Vol. 54, No. 3 WORLD WIDE SHIPPING May 1991

PRODUCTIVITY, CAPACITY AND EQUITY IN THE PORT OF SAN JUAN

A "Flow & Stock" Approach to System Analysis

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May 1991

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BACKGROUND *Terminal Capacity—a Perpetual Debate.* The subject of capacity of marine terminals, especially of those owned by the public seems to be in a perpetual state of debate. Capacity assessment is still the centerpiece of all port master/strategic planning efforts. A master/strategic plan, simply put, is a comparison, along time, of facilities capacity to expected (or perceived) needs. Though it may appear that assessing capacity of terminals is a straightforward technical matter, in reality, things are much more fuzzy. *The concept of capacity is closely associated with the companion concepts of utilization, productivity and level of service;* the more you utilize your terminals, the more productive is your operation and the less demanding you are regarding the level of service you provide your customer—the more "capacity" you have. Capacity of a given terminal is determined by the values assumed to these three companions.[1] This relationship, which characterizes any service industry, seems to have a specific relevance in marine terminals where port authorities, shipping lines, shippers, labor, environmentalists frequently have conflicting interests.[2]

Large-size, "Super" Terminals. Port capacity is especially critical when it comes to modern container terminals. The container terminals in the era of intermodalism and load-centering stand out among marine terminals in two important aspects. First, these terminals require much larger tracts of waterfront land and, accordingly, larger investments in construction and equipment. Second, the terminals are traffic intensive, adversely impacting their surrounding environment. This intensive interface with connecting water (feeder) and land transport modes, including the recent thrust for having on-dock railyard, require the creation of special transport corridors crossing through the surrounding urban area. Assessing the capacity of the "super", multi-mode terminal of tomorrow poses, indeed, a challenging task to port planners.[3]

Volatility. Unfortunately, the era of intermodalism brought about an instability to the port industry. In an intermodal marketplace, lines are quickly adjusting vessel deployment and ports of call to shifting patterns of shippers' demand. It is a marketplace where all ports compete against all ports, and none is immune against large and sudden relocations of lines and cargo. This volatility intensified the dealing with terminals and their capacities; when you constantly play "musical chairs" with your tenants you should be better equipped with a sound methodology for estimating capacity.

Purpose of Article. The emphasis on capacity, in light of these circumstances, is certainly understandable. The following article (a) presents a short review of popular capacity calculation methodologies, (b) elaborates on a specific one, a deterministic, spreadsheet simulation, which models the container yard inventory, and (c) concludes with a case study, based on a recent involvement of this author with the master planning of the Port of San Juan, Puerto Rico.

THREE GENERATIONS OF APPROACHES TO TERMINAL CAPACITY As already mentioned above, the subject of container terminal capacity has been discussed extensively throughout the last three decades of containerization. This author differentiates three "generations" in the approach to container terminal capacity:

- *Traditional Berth Approach*—a berth-oriented approach, which centers capacity calculation on berth utilization and dock transfer rate:
- *Performances Indicators Approach*—a broader approach, based on a series of productivity and utilization indicators for major terminal components; and
- *Operation Simulation Approach*—a more specific approach based on simulating the operational processes of a terminal in order to determine constraints and related capacities.

Traditional Approach. The berth-related approach traces its route to the pre-containers era, when vessel arrival was unscheduled and port handling took a long time and required plenty of berth space. In its simplistic form, the capacity calculation under this approach is contained in one linear formula, a direct multiplication of the average dock transfer rate by the available berth time. The common, through hidden assumption in this formulation, is that 100% utilization is achievable.[4]

In its more sophisticated form, the traditional approach abandons the full-utilization assumption in favor of a more realistic one. Based on queuing theory, a trade-off between berth utilization and vessels' level of service is defined. Pending on number of berths per terminal, allowing a waiting time of 25% of service time results in recommended utilization rates ranging 30-60%. These utilization coefficients, are then applied to the above-mentioned linear capacity formula.[5]

The one-line formula approach seems inadequate nowadays, except, perhaps, as a first-hand approximation. The built-in assumptions of randomality in most of the queuing models are incompatible with modern liner services based on a fixed scheduled. The service policy assumption is also invalidated by the fact that many lines have preferential berthage arrangements to assure that their vessels do not wait in line except for very unusual circumstances.

