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ABSTRACT

Available studies have not provided a satisfactory answer to the problem of making international comparisons of port efficiency. This study applies data envelopment analysis (DEA) to provide an efficiency ranking for five Australian and eighteen other international container ports. While DEA has been applied to a wide number of different situations where efficiency comparisons are required, this technique has not previously been applied to ports. The DEA technique is useful in resolving the measurement of port efficiency because the calculations are nonparametric and do not require specification or knowledge of a priori weights for the inputs or outputs, as is required for estimation of efficiency using production functions.

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1. Introduction

In order to support trade oriented economic development, port authorities have increasingly been under pressure to improve port efficiency by ensuring that port services are provided on an internationally competitive basis. Ports form a vital link in the overall trading chain and, consequently, port efficiency is an important contributor to a nation's international competitiveness, e.g., Tongzon (1989). UNCTAD (1987) emphasized the need to improve and measure port efficiency and concluded that available studies on port productivity have overall been unsatisfactory. The UNCTAD report goes on to say that any effort to analyze port efficiency is formidable due to the sheer number of parameters involved, as well as the lack of up-to-date and reliable data. At times, the inability to differentiate relevant factors contributing to port efficiency has resulted in unnecessary collection of significant amounts of data which were later found to be of limited use, thus resulting in a wastage of port management resources (Tongzon, 1995).

This study is concerned with the problem of making international comparisons of port efficiency. Since there are a number of inter-related aspects and activities in the port which cannot be captured by one single measure or indicator, port authorities have developed a number of efficiency indicators to use as a basis for classifying ports in terms of efficiency. The presence of different indicators raises problems for evaluating and comparing overall port efficiency across ports. For example, the straightforward method of using simple arithmetic means of the various efficiency measures is not suitable due to differences in the importance of the measures used. This paper proposes the use of Data Envelopment Analysis (DEA) for measuring and classifying port efficiency. This technique has been applied to a wide number of different situations where efficiency comparisons are required. However, the technique has not previously been applied to ports. In the following, Section 2 provides a literature review and a discussion of available measures of port efficiency. Section 3 outlines DEA and gives a brief review of related studies which have used this technique. Section 4 provides the empirical results for DEA applied to 23 container ports. Finally, Section 5 summarizes the main results in the paper.

Section 2. Port Output and Port Input Measures

Various studies have compared ports using selected performance and efficiency criteria. Examples from Australia include the Australian Bureau of Industry Economics (1993) and Australian Transport Advisory Council (1992). In DEA analysis, being efficient involves combining available inputs to achieve a higher level of outputs than comparable Data Management Units (DMUs). In this study, ports are the relevant DMUs. Using DEA to measure efficiency requires port outputs and inputs to be accurately specified. In contrast to conventional econometric techniques, an important feature of DEA is that more than one output measure can be specified. A number of different measures of port output are available, depending on which features of port operation are being evaluated. This study uses two output measures. The first output measure is the total number of containers loaded and unloaded. In addition, because the container handling aspect of port operation constitutes the largest component of total ship turnaround time, the speed of moving cargoes off and onto ships at berth, measured as the amount of cargo handled per berth hour, is the second measure of port output selected. Improving efficiency in this area is consistent with port authority intentions of maximizing berth utilization, a factor which will influence both port charges imposed on shipowners and the actual throughput handled.

The use of two output measures is useful because port output, measured using both the number of containers handled and the amount of cargo handled per berth hour, allows for various input factors to be identified. One fundamental input is the number of ship calls which is important to the number of containers handled as it influences the volume of cargo which can be moved through a port. The number of ship calls depends on both the geographical location of a port and ship sizes. Transhipment ports such as Singapore, Hong Kong, Rotterdam and Felixstowe are different from the Australian feeder ports such as Melbourne or Sydney which largely support local trade. The transhipment role carries with it benefits in storage area utilization and other areas of the port operation which may not be available in feeder ports. The number of containers handled is also affected by the quality and quantity of support infrastructure provided, such as the number of container berths and gantry cranes. Because the number of quay cranes is closely related to another input measure (the number of TEUs/per quay crane hour) only the number of gantry cranes is used an input measure in this study.[1]

