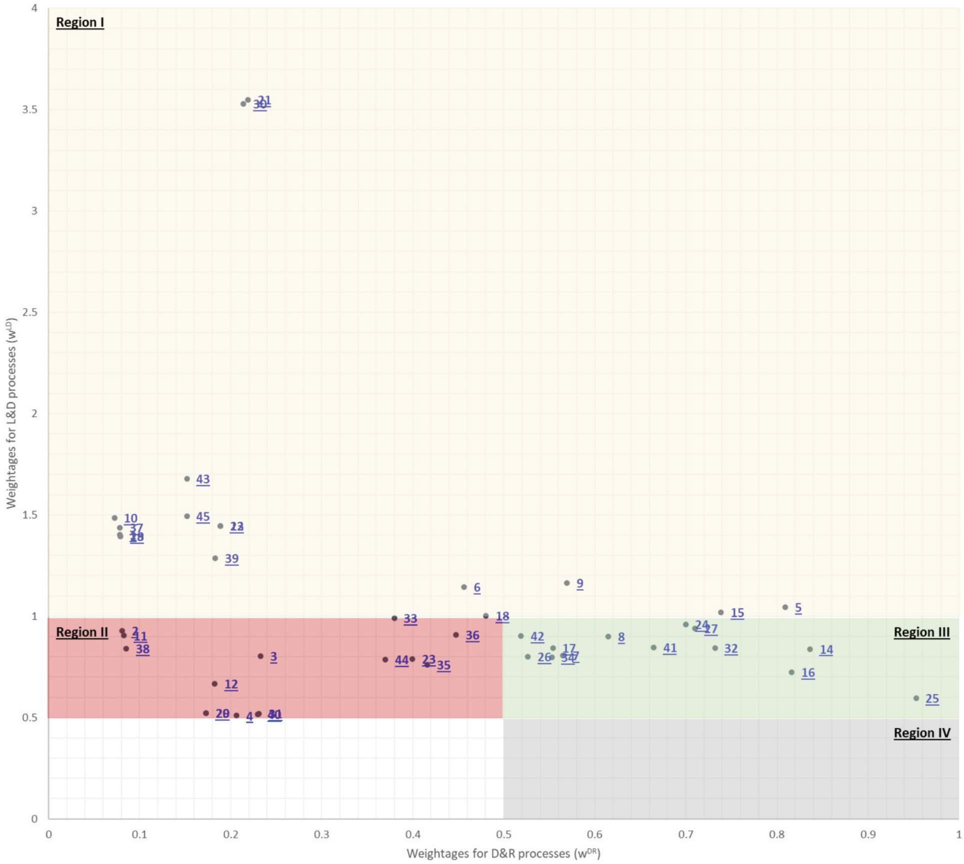

Figure 7. Resource allocations to L&D and D&R processes in the parallel-network DEA model.

together in the Region I. In the next level, the DMUs that receive higher contributions from the L&D process relative to the D&R process are identified and placed in the Region II. These terminals should ideally allocate more resources, above the averages of the 9 terminals, to their L&D process. If a DMU in Region I or II concurrently occupies a position on the upper-left quadrant on Figure 6, the effort of terminal operator on the L&D process can be said to be aligned with the operational capability of the terminal. The alignment between the management directive policy and terminal's competence allows the DMU has produced a more than proportionate volume of container flows from the L&D process relative to the amount of resources allocated. In contrast, the Region IV houses the DMUs where the efficiency of the D&R process carries more weights than the L&D process in determining the overall terminal performances. Nonetheless, there is no clear dominance of either process when a DMU falls into the Region III.

Across the years 2014–2018, New Pier 2 allocates large amount of resources to the L&D process compared to those to the D&R process (please refer to Table 3). The terminal is represented by DMUs 6, 15 and 33 in Region I with DMUs 24 and 42 in Region III in Figure 7. The management directive, as seen from the actual resource allocations between the two processes, is aligned with the operational capability of the system. As highlighted in the earlier discussion, New Pier 2 has set the record of remarkable efficiency scores in the L&D process (Figure 6) with the terminal achieving performance outcomes of full or almost full efficiency (Table 4). Similarly, the New Pier 5 has also allocated more resources to the L&D process. The terminal is represented by DMUs 9, 18 and 45 in

