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Evaluating Seaport Policy Alternatives: A Simulation Study of Terminal Leasing Policy and System Performance

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"Some of the port capacity being built today stems from the strong desire to entice carriers to divert cargo from another competing port rather than to serve incremental growth in cargo. Ocean shipping lines often play one port off against the other to get the best facilities at a low price. Thus, the major carriers want and are provided with their own dedicated terminals by public ports to maximize total transport system efficiency. This approach does not maximize, however, the efficiency of total port land, equipment and facilities and accounts for correspondingly low throughput productivity."[1]

1. Introduction

This paper employs simulation to examine the impact of marine container terminal leasing policy on seaport performance. Specifically the paper compares the impact of terminal leasing policy on container terminal utilization and container vessel time in system[2] using the Port of Seattle as a model. To examine the impact of policy on system performance, Seattle's current mixture of dedicated and common-user[3] terminals is compared to an alternative system of pooled common-user terminals resulting in a common-user *seaport*. Under this alternative, all carriers have equal access to all terminals. By creating detailed simulation modules for the six container terminals and 16 container carriers operating within the Port of Seattle, it is possible to examine the differential performance impact of policy change on these individual subsystems as well as overall system performance.

The paper is unique in that it recognizes the interdependence of container terminals and container carriers within a seaport treating the seaport itself as a system rather than a collection of independent terminals and carriers. Much of the current research focuses either on deterministic models of seaport optimization or stochastic simulation of individual terminals for capacity planning purposes. In contrast, this paper examines *seaport* performance, as opposed to terminal performance, using stochastic simulation. While simulation does not necessarily provide an optimum solution, it is a valuable tool for comparing alternatives.

This paper fills a gap identified by Heaver who observes: "There has been little study of the effect of port size, as distinct from terminal size and layout, on the efficiency and performance of ports."[4] By considering a policy in which a seaport is a single common-user system rather than a collection of smaller independent terminal facilities, this effort begins to address the potential impact of seaport size, as opposed to terminal size, on system performance. The potential advantage of large seaports rests in the theory of statistical economies of scale discussed in Section 2. Section 3 describes the data collection and preparation effort while Section 4 details the modeling process. Model validity is evaluated in Section 5 before proceeding to the analysis of results in Section 6. The paper ends with conclusions and a few brief comments presented in Section 7.

2. Literature and Theory

The paper draws its inspiration from a similar effort by Varaprasad.[5] Varaprasad contrasted the impact of dedicated and common-user conventional cargo berth distributions on vessel waiting time in the Port of Singapore. Varaprasad's findings showed "the policy of exclusive berthing privileges for high throughput shipping lines is not recommended, for it results in higher waiting costs all around."[6]

Varaprasad did not provide a theoretical basis for his study. By providing a theoretical basis and extending Varaprasad's effort to container operations, this paper effectively contributes to our understanding of this critical industry segment. The theoretical basis of this effort is *statistical economies of scale* as developed in recent inventory modeling research. Citing previous inventory research, Evers equates statistical economies of scale to economies of massed resources.[7] Citing Silver and Peterson[8], Evers notes "statistical economies result because higher-than-average demands at some locations are simultaneously offset by lower-than-average demands elsewhere." In analytical terms, he states "for an independent identically distributed random variable X_i, with a finite standard deviation, statistical economies of scale exist if the standard deviation of the sum of the X_i's is less than the sum of the standard deviations of the X_i's by a factor of the $\sqrt{n}$."[9] That is:

$$(\sigma\sum_{i=1}^{n} X_i) < \sum_{i=1}^{n}\sigma(X_i))$$

This theory has been applied to inventory modeling by Eppen and Schrage[10] and adapted to intermodal terminal operations analysis by Evers.[11]

Independence of demand has been identified as an important factor in achieving statistical economies of scale in inventory models.[12] Existing inventory modeling research has shown, under certain conditions, when uncorrelated customer demands are pooled the level of inventory required for a given customer service level declines. Even when correlation exits, research shows cost reductions are still attainable without jeopardizing customer service. Only when demand is perfectly correlated is there no benefit to pooling. This is the root concept of statistical economies of scale. In inventory literature, this result is referred to as the "portfolio effect" or, because of the factor $\sqrt{n}$, the "square root law."[13]

Evers, in his application of inventory theory to intermodal terminal services, contrasts product-oriented firms with service firms and observes:

> "Product-oriented firms rely primarily on inventory to meet temporal fluctuations in demand. By maintaining inventories of goods, these firms can satisfy customer requirements as they occur. Service-oriented firms, on the other hand, use capacity to meet temporal demand fluctuations. By maintaining excess service capacity, service firms, too, can satisfy customer requirements as they occur."[14]

Following Evers, the current effort equates vessel demand for berthing space and terminal services to customer demand for goods in a multiple-facility inventory allocation model. Marine terminals are equated to warehouse facilities and marine terminal resources such as berths and container gantry cranes are equated to inventory. A "stockout" occurs when an arriving vessel must wait in a queue for service. To provide service to carriers, a seaport invests in terminal space and resources. Some have argued, as noted above, that sub-optimal investment may be made to entice carriers to remain either at the seaport or move from a competing seaport. This is in effect an increase in "safety stock" to lower the probability of a "stockout" thus improving customer service. This investment increases the seaport's cost but lowers the carrier's cost by reducing the probability a vessel will not be serviced on arrival.

