casinos. Bus and passenger volumes can change significantly in response to variations in the incentives offered by a particular casino relative to its competitors. These results are confirmed by the relationships shown in Figure 4.

The preceding paragraphs discuss the various strategies followed by the casinos and their reliance on bus patrons. The importance of this transportation system is confirmed by the fact that all casinos operate a bus program. To indicate the economic impact of the casino buses, the number of patrons was converted to dollars spent. The casinos do not reveal market research data, but it is generally recognized that casino bus patrons spend an average of $50 to $70 each visit. Based on ten million annual visitors, the casino bus transportation system generates tourist expenditures that exceed one-half billion dollars and could reach $700 million. Clearly the casino bus transportation system plays a major role in assuring the economic viability of the casino industry and the Atlantic City region.

GOVERNMENT ROLE

The casino buses are owned and operated by private firms that recover all costs from farebox revenue. For this reason no government funds, either operating assistance or capital funds, are required. This contrasts with urban transit systems throughout the nation as well as intercity bus carriers to a certain extent. Although government funding is not required, a regulatory role is mandated. The large volume of buses can produce traffic congestion and delays for residents. Also, the routing of buses through and the storage of buses in residential areas can be disruptive. Recognizing these problem areas, the Atlantic County Transportation Authority (ACTA) has developed a management plan for routing and parking casino buses in Atlantic City. To assure the implementation of the plan, ACTA has requested and received power to regulate the flow and movement of buses. In this way the economic and transportation benefits of casino buses can be realized while the potential adverse consequences are limited. Such an approach is unusual for a local authority, but the unique conditions brought about by casino gambling called for such innovative solutions.

CONCLUSIONS

In this paper a brief overview of the casino bus transportation system has been provided. The casino bus system serves as an important transport mode to and from Atlantic City, and it also has encouraged the economic development envisioned with casino gambling. Of particular note is the evolution of this transportation system and its operation by the private sector. It is anticipated that the dimensions and importance of the casino bus system will grow and keep pace with the development of new casinos in Atlantic City in the future. Further, the casino buses will continue to constitute a significant approach to assuring the economic vitality of the tourist industry and the region.

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Optimizing the Use of a Containership Berth

PAUL SCHONFELD and STEPHEN FRANK

ABSTRACT

Total system costs, including those of berths, cranes, storage yards, dock labor, ships, containers, and cargo, are minimized for single-berth containership terminals under various assumptions. The analytic model accounts for queueing delays to ships, mutual interference among cranes, minimum work shifts, and storage yard requirements. Results indicate that total system costs per ship or per ton of cargo can be significantly decreased by increasing the number of cranes per berth and berth use above current levels. The results are especially sensitive to labor costs and work rules.

Containerization has been widely adopted in ocean shipping since the late 1950s because it offers some compelling advantages over break-bulk shipping. By handling the cargo in relatively large standardized intermodal containers, the time and cost of transferring cargo in ports can be reduced substantially. The cost and weight of cranes required to handle containers preclude their installation on modern specialized containerships. Thus, unlike older ships, most containerships have no self-loading or self-unloading capability.

Given the high cost of containerships and terminal facilities, it is desirable to use both ships and terminals as efficiently as possible. However, some current plans for containerport development may lead to underuse of containerport capacity as well as suboptimal turnaround times for ships. Typically such plans include the construction of large numbers of berths relative to the ship arrivals forecast. Some containerports seem to provide too many berths for the expected number of ships (e.g., 1.4 berth days per ship arrival is typical) and too few cranes (e.g., 1.43 cranes per berth at one modern facility). The combination of too many berths and too few cranes may result in underused port capacity and needlessly long turnaround times for ships. The theory presented here is that, for a given rate of ship arrivals, fewer berths and more cranes per berth would provide a better solution by reducing the capital cost of berths as well as reducing the total time each ship spends in port. To test that hypothesis, a mathematical model was developed to determine total system costs under a wide range of assumptions and circumstances, and to optimize the ratios of ships to berth and cranes to berth. In this paper the simplest version of the model and some initial results obtained with it are presented. The results presented here are limited to one-berth terminals. (The model has been extended to multiberth terminals, for which results will be published soon.) Such results are useful because many small ports and many private companies in large ports operate one-berth terminals.

LITERATURE REVIEW

Several authors including Plumlee (1), Nicolau (2), and Wanhill (3) have sought to optimize the number of general-cargo berths in a port by minimizing a sum of port costs and ship delays. Fratar, Goodman, and Brandt (4), Jones and Blunden (5), and Miller (6) have investigated the applicability of various queueing models and statistical distributions for arrival and service rates. Queueing theory has been applied by Wilson (7) to lock capacity analysis and by Freund (8) to barge fleeting operations.