In addition to the factors driving the size of port output measured using the number of containers handled, the efficiency of producing cargo throughput, the amount of cargo handled per berth hour, is influenced by other factors. In particular, the proportion of 40 ft. to 20 ft. containers, the container mix, is important. Larger ports, such as Singapore, tend to handle a higher proportion of 40 ft. to 20 ft. containers than smaller ports such as Brisbane and Fremantle. Although a 40 ft container is equivalent to 2 twenty-foot containers, it takes approximately the same time to handle as a 20 ft container. Hence, in order to more accurately account for the amount of cargo handled per berth hour, the number of twenty-foot container equivalent units (TEUs) is used instead of the total number of containers. The TEU/berth hr. output measure is then adjusted by taking the container mix to be an input. Work practices which produce delays affecting stevedoring can also affect port output. These delays could be due to meal breaks, equipment breakdown, perceived ship problems or weather. This input is measured using the difference between the time the ship is at berth and the gross working time for stevedoring gangs.

Quay crane efficiency, measured using the number of TEUs handled per quay crane hour is another indicator of how well working time is being used. There are two areas of crane efficiency: crane hours per gross working hour and effectiveness of crane operation. Crane hours depend on the number of cranes used to load/unload a vessel as well as on the hours worked per day. In some ports up to three cranes may be used to unload large ships while in other ports only one or two cranes are used. Ramani (1996) provides a detailed discussion of the logistics of crane scheduling and cargo container unloading and loading. This study uses the number of TEUs per crane hour to measure the efficiency of crane usage. The final input measure selected is port charges. This variable is used as a proxy to capture a number of factors, such as the presence of port competition and the quality of port management. Even though port charges account for a low proportion of overall costs of international trading, differentials in ports charges do not have to be large to impact the port choice decision. For example, marginally higher port charges in Rotterdam relative to Zeebrugge would cause container cargo bound to and from certain European areas to shift port transshipment location.

Section 3. Data Envelopment Analysis

Data Envelopment Analysis (DEA) is an efficiency evaluation model based on mathematical programming theory. DEA offers an alternative to classical statistics in extracting information from sample observations. In contrast to parametric approaches such as regression analysis which fit the data through a single regression plane, DEA optimizes each individual observation with the objective of calculating a discrete piece-wise frontier determined by the set of Pareto efficient Decision Management Units (DMUs).[2] In other words, the focal point of DEA is on *individual* observations as opposed to single optimization statistical approaches which focus on *averages* of parameters. In the present application, DEA refers to each port as a DMU, in the sense that each is responsible for converting inputs into outputs. DEA analysis can involve multiple inputs as well as multiple outputs in its efficiency evaluation. Furthermore, DEA calculations are nonparametric and do not require specification or knowledge of a priori weights for the inputs or outputs. For many applications, these features make DEA a more flexible tool as compared to other conventional efficiency measures derived from stochastic production frontier or economic value added (EVA), which are based on production function estimation involving many inputs but only one output.

Since its introduction by Charnes, Cooper, and Rhodes (1978), there have been many applications of DEA. Some applications have involved efficiency evaluation of organizations with characteristics similar to ports, such as hospitals (Banker et al. 1986), schools (Ray 1991), courts (Lewin et al. 1982), post offices (Deprins et al. 1984), and air force maintenance units (Charnes et al. 1985). DEA provides the flexibility to permit unconventional variables such as the number of students graduated, number of patients served, even journal ranking (Burton and Phimister 1995) to be used for efficiency evaluation. DEA has also been applied in the transportation sector to airlines (Banker and Johnston 1994, Charnes, Galleous and Li 1997), and railways (Oum and Chunyan 1994). A detailed bibliography related to DEA (1978-1992) can be found in Charnes et al. (1995, Chp. 22). Since the early work of Charnes, Cooper and Rhodes (CCR), there have been a number of extensions to the DEA model. For example, Charnes et al. (1985) introduced *window analysis* to handle panel data sets involving pooled cross section and time series observations.

The concept of DEA is developed around the basic idea that the efficiency of a DMU is determined by its ability to transform inputs into desired outputs. This concept of efficiency was adopted from engineering which defines the efficiency of a machine/process as Output/Input $\leq$ 1. In this approach, efficiency is always less than or equal to unity as some energy loss will always occur during the transformation process. DEA generalizes this single output/input technical efficiency measure to multiple outputs/inputs by constructing a relative efficiency measure based on a single "virtual" output and a single "virtual" input. The efficient frontier is then determined by selecting DMUs which are most efficient in producing the virtual output from the virtual input. Because DMUs on the efficient frontier have an efficiency score equal to 1, inefficient DMUs are measured relative to the efficient DMUs. The efficiency ranking is relative to other DMUs. It is not possible to determine if DMUs judged to be efficient are optimizing the use of inputs to produce outputs.