Existing seaport economics literature recognizes the trade-off between seaport investment and carrier costs and defines optimal investment in capacity as that which minimizes the sum of seaport and carrier costs.[15] What is overlooked in these deterministic models is the probabilistic nature of demand for seaport services. In contrast, inventory allocation theory recognizes the uncertainty of demand and seeks to minimize inventory carrying cost for a given level of customer service with this level defined as the probability of not stocking out. The appropriate level of customer service is established by management with reference to the cost of a stockout, the cost of holding inventory and the market environment faced by the firm. The more competitive the market, the higher the level of customer service required. The demands of a competitive market dictate establishment of lower stockout probabilities and correspondingly higher inventory levels. Current inventory allocation theories based on statistical economies of scale stress *consolidation of inventory locations as a means of maintaining customer service while decreasing aggregate inventory.*

Applying the general concept to seaports, under competitive conditions seaports may be forced to carry the burden of high customer service requirements. By investing in excessive terminal capacity, the seaport is in effect offering a reduction in "total port price" to entice carriers.[16] If the investment is for a dedicated terminal, the benefit of the price reduction is limited to a single carrier and its partners. This is often the case in the competitive environment seaports face; an environment shaped more often by seaport economic development objectives than seaport profitability. In addition to sub-optimal investment, if a seaport favors dedicated terminal leasing over common-user terminal leasing, the ability to pool demand and exploit statistical economies of scale is reduced.

This effort examines the possible consequences of seaport policy alternatives within this framework. By comparing a realistic model of an existing mixed dedicated/common-user seaport to an alternative policy that effectively pools all demand, the potential benefit of statistical economies of scale can be examined.

Based on the theory, the following hypothesis is made:

> H1: For a given level of throughput, when all carriers have equal access to all terminals, total seaport system cost will be reduced in comparision to a system which restricts specific carriers to specific terminals.

By employing stochastic simulation, this hypothesis will be tested using the Port of Seattle as an example.

3. Data Collection

The Port of Seattle was chosen as a subject for several reasons. Seattle currently has a mixture of dedicated and common-user container terminals clustered around a common waterway, Elliot Bay. These terminals are all served by common interstate highway access as well as two Class I rail carriers. These characteristics allow meaningful comparison of the existing system to the pooling of terminal capacity in a common-user seaport. Since in reality the terminals are centrally located and served by common inland access systems, the policy alternative of a single common-user seaport is technically feasible.

Another factor influencing the selection of the Seattle is the fact that it is a container port of significant size actively competing with the neighboring Pacific Northwest seaports of Tacoma, Portland and

Vancouver, B.C. The Seattle Port Authority has recently invested in container terminal expansion projects serving both dedicated and common-users. These projects have been well documented providing the detailed data necessary for this effort.

By modeling the current system as a base case and comparing its output to reality for the modeled year, model validity can be evaluated. Once validated, the base case model can be compared to the policy alternative under study. Modeling the base case system required data on the following ocean carrier and terminal variables and characteristics:

<u>For ocean carriers</u>

1. Vessel inter-arrival times by carrier (stochastic)
2. Vessel size distribution (TEU) by carrier (stochastic)
3. Current terminal assignment by carrier

<u>For container terminals</u>

1. Number of container terminals
2. Type of terminal operation (dedicated or common user)
3. Number of container gantry cranes by terminal
4. Handling rate (moves/hour) of container gantry cranes (stochastic)

Stochastic variables, as noted, are vessel inter-arrival times, vessel size distributions and container gantry crane handling rates.

Various sources were used to provide the data necessary to model terminal facilities. These included several recent articles published in the American Society of Civil Engineers (ASCE) Ports series,[17,18,19] Containerization International Yearbook (CIY)[20], U.S. Army Corp of Engineers (CoE) Port Series[21], and the Port of Seattle's own Internet site[22]. CIY was also referenced to identify terminal assignments by carrier as shown in Table 3 below. Additional data were collected from various trade publications and newspapers including *The Journal of Commerce*, *American Shipper* and *The Seattle Times*.

The CoE Navigation Data Center (NDC) provides detailed vessel entrance and departure information on a monthly basis for each major seaport in the U.S. These data include vessel name and month of entrance and clearance. While it would be preferable to employ data identifying the day and possibly hour of each vessel's arrival, such data is difficult to obtain and beyond the resources of the current effort.

Fortunately, existing research investigating actual vessel arrivals generally agrees that arrivals can be approximated by a Poisson distribution with a specified mean.[23] What is required is an estimate of individual carrier inter-arrival means. For the current effort, 1996 NDC monthly vessel arrival data for Seattle was employed to estimate mean inter-arrival time by carrier. Vessel name and month of arrival was identified for 662 container vessel arrivals in the Port of Seattle.

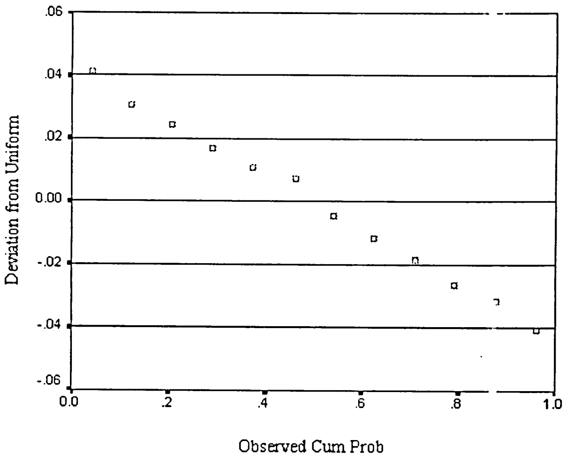
Consultation with various issues of CIY yielded the TEU capacity of 648 (97.9%) of the vessels identified in the NDC data set. These data were used to estimate discrete vessel size distributions by carrier, which appear in Appendix 1. Descriptive statistics for actual monthly carrier arrivals and TEU capacity are shown in Table 1.

Table 1. - Carrier Arrivals and TEU Capacity by Month

	Carrier Arrivals		TEU Capacity	
Carrier	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
APL	8.5	1.0	37,521.7	5,748.0
BSL	1.2	1.0	1,474.8	1,305.2
COL	1.8	0.9	1,952.8	1,088.0
COS	4.2	0.6	11,249.2	1,476.8
FES	2.3	0.6	2,425.0	708.0
FMG	0.7	0.5	553.3	408.7
HAN	4.4	0.5	11,309.7	3,485.9
HL	2.2	0.7	6,325.8	2,0[illegible]7.7
HYU	12.4	1.7	37,769.1	6,847.7
MAR	0.5	0.5	284.5	297.2
MAT	0.5	1.2	1,004.5	2,351.6
MOL	2.9	0.7	7,993.3	1,830.7
NOL	2.8	0.9	9,657.8	3,2[illegible]1.0
NYK	7.3	1.5	21,280.6	4,[illegible]08.6
OCL	1.8	0.9	5,303.7	2,950.1
PO	0.6	0.7	2,008.6	2,303.0

The 662 arrivals were first examined for seasonal trends by aggregating carrier monthly arrivals into monthly arrivals for the port and fitting the result to a uniform distribution. This was a necessary step, as seasonal variability in vessel arrivals would make estimation of carrier mean inter-arrival times more complex. A detrended uniform P-P plot shows a +/- 0.04 deviation from the expected value of the uniform distribution thus supporting the lack of a seasonal trend in aggregate monthly vessel arrivals. This plot is shown in Figure 1.