Boyer (9) discusses various aspects of containerization including berth use and productivity. Boyer defines berth use as ship calls per week divided by 7 days per week rather than occupied hours divided by total hours per week. He also suggests that four ship calls per week represent practical berth capacity and that "scheduling beyond four days (i.e., four ships per week) means that ships will frequently be kept waiting for berths, and containership operators will not tolerate delays." Furthermore, he states that "one crane (i.e., per ship) operating on a single shift will handle this demand (i.e., four ships per week) with time to spare" (9,p.463). These two statements do not seem fully consistent. The results presented here indicate that with more cranes per berth more than four ships per week can be handled without unacceptable delay, especially if the savings in facilities costs can be passed to shipowners through reduced port charges.

MODEL FORMULATION

The optimization of containerport design and operation requires trade-offs among several important elements, including berths, cranes, storage facilities, work crews, ships, containers, and cargo. Interaction, both competitive and cooperative, with surface transportation and other ports should also be considered in a complete analysis, although a relatively simple model can incorporate most of the important cost relations. The full capacity of a port and its components cannot be used without imposing excessive delays on ships. Because ship arrival rates, container handling (or transfer) rates, and the number of containers transferred per ship are all stochastic variables, there are inevitably times when ships must wait in queues for a berth to become available. To properly balance the costs of delays to ships and cargo versus the cost of facilities, a total system cost function can be formulated. This function can be used to summarize the total costs to the relevant parties (shipowners, shippers, and port operators). A subset of this total cost function may be used in conjunction with appropriate revenue functions to optimize the system from a narrower viewpoint, for example, that of a port authority. It should be noted that some companies own and operate both containerships and terminal facilities and hence would be concerned with the combined cost of ships and terminals.

The total cost function consists of the following six components:

$$C = C_b + C_r + C_y + C_\ell + C_s + C_u \tag{1}$$

where, in dollars per hour,

C = total system cost,
C_b = berth cost,
C_r = cost of cranes,
C_y = cost of storage yards,
C_ℓ = labor cost for crane gangs,
C_s = cost of ships in port, and
C_u = cost of containers and their cargo.

Using the definitions of variables presented in Table 1, these cost components may be formulated as follows.

$$C_b = bB \tag{2}$$

$$C_r = bnR \tag{3}$$

$$C_y = zaY \tag{4}$$

$$C_\ell = \lambda n\ell L \tag{5}$$

$$C_s = \lambda sS \tag{6}$$

$$C_u = \lambda spU \tag{7}$$

The cost per berth hour B of Equation 2 is obtained by multiplying the initial berth cost B_i by the capital recovery factor to get the yearly cost, adding the annual maintenance cost M_b, and dividing the entire sum by 365 x 24 hours per year.

$$B = \left(\left\{B_i\,[i\,(1+i)^N]/[(1+i)^N - 1]\right\} + M_b\,(365 \times 24)\right)/(365 \times 24) \tag{8}$$

The cost per crane hour R in Equation 3 is similarly derived from the initial and operating costs of individual cranes, although the economic lifetime of cranes is usually shorter than that of berths.

The required container capacity of the storage yard (z in Equation 4) is the product of ship arrival rate λ, containers exchanged per ship x, average yard dwell time d, and a safety factor d_s:

$$z = \lambda x d d_s \tag{9}$$

The safety factor d_s provides sufficient yard capacity for larger than average λ, x, and/or d. Alternatively, for a given yard capacity z, the maximum allowable average dwell time d_{max} is obtained by letting d_s = 1.0 and dividing Equation 9 by λx:

$$d_{max} = z/\lambda x \tag{10}$$

The maximum λ or x allowed by the yard storage capacity can be similarly determined from Equation 9.

Transfer (i.e., loading and unloading) time of a ship depends on the number of containers x exchanged per ship at that terminal; the container handling rate y, which is also called the crane cycle time; and the number of cranes n servicing the ship. If the cranes could operate without mutual interference and if the work load were equally distributed among the n cranes, the transfer time would be

$$t = xy/n \tag{11}$$

However, because interference may occur, especially truck movements under the cranes, and because the containers are unlikely to be evenly distributed in the ship, the following function is used in this model:

$$t = xy/n^f \tag{12}$$

in which the exponent F may be less than 1.0. A typical f value of 0.85 means that 2 cranes can do $2^{.85}$ = 1.8 times the work of one crane, three cranes can do $3^{.85}$ = 2.54 times the work of one crane, and so on. Although the interference function may not be precisely known for large values of n, its possible implications can be examined through parametric analysis. An f value of 1.0 in Equation 12 is equivalent to assuming no interference and reverting to Equation 11.