Performance Indicators Approach. This approach is based on calculating a series of indicators or ratios between terminal throughput and the main terminal facility components. Typical indicators include TEU/yard acre, vessel-shifts/berth, gang-hours/crane, vessel-moves/gate-lane, etc. The various "density" indicators, all calculated from actual data, serve as guidelines to size terminal components and determine their capacity. They also serve for monitoring terminal performance as part of the overall port management function.

The Indicator Approach, which has obvious advantages over the Traditional Approach, has two inherent problems: (1) the indicators yield a broad spectrum of values following the diverse nature of terminals from which they are derived, and (2) the indicators reflect reality but not optimality, i.e. they do not suggest what could (should) be a desirable (optimum) value. Despite these problems, the Indicator Approach is quite effective in dealing with master planning, whereby the exact operational setting is unknown, and the capacity indicators are used for delineation of broad scenarios.

A case in point is the Terminal Management System developed at the Port of Seattle's Department of Planning and Research. Seattle's unique system involves the collection of periodical, uniform operational data from the various terminals and calculation of a series of "productivity indicators." The indicators were indispensable in preparation of several master plans. During these planning assignments Seattle's planners realized that the capacity of container terminals was determined by the capacity of their container yards—and not of their berths. The relevant indicator, namely the vessel moves per net yard acre, was found to be the constraint on Seattle's overall terminal capacity (as well as that of other ports).[6]

> *"The more land-efficient line was three times more congested than the least efficient."*

Figure 1 presents a recent sample data taken from the Port of Seattle.

Operational Simulation Approach. The simulation approach, unlike its two predecessors, is dynamic in nature, focusing on *terminal processes* instead of static facilities. The simulation model decomposes terminal operation into several processes, each with its own operational parameters. Then the model "runs" the terminal operation by reconstructing the various processes under different facility and operational scenarios, in response to a "what if" or sensitivity tests of the model's parameters. Typically, the simulation progresses according to "clock" time (e.g. the updating is done every hour or at the beginning of each shift), or according to major events (e.g. vessel arrivals, truck arrival).

Simulation models vary in concept, size and complexity. The concept can be either deterministic or probabilistic (stochastic); the size and complexity relates to the number of terminal processes included and to length of time (simulation points). In their basic, deterministic form, the model can be easily programmed through a common spreadsheet software; in their more complicated form they require a special simulation language and, for the larger models, a main-frame computer to run.[7]

Even in their simple form, simulation models are by far superior than the other approaches. The dynamic nature of a simulation provides important insight into the complex relationship between the various operational processes of a terminal and the facilities used for accommodating them. Simulation is especially useful in dealing with terminals with unusual setting whereby the more traditional approaches can lead to erroneous estimates. For example, in case where the terminals are subject to wide fluctuations in activities (peaking). Simulations are not limited to capacity estimation; they can be used to support decisions on terminal layout, equipment, administrative procedures and almost any aspect of port planning and operation.

SAN JUAN TERMINAL SIMULATION MODEL

A "Flow and Stock" Approach. A convenient, though quite uncommon way of describing a container terminal, is as a storage of containers with two gates: a "water" gate and a "land" gate. The terminal's primary process or "flow" is moving containers between the "gates", from water to land in case of import, and from land to water in case of export. Since direct, gate-to-gate movements of boxes are impractical in most cases, most of the movements are between the gates and various in-terminal "stocks" that provide temporary holding place. Other, secondary terminal processes involve movements of containers (or chassis)

Figure 1
Port of Seattle Productivity Indicators

Indicator	*1987*	*1988*	*1989*	*1990*
TEUs/Terminal Acre	2,814	2,991	2,771	3,016
TEUs/Yard Acre	3,808	4,041	3,739	4,024
Moves/Crane-Hour	21.8	23.1	23.8	24.0
Berth utilization	17.5%	16.0%	13.0%	11.6%

