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# Optimum Port Throughput

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## Abstract

This paper presents various measures of a port's optimum throughput to which its actual throughput can be compared in order to evaluate its performance. A port's engineering optimum throughput is its maximum (technically efficient) throughput that physically can be handled by the port under certain conditions. A port's economic optimum throughput is that throughput that satisfies an economic objective. It may be either an economic: (1) technically efficient optimum throughput (based upon the port's economic production function), (2) cost efficient optimum throughput (based upon the port's economic cost function) or (3) effectiveness optimum throughput (based upon the port's effectiveness operating objective such as maximizing profits).

## INTRODUCTION

A port is a place that provides for the transfer of cargo between waterways and land. It is an intermodal node in the transportation network, where cargo is transferred from one mode to another, e.g., from a ship to an inland transport carrier and vice versus.

Ports handle general and bulk cargoes. General cargoes are either (1) goods of various sizes and weights shipped as packaged cargo in containers or as breakbulk cargo or (2) goods of uniform sizes and weights shipped as loose (non-packaged) cargo, i.e., neobulk cargo. Container cargo is stored in standardized boxes or containers, generally 20 or 40 feet in length without wheels and referred to as one TEU (twenty-foot equivalent unit) or one FEU (forty-foot equivalent unit). Breakbulk cargo is general cargo that is packaged on pallets or in wire or rope slings for lifting on and off a ship. Neobulk cargo, for example, includes automobiles, steel and lumber. Bulk (dry and liquid) cargoes include goods neither packaged nor of uniform sizes and weights. Dry-bulk cargo, for example, include coal and grains; crude oil and refined petroleum products are examples of liquid-bulk cargo.

In evaluating their performance, ports often compare their actual throughput to their optimum throughput. For container (bulk) cargo, port throughput is measured by the number of TEUs (cargo tons) that are moved through the port. If actual throughput over time is approaching the optimum, the port's performance is improving and conversely, it is deteriorating over time. Hence, the questions arise: What is a port's optimum throughput? How is it determined?

The purpose of this paper is to present various measures of a port's optimum throughput and how these optimum throughputs are and may be determined. The port industry has historically restricted optimum port throughput to that throughput for which ports are technically efficient (i.e., maximum throughput in the use of resources) for evaluating their performance. However, there are alternative optimum throughputs, e.g., cost efficient and effectiveness optimum throughputs, that may be used in evaluating a port's performance.

A discussion of engineering optimum (technically efficient) port throughput measures that have been used in practice in evaluating the performance of ports appears in the next section, followed by a discussion in Section 3 of determining the relative technical efficiency ratings among a group of ports. Section 4 discusses port economic optimum (technical, cost and effectiveness) throughput measures and how the economic optimum throughputs may be determined. Finally, a summary of the discussion is provided.

## ENGINEERING OPTIMUM PORT THROUGHPUT

From an engineering perspective, a port's technically efficient optimum throughput is the maximum throughput that it can physically handle under certain conditions. This optimum throughput is often referred to as the port's capacity.<sup>1</sup> The engineering optimum port throughput (or capacity) may be determined theoretically or empirically.

The theoretical engineering optimum throughput of a port has been classified as: (1) design capacity, (2) preferred capacity and (3) practical capacity (Chadwin, Pope and Talley, 1990). A port's design capacity is its maximum utilization rate. For example, the design capacity of the storage area of a container port is the maximum number of containers that can physically be stored in the storage area. A port's preferred capacity is the utilization rate beyond which certain utilization characteristics or requirements cannot be obtained, e.g., the utilization rate beyond which port congestion occurs. Port congestion at the gate of a container port occurs when the waiting times for trucks to enter the gate increase beyond normal waiting times due to the increase in the number of trucks seeking entrance. A port's practical capacity is its maximum

utilization rate under normal or realistic conditions. For example, the practical capacity for a container port's ship-side crane is the maximum number of containers that the crane is expected to load and unload from a ship per hour under normal working conditions.

The empirical engineering optimum port throughput is the estimated maximum throughput for the port. In Hockney and Whiteneck's (1986) port handbook, a modular method for estimating the capability of a given port is presented, where capability is defined as the maximum annual throughput (in tons of cargo) that a port can handle under normal working conditions. To determine the capability estimate for a given port, the handbook first estimates the maximum annual throughput for the various components of the port: ship-to-apron transfer capability, apron-to-storage transfer capability, yard storage capability, storage-to-inland transport transfer capability and inland transport unit processing capability. The port's capability estimate is that estimate with the lowest throughput value among the five estimates. The lowest throughput estimate is the constraining capability of the port (or choke point) and thus is selected as the maximum annual throughput that the port can handle under normal working conditions. An empirical engineering optimum port throughput may also be obtained via an estimation based upon the actual throughput of several similar ports.