Figure 1 – Detrended Uniform P-P Plot of Aggregate Monthly Arrivals



To further test the assumption of a uniform monthly distribution of vessel arrivals, disaggregate data for all of the 16 carriers where also examined using detrended uniform P-P plots similar to Figure 1. The maximum that any single observation deviated from the corresponding uniform distribution was +/- 0.14. Finding the data fit a uniform distribution by month, the effort proceeded to estimate individual carrier mean inter-arrival times in hours assuming the distribution of arrivals *within each month* was also uniform. With this assumption, the mean inter-arrival time in hours for each carrier_x was estimated using equation (1):

$$\text{Mean Inter-arrival Time Carrier}_x \text{ (hours)} = 8760/\text{Annual Vessel Arrivals Carrier}_x \qquad (1)$$

Carrier annual arrivals, mean inter-arrival times, mean TEU/vessel and terminal assignment are presented in Table 2.

Table 2. - Carrier Data

Carrier	Entrances (annual)	Inter-Arrival time (hours)	Mean TEU/Vsl	Terminal Assignment
APL	102	86	4,414	T5
BSL	14	626	1,264	T25
Columbus	22	398	1,065	T25
Cosco	50	175	2,700	T18
Fesco	27	324	1,078	T18
FMG	8	1,095	830	T25
Hanjin	53	165	2,730	T46
HL	26	337	2,919	T37
Hyundai	149	59	3,438	T18
Maruba	6	1,460	569	T18
Matson	6	1,460	2,009	T25
MOL	35	250	2,741	T30
NOL	35	250	3,311	T37
NYK	87	101	2,935	T37
OOCL	21	417	3,031	T5
P&OCL	7	1,251	3,443	T37

The assumption that carrier arrivals are uniformly distributed within each month is reasonable given the container segment is characterized by regularly scheduled service with vessel arrivals scheduled for specific days of the week. It is assumed each carrier uniformly distributes its capacity and arrivals throughout the month in order to minimize vessel queue time, at least in dedicated terminals, and to minimize dwell time at the origin and destination terminals. Any randomness in the inter-arrival times is attributed to exogenous factors with in-transit weather conditions being the most significant. This randomness is modeled as a Poisson distribution based on individual carrier mean inter-arrival times estimated using equation (1).

To simplify the model, it was assumed a terminal's throughput capacity was a function of the number of container gantry cranes serving the terminal. Thus terminal storage space, container yard handling equipment, landside access and intermodal services are not active constraints on terminal throughput. In this way, a vessel's service time at a given terminal is solely a function of the vessel's size and the number of cranes servicing it. This simplification was necessary due to the limitations of the simulation package in use. The application was a limited version with restricted capability. A more thorough modeling of terminal operations would be possible using an unrestricted version of the simulation application. Crane counts by terminal as well as marine terminal operator (MTO) are shown in Table 3.

Table 3.
Terminal Data

Terminal	MTO	Cranes
Term 5	Eagle (APL)	6
Term 18	SSA	5
Term 25	Matson	3
Term 30	Trans Pacific	3
Term 37	SSA	3
Term 46	ITC	3

Data on cranes lifts per hour (LPH) where collected from several published studies of container crane productivity[24,25,26] and terminal simulation.[27] All cranes, regardless of terminal, were modeled as single-hoist units and assumed to have identical service rate distributions. Based on these assumptions, LPH was modeled as a triangular distribution with a mean of (25), a maximum of (27) and a minimum of (22).

4. Modeling

To compare the impact of leasing policy, it was necessary to first create a base case model of the Port of Seattle using 1996 data. The base model's validity could then be evaluated by comparing its output to actual annual data. Once validated, the model would serve as a base for the alternative policy model. The impact of the change in policy would be determined by comparing the means of key performance measures across the two models.

To assure the independence of each carrier's arrivals from those of the other carriers, the arrival process for each of the 16 ocean carriers was modeled by a separate arrival module. These modules generated arrivals from a Poisson distribution with the mean inter-arrival times shown in Table 2. For each arriving vessel, unique attributes were assigned identifying the carrier and, based on the unique carrier discrete distributions shown in Appendix Table 1, the TEU capacity of the vessel. The carrier attribute was used to direct the vessel to the appropriate terminal in the base case. Given the independence of arrivals, the pooling of carriers' demand in a common-user seaport should result in reduced variation compared to the mixed common-user/dedicated terminal policy of the base case. The impact reduced variation will have on terminal utilization and time in port is the focal question.

The relationship between vessel size (TEU capacity) and available resources at the assigned terminal determine the service time of each vessel. For each arriving vessel, TEU capacity must be converted to lifts and then divided by the terminals LPH capability to derive estimated service time. The service time function employed in the models is described by equation (2).

$$\text{Service time} = [(\text{TEU} * 0.75)/1.7]/(\#\text{ of container cranes})*(\text{LPH}) \qquad (2)$$

This function assumes the number of TEU handled is equal to a constant 75% of each vessel's TEU capacity.[28] This constant was obtained through trial and error manipulation of the base model. Given the vessel arrival and size distributions, the constant was manipulated with the objective of matching Seattle's total annual TEU volume for 1996. The factor 1.7 converts the estimate of TEU handled to lifts assuming 70% of the lifts are forty-foot equivalent units (FEU). This estimate is based on Vandeveer.[29] Thus, the bracketed expression in equation (2) yields the total lifts required to service each vessel. Multiplying the number of container cranes at the terminal by LPH yields the capability of the terminal in lifts per hour. By dividing total lifts required by terminal LPH capability yields vessel service time. Obviously, actual data on TEU capacity utilization and the ratio of TEU to lifts for each vessel would be preferable. However, lacking this, the estimation of service time as described in equation (2) must suffice.