Figure 2
Major Terminal Processes

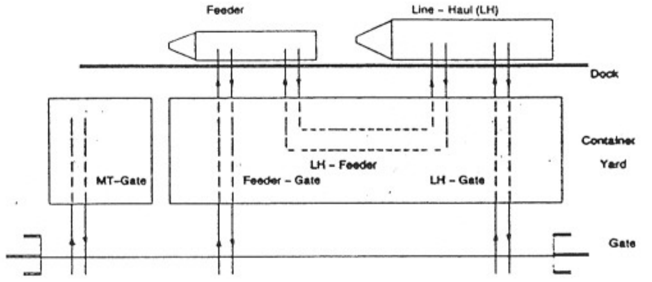
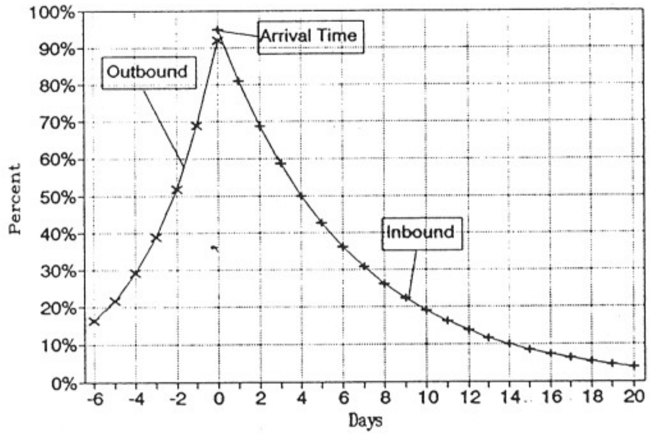


Figure 3
Distribution of Dwell Time
Line-Haul Vessel



between and within the "stock" and do not require gate crossing. The terminal simulation model presented in the following sections is, indeed, based on this concept of "flows and stocks".

San Juan Port. The Port of San Juan is the major port of the Caribbean island of Puerto Rico. It is a large, 1-million TEU/year port, which is expected to grow by 60% in the 20-year planning horizon addressed by the master plan. Most of the container activity is concentrated in two areas, whereby each of the major carriers has its own terminal including berthage (preferential usage), cranes and gates. A preliminary analysis indicated that, as expected, the overall constraint on capacity in San Juan revolves around yard space. Put differently, San Juan, like many world ports, suffers (presumably) from a severe shortage of port-usable waterfront land. Consequently, the simulation model that was developed for the purpose of terminal capacity estimation was, in essence, a *container yard simulation,* following the principles of any inventory model.

Unique Terminal Settings. San Juan's operational settings are unique since the terminals serve a complex of line-haul and feeder vessel services. Also, since the island is relatively small and most of the population is concentrated within a short drive from the port, the marine terminals serve as distribution centers. The result is an unusual on-terminal accumulation of boxes. Another unusual phenomenon is, that despite the shortage of terminal land, most of the terminals use an all-wheel yard (chassis) system.

Terminal Processes. A typical San Juan terminal accommodates (1) three weekly services to different port regions in the mainland U.S.; and (2) a complex network of feeder services from Puerto Rico to the satellite islands. *Figure 2* describes the major terminal processes that were found under these circumstances in a typical San Juan terminal. They include:

1) *Line-Haul to Gate*—Moving boxes from line-haul vessel to yard, and, later on from yard to the gate and vise versa.
2) *Line-Haul to Feeder*—Moving boxes between the two vessels either directly but most commonly through the yard.
3) *Feeder to Gate*—Moving boxes from feeder vessel to yard, and from yard to gate and vise versa.
4) *Empty to Gate*—Moving boxes from yard to gate to be stuffed or receiving them after being destuffed.

Flows and Stocks in San Juan. As already suggested above, the simulation model is based on identifying the major terminal "flows" and their respective "stocks", i.e. the on-terminal holding place where they originate or terminate. For example, the most voluminous flow in the San Juan terminal is the Line-Haul to Gate, or the inbound (import). The process is divided into two stages. First, during the two-days of vessel handling, the on-board box is unloaded and staged in the yard. Later-on, following shippers request, the box is dispatched through the gate. Meanwhile, the box spends a so-called dwell time during which it occupied a yard space.

Dwell Time Distribution. Dwell time distribution was found to be the key factor in determining San Juan's terminal capacity. In the case of Line-Haul to Gate, for example, it was found that outbound boxes started to show up in the terminals as early as 6 days before arrival, an understandable phenomenon in a weekly service. The inbound boxes, however, stayed up to 3 weeks before being removed. *Figure 3* depicts a typical dwell-time distribution for a line-haul vessel. The data, for the benefit of the "what if" analysis, is expressed in percentage of the vessel load. It is based on a sample of actual terminal operation documents.[8]

Weekly Exchange. The most time consuming task in constructing a simulation is defining the various flows and stocks and mathematically analyzing their characteristics. The simulation program itself imitate the terminal processes by moving boxes in case of flows and accumulating them in case of stocks following two events. In the case of San Juan, the terminal activities centers around the "weekly exchange", when both the line-haul and feeder vessel arrive to exchange boxes among themselves and with the yard (gate). As seen from *Figure 4,* every flow requires a certain amount of stock to support it, and the size of flows and stocks changes relative to the time of arrival of the line-haul vessel. Each line-haul service has its own typical exchange and its overall requirements in yard inventory. The profile of the weekly exchange is general in nature but subject to seasonal fluctuations.