#### RELATIVE TECHNICAL EFFICIENCY THROUGHPUT RATINGS

Rather than determining the technically efficient optimum throughput for a given port, a number of studies (using frontier statistical models) have instead estimated relative technical efficiency throughput ratings for similar ports, allowing for technical efficiency (or inefficiency) comparisons among the ports.

Although it is tempting to compare the performance of one port to that of another, such comparisons may be misleading. Ports operate in different economic, social and fiscal environments. For example, even if ports has the same economic objective of maximizing annual throughput subject to a profit constraint, the profit constraint is likely to differ among ports. Also, one port may have a negative profit (or deficit) constraint that is to be subsidized, while another port may have a positive or break-even profit constraint. Ports may also have different economic objectives (see Suykens, 1986). Thus, in multi-port performance evaluations, similar ports should be used in the comparisons. A principal component analysis for identifying similar ports in a group of ports is found in a study by Tongzon (1995).

Frontier statistical models have been used to obtain multi-port performance evaluations of the technical efficiency of ports. These models utilize the throughputs and resources of a group of ports to investigate whether the ports are technically efficient or inefficient relative to each other. The models generally utilize Data Envelopment Analysis (DEA) techniques -- non-parametric mathematical programming techniques for deriving the specification of the frontier model. DEA techniques derive relative efficiency ratings for the ports that are used in the analysis and make no assumptions about the stochastic properties of the data.<sup>2</sup>

A study by Tongzon (2001) utilizes DEA to investigate the relative technical efficiency of sixteen international (including four Australian) container ports for the year 1996. Initially, two port output and six input variables were utilized in the investigation. The output variables include the total number of TEUs loaded and unloaded (cargo throughput) and the number of containers moved per working hour (ship working rate). The input variables include: (1) number of cranes, (2) number of container berths, (3) number of tugs, (4) delay time (the difference between total berth time plus time waiting to berth and the time between the start and finish in working a ship), (5) terminal area and (6) the number of port authority employees. Due to the study's small

sample size, only one output measure -- cargo throughput -- was utilized in the final analysis. Two separate versions of the DEA model were used in the investigation – the CCR version that assumes constant returns to scale in production and the Additive version that allows for variable returns to scale. A discussion of these two DEA versions is found in Cullinane (2002).

The Tongzon (2001) study found more ports to be technically inefficient based upon the CCR version than for the Additive version. This is not surprising, since the CCR version has the restrictive assumption of constant returns to scale. For both DEA versions, the ports of Melbourne, Rotterdam, Yokohama and Osaka were identified as technically inefficient and the ports of Hong Kong, Singapore, Hamburg, Keelung, Zeebrugge and Tanjung Priok were identified as technically efficient. Since a number of the ports within each group are quite different with respect to size and function (e.g., hub versus a non-hub container port), the results suggest that the technical efficiency of ports does not depend only upon port size or function. For example, in the technically inefficient group, Rotterdam is large relative to the port of Melbourne and is a hub container port as opposed to the ports of Melbourne, Yokohama and Osaka.

### ECONOMIC OPTIMUM PORT THROUGHPUT

A port's economic optimum throughput is that throughput that satisfies an economic objective of the port. It may be either an economic: 1) technically efficient optimum throughput (based upon the port's economic production function), 2) cost efficient optimum throughput (based upon the port's economic cost function) or 3) effectiveness optimum throughput (based upon a port's effectiveness operating objective such as maximizing profits).<sup>3</sup> Thus, in addition to evaluating the performance of a port from the perspective of technical efficiency, a port may also be evaluated from the perspective of cost efficiency and effectiveness, i.e., by comparing its actual throughput with its cost efficient and effectiveness optimum throughputs.

A port's economic production function represents the relationship between the port's maximum throughput and levels of resources used in the provision of throughput, i.e.,

$$\text{Maximum Port Throughput} = f(\text{Port Resources}) \quad (1)$$

where, port resources include labor, mobile capital (e.g., cranes and vehicles), immobile capital (e.g., berths and buildings), fuel and ways (e.g., port roadways and railways). If the port achieves the maximum throughput in the use of a given levels of resources, then it is technically efficient; otherwise it is technically inefficient.

A port's economic cost function represents the relationship between the port's minimum costs to be incurred in handling a given level of throughput, i.e.,<sup>4</sup>

$$\text{Minimum Port Costs} = g(\text{Port Throughput}) \quad (2)$$

If the port provides throughput at a minimum cost (given the prices or unit costs of resources), then it is cost efficient; otherwise it is cost inefficient.

In order for a port to be cost efficient, it must be technically efficient, i.e., the latter is a necessary condition for the former. If a port is technically inefficient, it can handle more throughput with the same resources by becoming technically efficient. Further, given the same resources and thus the same unit resource costs, the average cost per unit of throughput will decline with the port becoming technically efficient. Alternatively, if the port is technically inefficient, it must follow that it is also cost inefficient.