The labor cost C_ℓ (Equation 5) is determined either by the service time t or the minimum shift duration ℓ_{min}, which is typically 4 hours. Hence the labor time ℓ (in hours per ship) is expressed as

$$\ell = \text{Max}\,(t, \ell_{min}) \tag{13}$$

In Equation 5 ℓ is multiplied by the number of crane gangs per ship n, which is equal to the number of cranes per ship; by the cost per gang hour L; and by the ship arrival rate λ to obtain the total labor cost per hour C_ℓ.

The total service time μ includes the container transfer time to as well as the maneuvering (i.e., docking and undocking) time m, during which the berth is inaccessible to other ships. The service rate μ is therefore

$$\mu = 1/(t + m) \tag{14}$$

The average time that a ship spends in port is the sum of the service time $1/\mu$ and the queue wait time w. Queue wait time depends on arrival and service rates, on the number of berths, and on the distributions of arrival rates and service times. Simple functions for the queue wait time are available for any service time distributions (including arbitrary distributions the standard deviation of which is known) for single-server cases (10). For multiserver cases, a simple wait time function is available for exponential service times only (10), but several studies (4-6) confirm that exponential service times are applicable. Those studies also verify the applicability of Poisson arrival times. In the single-berth case analyzed here, Poisson arrivals and exponential service times mean that the queue wait time is

$$w = [1/(\mu - \lambda)] - 1/\mu \tag{15}$$

and that the average time in port is

$$s = w + 1/\mu = 1/(\mu - \lambda) \tag{16}$$

Port time s is a factor in ship costs (Equation 6) as well as shipper costs (Equation 7). For each hour in port, a ship incurs depreciation, crew, auxiliary power, insurance, and other costs, totaling S \$/hr, which is multiplied by the time in port s to obtain the cost per ship. That in turn is multiplied by the hourly ship arrival rate λ to obtain the hourly cost C_s for all ships idling in port (Equation 6).

Similarly, to obtain the time cost C_u for all containers on board ships (Equation 7), multiply p, the average number of containers on board each ship (not the number exchanged) by the hourly cost (i.e., value of time) of containers U, the port time per ship s, and the ship arrival rate λ. The hourly cost of containers is a weighted average of the capital recovery factors (Equation 8) for all cargoes and containers, including empty containers. A weighted average accounts for widely differing values for different types of cargo and for the relatively high time value of cargoes with short economic lifetimes (e.g., perishables and rapidly obsolescing items).

The foregoing formulation provides a cost model more comprehensive than those of Plumlee (4), Nicolau (5), and Wanhill (6). It would be desirable to model and optimize the storage element in more detail because a reduction in container dwell time would reduce (a) the size and cost of the storage yard, (b) the time cost (depreciation and interest) for stored containers, and (c) the average length of movements within the yard.

It should be noted that the model is simple enough that the cost for any combination of input variables can easily be computed with a nonprogrammable calculator. A personal computer can be, and has been, programmed to run the model.

PARAMETER VALUES

The baseline analysis used the parameter values given in Table 1. These values are based on information obtained from trade publications and port plans, discussions with port officials, and Maritime Administration data on ship costs. In very few cases (e.g., for the lifetimes of cargoes in containers) there was no reliable data and estimates were used. Although the baseline parameter values are typical, their precision is not critical in this paper because the basic conclusions hold for a wide range of values. For specific applications, model users should, of course, input the best available values and use sensitivity analysis to check how changes in parameter values affect their decisions.

The baseline values (Table 1) for the berth costs (B = \$350/hr) assume the initial berth cost is \$28 million, the interest rate is 12 percent, the economic life is 40 years, and the annual maintenance cost is about 10 percent of the initial cost. The same values, except for an initial cost of \$200,000 per acre, are used to obtain an initial cost of \$12 million and hourly cost of \$150 for a 60-acre storage yard. At 12 percent interest, lifetimes beyond 30 years have very little additional effect on hourly costs. However, the hourly costs of containers and cargoes are sensitive to the shorter assumed weighted average lifetimes of 7 and 3 years, respectively. Containers are assumed to cost \$5,000 initially, and the average cargo value is assumed to be \$30,000 per container.

RESULTS

The model presented here was used mainly to examine the effects of the number of cranes n, ship arrival rate λ, and various exogenous parameters on total system costs. Four cases were defined using the following assumptions.

A--No interference among cranes and no minimum labor shift,
B--No interference among cranes and a 4-hr minimum shift,
C--Mutual interference among cranes and no minimum labor shift, and
D--Mutual interference among cranes and a 4-hr minimum shift.

