September, 1998

Cost engineering optimum seaport capacity

Douglas D. Gransberg, *Texas Tech University*
John P. Basilotto, *Texas A&M University*

TECHNICAL ARTICLE

Cost Engineering Optimum Seaport Capacity

Dr. Douglas D. Gransberg, PE CCE, and John P. Basilotto

Using queuing theory to solve port optimization problems can result in large potential savings by both ports and shippers. This methodology generally makes the assumption that minimizing ship waiting time optimizes the entire port system. However, this overlooks the contribution to the system given by the port itself. There is a fixed cost of facilities that must be incurred to open a berth at a port. By minimizing ship waiting time alone, the current algorithm tends to encourage ports to build excess capacity. When a port's cargo transfer capacity is idle, the port authority suffers a capital cost of lost revenue. This article offers an extension of the existing principles of queuing theory to include port facilities. Our algorithm is tested with case study data from the Port of Galveston, TX, and is a promising solution for the operational analysis of seaports. The article concludes that this method of analysis can be used to assist in making both port capacity expansion and reduction decisions.

In French, the word *queue* means a line. Queuing theory deals with the formation and operation of lines. By using the fundamental laws of probability and statistics, a planner can model almost any system in which a line is formed by using queuing theory. The three basic components of a queuing system are:

- the arrival of customers (ships in this case);
- the queue discipline; and
- customer service.

In some cases, these components are independent of each other, while in others, they are not. For purposes of analysis and illustration, the components here are assumed to be independent. Random arrivals and scheduled arrivals are the two primary types of arrival patterns. Scheduled arrivals include patterns in which some customers arrive early and others late. Random arrival patterns are assumed to conform to a Poisson distribution [7]. It is generally possible to solve queuing problems that involve random arrivals, but it is generally impossible to solve scheduled arrival problems by exact methods [4]. Both patterns use the mean arrival rate of customers as the salient parameter. This is normally described using a customers-per-unit time dimension.

Average ship waiting time is the parameter of interest in applying queuing theory to port operation, and it is not affected by queue discipline [5]. The number of servers (usually berths) and their service rate are the principal parameters that describe the servicing of customers. The service rate is defined as the rate per server at which customers can be served while there are customers wanting to be served. Servicings are usually assumed to follow an exponential distribution [8]. However, port operation models also have used Erlang distributions and constant service rates [1, 3]. Jones and Blunden found that the negative exponential distribution provided the best representation, when compared to observed data at the Port of Bangkok. As the number of servers increases, the difference between the values predicted by different distribution assumptions decreases [10, 3]. In practice, it is best to make a careful analysis of the servicing characteristics before making an assumption about how service times will be distributed.

General queuing formulae can be broken down into two categories: single channel and multichannel. Single channel queuing systems involve only one server, while multichannel systems have two or more servers. In both cases, there is only one queue. In port operations and planning, two primary answers are sought through queuing formulae: mean waiting time in the queue and the probability that the system will be idle (no ships wanting service). Classical queuing system performance measures also constitute the major factors for recognizing and planning for port congestion and system capacity [12]. These factors include the following:

- queue length;
- berth occupancy (berth use);
- port idle time;
- mean turnaround time (waiting time plus service time, plus other delays); and
- mean waiting time (demurrage hours)[the detention of a ship during loading/unloading beyond the scheduled time of departure].

The work done by Jones and Blunden illustrates the classical approach to port queuing problems. A port is classified as either a single channel or multichannel system. The appropriate assumptions are made for service at the berth, and these values are plugged into a series of equations that seek to optimize the system by minimizing the mean waiting time of ships seeking a berth. The argument is focused on shipping, and generally treats the port as a collection of constants. Plumlee [6] put forth an interesting method based on the volume of cargo that must pass through a port and the port's ability to handle that cargo. In effect, he reversed the analysis and recognized, for the first time, the capital-intensive commitment that a port authority must make to increase its capacity. His algorithm combined the costs of demurrage and idle facilities; therefore, Plumlee's algorithm comes the closest to yielding a fully-optimized system. The weakness in this model is that it treats the cargo volume and the port's ability to transfer the cargo as a continuum and does not allow for typical interruptions due to weather, mechanical breakdowns, and the time it takes to prepare to begin unloading/loading cargoes. Therefore, the Plumlee model tends to cause ports to undersize their berthing facilities. This creates an unexpected increase in demurrage costs to shippers, which make a small port less competitive.