More formally, assume that there are n DMUs to be evaluated. Each DMU consumes varying amounts of m different inputs to produce s different outputs. Specifically, DMU_j consumes amounts $X_j = \{x_{ij}\}$ of inputs ($i = 1,\ldots\ldots, m$) and produces amounts $Y_j = \{y_{rj}\}$ of outputs ($r = 1,\ldots\ldots, s$). The $s \times n$ matrix of output measures is denoted by Y, and the $m \times n$ matrix of input measures is denoted by X. Also, assume that $x_{ij} > 0$ and $y_{rj} > 0$. Consider problem of evaluating the relative efficiency for any one of the n DMUs, which will be identified as DMU_0. Relative efficiency for DMU_0 is calculated by forming the ratio of a weighted sum of outputs to a weighted sum of inputs, subject to the constraint that no DMU can have a relative efficiency score greater than unity. Symbolically:

$$\underset{u,v}{Max} \; \frac{\sum_r u_r \, y_{r0}}{\sum_i v_i \, x_{i0}} = \frac{u^T \, Y_0}{v^T \, X_0} \qquad where \qquad u = (u_1,.....,u_s)^T \quad v = (v_1,.....v_m)^T$$

Subject to:

$$\frac{u^T \, Y_j}{v^T \, X_j} = \frac{\sum_r u_r \, y_{rj}}{\sum_i v_i \, x_{ij}} \leq 1$$

$$for \;\; j = 1,2,.....n; \quad u_r, \, v_i \geq 0 \;\; for \;\; r = 1,2.....s \;\; and \;\; i = 1,2....n$$

where u_r and v_i are weights assigned to input r and output i respectively.

For this fractional programming problem with a potentially infinite number of optimal solutions, CCR (1978) were able to specify an equivalent Linear Programming problem (LP). This requires introduction of a scalar quantity (θ) to adjust the input and output weights:

$$\theta = \frac{1}{v^T \, X_0} \qquad \mu^T = \theta \, u^T \qquad \omega = \theta \, v^T$$

Appropriate substitutions produce the CCR LP problem:

$$\underset{\mu,\, v}{Max} \;\; \Lambda_0 = \sum_r \mu_r \, y_{r0} = \mu^T \, Y_0$$

Subject to:

$$\omega^T \, X_0 = \sum_i \; \omega_i \, x_{i0} = 1 \qquad \sum_r \; \mu_r \, y_{rj} - \sum_i \; \omega_i \, x_{ij} \leq 0 \qquad \mu_r, \, \omega_i \geq \epsilon$$

where the value of Λ_0 is the relative efficiency of DMU_0 and ϵ is positive constant, called the non-Archimedian infinitesimal, which is introduced to facilitate solving of the LP problem. In DEA, this LP is known as the CCR Model, as it was developed by <u>C</u>harnes <u>C</u>ooper and <u>R</u>hodes.

In addition to the CCR DEA model, two other DEA models are also often associated with the DEA methodology (e.g., Ali et al. 1995): the BCC model and the Additive model. The models differ mainly in their envelopment surface orientation and projection path to the efficient frontier for an inefficient DMU. The CCR model results in a **constant returns to scale**, piece-wise linear envelopment surface with both input and output orientations for projection paths. The BCC model provides a variable returns to scale, piece-wise linear envelopment surface, which is similar to Additive model. However, its projection path has both input and output orientations, which differs from Additive model. The Additive model was introduced by Charnes et al. (1985). The envelopment surface derived from the Additive model has a piece-wise linear, **variable returns to scale** property. The model is based on the concept of a Pareto efficient (minimum) function. For any particular one of the n DMUs, again denoted by DMU_0, the LP for the Additive model is:

$$\underset{\mu,\, v,\, u_0}{Max} \quad \Omega_0 = \mu^T Y_0 - \omega^T X_0 + \gamma_0$$

Subject to:

$$\mu^T Y - \omega^T X + \gamma_0 \iota \leq 0$$

$$-\mu^T, -\omega^T \leq -\iota \text{ (where } \iota \text{ is a column vector of 1)}$$

The presence of an unconstrained **vector** variable γ_0 in the objective function results in variable returns to scale for the Additive model, as opposed to constant returns to scale in the CCR model.[3] When $\gamma_0 = 0$, the Additive model reduces to the CCR model.