These cases represent assumptions that range from quite ideal (A) to quite realistic (D). Case D offers the most useful baseline for practical results under currently prevailing conditions. Using the baseline parameter values from Table 1, Figure 1 shows how the total system cost C varies with the number of cranes n in the four cases A, B, C, and D, and also in case D' that has a more extreme interference parameter ($f = 0.7$ instead of 0.85 in cases C and D, and 1.00 in cases A and B). The optimal (i.e., minimum total cost) number of cranes n is circled on the cost curves. As should be expected, case A has the lowest cost at any number of cranes n. It is notable that, without 4-hr minimum shifts in cases A and C, the costs are lowered by using more cranes during shorter transfer times. In cases B and D, with 4-hr minimum shifts, it is not cost-effective to seek transfer times below 4 hr, and the optimal number of cranes is whatever will bring the transfer time t (Equation 12) close to 4 hr. As the minimum shift duration decreases, the optimal number of cranes increases and total cost decreases.

As expected, with mutual interference among cranes in cases C and D, costs are higher than in the corresponding cases A and B without interference. Cases B, D, and D' show the increase in costs as the interference exponent f goes from 1.0 (i.e., no interference) to 0.70 in D'. The increase in interference increases the optimal number of cranes n* only enough to bring the transfer time down to about 4 hr, which is the minimum shift in cases B, D, and D'. (All parameters other than f are also equal in those three cases.)

Figures 2 and 3 show the effect of the number of cranes on the relative magnitude of the various cost components and the composition of the total cost in case D. In Figure 2 ship cost C_s and container user cost C_u decrease sharply as additional cranes reduce the transfer time in port. The crane cost C_r increases proportionally with n. The labor cost C_L also increases proportionally with the number of cranes when many cranes are used because each crane's labor gang is paid for 4 hr even though the transfer time decreases with n. At small values of n (1 and 2 cranes) the labor cost does not decrease proportionally with n because the small number of cranes requires shifts longer than 4 hr. The berth cost C_b and storage yard cost C_y do not vary at all with the number of cranes used.

Figures 4 and 5 show for cases A and D, respectively, the sensitivity of the total costs C and of the optimal number of cranes n* to a 50 percent increase in various parameters. Of interest here are the cost parameters for berths B, cranes R, ships S, containers and their cargo U, labor L, the average ship payload p, and the exchange volume x. As each of these parameters is increased by 50 percent, the total costs increase and the optimal number of cranes n* changes in the expected direction. Specifically, n* tends to increase as the ship cost S, container cost U, ship payload p, and exchange volume x increase; and n* tends to decrease as crane

TABLE 1 Variables

Symbol	Definition	Baseline Value
a	Number of acres of storage yard per container	0.0177
b	Number of berths in terminal	1
B	Hourly berth cost ($)	350
B_i	Initial berth cost ($)	28,000,000
C	Total system cost ($/hr)	
$\overline{C}$	Average system cost ($/ship served)	
C_b	Berth cost ($/hr)	
C_ℓ	Dock labor cost ($/hr)	
C_r	Cost of cranes ($/hr)	
C_s	Cost of ships in port ($/hr)	
C_u	Cost of containers and cargo	
C_y	Cost of storage yards ($/hr)	
d	Average yard dwell time (hr/container)	
d_{max}	Allowable yard dwell time (hr/container)	
d_s	Dwell margin	
f	Crane interference exponent	0.85
i	Interest rate	0.12
ℓ	Paid labor time (hr/gang/ship)	
ℓ_{min}	Minimum shift duration (hr)	4
L	Labor cost ($/gang hour)	600
m	Maneuver (docking and undocking) time (hr/ship)	1.0
M_b	Annual maintenance cost per berth	2,800,000
n	Number of cranes per berth	
n*	Optimal number of cranes per berth	
N	Economic lifetime (yr)	
P	Average payload (containers/ship)	600
R	Crane cost ($/crane hr)	42
s	Average time in port (hr/ship)	
S	Ship cost in port ($/ship hr)	700
t	Container transfer time (hr/ship)	
U	Average cost of container and its contents ($/container hr)	1.50
w	Average queueing time (hr/ship)	
x	Exchange volume (containers transferred/ship)	180
y	Crane cycle time (hr/container)	0.045
Y	Storage yard cost ($/acre hr)	2.5
z	Number of container slots per berth	
λ	Arrival rate (ships/hr)	0.1
μ	Service rate (ships/hr)	