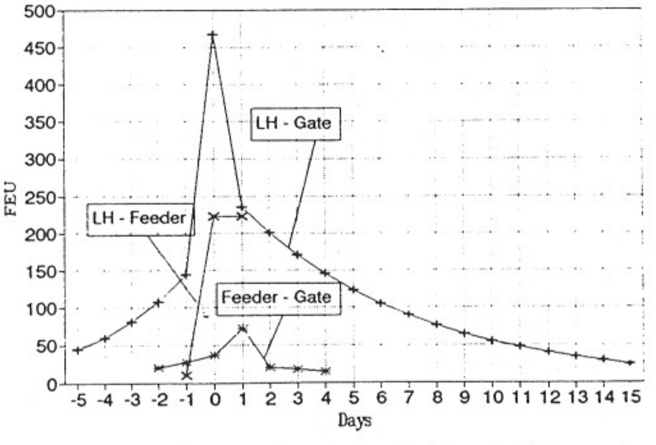
Periodical Accumulation. Each service at each week requires its own inventory. The accumulation of these inventories defines the overall demand on yard space. As presented in *Figure 5* the overall terminal inventory is characterized by periodic peaks around the arrival times of the line-haul vessels. This peaking phenomenon is typical to any terminal that is attuned to the operation of liner services. The peak inventory is, indeed, the critical factor for calculating terminal capacity.

Primary and Secondary Inventory. The primary (or live) inventory is the one required to support the weekly exchange. In addition, there was a need to include several secondary inventories to support other, related terminal process. This included a buffer for empty chassis for double cycling, area for hazardous materials, storage of bad boxes and other. Also, there was a need to define a special area for reefers.

Inventory Ratio. The main result of this simulation was a set of inventory ratio functions which, for each type of operation, defines the number of yard slots required to support the respective annual vessel moves. The overall ratio, in the case of San Juan averaged about 70 (i.e., roughly, each 1000 vessel moves/year, required approximately 130 yard slots). Interestingly, this result is not far apart from Seattle's figure, despite the fundamental differences between the two port systems.

Terminal Requirements. Up to this stage, the model and related calculation were expressed in boxes, moves and yard slots. Port planners, however, need more concrete figures to define terminal facilities. For the purpose of master planning, there is a need to define, at least, the required terminal berthage (linear feet) and overall terminal area (acres).

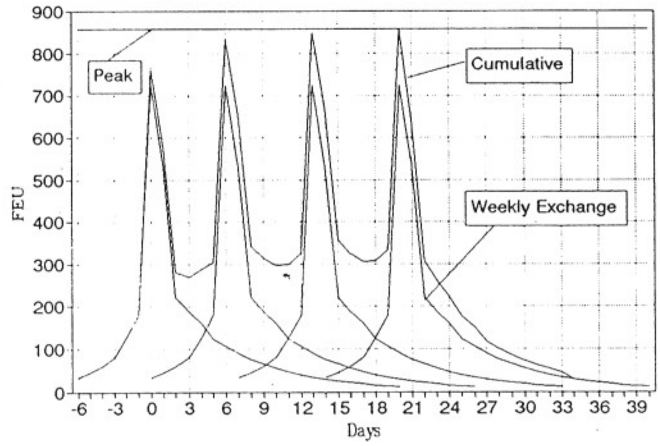
Figure 4
Yard Inventory
(Weekly Exchange)



Consequently, San Juan simulation model consisted of two blocks:

- *Operational Block*—including the functional "flow and stock" relationships of the operational processes, or the operation simulation; and
- *Facilities Block*—including a conversion of the simulation results into required terminal facilities according to various assumptions on yard and vessel handling equipment.

Figure 5
Yard Inventory
(Periodical Accumulation)



Storage Density. The main capacity determinant and the larger terminal component is the container yard (CY). The size of the CY area, which usually takes about 80% of the terminal area is determined by number of boxes ("slots") in need of on-terminal storage as determined by the operation simulations. The actual dimensions of the various inventories (the various "stocks") is determined by the storage system. In case of San Juan, the majority of the terminal are chassis operation with a typical storage density of about 40 units per acre (mixture of 40 and 45-foot, including service isle but excluding main traffic isles) . Other yard systems which involve grounding and stacking containers have density which is up to three times higher. All-wheel system, however, is the only one that provides for direct access and quick service which was considered critical for San Juan terminals.