The assumption is that all cranes at a terminal are dedicated to the service of one vessel until that vessel is completed and released at which time the cranes become available to the next vessel in the queue. Modeling only the capability and performance of container gantry cranes assumes adequate berthing space, land for storage of containers, terminal container handling equipment and landside access is provided in proportion to the number of container gantry cranes.

Time was measured in hours for both models. To allow comparison of model output to actual reported annual throughput for the Port of Seattle, the run length for each repetition was 8,760 hours. A warm-up period of 240 hours was established to initialize the system. All terminal resources operate 16 hours/day and 7 days/week. The remaining 8 hours per day terminals are idle. Vessel arrivals continue 24 hours/day and 7 days/week. This is similar to the operating practices at the Port of Seattle. 100 repetitions were made for each of the two policies under study with statistical accumulators cleared after each replication thus assuring independent observations across replications. In effect the model repeats the same year, 1996, 100 times.

The base case model employs a "pick-station" module to assign arriving vessels to terminals based on actual carrier terminal assignments for the Port of Seattle. This station is referred to as the "Pilot Station" in that it directs carriers to the appropriate terminal or terminal queue. The transit time between arrival at the "Pilot Station" and entry to the terminal or terminal queue is a random variable following a uniform distribution with a minimum of two and a maximum of three hours. This reflects the time required to berth the vessel. It is assumed that adequate berthing space exists even when other terminal resources are busy or that vessels will adjust speed on the final leg of the voyage to avoid the extra step of anchoring to await a berth.

For the alternative common-user seaport policy, the "Pilot Station" directs the entity to the terminal that has the minimum values of number in route to terminal, number in terminal queue and number of terminal resources busy. The logic of the common-user alternative examined each terminal in a specified order based on the throughput capabilities (number of cranes) of each terminal beginning with the highest throughput, Terminal 5, and ending with the lowest, Terminals 25-46. This logic assured that the highest capacity terminal is the preferred assignment all else being equal.

For both models, statistics where collected on vessel time in system by carrier, average time in queue by terminal, terminal throughput in TEU and terminal utilization. Appendix Table 2a and Table 2b present the complete statistical outputs corresponding to the two policy alternatives.

5. Model Validity

For purposes of evaluating model validity, the output of the base model was compared to actual output for the Port of Seattle in 1996 as well as established standards of terminal productivity. Table 4. presents the key inputs (acres and cranes), outputs (vessels and TEU) and productivity ratios (TEU/Vessel, TEU/acre, TEU/crane and Lifts/crane/operating hour) used to validate the base case model.

Total TEU for 1996 was not available for the Port of Seattle. However, the TEU total for 1995, according to the Port of Seattle, was 1,371,636. This represented a 5% increase from 1994. The total TEU for the base model was 1,431,315, which is 4.4% increase over 1995's actual total. Given the 1994 to 1995 trend at Seattle, the general trend in Pacific rim volume and the investment in facilities at the Port of Seattle, this increase seems reasonable if not conservative.

Unfortunately, terminal specific TEU throughput data was not available for the year under study or for any comparable years. It was therefore necessary to compare the base case model's key productivity ratios to the Port of Seattle's average and to industry productivity standards for similar terminals.

Table 4. - Key Terminal Inputs and Outputs from Base Model
(100 replications)

Terminal	Total TEU	Vessels	Acres (1996)	Cranes	TEU/Vessel	TEU/Acre	TEU/Crane	Lifts/Crane /Op Hr*
Term 5	384,870	123	158.0	6	3,129	4,014	64,145	6.46
Term 18	464,770	232	107.0	5	2,007	4,374	92,954	9.36
Term 25	47,112	50	36.5	3	942	1,538	15,704	1.58
Term 30	72,533	35	37.0	3	2,053	1,957	24,178	2.44
Term 37	354,030	155	38.0	3	2,283	8,844	118,010	11.89
Term 46	108,000	53	50.0	3	2,043	2,401	36,000	3.63
Total	1,431,315	648	426.5	23	2,209	4,034	62,231	6.27

*(TEU/1.7)/crane/operating hour

The individual TEU/acre throughput estimations support the base model's validity. Sources place the annual TEU/acre throughput of US terminals between 3,000-6,000.[30] The actual average for all Port of Seattle terminals in 1995 was 3,866 TEU/acre compared to an average of 4,034 TEU/acre in the base model. With the exception of Terminal 37, all terminals fall within the 3,000-6,000 TEU/acre performance range. While Terminal 37's TEU/acre throughput is high, it should be noted that throughputs of 20,000 TEU/acre are achieved in some Asian seaports. In addition, the TEU/vessel of 2,283 supports the validity of the model's estimate of Terminal 37 throughput.

According to Vandeveer, the most efficient US seaports averaged 3,600 TEU/acre during 1994/95.[31] Thus, the validity of the model with respect to average TEU/acre is supported. It is also interesting to note Terminal 5 and Terminal 18 have above average TEU/acre results. This may also be seen as supporting the model's validity as both American President Lines (APL), Terminal 5's tenant, and Stevedoring Services of

America (SSA), Terminal 18's tenant, were aggressively pursuing the Port of Seattle's support for significant terminal expansion projects possibly indicating existing terminal space was well utilized. With respect to Terminal 5, APL estimates an annual throughout capacity of 576,000 TEU or 3,645 TEU/acre with the terminal's recent expansion to 158 acres.[32]

Port of Seattle 1995 actual throughput and crane counts yield an average annual TEU/crane of 59,636. The average annual TEU/crane of the base model is 62,231. MARAD indicates annual TEU/crane figures ranging from 75,000 and 90,000.[33] With the exception of Terminal 18 and Terminal 37, the base case performance measures are within this range. Since the lifts/crane/operating hour of the base model are all well below the reported performance range of the standard container gantry cranes,[34] the TEU/crane outputs for Terminal 18 and 37 are not a cause for concern. It is interesting to note that both Terminal 18 and Terminal 37 are operated by SSA and not by individual carriers.