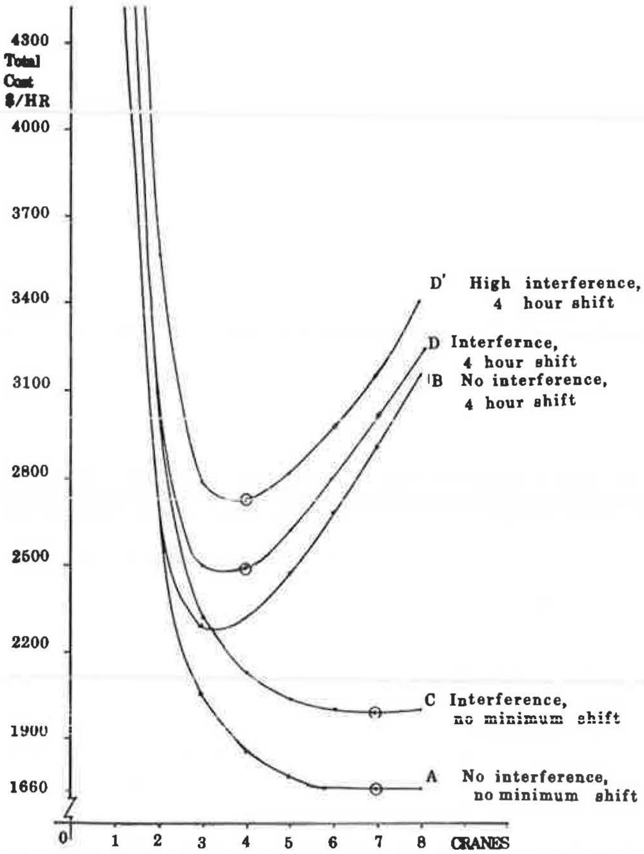

FIGURE 1 Total costs for various assumptions and numbers of cranes.

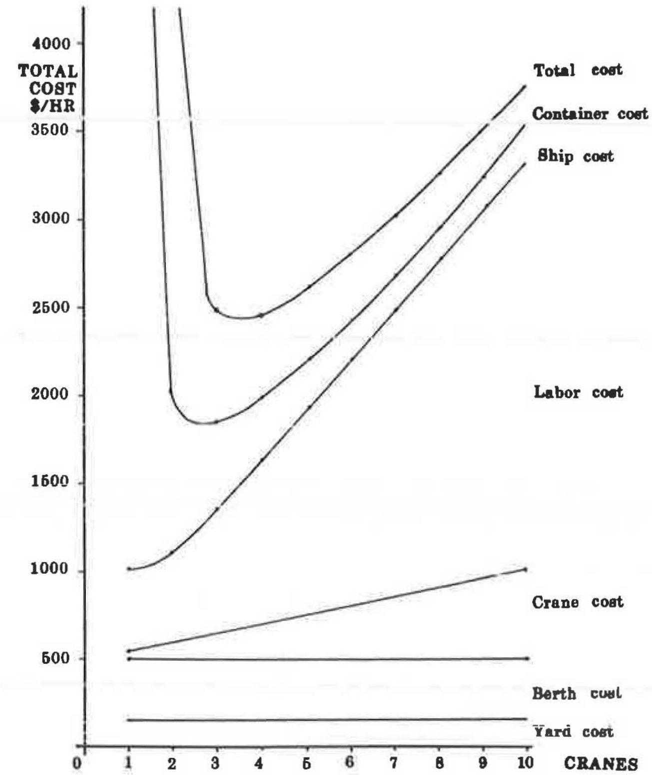

FIGURE 3 Composition of total costs: case D.

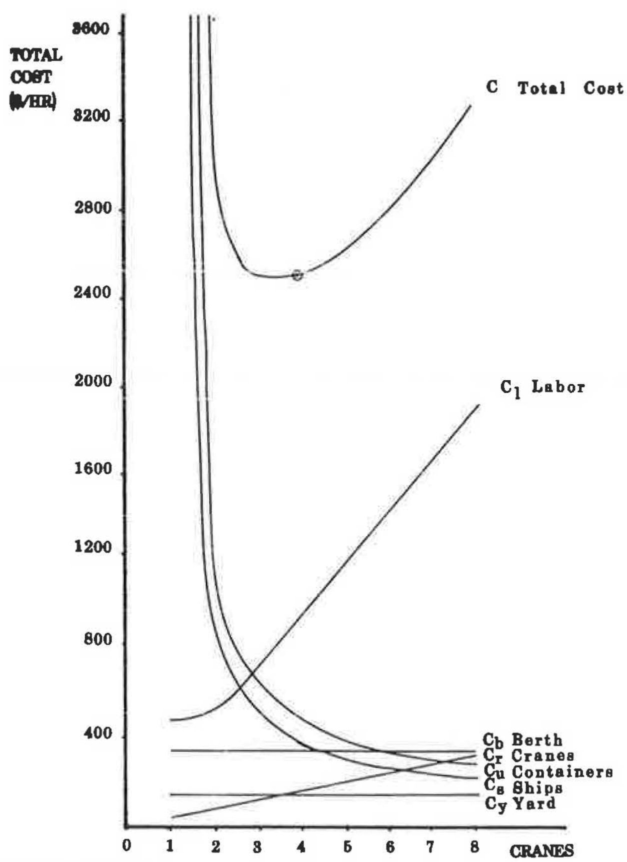

FIGURE 2 Variation of cost components with number of cranes: case D.