The term "relative efficiency" is used in DEA because the efficiency of each DMU is calculated with reference to all the other DMUs that are being selected for assessment. For multiple inputs and/or outputs, the envelopment surface will be multidimensional. All those DMUs that lie on the frontier have an efficiency score of 1 and are considered DEA efficient, while those below will be classified as DEA inefficient and have efficiency scores of less than 1. For an inefficient DMU, the **facet** is the combination of efficient DMUs which are used to determine the relative inefficiency. The relative weightings of the efficient DMUs in the facet, the lambdas, are available for the Additive model, because the convexity constraint imposes the condition that the sum of the lambdas equals 1. No such restriction is available for the CCR model. One useful feature of DEA is the power to identify the sources and amount of wastage in inputs, or shortfalls in outputs, for each DEA-inefficient DMU. The level of inefficiency is determined by comparison to the **facet** located on the efficient frontier. In practice, the sources of inefficiency can be important piece of information as it can enable managers to identify the problem areas for these inefficient DMUs and provide precise information about the corrective efforts required to achieve efficient performance.

Section 4. Empirical Results

A. Sample Selection

Due to the large number of ports and substantive differences in the types of cargoes handled, only the performance in handling containerised cargoes across selected ports is examined.[4] Initially, thirty **container** ports were selected based on size, geographical location, and data availability. Questionnaires requesting 1991 data on port performance and efficiency were sent out to these selected ports. Due to reasons such as confidentiality and lack of data, only 23 of the sampled ports provided usable information. The survey results were supplemented with data from secondary sources, such as the Port of Melbourne Comparative Port Study (1992) and the Bureau of Industry Economics (Australia) International Performance Indicators in the Waterfront (1993). Lloyd's Ports of the World (1993) and Containerisation International Yearbook (1992) also provided information. The sampled ports, together with summary information on the statistics collected are given in the Appendix, Tables A.1 and A.2.

The DEA empirical results use two output measures: TEUBH, the number of twenty foot container equivalent units (TEUs) handled per berth hour, and TH, the total number of containers handled per year, both 20 and 40 foot. As discussed in Section 2, TH treats 40 and 20 ft. containers equivalently, while TEUs/per berth hour accounts for the amount of cargo handled by adjusting for the difference between container sizes. The input measures used are: CONMIX, the mixture of twenty-foot and forty-foot containers (proportion of forty foot containers); BRLWT, average delays in commencing stevedoring, difference between the berth time and gross working time; TEUCH, average quay crane productivity represented by the number of containers lifted per quay crane hour; CRANE, the number of gantry cranes present at the port; FS, the frequency of ship calls (containers ships only); and, CH, the average government port charges per container. The DEA software employed was developed at the Centre for Cybernetic Studies, University of Texas and is described in Assad (1986).

B. Empirical Results

Without precise information on the returns to scale of the port production function, two sets of results, for the CCR and Additive DEA models, are presented and discussed. The efficiency rankings calculated using these two approaches are given in Table 1. Comparison of these results reveals that the CCR model identifies more substantially more inefficient ports (13 vs. 4) than the Additive model and, ignoring a marginal increase for Jakarta, attributes a higher level of inefficiency to those ports which are judged to be inefficient using both methods. Following the discussion in Section 3, this is not surprising, as the CCR model fits a linear production technology and the Additive model features variable returns to scale, which is more flexible and will, typically, require a **larger** number of ports to define the efficiency frontier. An analogy to conventional economics would feature a linear production possibilities frontier with a piecewise convex frontier (e.g., Favero and Papi 1995, p.387). The linear frontier would be tangent to the convex frontier only over a segment, being above the convex frontier elsewhere.

Interpreting the results of Table 1 depend on assumptions made about the production technology for ports. Ports that are judged to be inefficient with variable returns to scale will also be inefficient with linear production relations, but not the converse. The two most inefficient ports identified with the Additive model, Fremantle and Manila, are also found to be the most inefficient using CCR. The other two ports identified as inefficient using the Additive model, Jakarta and Montreal, improved rankings somewhat under CCR, because a number of ports, such as Baltimore, Le Havre, and Wellington, had lower relative efficiency scores. The primary characteristic of the four ports judged to be inefficient with both DEA models is size; these four ports are among the smallest in terms of number of containers handled. The ten out of twenty-three ports found to be efficient using CCR, the group of most efficient ports, does not have any discernible characteristics. Both large ports, such as Singapore and Hong Kong, and small ports, such as Brisbane and Bombay, are included in the group. When found to be inefficient using CCR, large ports such as Rotterdam and Zeebrugge, do not exhibit large deviations from the efficient frontier.