PROPOSED ALGORITHM

As a result of the inherent weaknesses of existing analytical techniques, a fresh approach is needed that not only provides a method to accurately model port operations but also fully uses the existing body of knowledge on queuing at ports to reduce demurrage costs. Our approach uses the work of Plumlee to find a starting point for potential port facility capacity, and combines the works of Jones and Blunden, Wadhwa, and Radmilovich to confirm that the system is indeed optimized from both ends. Additionally, as all of the research to confirm the validity of queuing applications has been performed at major ports, the peculiarities of small-port operation must be studied to validate the usefulness of this methodology in identifying quantifiable savings to both shippers and port authorities by making the changes indicated by the analysis.

One peculiar small-port characteristic is sensitivity to cargo types. Because of their low cargo volumes, the effort to find an optimum number of berths can be driven one way or the other by the demurrage costs for the actual type of cargo that passes through a small port. The demurrage cost varies greatly between cargo types. The costs quoted ranged from \$100 per hour [6] to \$100,000 per hour quoted by a clerk for a major container company. To develop a methodology that can be applied to any given small port, our algorithm extends the work done by previous authors on calculating typical queuing parameters, adds the cost of idle facilities in the port, and computes a demurrage break-even point with respect to facility cost, which can be compared to the actual demurrage figures of a port under analysis. Knowing the demurrage break-even point permits the analyst to objectively decide which way to round the actual number of berths provided at the port.

QUEUING FORMULAE

General queuing formulae can be broken down into two categories: single channel and multichannel. Single channel queuing systems have only one server; multichannel systems have two or more servers. In both cases, there is only one queue. General formulae are available in the literature for both single and multichannel systems.

As is the case with all good things, these basic formulae have been modified to improve their output for specific cases. One of the most widely-used modifications is the Pollaczek-Khintchine formula [4]. It is used for random arrivals and service times that are independent of each other and of queue length. This formula uses the ratio of the arrival rate to service rate as a parameter and calls it the traffic intensity, or utilization ratio (this is not peculiar to this method). This parameter is shown below in algebraic form:

$$\rho = \frac{\lambda}{N\mu}$$

where
ρ = traffic intensity;
λ = mean arrival rate (ships/day);
μ = mean service rate (ships/day); and
N = number of berths.

(equation 1)

$$P_o = 1 - \rho$$

where
P_o = probability that the facility is idle.

(equation 2)

The Pollaczek-Khintchine formula [4] calculates the mean waiting time in the following form:

$$W_q = \frac{\mu\rho(1 + C^2)}{2(1 - \rho)}$$

where
W_q = mean waiting time; and
C = coefficient of variation of service times (the ratio of the standard deviation of the service times to mean service time, μ [4, 9]).

(equation 3)

To fully optimize the system, one must minimize the total cost of both idle port facilities and waiting ships. Equation 4 illustrates this simple relationship. If one defines a small port as having only one or two berths, the problem becomes determining whether doubling the potential capacity of the port is justified by the increased cost of idle facilities. Thus, at the break-even point, the total cost for waiting ships and the cost of idle facilities for one berth, Tc_1, would equal the same total cost for two berths, Tc_2. The following formulae can be used:

$$Tc_x = C_{wx} + C_{ix}$$

(equation 4)

where

$$C_{wx} = D(W_x)$$

(equation 5)

and

$$C_{ix} = C_{0x}(1 - \rho_x)$$

where
Tc_x = total cost for x number of berths (\$);
C_{wx} = cost of ships waiting to berth at x berths (\$);
C_{ix} = cost of idle facilities at x berths (\$);
D = daily cost for a waiting ship (\$/day);
W_x = annual amount of waiting with x berths (ship-days/year);
C_{0x} = annual facility cost with x berths (\$/year); and
$1 - \rho_x$ = probability that the facility will be idle with x berths.

Therefore, at break-even:

$$Tc_1 = Tc_1$$

and

$$C_{w1} + C_{i1} = C_{w2} + C_{i2}.$$

(equation 6)

Substituting equation 5 into the above equation and algebraically solving for D, we get the following equation for the break-even ship waiting cost:

$$D = \frac{(1 - \rho_2)C_{o2} - (1 - \rho_1)C_{o1}}{W_1 - W_2}$$

(equation 7)

This break-even ship waiting cost (demurrage) is very important to the analysis, because actual demurrage costs vary from cargo to cargo. This number can be compared to the costs of waiting for expected high-volume cargoes to provide a benchmark from which to make port design and expansion decisions. This analysis is illustrated below with actual data from the Port of Galveston's container terminal.