The 648 vessel calls generated in the base case compare favorably to the 662 actual vessel entrances in 1996. The difference is entirely due to a lack of data on four carriers serving the port.[35] The annual terminal vessel calls generated by the base model precisely match the actual annual vessel calls of carriers assigned to those terminals. This is expected as the distributions used to create the carrier arrivals were based on actual data.

Given the available data, the validity of the model was well supported. Comparison of the base case model to the alternative policy can be expected to illuminate the potential impact of policy change on actual system performance.

6. Results

Table 5 presents the key inputs and outputs from the alternative policy model for comparison to the base case model. As expected, the total throughput of 1,431,937 TEU is virtually identical to 1,431,315 TEU of the base case. The primary differences are in the throughputs of the individual terminals as well as the key productivity ratios of those terminals. In addition, as expected, owing to its large capacity, Terminal 5 has assumed a greater role in overall throughput of the Port of Seattle. TEU for Terminal 5 has risen from 384,870 to 761,360; a 97.8% increase. While this value exceeds the 576,000 annual TEU estimated by APL, it must be noted that the TEU/acre value of 4,819 is still below the stated US industry maximum of 6,000 TEU/acre. The lifts/crane/operating hour at Terminal 5 (12.78) is likewise well within the capabilities of the current generation of container gantry cranes. As noted, a mean of 25 LPH is widely accepted. While the figure of 576,000 TEU per year may be optimal from the standpoint of a single carrier with a dedicated lease at Terminal 5, it may not be optimal when the terminal is considered a component of the entire system and system optimization is the goal.

Table 5. - Key Inputs and Outputs from Common-User Model

(100 replications)

Terminal	Total TEU	Vessels	Acres (1998)	Cranes	TEU/Vessel	TEU/Acre	TEU/Crane	Lifts/Crane /Op Hr*
Term 5	761,360	342	158.0	6	2,227	4,819	126,893	12.78
Term 18	434,310	197	107.0	5	2,206	4,059	86,862	8.75
Term 25	176,730	81	36.5	3	2,178	4,842	58,910	5.93
Term 30	49,531	24	37.0	3	2,100	1,339	16,510	1.66
Term 37	8,953	4	38.0	3	2,039	236	2,984	0.30
Term 46	1,053	1	50.0	3	1,816	21	351	0.04
Total	1,431,937	648	426.5	23	2,208	3,357	62,258	6.27

(TEU/1.7)/crane/operating hours

Tables 6, 7 and 8 display difference of means tests between the two policy alternatives. The key measures are time in queue by terminal, terminal utilization and carrier time in port. A negative sign indicates a reduction in the mean when moving from the base case to the alternative. With the exception of Terminal 30, all terminals experience a significant reduction in time in queue at the 0.05 level with all such values negative. The negative sign indicates a reduction when moving from the base case to the common-user seaport alternative. The largest timesavings occur at Terminals 37 and 18. Terminal 30's utilization is not significantly different from zero at the 0.05 level.

Table 6. –Difference of Means – Time in Queue (hours) by Terminal
Change from Base to Alternative
(paired t comparisons)

IDENTIFIER	ESTD. MEAN DIFF	STD DEV	0.95 CI +/-
Avg Time in Queue T5*	-0.23	0.29	0.057
Avg Time in Queue T18*	-1.24	0.35	0.069
Avg Time in Queue T25*	-0.27	0.43	0.086
Avg Time in Queue T30	-0.00	0.66	0.131
Avg Time in Queue T37*	-4.24	1.39	0.275
Avg Time in Queue T46*	-0.76	1.53	0.303

n=100
*Means are not equal at 0.05 level

An interesting result of the model is shown in Table 7. Utilization for Terminals 18, 30, 37 and 46 have all declined with Terminals 5 and 25 taking up the slack. In the case of Terminals 30, 37 and 46, further examination shows that Terminals 37 and 46 are in fact virtually closed and Terminal 30 is nearly closed. The effect of the policy change is elimination of two terminals and near elimination of a third.

Table 7. - Difference of Means – Terminal Utilization (% of total time)
Change from Base to Alternative
(paired t comparisons)

IDENTIFIER	MEAN UTIL. (Base)	MEAN UTIL. (Alternative)	ESTD. MEAN DIFF	STD DEV	0.95 CI +/-
Utilization T5*	0.18	0.35	0.17	0.01	0.002
Utilization T18*	0.25	0.24	-0.02	0.01	0.002
Utilization T25*	0.04	0.16	0.12	0.01	0.002
Utilization T30*	0.07	0.05	-0.21	0.01	0.001
Utilization T37*	0.32	0.01	-0.31	0.01	0.001
Utilization T46*	0.10	0.00	-0.10	0.01	0.000

n=100
*Means are not equal at 0.05 level

Table 8 presents difference of means test for carrier time in port. All results are statistically significantly different from zero at the 0.05 level. Examination reveals that only Carriers 1 and 15, the current users of Terminal 5, experience a degradation in service time under the alternative policy. Returning to the inventory allocation model, for most of the Port of Seattle's customers, the consolidation of demand has resulted in a higher level of customer service (reduced carrier time in port) while serving the same level of demand (throughput) and reducing the investment in inventory (terminals eliminated). The findings support the presence of statistical economies of scale.

For the two policy alternatives, Table 9 compares the key aggregate performance measures for the Port of Seattle. The policy change under analysis has reduced total time in port for all carriers 17.1% with virtually no reduction in TEU throughput or the number of vessels served. Applying recent estimates of average vessel cost per day and lease costs at the Port of Seattle, the policy alternative produces an annual savings of $8.3 million.