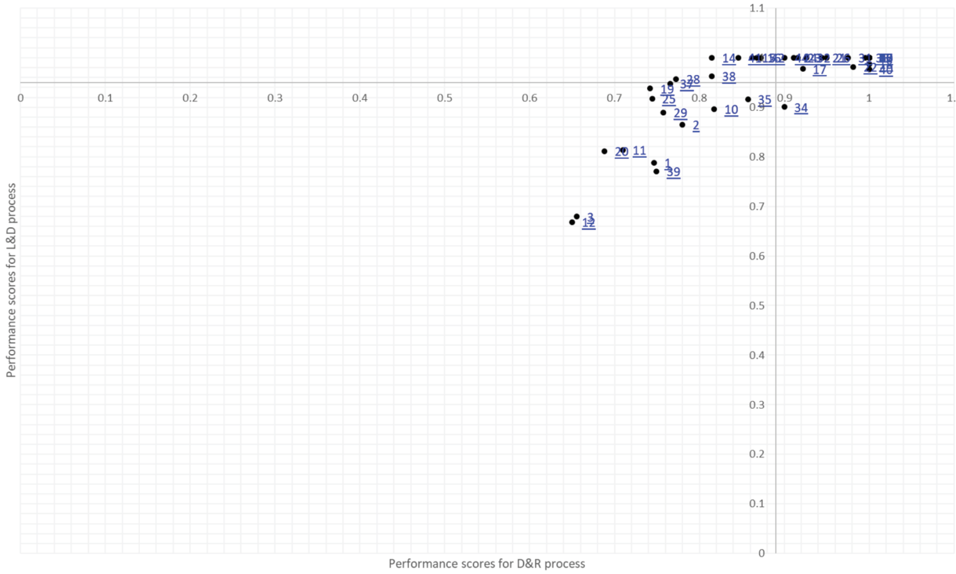

Figure 8. Partial efficiency scores in the L&D and D&R processes in DEA-CCR model.

Region I, and DMUs 36 and 27 in Regions II and III, respectively. The larger resource apportionment has allowed the terminal to attain good combined performances.

On the other hand, discrepancies between the management directive in the form of resource allocations and operational capability of the system show up in the piers at the Northern Port District. This misalignment is generally observed as a disproportionately large amount of resources being allocated to a specific process that co-exists with poor operational efficiency. In the first illustration, Gamman pier allocates a significantly larger amount of resources to its L&D process compared to the D&R process but achieve much superior performance in the latter. Referring to Figure 7, DMUs 21, 30 and 39 lie in Region I, carrying weightages of 3.55, 3.53 and 1.27 on the L&D process and weightages of 0.22, 0.21 and 0.18 on the D&R process. Despite the significantly stronger management's emphasis on the L&D processes, Gamman has attained low-efficiency scores of 0.10, 0.11 and 0.22, respectively, on its L&D process as presented by the same DMUs in Figure 6. The mismatch between the intrinsic operational capability of the terminal and management intent subsequently manifest itself the low overall performance scores that ranges from 0.42 to 0.61 over the study period. In another illustration, Jaseongdae pier also allocates a significantly larger amount of resources to its L&D process compared to the D&R process but achieve much superior performances in the latter. Represented by DMUs 28, 37, 19, 10, and 1 that lie in Region I, Jaseongdae pier is seen to place weightages of 1.40, 1.44, 1,39, 1.49, and 1.40 on its L&D process and weightages of 0.08, 0.08, 0.08, 0.07, and 0.08 on the D&R process (Figure 7). However, the terminal has attained relatively low-efficiency scores of 0.42, 0.40, 0.36, 0.33, and 0.29, respectively, on its L&D process as presented by the same DMUs in Figure 6.

The merits of the proposed parallel network DEA model are evidenced when the results obtained from the network model are compared against those of the conventional DEA-CCR model plotted in Figure 8. As highlighted in the Introduction, the conventional model has little discriminative power due to the design of 'black-box' DMUs. When the partial performance scores computed from the conventional DEA-CCR model are plotted in Figure 8, almost all the DMUs fall near to the center of the quadrant graph. The plot also presents a positive and proportionate association between the two L&D and D&R operational processes, which does not explain the performance outcomes in a real-world setting.

6. Conclusions

This study proposes a parallel-network DEA model to describe and analyze the operational capability of container terminals in achieving throughputs from two typical container-handling processes, namely, loading-discharging and the delivery-receiving processes. Each DMU represents a container terminal facilitating multiple streams of container flows from the integrated L&D and D&R processes. Due to the interoperability nature of L&D and D&R processes, some of the resources in the form of infrastructural facilities, machines and service peripherals will inevitably shared. As such, an optimal allocation and utilization of resources will affect the total volume of throughput, consisting of hinterland and transhipment containers, produced at a terminal.