When a port faces price competition from other ports, it should not only be concerned with whether it is technical efficient but also with whether it is cost efficient. If it is cost inefficient, it can lower throughput costs and prices by coming cost efficient. The given combination of resources used to provide a given level of port throughput may be a technically efficient

combination but not a cost efficient combination. Alternatively, there may be another combination of resources used to provide the given level of port throughput that is also technically efficient as well as cost efficient.

In Figure 1, it is assumed that a port uses labor (L) and capital (K) to provide throughput. The curve  $T_1$  represents the various combinations of labor and capital that are technically efficient in providing  $T_1$  level of throughput. At point A, the labor intensive combination of resources and at point C, the capital intensive combination of resources are technically efficient in providing  $T_1$  level of throughput. Suppose the prices per unit of labor and capital paid for these resources by the port are  $P_L$  and  $P_K$ , respectively. Hence, in the employment of L and K amounts of labor and capital, the port will incur the cost (C):

$$C = P_L L + P_K K \quad (3)$$

Solving equating (3) for L, it follows that:

$$L = C/P_L - (P_K/P_L)K \quad (4)$$

If  $C_3 > C_2 > C_1$ , the intercept terms of equation (4) become  $C_3/P_L$ ,  $C_2/P_L$  and  $C_1/P_L$ , respectively. A cost line based upon equation (4) with these intercept terms are plotted in Figure 1. Notice that at point C in Figure 1 a technically efficient combination of resources is used to provide  $T_1$  level of throughput. However this combination is cost inefficient, since the port can lower its cost from  $C_3$  to  $C_2$  and remain technically efficient in providing  $T_1$  level of throughput by moving to point A. However, point A also represents a cost inefficient resource combination. At point B, where the cost line is just tangent to the  $T_1$  curve, the combination of resources is both technically and cost efficient in the provision of  $T_1$  level of throughput, since B is on the  $T_1$  curve and  $C_1$  is the least cost to be incurred in the provision of  $T_1$  throughput.

(Figure 1 here)

A port in service competition with other ports is also not only concerned with whether it is cost efficient but also whether it is effective in providing throughput. Effectiveness relates to how well the port provides throughput services to its users – shippers and carriers (ocean and inland). Port effectiveness operating objectives will differ between privately-owned and government-owned ports. If the port is privately owned, its effectiveness economic operating objective might be to maximize profits or to maximize throughput subject to a minimum profit constraint. If the port is owned by government, its effectiveness economic operating objective might be to maximize throughput subject to a zero operating deficit (where port revenue equals cost) or subject to a maximum operating deficit (where port revenue is less than cost) that is to be subsidized by government.

In order for a port to be effective, it must be efficient -- i.e., it must be cost efficient which in turn requires that it must be technically efficient. Alternatively, cost efficiency is a necessary condition for a port to be effective. For example, if a port has the effectiveness operating objective of maximizing profits and is cost inefficient, it can obtain greater profits for the same level of throughput by lowering its costs in becoming cost efficient. As in the case of a port being technically efficient but cost inefficient, a port can also be cost efficient without being effective.

A port's effectiveness operating objective function includes the demand function for throughput. A port's throughput demand function represents the relationship between the port throughput demanded by its users and the generalized port price (per unit of throughput) incurred by these users, i.e.,

$$\text{Port Throughput} = h(\text{Generalized Port Price}) \quad (5)$$

where,

$$\text{Generalized Port Price} = \text{Port Price Charged} + \text{Ocean Carrier Port Time Price} + \text{Inland Carrier Port Time Price} + \text{Shipper Port Time Price} \quad (6)$$

The Port Price Charged per unit of throughput represents prices charged by the port for various port services, e.g., wharfage, berthing, cargo handling and wharfage charges. The Ocean Carrier Port Time Price per unit of throughput represents the time-related costs incurred by ocean carriers while their ships are in port, e.g., ship fuel, labor and depreciation costs. The Inland Carrier Port Time Price per unit of throughput represents the time-related costs incurred by inland (rail and truck) carriers while their vehicles are in port, e.g., vehicle fuel, labor and depreciation costs. The Shipper Port Time Price per unit of throughput represents the time-related costs incurred by shippers while their shipments are in port, e.g., inventory costs such as insurance, depreciation and obsolescence costs.