Table 8. - Difference of Means – Carrier Time (hours) in Port
Change from Base to Alternative
(paired t comparisons)

IDENTIFIER	ESTD. MEAN DIFF	STD DEV	0.95 CI +/-
Avg Time in Port C1*	2.69	0.62	0.123
Avg Time in Port C2*	-2.91	1.15	0.227
Avg Time in Port C3*	-2.57	0.92	0.182
Avg Time in Port C4*	-1.90	1.07	0.213
Avg Time in Port C5*	-2.81	1.32	0.262
Avg Time in Port C6*	-1.98	1.15	0.228
Avg Time in Port C7*	-5.92	0.76	0.150
Avg Time in Port C8*	-12.20	1.82	0.361
Avg Time in Port C9*	-0.47	0.61	0.120
Avg Time in Port C10*	-2.58	2.38	0.473
Avg Time in Port C11*	-5.58	1.87	0.371
Avg Time in Port C12*	-5.97	0.84	0.168
Avg Time in Port C13*	-12.30	1.64	0.325
Avg Time in Port C14*	-9.64	0.77	0.1[illegible]2
Avg Time in Port C15*	0.71	1.49	0.295
Avg Time in Port C16*	-14.90	4.62	0.9[illegible]7

n=100
*Means are not equal at 0.05 level

Table 9. – Comparison of Key Performance Measures and Estimated Carrier Cost Reduction

Key Performance Measures				
	Common	Base	Diff	% Diff
Total TEU Throughput	1,431,937	1,431,315	622	0.04%
Total Vessels Served	648	648	1	0.09%
TEU Throughput/Vessel	2,208	2,209	-1	-0.05%
Total Time in Port	11,209	13,525	-2,316	-17.13%
Carrier Annual Cost Reduction				
Vessel costs/day[36]	$40,000			
Lease costs/acre[37]	$50,000			
Annual reduction in vessel costs	$3,860,412			
Annual reduction in lease costs'	$4,400,000			
Total annual reduction in costs	$8,260,411			

'Assuming total reduction of 88 acres by eliminating Terminals 37 and 46.

As noted, statistical economies of scale exist when, for a random variable X_i, the standard deviation of the sum of the X_i's is less than the sum of the standard deviations of the X_i's. To test this, all observations of vessel TEU arriving at each terminal were collected for both the base case and the alternative model across 100 replications. TEU was used rather than vessel arrivals as the former more accurately reflects the demand placed on terminal resources as a result of the later. This approach yielded a sample of 67,385 observations for each model.[38] For the alternative (common-use seaport), the standard deviation of all observations was estimated. For the base case model, each terminal's standard deviation was estimated and the results summed. The respective values were 864.68 and 5261.78. The standard deviation of demand at the common-user seaport, the alternative policy, is less than the sum of standard deviations at the individual terminals under the existing base case policy. This result supports a finding of statistical economies of scale in seaport services.

The results yield a factor greater than the square root of the number of terminals. The $\sqrt{6} = 2.449$ which is compared to $\frac{5261.78}{864.68} = 6.085$. Since the square root law assumes identically distributed random variables, such a result is not surprising. TEU capacities for carriers are modeled using unique discrete distributions thus the assumption of identical distributions necessary to apply the square root law is not valid in this application.

7. Conclusion

The hypothesis that pooling independent demands for terminal services will reduce total seaport cost for a given level of throughput has been unequivocally supported by the simulation model. The policy of pooling carrier demand has been shown to result in a direct annual cost reduction to seaport users totaling $8.3 million. Other savings would accrue to shippers whose lead times and in-transit inventories would be reduced with the reduction in carrier time in port. In addition, improved utilization of existing terminal facilities could lead to reduced pressure for seaport expansion and the many costs that accompany it.

Future research should seek out more detailed data regarding carrier arrival patterns for specific seaports as a check on the validity of the current papers findings. Further detail in the modeling of terminal operations would also add value to the effort. Modeling terminal storage capacity, intermodal interchanges and container dwell time would shed light on shipper costs and benefits. These are not significant challenges and should be addressed.

Turning to the possibility of implementing a common-user seaport policy in the current environment, a greater challenge is found. The most significant obstacle to implementation of this policy results from the negotiating tactics of large carriers and the seaport authorities' response to these tactics.[39] In most cases, seaport authorities favor leasing to large carriers rather than independent MTOs.[40] Likewise, many large carriers prefer dedicated terminals to common-user terminals. As Kraman, Headland and McNeal note: "Under present market conditions, shipping companies tend towards terminals that have sufficient berths to avoid any significant waiting." In lease negotiations, individual carriers may be able to lower their own costs at the expense of the seaport by securing low-cost leases for excess capacity thus reducing or eliminating vessel queue time. In effect, the carrier seeks a 100% customer service level ("zero" stockouts).

Under the assumption of normally distributed demand, inventory theory suggests inventory costs climb exponentially as the system approaches such a level of service. However, as long as seaports are willing to carry the burden of this level of service for their customers, the carriers enjoy the benefits without the costs. In short, as indicated by IAPH in the introduction, the market dynamics may benefit the operations of a few large carriers while decreasing the productivity of seaport and increasing total system costs.

In comparison to carrier-owned MTOs, independent MTOs may have greater incentives to increase terminal throughput. The independent, as a profit-maximizing entity, seeks to maximize return on the terminal lease by increasing throughput. From this perspective, positive values of vessel queue time are beneficial in that terminal idle time is reduced. This is in direct opposition to the carrier's motivation. This hypothesis is supported by the estimates of the base case model which show TEU/acre and TEU/crane for Terminals 18 and 37, both operated by the SSA, an independent MTO, above the average for the Port of Seattle.

It is arguable that negotiations between profit-maximizing carriers and independent MTOs are more likely to result in the minimization of total cost than negotiations between carriers and not-for-profit seaports. To be successful, the independent MTO must not only minimize its cost subject to customer service requirements dictated by the market but it must also earn an adequate return. This tension, normal in the for-profit business environment, theoretically results in optimal investment in inventory for given levels of competition and customer service. Such an outcome might also be the case for seaports if it where not for the absence of a profit motivation on their part and the possibility of their bias toward carriers over independent MTOs.