GALVESTON CONTAINER TERMINAL ANALYSIS

Container terminal activity data was obtained for January 1994 through May 1995. The data showed a fairly constant level of traffic over the 17-month period. Table 1 shows a summary of ship visits and container throughput for the two container berths in the port. The port receives an average of 12 ship visits per month, which requires it to handle an average of 4,204 containers during that period. Its cranes are occupied in transferring those containers at an average rate of 21.74 containers per hour, for an average of 194 hours each month. Analyzing the number of visits per month and the amount of time each ship spent at the dock provides the critical queuing parameters of arrival rate, λ, service rate, μ, traffic intensity, ρ, and the coefficient of variation, C. These parameters were established on an average monthly basis and are shown in table 2.

The container terminal contains two operating berths, so it is classified as a multichannel queuing system. Using equation 3 to compute the mean waiting time for container ships requiring a berth, one finds that the average ship waits in the queue for 0.13 days, or about 3 hours upon arrival. This is a very short queuing time when compared to other major ports in the world [2, 3, 12]. With a traffic intensity of 0.19, one would expect that the probability that a berth would be empty to be 81 percent. This causes an analyst to ask what would happen if the container terminal operated with only one berth. To do so would change the analysis to a single channel queuing system. From equation 1, the traffic intensity would double to 0.38, with a corresponding drop in idle facility probability to 62 percent. Applying the single channel average waiting time equation yields an average queuing wait of 0.61 days per ship (about 14.6 hours). The doubling of available facility use time is achieved with a fivefold increase in waiting time for ships requiring a berth. It should be noted that 14.6 hours is still well below the world average for queuing at a major port [2, 3, 12]. Deciding to mothball one container berth requires a significant financial incentive.

Looking at an analysis of the *Board of Trustees Galveston Wharves Income Statement for 1994 for the Container Terminal* [11], the applicable facility cost data shown in table 3 were found.

Dividing the total of fixed and variable costs by the 8,760 hours in a calendar year yields an hourly facility cost of $441.56 for two container berths. Making a very conservative assumption that mothballing one berth would only save one-half of the variable cost, one finds that the hourly facility cost for a single-berth terminal would be $427.52. Taking the average waiting time for a single-berth terminal of 0.61 days per ship, the two-berth terminal waiting time of 0.13 days per ship, and the mean arrival rate of 0.40 ships per day, one can calculate the total number of ship-days that are spent in the queue as follows.

Average number of ship visits per year
= (0.40 ships/day)(365 days/year)
= 146 ships per year.

Waiting time with one berth
= (0.61 days/ship)(146 ships/year)
= 89 ship-days/year.

Waiting time with two berths
= (0.13 days/ship)(146 ships/year)
= 19 ship-days/year.

As previously mentioned, the optimum size of a port is found when the cost of ships waiting for a berth is minimized with respect to the cost of idle facilities at the port. In this research, a reliable cost for container ships waiting for a berth at

Table 1—Galveston Container Terminal Historical Data

Month/Year	Number of Ships	Total Containers	Crane Hours	Transfer Rate Containers/Hour
JAN 94	13	4,191	196	21.38
FEB 94	12	3,973	203	19.57
MAR 94	13	5,034	229	22.01
APR 94	14	4,754	244	19.52
MAY 94	12	4,520	196	23.09
JUN 94	13	3,774	180	21.03
JUL 94	15	4,267	196	21.74
AUG 94	13	3,800	174	21.81
SEP 94	12	4,435	205	21.58
OCT 94	12	4,396	199	22.09
NOV 94	10	3,872	179	21.66
DEC 94	12	3,924	183	21.41
JAN 95	11	3,864	171	22.63
FEB 95	14	5,419	244	22.21
MAR 95	11	3,920	185	21.16
APR 95	12	3,991	167	23.86
MAY 95	9	3,339	146	22.87

Table 2—Queuing Parameters for the Galveston Container Terminal

Parameter	Monthly Mean	Monthly Standard Deviation
Arrival rate, λ [ships per day]	0.40	0.05
Service rate, μ [ships per day]	1.04	0.23
Traffic intensity, ρ	0.19	N/A
Coefficient of variation, C	0.22	N/A

Table 3—Facility Cost Data

	Variable	Fixed	Total
Subsidies	0	$1,866,514	$1,866,514
Direct expenses	$246,059	$97,630	$343,689
Allocated expenses	0	$1,067,447	$1,067,447
Depreciation		$590,447	$590,447
Total	$246,059	$3,622,038	$3,868,102

Galveston was not obtained. However, sufficient information is available to conduct a break-even analysis and solve for the break-even ship waiting cost. Plugging the data for the Galveston container terminal into equation 7, the break-even ship waiting cost is found to be \$11,588.81 per day, or \$482.85 per hour. If the actual ship waiting cost due to the type of cargo onboard is greater than this amount, both berths should remain open. If the actual ship waiting cost is less than this value, the port authority should seriously consider putting one berth in mothballs and operating with only one container berth.