If a port seeks to maximize profits, its profit (or effectiveness operating objective) function may be written as,

$$\text{Profit} = \text{Port Price Charged} * \text{Port Throughput} - \text{Minimum Costs} \quad (7)$$

Substituting the port's throughput demand function (5) and economic cost function (2) into profit function (7) and rewriting, it follows that:

$$\text{Profit} = \text{Port Price Charged} * h(\text{Generalized Port Price}) - g(\text{Port Throughput}) \quad (8)$$

Finally, substituting the economic production function (1) into profit function (8) and rewriting, it follows that:

$$\text{Profit} = \text{Port Price Charged} * h(\text{Generalized Port Price}) - g[f(\text{Port Resources})] \quad (9)$$

The resources in profit function (9) in turn may be expressed as functions of the port's operating options and the amounts of given types of cargo (provided by carriers and shippers) to be handled by the port. A port's operating options are the means by which it can vary the quality of its throughput service. The relationship between the minimum amount of a given resource employed by a port and its levels of operating options and amounts of given types of cargo to be handled is referred to in the literature as a resource function (see Talley, 1988b):

$$\text{Minimum Port Resources} = j(\text{Port Operating Options; Amounts of Given Types of Cargo Provided by Carriers and Shippers}) \quad (10)$$

Substituting the resource function (10) into profit function (9) and rewriting, it follows that:

$$\text{Profit} = \text{Port Price Charged} * h(\text{Generalized Port Price}) - g\{f[j(\text{Port Operating Options; Amounts of Given Types of Cargo Provided by Carriers and Shippers})]\} \quad (11)$$

A port can differentiate the quality of its service with respect to such operating options as: (1) ship loading and unloading service rates – ship loading and unloading times incurred per port call, (2) ship berthing and un-berthing service rates – ship berthing and un-berthing times incurred per port call, (3) inland-carrier vehicle loading and unloading service rates – vehicle loading and unloading times per port call, and (4) inland-carrier vehicle entrance and departure service rates – vehicle entrance and departure queuing times per port call. Entrance (departure) time for an inland-carrier vehicle is the queuing time incurred to be cleared for entrance into (departure from) the port once arriving at the port's entrance (departure) gate.

What are the means by which port management can optimize its effectiveness operating objective and thus determine its effectiveness optimum throughput? That is to say, what are the

choice variables to be utilized by port management in the optimization? For a variable to qualify as a choice variable, its value must be under the control of port management. Suppose the port's effectiveness operating objective is to maximize profits, where profits are expressed as in profit function (11). In this function, Port Price Charged is a choice variable, unless constrained by port competition. The other choice variables are the port's operating options. Changes in the values of operating options not only affect the level of resources used by the port and thus port costs, but also the times incurred in port by ocean carriers' ships, inland carriers' vehicles and shippers' cargo. These times in turn affect the port time costs incurred by these port users – consequently, affecting the port's profits.

A port's economic optimum throughputs are generally more difficult to determine than engineering optimum throughputs. The former are usually derived from estimated port economic production, cost and effectiveness operating objective functions; the specific forms of these functions are generally unknown. Estimated port production and cost functions are found in studies by Kim and Sachish (1986) and De Neufville and Tsunokawa (1981). A port's estimated effectiveness operating objective function not only contains an estimated port cost function, but also estimated port demand and revenue functions.

## SUMMARY

This paper has presented various measures of a port's optimum throughput to which its actual throughput can be compared in order to evaluate its performance. A port's engineering technically efficient optimum throughput is the port's maximum throughput that physically can be handled by the port under certain conditions. The engineering design capacity is the port's maximum utilization rate. The engineering preferred capacity is the utilization rate beyond which certain port utilization requirements cannot be obtained. The engineering practical capacity is the port's maximum utilization rate under normal conditions. As opposed to determining a port's specific optimum throughput, the relative technical efficiency throughput ratings for a group of ports can be determined, allowing for technical efficiency (or inefficiency) comparisons among ports.

A port's economic optimum throughput is that throughput that satisfies an economic objective of the port. It may be either an economic: (1) technically efficient optimum throughput (based upon the port's economic production function), (2) cost efficient optimum throughput (based upon the port's economic cost function) or (3) effectiveness optimum throughput (based upon the port's effectiveness operating objective such as maximizing profits).



## Notes

1. For a discussion of capacity with respect to a port's infrastructure, see Jansson and Shneerson (1982). For a general discussion of economic capacity, see Wilson (1980).
2. When assumptions about the stochastic properties of the data are made, the frontier statistical model is referred to as a stochastic frontier model. Multi-port technical-efficiency performance evaluation studies that utilize stochastic frontier models include studies by Notteboom, Coeck and van den Broeck (2000), Coto-Millan, Banos-Pino and Rodriguez-Alvarez (2000) and Cullinane, Song and Gray (2002).
3. For a discussion of technically efficient, cost and effectiveness operating objectives of ports, see Talley (1988a, 2006a, 2006b).
4. A discussion of port cost functions are found in studies by Jansson and Shneerson (1982), Schonfeld and Frank (1986) and De Weille and Ray (1974).

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Figure 1  
Port Throughput and Costs