In addition to providing efficiency rankings, DEA also provides other information relevant for the inefficient DMUs. In particular, DEA identifies the efficient facet being used for comparison as well a combination of the inputs which are being inefficiently utilized and the deviation of specific outputs from the efficient level. Because efficient DMUs do not have any slack, this information is only of interest for inefficient DMUs. Table 2 provides the Additive model results for the inefficient DMUs, as well as the facet port numbers and associated lambdas. As mentioned in Section 3, for the Additive model the convexity constraint requires the lambdas to sum to one, permitting the lambdas to be interpreted as relative weights. Higher lambda values indicate which efficient port was more important in determining the inefficiency of the particular inefficient DMU. For all the inefficient ports except Fremantle, port #16, Bombay, has the highest weight in the facet. Sensitivity analysis (not reported) was conducted to determine if dropping Bombay from the sample had a significant impact on the efficiency ranking. Excluding Manilla, which became an efficient port, the relative efficiency of the other three ports did not change appreciably. Other ports replaced Bombay in the facet.

Interpreting the information from the facet is more straight forward than evaluating the sources of inefficiency. For example, the inputs levels at Fremantle were roughly consistent with efficient levels, but output, both in terms of TEUBH and TH could have been significantly higher. Presumably, this indicates that the port, when loading and unloading ships, is efficient, but there is an insufficient amount of traffic arriving at the port, resulting in idle capacity. Jakarta provides different information, as all the inputs except CRANE are inefficient. Higher levels of both outputs could be achieved, with improvements in the usage of inputs. However, some of the inputs variables are not directly controllable. The frequency of ship calls depends on the types of ships using the port. The sizable difference between the observed and efficient level indicates that the types of ships which are using Jakarta tend to have too small a number of containers per ship to unload. While it may be possible for a port to encourage larger ships to use port facilities, it is incumbent on the port authority to support the ships which do use the port. All the ports had a level of port charges which were too high. However, sensitivity analysis (not reported) indicated that dropping this variable did not change the efficiency rankings substantially.

Table 3 provides the CCR DEA model results for the same ports as in Table 2. Comparison of Table 2 and 3 results reveals some differences. The facets are different. Though port #22, Singapore, still appears in all facets, Bombay is no longer in the facet for Fremantle and Montreal. Another difference is in the identified sources of inefficiency. While the Additive model identified efficient output and input levels, with the exception of Montreal, the CCR model has emphasized only input levels. This type of difference is sample specific and does not always occur when comparing Additive and CCR model results. Heuristically accounting for the differences in emphasis between input and output inefficiencies, the CCR and Additive models do tend to identify similar sources of inefficiencies in inputs. For example, the Additive Model finds the efficient level for FS is 1449 vs. the observed 12106 while the CCR model finds the efficient level to be 2866. Table 4 provides CCR results for ports which were found to be efficient with the Additive model but inefficient with CCR. A similar bias toward emphasizing input inefficiencies and taking outputs to be efficient is also evident in these results.

Section 5. Conclusions

Available studies of port efficiency have not provided a satisfactory answer to the problem of making efficiency comparisons across ports. With considerable success, this study applies DEA analysis to evaluate relative port efficiency. The efficiency results obtained depend on the type of DEA model employed which, in turn, depends on an assumption made about the returns to scale properties of the port production function. If a linear technology is assumed, then three of the five Australian ports examined are found to be inefficient in a 1991 sample of 5 Australian and 18 other international ports. One Australian port, Fremantle, is found to be the most inefficient port in the sample using both constant or variable returns to scale assumptions. Two Australian ports, Sydney and Brisbane were found to be efficient independent of the returns to scale assumption, indicating that port size alone is not the primary determinant of port efficiency. Adelaide was found to be efficient with variable returns to scale, but had one of the lowest efficiency scores with CCR. The remaining Australian port, Melbourne, also exhibited a sizable change in efficiency score, being efficient with variable returns to scale and having an efficiency score of .5778 under CCR.