Currently, land for seaport expansion in the U.S. is in short supply. At the same time, North American seaport container volumes are growing between 6 and 7% annually. Given the market conditions that exist, specifically with respect to carriers demands for dedicated terminals and seaports' responses to these demands, concern about future "hub-dominance" of the seaport system by a few large carriers may be warranted. The current effort adds support for this concern as it shows both a possible negative effect on seaport efficiency resulting from dedicated terminal leases and the interdependence of carriers serving a seaport. In addition to elimination of "stockouts" as a motivation driving carriers toward dedicated terminals, the possibility exists that larger ocean carriers, knowingly or not, are playing a game of musical chairs at the expense of smaller carriers and independent MTOs. The recent regulatory changes embodied in the Ocean Shipping Reform Act of 1998 may exacerbate this potential problem by incentivizing shippers to concentrate volume in the hands of a few large carriers. The public policy implications alone are enough to justify continued research.

Appendix.

Appendix Table 1.
Carrier Size Distributions

Carrier	TEU Distribution (discrete)
APL	disc(.049,1920,.078,2700,.510,4340,1,4832)
BSL	disc(.286,992,.643,1334,1,1412)
Columbus	disc(.318,807,.545,1157,.773,1189,1,1211)
Cosco	disc(.12,2386,.48,2716,1,2761)
Fesco	disc(.778,1012,1,1308)
FMG	disc(1,830)
Hanjin	disc(.057,2662,.377,2668,.472,2678,.981,2692,1,5300)
HL	disc(.269,2594,.577,2803,.846,2984,1,3610)
Hyundai	disc(.121,1747,.289,1837,.490,1965,.497,2808,.557,2908,.64',2984,.671,3547, .886,4411,.913,5541,1,5551)
Maruba	disc(1,569)
Matson	disc(.167,1979,1,2015)
MOL	disc(.257,2542,.486,2676,.514,2846,.771,2852,1,2890)
NOL	disc(.20,2966,.886,3327,1,3821)
NYK	disc(.046,2555,.161,2709,.218,2807,.379,2832,.414,2902,1,3054)
OOCL	disc(.095,2544,.905,2968,.952,3161,1,4960)
P&OCL	disc(.571,3424,1,3469)

Appendix Table 2a.
Outputs - Base Model

Identifier	Average	Half-width	Minimum	Maximum	# Reps
Avg Time in Port C1	19.72	0.07	18.95	20.47	100
Avg Time in Port C2	14.10	0.16	12.34	16.31	100
Avg Time in Port C3	12.99	0.13	11.25	15.20	100
Avg Time in Port C4	18.50	0.17	16.82	20.62	100
Avg Time in Port C5	13.35	0.25	10.65	17.58	100
Avg Time in Port C6	11.59	0.21	9.75	15.42	100
Avg Time in Port C7	22.64	0.09	21.87	24.05	100
Avg Time in Port C8	29.72	0.35	24.87	33.82	100
Avg Time in Port C9	17.80	0.09	16.50	18.81	100
Avg Time in Port C10	11.25	0.47	7.23	17.82	100
Avg Time in Port C11	21.56	0.23	19.35	24.76	100
Avg Time in Port C12	22.71	0.10	21.24	24.07	100
Avg Time in Port C13	31.14	0.29	28.01	35.37	100
Avg Time in Port C14	26.91	0.14	25.37	28.64	100
Avg Time in Port C15	17.27	0.24	14.60	20.80	100
Avg Time in Port C16	34.67	0.89	26.60	47.49	100
Avg Time in Queue T5	1.84	0.06	0.96	2.54	100
Avg Time in Queue T18	2.68	0.07	1.97	3.56	100
Avg Time in Queue T25	1.59	0.08	0.67	2.46	100

Appendix Table 2a.
(continued)

Identifier	Average	Half-width	Minimum	Maximum	# Reps
Avg Time in Queue T30	1.38	0.08	0.31	2.33	100
Avg Time in Queue T37	5.53	0.12	4.13	7.19	100
Avg Time in Queue T46	1.37	0.06	0.91	2.48	100
Total TEU Term 5	384,870	1,430	365,540	[illegible]8,990	100
Total TEU Term 18	464,770	2,594	432,430	4[illegible]3,710	100
Total TEU Term 25	47,112	168	44,533	48,717	100
Total TEU Term 30	72,533	253	68,907	74,884	100
Total TEU Term 37	354,030	688	346,640	362,380	100
Total TEU Term 46	108,000	460	104,480	116,360	100
Utilization T5	0.18	0.00	0.16	0.18	100
Utilization T18	0.25	0.00	0.24	0.27	100
Utilization T25	0.04	0.00	0.04	0.04	100
Utilization T30	0.07	0.00	0.06	0.07	100
Utilization T37	0.32	0.00	0.32	0.33	100
Utilization T46	0.10	0.00	0.09	0.11	100
Vessel Depart 1	101.95	0.22	99.00	104.00	100
Vessel Depart 2	13.99	0.02	13.00	14.00	100
Vessel Depart 3	22.03	0.03	22.00	23.00	100
Vessel Depart 4	49.79	0.13	48.00	51.00	100
Vessel Depart 5	27.17	0.08	26.00	28.00	100
Vessel Depart 6	8.00	0.00	8.00	8.00	100
Vessel Depart 7	52.85	0.11	52.00	54.00	100
Vessel Depart 8	26.05	0.05	25.00	27.00	100
Vessel Depart 9	148.59	0.34	145.00	152.00	100
Vessel Depart 10	5.99	0.02	5.00	6.00	100
Vessel Depart 11	5.99	0.02	5.00	6.00	100
Vessel Depart 12	35.33	0.10	34.00	36.00	100
Vessel Depart 13	35.46	0.11	35.00	37.00	100
Vessel Depart 14	86.60	0.22	84.00	89.00	100
Vessel Depart 15	21.04	0.04	21.00	22.00	100
Vessel Depart 16	6.99	0.02	6.00	7.00	100
Performance Statistics					
Total TEU Throughput	1,431,315				
Total Vessels Served	648				
TEU Throughput/Vessel	2,209				
Total Time in Port	13,525				