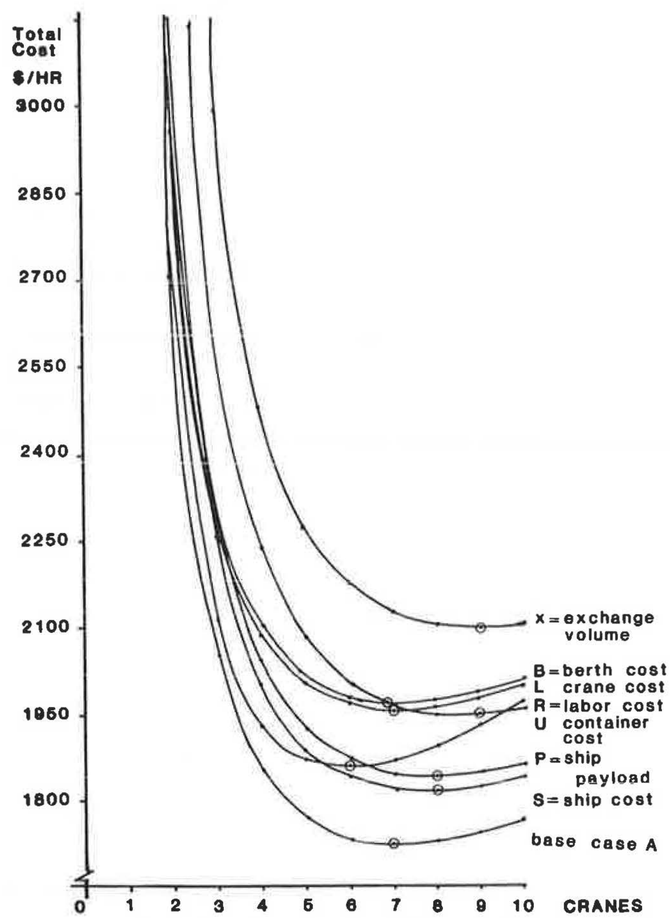

FIGURE 4 Sensitivity of total costs to a 50 percent increase in major parameters: case A.

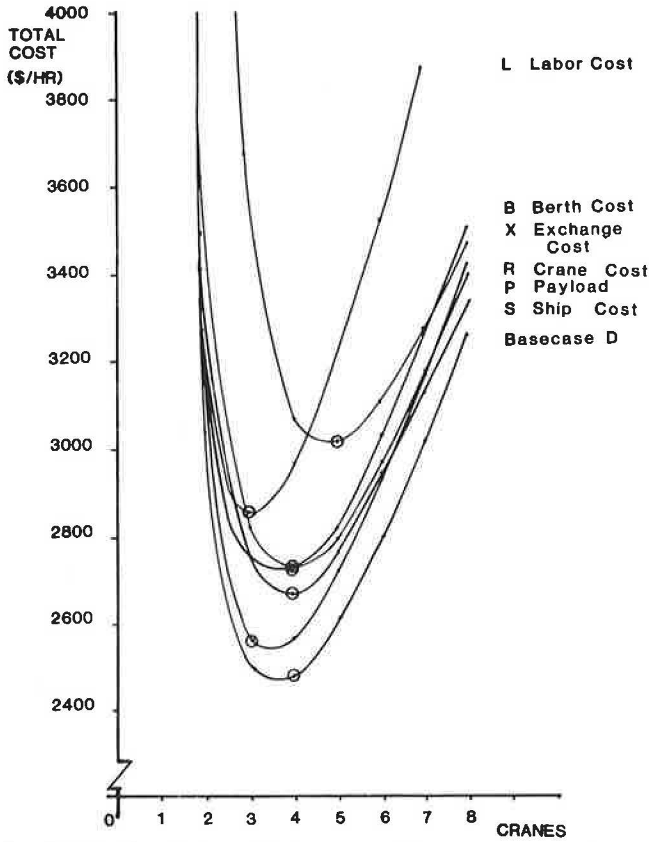

FIGURE 5 Sensitivity of total costs to a 50 percent increase in major parameters: case D.