The primary contribution of this study is methodological. It demonstrates that DEA provides a viable method of evaluating relative port efficiency. DEA has recently been successfully applied to a number of different economic efficiency measurement situations. The technique offers a significant alternative to classical econometric approaches to extracting efficiency information from sample observations, such as the use of stochastic frontier production functions. Important features of DEA are that the technique is nonparametric and that more than one output measure can be specified. In the case of port efficiency, the ability to handle more than one output is particularly appealing because a number of different measures of port output are available, depending on which features of port operation are being evaluated. In addition to providing relative efficiency rankings, DEA also provides results on the sources of input and output inefficiency, as well as the ports which were used for the efficiency comparison. The ability to identify the sources of inefficiency could be useful to port authority managers in inefficient ports, acting as a guide to focusing efforts at improving port performance.

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Appendix

Table A1. List of Sampled Ports and Selected Information*

Name of Port	Country	TEU/Berth Hr.	# of Containers	Ship Freq.
1. Melbourne	Australia	7.0	667475	2489
2. Sydney	Australia	11.0	477395	2541
3. Brisbane	Australia	4.0	173800	1607
4. Fremantle	Australia	2.0	123500	1495
5. Adelaide	Australia	3.0	43450	786
6. Rotterdam	Netherlands	23.0	3766000	33377
7. Tacoma	USA	15.0	1020708	1530
8. Zeebrugge	Belgium	4.0	363787	1348
9. Wellington	New Zealand	2.0	69760	2842
10. Montreal	Canada	4.0	575554	2247
11. Baltimore	USA	4.0	465491	2293
12. Auckland	New Zealand	7.0	229200	1553
13. Le Havre	France	7.0	920000	7900
14. HongKong	Hong Kong	50.0	6161912	129303
15. Kaohsiung	Taiwan	24.0	3913107	11465
16. Bombay	India	11.0	279556	560
17. Felixstowe	United Kingdom	38.0	1433859	5291
18. Puerto Rico	USA	15.0	1584038	5727
19. Jakarta	Indonesia	14.0	736437	12106
20. Manila	Philippines	3.0	168437	1658
21. Klang	Malaysia	17.0	607626	5910
22. Singapore	Singapore	43.0	6350000	9784
23. Bangkok	Thailand	22.0	1170697	2422

* Data is for 1991.

Table A.2. Descriptive Statistics

(Based on the 23 sampled ports)

Variable	Maximum	Minimum	Mean	Standard Deviation	Coeff. of variation
TEUs per berth hour	50.0	2.0	14.4	13.6	0.95
CONMIX (%)	67.0	4.0	28.0	17.7	0.63
BRLWT (hours)	31.0	0.8	5.0	6.5	1.29
TEUCH (TEUs per Crane hour)	44.0	13.1	24.8	8.6	0.35
FS (number of ship calls)	129303	560	10706	26783	2.50
CH (A$)	151.1	30.68	90.40	33.25	0.37
TH (number of TEUs)	6350000	43450	1360947	1852359	1.36
CE (average # of TEUs per ship call)	667	25	232	186	0.80

NOTES

1. There are two types of cranes, quay cranes and gantry cranes. Quay cranes are located at either a fixed berthing point or are moveable. These cranes are used exclusively for the loading and unloading of containers. Gantry cranes have a light, bridge-like overhead framework supporting a moveable crane. Gantry cranes have a number of uses. Some gantry cranes are used exclusively for on-line operations, loading and unloading containers from prime movers which transport the containers to and from dockside. Some gantry cranes are used for off-line operations, e.g., handling of containers prior to ship loading, which involves stacking the containers (Ramani 1996). Gantry cranes are particularly important in the handling of 40 containers. In this study, only gantry cranes are counted as quay crane performance is captured in the number of TEUs per quay crane hour measure.

2. Two of the many studies comparing DEA with the traditional production function approach to measuring efficiency are Gong and Sickles (1992) and Bowlin et al. (1985).

3. A variation on the Additive model, referred to as the multiplicative model, yields a piece-wise Cobb-Douglas (variable returns to scale) or a piece-wise log-linear (constant returns to scale) envelopment surface which results from the application of Additive model to the logarithms of the data, with (for variable returns to scale) or without (for constant returns to scale) the unconstrained variable γ_0.

4. There are four general categories of cargoes that are handled in ports: dry bulk, liquid bulk, containerised cargo and noncontainerised nonbulk cargo. Each of these types require certain type of ships and specialized cargo handling equipment.