Appendix Table 2b.
Outputs - All Common Terminals

Identifier	Average	Half-width	Minimum	Maximum	# Reps
Avg Time in Port C1	22.42	0.11	20.94	24.12	100
Avg Time in Port C2	11.20	0.15	9.45	13.23	100
Avg Time in Port C3	10.42	0.13	8.93	12.31	100
Avg Time in Port C4	16.60	0.12	15.20	18.17	100
Avg Time in Port C5	10.54	0.10	9.46	11.82	100
Avg Time in Port C6	9.61	0.18	7.85	11.93	100
Avg Time in Port C7	16.72	0.11	15.66	18.44	100
Avg Time in Port C8	17.48	0.16	15.88	19.82	100
Avg Time in Port C9	17.36	0.10	16.38	18.66	100
Avg Time in Port C10	8.66	0.18	7.05	11.43	100
Avg Time in Port C11	15.98	0.29	13.30	20.06	100
Avg Time in Port C12	16.74	0.12	15.24	18.27	100
Avg Time in Port C13	18.88	0.15	17.07	21.16	100
Avg Time in Port C14	17.28	0.07	16.46	18.25	100
Avg Time in Port C15	17.99	0.19	15.96	20.98	100
Avg Time in Port C16	19.77	0.36	15.47	24.03	100
Avg Time in Queue T5	1.61	0.03	1.30	1.95	100
Avg Time in Queue T18	1.43	0.03	0.91	1.87	100
Avg Time in Queue T25	1.32	0.05	0.87	1.88	100
Avg Time in Queue T30	1.38	0.10	0.31	2.66	100
Avg Time in Queue T37	1.28	0.25	0.00	4.72	100
Avg Time in Queue T46	0.62	0.31	0.00	7.20	100
Total TEU Term 5	761,360	3,569	726,690	797,610	100
Total TEU Term 18	434,310	2,949	401,470	461,320	100
Total TEU Term 25	176,730	2,764	144,630	218,240	100
Total TEU Term 30	49,531	1,616	29,933	66,282	100
Total TEU Term 37	8,953	884	0	18,621	100
Total TEU Term 46	1,053	319	0	7,212	100
Utilization T5	0.35	0.00	0.33	0.36	100
Utilization T18	0.24	0.00	0.22	0.25	100
Utilization T25	0.16	0.00	0.13	0.20	100
Utilization T30	0.05	0.00	0.03	0.06	100
Utilization T37	0.01	0.00	0.00	0.02	100
Utilization T46	0.00	0.00	0.00	0.01	100
Vessel Depart 1	101.89	0.23	99.00	105.00	100
Vessel Depart 2	14.00	0.00	14.00	14.00	100
Vessel Depart 3	22.03	0.06	21.00	23.00	100
Vessel Depart 4	49.97	0.13	49.00	51.00	100
Vessel Depart 5	27.25	0.09	27.00	28.00	100
Vessel Depart 6	8.00	0.00	8.00	8.00	100
Vessel Depart 7	52.94	0.12	51.00	54.00	100
Vessel Depart 8	26.15	0.08	25.00	27.00	100
Vessel Depart 9	148.96	0.31	146.00	153.00	100
Vessel Depart 10	5.99	0.02	5.00	6.00	100
Vessel Depart 11	5.99	0.02	5.00	6.00	100

Appendix Table 2b.
(Continued)

Identifier	Average	Half-width	Minimum	Maximum	# Reps
Vessel Depart 12	35.34	0.12	34.00	36.00	100
Vessel Depart 13	35.40	0.11	34.00	36.00	100
Vessel Depart 14	86.49	0.19	85.00	89.00	100
Vessel Depart 15	21.02	0.04	20.00	22.00	100
Vessel Depart 16	7.00	0.00	7.00	7.00	100
Performance Statistics					
Total TEU Throughput	1,431,937				
Total Vessels Served	648				
TEU Throughput/Vessel	2,208				
Total Time in Port	11,209				

Endnotes

[1] International Association of Ports and Harbors (IAPH) (1989), *Port development in the United States,"* prepared by United States Maritime Administration (MARAD), Office of Port and Intermodal Development, April 1989.
[2] "Time in system" is defined as "time in queue" plus "service time."
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[20] *Containerization Yearbook International*, National Magazine Co., LTD., London.

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[23] Nicolaou, S (1967), "Berth planning by evaluation of congestion and cost," Journal of the Waterways and Harbors Division, ASCE, November 1967, v93-ww4, pp. 107-132.
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[26] Tabernacle, J. (1995), "A study of the changes in performance of quayside container cranes," Maritime Policy and Management, v22-n2, pp. 115-124.
[27] Kraman, M., J. Headland and P. McNeal (1998), "Probabilistic analyses of port throughput and berth optimization, in *Ports '98*, ASCE.
[28] If 100% of vessel's TEU capacity was first discharged then the vessel was reloaded to 100% capacity, the resulting factor would be 200%.
[29] Vandeveer, D. (1998), "Port productivity standards for long-term planning, in *Ports '98*, ASCE.
[30] MARAD (1997), "Congressional Ports Report," p. I-1.
[31] Vandeveer, D. (1998).
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[33] MARAD (1997), *Congressional Ports Report*, p. I-1.
[34] See Rudolf, C. (1995), Jordan, M. (1995) and Tabernacle, J. (1995).
[35] CSAV, DSR-Senator, Poseidon and Sunmar.
[36] Based on Veldman, S (1993), "The optimum size of ship and the impact of user cost – an application to container shipping," in *Current Issues in Maritime Economics*, K.M. Gwilliam, ed., Kluwer Academic, Dordrecht. Cost is for a 2,400 TEU vessel and is comprised of capital, labor, administrative and auxiliary engine fuel. Cost is in 1996 dollars adjusted from 1993 dollars at a 5% annual rate of inflation
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[39] See the actions of Atlantic coast seaports in response to Sea-Land/Maersk's 1998 request for a new terminal.
[40] Corr, O. (1996).