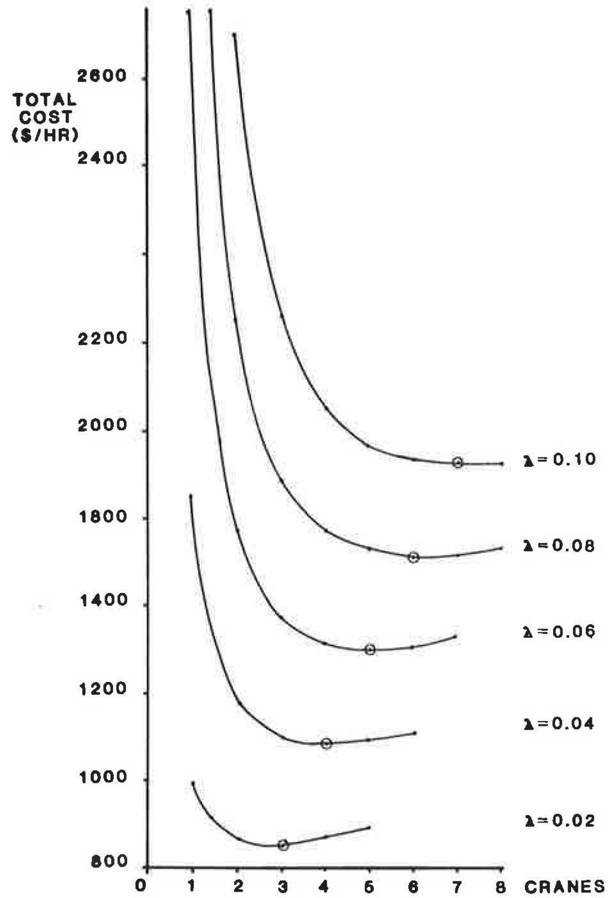

FIGURE 6 Total costs for various ship arrival rates: case A.

cost R and labor cost L increase. An increase in berth cost B (and/or yard cost Y) simply shifts the whole curve upward without shifting the optimal number of cranes n* at its minimum point (Figure 2).

Figures 6-9 show the effects of ship arrival rate λ on the optimal number of cranes n*, on total costs (Figures 6 and 8), and on the average cost per ship served $\bar{C}$ (Figures 7 and 9). The average cost is the total cost C divided by the arrival rate λ:

$$\bar{C} = C/\lambda \tag{17}$$

Although total costs (Figures 6 and 8) always increase with λ, the average cost (i.e., the total system cost per served ship) decreases with λ up to higher values of λ than are encountered in current port practice. Thus in case D (Figure 9) the cost per ship $\bar{C}$ continues to decrease up to arrival rates of approximately 0.1 ship per hour (= 2.4 ships per day = 72 ships per month). The most cost-effective arrival rate per berth would be even higher in multiple-berth terminals.

The assumption of exponential service times may also exaggerate somewhat the queueing delays and lead to a slight underestimate of the optimal ships to berth ratio. Figures 6 through 9 also show, as expected, that the optimal number of cranes n* increases as the arrival rate increases. For the realistic case D, the optimal combination, in terms of total system cost per ship served, is approximately 0.1 ship per hour (16.8 ships per week) and 4 cranes at the one-berth terminal. This represents more intensive berth use than the four ships per week limit suggested by Boyer (9) and involves more cranes per berth than are currently provided at most

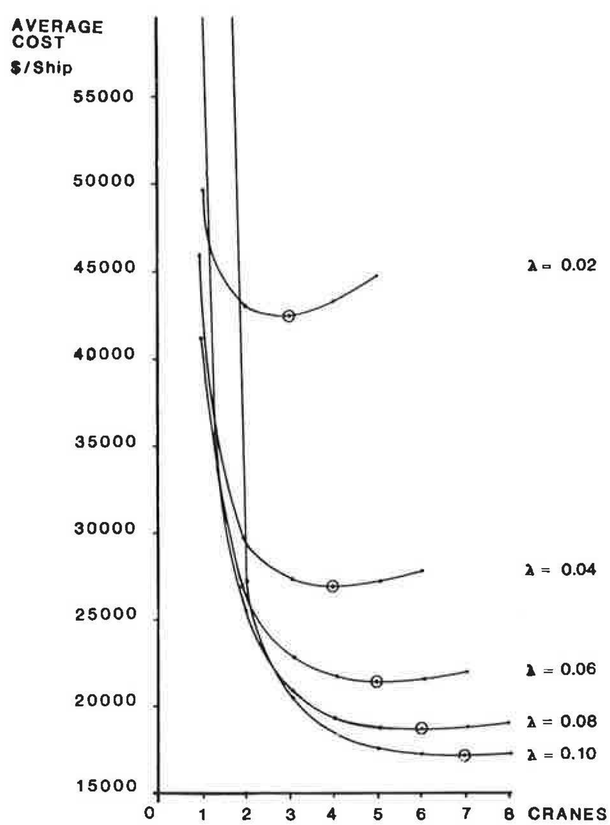

FIGURE 7 Average costs for various ship arrival rates: case A.