CARGO-BASED ANALYSIS

A transportation manager must achieve a balance between the cost of building and maintaining port facilities that will sit idle for a percentage of the year and the cost of ships waiting for a place to berth. Plumlee developed an analytical method for doing just that. While his method uses the basic concepts of queuing theory, he attacks the problem of optimizing port size from a different angle. Rather than calculating mean arrivals and service times in the classical manner, Plumlee starts with the amounts of various cargoes that must pass through a port. Using the cargo transfer rate and a fixed time period, he then develops a mathematical model to describe the queuing problem. Cost functions are applied to the model, and the objective function is combinatorially optimized to find the minimum cost situation. This method uses the following three basic formulae.

Berth utilization, U:

$$U = \frac{T_b/R_b + T_g/R_g}{HN} .$$

(equation 8)

Berth requirement time, F, (the number of time units that n ships are present):

$$F = \frac{H(\overline{n})^n e^{-\overline{n}}}{n!}$$

(equation 9)

Average berth requirement $\overline{n}$, (average number of ships requiring a berth):

$$\overline{n} = \frac{T_b/R_b + T_g/R_g}{H}$$

where
H = fixed time period;
N = number of berths;
T_b = total amount of bulk cargo;
T_g = total amount of general cargo;
R_b = average rate of bulk cargo transfer; and
R_g = average rate of general cargo transfer.

(equation 10)

It should be noted that Plumlee's U contains customers/day, which are the same units as classical queuing theory's ρ. However, we are reluctant to equate the two because ρ is derived by analyzing the queue; U is derived by analyzing the capacity of the server. Therefore, it can be hypothesized that $U = 1 - \rho$. A number of previous authors define ρ as "berth occupancy" [4], "utilization ratio" [3], and "utilization factor" [7]. All three present queue-based arguments, thus it must be assumed that the naming of ρ is merely an accident of language and therefore mathematically unrelated to Plumlee's U.

Applying Plumlee's formulae to the Galveston container terminal and accounting for the fact that the only units of cargo handled are containers, the formula for berth use, U, and average berth requirement can be simplified, as shown below:

$$U = \frac{T_c/R_c}{HN}$$

(equation 11)

and

$$\overline{n} = \frac{T_c/R_c}{H}$$

where
T_c = annual number of containers passing through the port; and
R_c = average rate of container transfer.

(equation 12)

Taking the mean monthly number of containers found at Galveston (4,204) and multiplying that number by 12 months will yield T_c equal to 50,448 containers per year. R_c was found to average 21.74 containers per hour in the previous analysis. By taking the break-even ship waiting cost and dividing it by 24 to convert it to an hourly cost (\$482.85/hour), we have sufficient input to complete the analysis using Plumlee's methodology. Table 4 shows the results of this analysis.

The analysis shows potential annual combined savings of \$760,000, which

Table 4—Cargo-Based Analysis of Galveston Container Terminal

Number of ships present n	Number of annual hours n ships are present F	Annual hours berths are idle with one berth	Cost of idle berths @ \$427.52/hr \$ one berth	Cost of waiting ships @ \$482.85/hr \$ one berth	Annual hours berths are idle with two berths	Cost of idle berths @ \$441.56/hr \$ two berths	Cost of waiting ships @ \$482.85/hr \$ two berths
0	6,754	6,754	2,887,646		13,509	2,982,478	
1	1,756	1,756	none	none	3,512	775,444	
2	228	228		110,234	457	none	none
3	20	20		9,554	40		9.554
4	1	1		621	3		621
Totals	8,760		\$2,887,646	\$120,409	17,520	\$3,757,922	\$10,175
			Combined Costs	\$3,008,055		Combined Costs	\$3,768,097

would seem to point to the need to consider mothballing one berth. One must remember that under the assumptions made in this study, the port authority would only have an actual direct savings on the order of $120,000. Once a facility is built, its capital cost in many ways becomes a sunk cost and is not recoverable except by amortizing the investment through an associated revenue stream. Mothballing an existing berth is a significant operational decision. Before implementing it, the port authority should ensure that all of the assumptions made in this analysis are correct and that there are no other external factors surrounding this decision that would materially affect the results of either approach.