Ancillary Terminal Components. In addition to the CY, there are several other ancillary components that, unlike the CY, tend to be fixed over a wide range of terminal throughput. The ancillary components include the apron, gate, general parking, offices, maintenance shop and others. The inclusion of some of the ancillary components in the immediate waterfront area is subject to discretion. For the purpose of San Juan master plan, it was decided to only include the necessary minimum in the "typical" terminal.

Gross and New Productivity. Consequently, for the purpose of master planning, there was a need to define two broad measures in order to translate the overall forecast of the containerized trade into acres of terminal facilities. The two so-called productivity measures were defined as:

- *Gross Productivity*—The ratio between the terminal throughput and total terminal area; and

Figure 6
Terminal Requirements

Parameter	Unit	Value	Explanation
Terminal Apron	Acres	1.84	For Linehaul plus Feeder
Terminal Gate	Acres	1.49	6 lanes @ 12 working slots
Circulation	Acres	2.00	
Offices, Maint. & Misc.	Acres	2.00	
Truck/Chassis Parking	Acres	2.00	
Total Non-Yard Area	Acres	9.32	
Required Yard Slots	FEU-Slots	2,148	Peak Value from Simulation
Storage Density		40	
Container Yard Area	Acre	53.70	40/acre for Wheel Storage
Total Terminal Area	Acre	63.02	
Total Vessel Moves	FEUs/year	146,172	From simulation
Terminal Gross Production	FEU-Vessel	2,319	Total Moves/Total Terminal Area
Terminal Net Production	FEU-Vessel	2,722	Total Moves/ Total Yard Area

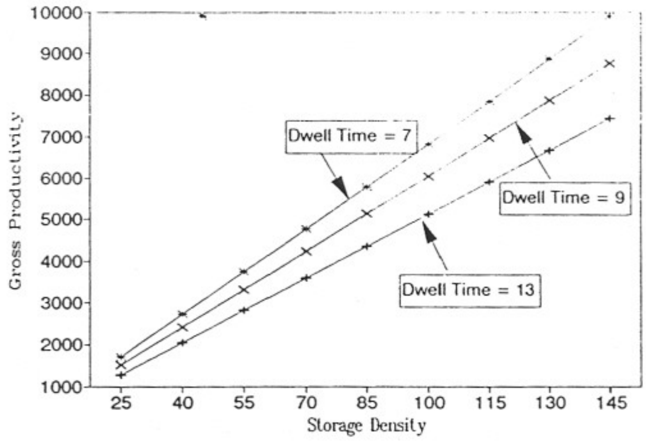
- *Net Productivity*—The same, but only using the CY area.

The overall averages gross and net productivities for the Port of San Juan were 2500 and 2900 moves per acre, respectively, *Figure 6* presents the results of the facility block in one simulation run.

Sensitivities. Both gross and net productivity are affected by two factors: dwell time and storage density.[9] *Figure 7* presents the results of a sensitivity analysis. As seen from this figure's chart, if, for example average dwell time can be shortened to 5 days (from the present 7 days) and storage density increased to 70 FEU/acre (from 40), Net Productivity can be doubled to about 6000 moves/acres. Theoretically, at least, doubling productivity can half the demand on waterfront land. Changes in dwell-time require, however, fundamental changes in the present distribution and consumption pattern. Changes in yard storage system are easier to adapt. For example, if loaded boxes are kept on wheels while most of the empty are stacked 5-high the overall (loaded and empty) storage density will be about 70 FEU/acre.

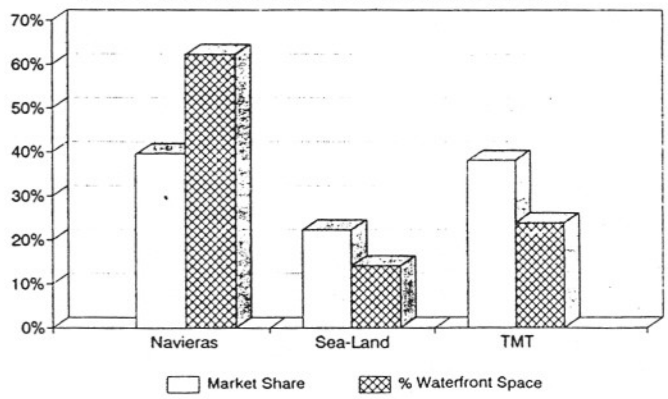
SUMMARY *Productivity and Actual Usage.* Capacity and productivity are companion terms, as was already claimed in the Background section. The operation simulation and the following calculation in the Facility Block suggested productivity indicator that characterize a "typical" San Juan terminal, obviously, these productivity indicators could also be used to assess the land usage of existing terminals. *Figure 8* suggest the differences between actual productivity of San Juan terminals were quite significant. The productivity of the most efficient terminal was three times (!) the least efficient one (all terminals used the same terminal system under similar vessel schedule). Another way of interpreting these differences is to say that the more land-efficient line was three times more congested than the least efficient.