All the nine terminals considered in this study deal with transhipment and hinterland traffic that jointly contribute to their aggregate throughput. A large volume of throughput at a terminal helps to reap economies of scale where the huge capital investment in physical facilities can be spread across larger volumes. In terms of resource usage, the handling of transhipment containers take up less resources time as it only involves L&D operations, whereas hinterland containers are required to go through both L&D and D&R operations in tandem. Myopically, a terminal should concentrate on the transhipment traffic since it consumes less resources and an extensive involvement in transhipment will also potentially lend the terminal a key position in the sea cargo value chain. Conversely, the reliance on hinterland traffic not just means that more resource time needs to be devoted but also it limits the market to the port hinterland. Particularly, in the era of logistical advances and carriers are becoming increasingly more footloose with the homogeneity of port services, the boundaries of the captive hinterland appear to be more greyish than before (Low, Lam, and Tang 2009). Nevertheless, the concurrent handling of both transhipment and hinterland throughput allows the terminal to achieve further cost savings via economies of scope. In doing so, it also gives rise to more incidents of resource sharing, which is the main subject dealt in this study.

Statistics used in this study indicate that the terminals in the New Port District not only produce a high volume of transhipment throughput, also report greater volume of hinterland traffic in aggregate. The model was run on a set of real-world data spanning across 5 years from 2014 to 2018 inclusive, published by BPA and the results are compared against with those of the conventional CCR model. The parallel-network model is shown to be able to provide more accurate efficiency results with greater discriminative power than the conventional DEA-CCR model. In order to examine the operating dynamics, the values of the variables from a container terminal in different operating years are treated as different DMUs. The partial performance results of the DMUs on the L&D and D&R processes were plotted in the quadrant graph.

Despite the fact that D&R (in addition to L&D) operations are required to handle hinterland containers, terminals in the New Port district are found to put a stronger focus on their L&D operations and attain impressive levels of L&D efficiencies. In comparison, terminals in the Northern Port district allocate a proportionately larger amount of resources to D&R operations. From the results obtained in this study, some evidences suggest the presence of trade-off between L&D efficiency and D&R efficiency. Terminals in the New Port district (Northern port district) registered higher (lower) in L&D efficiencies but lower (higher) D&R efficiencies. Overall, terminals in the New Port district are found to exhibit higher efficiencies than those in the Northern port district. This confirms our conjecture in the Introduction that the prioritization of L&D operational process over the D&R operational process will improve the throughput efficiency of the terminal. The reason is because throughput is measured as the amount of TEUs (twenty-foot equivalent units) handled by QCs for ships and the L&D process deals directly with the loading and unloading of containers from ships.

Subsequently, the study examines the dynamics of resource allocations and the effect on the terminal throughputs in the New Port and Northern Port districts and arrives at some interesting findings. Firstly, there appears to be a regional network effect whereby terminals in the New Port district generally allocate more resources to the L&D operations to manage a bigger bulk of the transhipment containers. Meanwhile smaller terminals (for example, the Shingamman pier) in the Northern port district, which handle a proportionately larger volume of hinterland containers report higher D&R and overall operations efficiencies compared to their counterparts. Secondly, it could be inferred that that lean operations drive efficiency and, when complemented with service peripherals, attract greater volume of traffic, and enhance terminal performances. For examples, some terminals in the New Port District, in particular New Pier 3, have engaged in a series of resource expansions and contraction during the study horizon. The resulting effect on the throughputs reveals that efficient operations are qualifiers for container traffic, whereas the extent of market presence and degree of market aggressiveness (captured in the 'service peripherals' variable) are the supporting factors that confer the terminal a competitive edge, which helps it to sustain the good overall performance over time. Thirdly, the alignment between the management directive policy and terminal's competence is demonstrated to be of utmost importance. Terminals, especially those in the New Port District, are found to achieve better performance outcomes when operational capability and the management directive (via resource allocation) are aligned.

The proposed parallel-network DEA model can be made applicable to container terminals belonging to different port authorities (regions) by augmenting it with an additional set of contextual variables (e.g. gross domestic product, regional employment rate, population density, accessibility, and regulatory) as well as structural variables (e.g. water draft, vessel arrivals resulting from voyages, inter-modal connectivity, etc.) exemplified by Bergantino, Musso, and Porcelli (2013) and Wiegmans and Witte (2017), respectively. A further development of variable return-of-scales on the parallel-network model could enrich the management implications of the experiment.

Note

1. The DEA measures the relative performances among homogeneous Decision-Making Units (DMUs) by using a set of multiple performance metrics classified into inputs and outputs. It evaluates the performance as the level of outputs under the given inputs, or vice versa. Each DMU is evaluated by comparing its performance with those of the other DMUs in its peer group. A major advantage of DEA is that the relative importance or weights of multiple performance metrics is not necessarily known a priori. The defined operational capability is equivalent to the performance score evaluated by a DEA model.

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