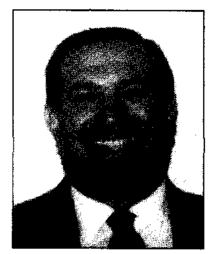
This study has proved that the contribution made by the port authority in terms of capital costs of facilities is indeed a significant one in situations where cargo volume is low. If an analyst neglected the cost of idle port facilities and focused only on minimizing the waiting time for inbound ships, the study would have recommended the maintenance of both container berths. By looking at the sum of the cost of ships waiting and the cost of idle berths, a potential combined savings of over $700,000 is found.

Obviously, the use of this algorithm is better suited to analyzing the problem of how many new berths should be built in an existing port rather than the one described above. Once an investment in facilities is made, it becomes extremely difficult to justify reducing the level of service to save a direct amount that is less than 3 percent of the total operating cost. It must be recognized that the decision discussed above is not a simple one. All other factors, including ongoing contracts with stevedores, existing relationships within the community, and other factors must be carefully considered when making this decision. A great deal of further study is required before all of the necessary information can be made available to the port authority.

REFERENCES

1. Bruun, P. **Port Engineering**. Houston: Gulf Publishing Company, 1976.
2. Fratar, T.J., A.S. Goodman, and A.E. Brant. *Prediction of Maximum Practical Berth Occupancy.* **Journal of Waterways and Harbors Division** 126, no. VI (June 1961): 632-641.
3. Jones, J.H., and W.R. Blunden. *Ship Turn Around Time at the Port of Bangkok.* **Journal of Waterways and Harbors Division** 94, no. WW2 (May 1968): 135-148.
4. Miller, A.J. *Queuing at Single-Berth Shipping Terminal.* **Journal of Waterways and Harbors Division** 97, no. WW1 (February 1971): 43-65.
5. Nazarov, A.A. **Optimal Formation of Queues in Multi-Channel Queuing Systems, Automation and Remote Control** 36 (August 1974): 1,242-1,244.
6. Plumlee, C.H. *Optimum Size Seaport.* **Journal of Waterways and Harbors Division** 92, no. WW3 (August 1966): 1-24.
7. Radmilovich, Z.R. *Ship-Berth Link as Bulk Queuing System in Ports.* **Journal of Waterway, Coastal, and Ocean Engineering** 118, no. 5 (September/October 1992): 474-493.
8. Riggs, J.L. **Production Systems**. New York: John Wiley and Sons, Inc., 1976.
9. Riggs, J.L., D.D. Bedworth, and S.U. Randhawa. **Engineering Economics**. 4th ed. New York: McGraw-Hill, 1996.
10. Saaty, T.L. **Elements of Queuing Theory**. New York: McGraw-Hill, 1961.
11. Selig, O. *Galveston Wharves, Analysis of Container Terminal Operating Expenses* 1994. Memorandum dated March 13, 1997 to Douglas Gransberg.
12. Wadhwa, L.C. *Planning Operations of Bulk Loading Terminals by Simulation.* **Journal of Waterway, Coastal, and Ocean Engineering** 118, no. 3 (May/June 1992): 300-315.

***Dr. Douglas D. Gransberg, PE CCE**, is an associate professor in the Department of Engineering Technology at Texas Tech University. He served for 20 years in the U.S. Army Corps of Engineers, retiring with the rank of lieutenant colonel. Dr. Gransberg holds B.S. and M.S. degrees in civil engineering from Oregon State University, and a Ph.D. from Somerset University in England. He is a member of AACE International, and is the Chair of the General Construction Committee. He is the author of many technical articles, reports, and manuals.*



***John P. Basilotto** is an associate research scientist and director of the Center for Ports and Waterways at the Texas Transportation Institute of Texas A&M University. Before joining the Institute, Colonel Basilotto was Commander and District Engineer of the U.S. Army Corps of Engineers' Galveston Engineer District, where he was responsible for all U.S. federal navigation projects in Texas. He has co-authored or directed 14 technical reports concerning navigation and port operations. Additionally, he is a lecturer in the Maritime Administration Department at Texas A&M in Galveston.*◆

Errata—

Patrick B. Mitchell was incorrectly listed in the July issue as a new CCC;

he is actually a new CCE.