Figure 7
Productivity as Function of:
Dwell Time & Storage Density



Productivity and Equity. What is the connection between a methodology for calculation of terminal capacity and equity? Waterfront, public port-usable land in San Juan is a scarce resource which cannot be expanded or generated but by incurring unreasonably high cost. The only reasonable way of increasing capacity of the entire port is by better allocating the land base among the lines. Fortunately, it was found, that overall, developable waterfront land base, can accommodate San Juan need for the plan horizon. At the time of the study, it was found that terminal operators were divided into those who had and those who did not have sufficient terminal land as reflected by their throughput. A better allocation of the overall terminal area among its users, to insure its overall usage at the level

Figure 8
Comparison of Market Share and Waterfront Land Allocation



found by the simulation model, is a primary solution to the land shortage.

Plan Recommendations. Re-allocation of waterfront land was, indeed, a central recommendation of the master plan. Other recommendations related to the above mentioned sensitivity tests, i.e. investigating the possibility to shorten dwell time and increase density of yard storage. The recommendations drew heavily on an operation simulation that the efforts invested in its development proved, indeed useful. The simulation was responsible to the unusual shift in focus that the San Juan master took in its quest for productivity as an alternative to physical expansion. □

[1] *Productivity and utilization, by themselves, are close complements, both convey the idea of efficiency. While productivity is commonly defined as an input/output ratio, utilization is a "pure" ratio (percentage) whereby the actual performance is compared to a standard (expected or target value). While productivity is commonly used in the context of production (e.g. moves per gang-hour), utilization relates to time usage of static facilities (e.g. berth utilization).*

[2] *E.g., typically labor is interested in jobs, management in higher productivity and less labor, management is interested in higher utilization but lines are interested in better level service, etc.*

[3] *A case in point is the recent, front-page interview with Long Beach's new executive director whereby he complained that the terminals that used to be 50-60 acres in size, are transforming into 150-acre, "super" terminals ("The Journal of Commerce, March 22, 1991).*

[4] *Interestingly, the formulation is recommended in several well-known publications. Moreover, a few of them are still measuring capacity of container terminals in—tons. See for example Moffat & Nicholas "Port Handbook for Estimation Marine Terminal Cargo Handling Capability," A U.S. Maritime Administration Publication, 1979, pp. 140-161; or Frankell & Diomedes, "A Method for the Determination of Container Terminal Size and Facilities," Cargo Systems, 1982(?); G. De Monie, "Container Terminal Capacity Calculations," Seminar on Container Terminal Management, UNCTAD, 1983, pp. 162-191.*

[5] *The model commonly used model is the M/M/C with FCFS (First Come First Served) Policy. See Berth Throughput, UNCTAD, 1973, pp. 41-43; Jansson & Shneerson, Port Economics, MIT Press, 1982, pp. 34-38; or even in several newer academic articles such as Schonfeld & Shrafeldien, "Optimal Berth and Container Combinations in Containerports," Journal of Waterways, Ports, Coastal and Ocean Engineering, Nov. 1985; A. Ashar, "Capacity Analysis of Port Cortes, Honduras", FPX, 1991.*

[6] *A detailed description of Seattle's system (which is still in operation) is presented in an article on "Container Terminal Productivity and Capacity," A. Ashar, WWS/World Wide Shipping, October/November, 1985. A similar system was also adopted by the National Research Council's Improving Productivity in U.S. Marine Terminals, 1986.*

[7] *An early though comprehensive simulation model is described in Berth Throughput, United Nations, 1973. A more recent simulation model, including animation, was presented by Liftech Consultant, Inc. at the AAPA Facilities Engineering Seminar, 1991.*

[8] *The distribution is, in fact, a cumulative probability function, i.e. 95% of the boxes stayed 1 day or more (or, alternatively, 5% left the terminal in the first day of arrival), 81% stayed 2 or more days, etc. The data in the chart was approximately using the negative exponential function.*

[9] *Shifting of vessel scheduled, in order to smooth down the peaks was considered impractical due to the tight schedule situation.*