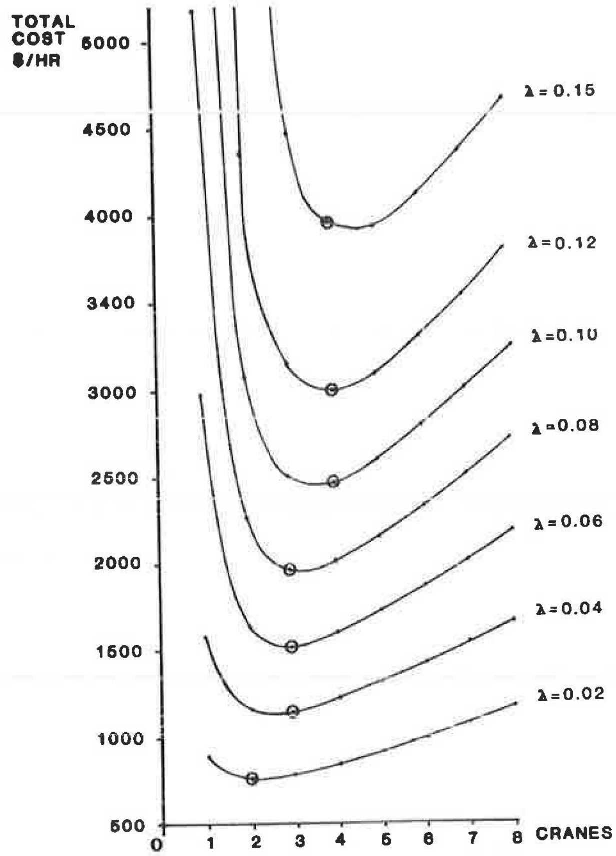

FIGURE 8 Total costs for various ship arrival rates: case D.

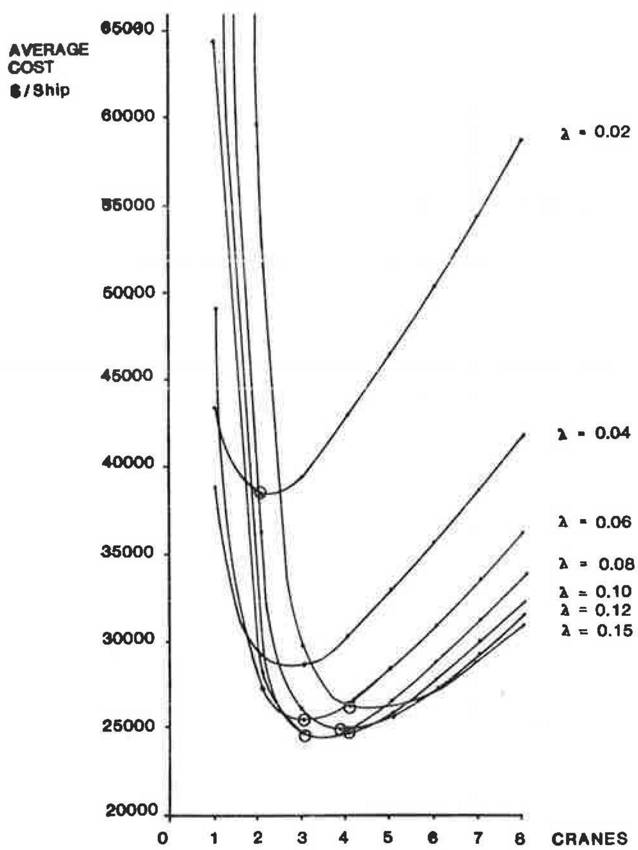

FIGURE 9 Average costs for various ship arrival rates: case D.

terminals. The assumption that container transfer operations can proceed 24 hours per day 365 days per year is implicit in the results obtained from Boyer's guidelines (9), and much current practice would appear more reasonable if that assumption were truly unrealistic.

CONCLUSIONS

The results presented here indicate that the total system cost per ship (or per container, or per ton) served could be decreased by increasing the number of cranes per berth and berth use (e.g., by building fewer berths for a given ship arrival rate) considerably beyond present levels. These results are especially sensitive to institutional factors such as the minimum duration of labor shifts and the possibility of working around the clock. The effects of other parameters on the optimal number of cranes, optimal berth use, and system costs can also be analyzed with the model developed here.

With appropriate modifications, this model could also be used to examine multiple-berth terminals with variable-length berths, improved crane interference functions and service time distributions, storage yard operation, and the possibility of having labor gangs work on more than one ship per shift.

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