QUAY LENGTH OPTIMIZATION USING INVENTORY AND STOCHASTIC KNAPSACK MODELS

by

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ABSTRACT

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Within this study, it is aimed to develop a method to determine the optimal quay length. Since one of the most significant drawbacks of the maritime transportation is the delays encountered in ports where loading and unloading takes place, an optimal quay length possesses great importance to reduce the handling time in an efficient manner. Besides, the larger is the capacity of a port, the higher is the number of ships served and the revenue obtained. Another important issue is that it is very important to avoid unnecessary investment and to reduce the capital cost. Hence, the determination of optimum capacity of a port becomes a very important issue especially during the port planning and design stage. Our goal in this work is to try to solve this problem by working on a particular subject: Optimum quay length determination. For this purpose, we first propose the use of inventory based models. These are static models and disregard the dynamic nature of the ship arrivals and departures. We therefore extended them to also handle this aspect, through dynamic programming. However, these models are also restrictive since they do not consider the stochasticity of ship arrivals. Finally, we propose a method based on the stochastic knapsack model to determine the optimum length of a single quay. For the validation of the model, real data from the ports all over the world are used. The model can also be used to determine approximately the situations, where there are more than one quay in parallel. Finally, the model is generalized into a scheme so that the optimal quay length can be obtained by just knowing the daily number of ships, average length of ships arriving, and the average handling rate per day.

ÖZET

STOKASTİK KNAPSACK VE ENVANTER MODELLERİ İLE İSKELE UZUNLUĞU ENİYİLEMESİ

Bu çalışma ile, optimum iskele uzunluğunu tayin etmeye yönelik bir metod bulunması amaçlanmıştır. Deniz taşımacılığındaki en büyük handikaplardan biri yükleme ve boşaltma işlemlerinin gerçekleştiği yerler olan limanlardaki gecikmeler olduğundan, optimum bir iskele uzunluğu elleçleme zamanını azaltmak açısından büyük önem taşımaktadır. Ayrıca, bir liman için daha çok kapasite demek daha çok gemiye hizmet edilmesi ve daha fazla gelir elde edilmesi anlamına gelmektedir. Bir başka önemli konu ise, gereksiz yatırımlardan kaçınılması ve sermaye maliyetinin azaltılmasıdır. Dolayısıyla, özellikle planlama ve dizayn aşamasında bir limanın optimum uzunluğunun tespiti büyük önem taşımaktadır. Bu çalışmadaki amacımız, optimum iskele uzunluğunun tespiti üzerinde çalışarak, bu genel problemin çözümüne katkıda bulunmaktır. Bu amaçla, ilk olarak envanter tabanlı çalışmalar yapılmıştır. Bunlar statik modeller olup, gemi geliş ve gidişlerinin dinamik doğasını yansıtmamaktadırlar. Bu nedenle, modeller dinamik programlama teknikleri kullanılarak bu doğrultuda geliştirilmiştir. Ancak, bu modeller de gemi gelişlerinin stokastik özelliklerini yansıtmadıklarından çok sınırlı kalmaktadırlar. Son olarak, tek bir iskelenin uzunluğunu optimize etmek için stokastik knapsack tabanlı bir metod önerilmektedir. Modeli doğrulayabilmek için tüm dünya çapındaki limanlardan elde edilen veriler kullanılmıştır. Oluşturulan bu son model, birden fazla paralel iskelenin bulunduğu durumları yaklaşık olarak yansıtmak üzere kullanılabilir.

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a_i	offered load of type i customer
A	arrived ship length
b	random amount of requirement at an arrival
b_i	customer demand/ship length
B	knapsack volume/resource
c	unit cost
c_h	holding cost per unit length
C	reservoir capacity
$c(y)$	expected cost/production cost
$Cost_{in}$	total cost before the decision
$Cost_{out}$	total cost after the decision
c_h/c_o	unit holding/overage cost
c_p/c_u	unit underage cost
D	unit continuous demand/departed ship length
$f_t(x)$	expected contribution function
i	customer type/annual interest rate
j	total number of resource units occupied
L/L_{empty}	unoccupied length of ships
L_{in}	empty length before the decision
L_{out}	empty length after the decision
n	total number of periods
N	total number of periods/number of classes, ships or customers
p	unit sales price/revenue/opportunity cost per unit length
p_1	construction cost per unit length
p_2	cost of punishment per unit length
P	unloading rate
q	order quantity/quay length
q_i	occurrence probability of each customer
q_j	occurred length distribution of j

Q	inventory quantity at disposal/quay length
Q_{in}	quay length before the decision
Q_{out}	quay length after the decision
t	period number
T	period duration/length
u	additional quay length
u_k	order
$v(y)$	expected contribution
V	velocity/dicharge rate
w_k	demand
x	stock level before ordering
x_i	number of type i customers
y	stock level after ordering
α	one period discount factor/quay angle/confidence level for Chi-square test
β_i	blocking probability for each class
λ	poisson distribution parameter
μ	sample mean of daily ship data
μ_i	sojourn time parameter
Ω	sharing policy
ϕ	probability density function of demand
Φ	cumulative distribution function of demand
π	mean of normal distribution
σ	standard deviation of normal distribution/sample standard deviation of daily ship data
τ_i	mean residency of type i customers
$\varkappa$	Chi-square value
TEU	twenty-foot equivalent unit

1. INTRODUCTION

On account of increasing global trade, the ports working efficiently and optimally have gained great importance in order to reduce the days of handling and gain more revenue. Actually, 71% of all freight shipped globally is made by maritime transportation, a figure similar to the share of the world's surface covered by oceans. In terms of weight, about 96% of the world trade is carried in terms of maritime shipping. Furthermore, the main advantage of maritime transportation is obviously its economies of scale, making it the cheapest per unit of all transport modes and, in some situations, it becomes the only means of transportation. Therefore, there is a real demand on maritime transportation in the world, and hence the port efficiency and capacity become crucial issues. As the ports gain revenue while they are serving ships, the major issue for the capacity of a port should be satisfying the ship demand, that is, basically, the more the capacity is, the more the ships served. If any ship is not served due to the lack of available space, then the revenue from that ship cannot be achieved. If the ship leaves, or there is a loss of time and money since the ship waits until there is sufficient space for berthing. Actually, these port efficiency and capacity issues mostly depend on the effectiveness of certain key elements, specifically the length of quays the port consists of, the yard space for loading, unloading and storage, and the quay crane usage if the quay is a part of a container terminal. One can easily guess that the most significant element is the quay length, as the critical point is the available space for the ships to be served. Therefore, if the lengths are sufficient enough to serve the ships effectively, then a port, consisting of several different quays, can be considered as working in an optimal fashion. Here, a quay is defined as a *"type of wharf or pier, parallel to the shoreline, accommodating ships only one side".*

As a result, following immediate questions arise: *"How much does the quay length effect the efficiency of a terminal?", "Is there sufficient quay length to optimally operate a given volume?"* More specifically, as the purpose is always to make an optimal utilization of the quay, it is logical to have an intention of chasing the optimal quay lengths in a port for the given daily ship arrival and length data. To illustrate, for a container terminal, the number of container units per meter of a quay is considered as a commonly good measure, therefore the quay length and productivity of the use of the quay length can be viewed as the main determinants of the capacity. The revenues in the ports are actually earned from the movements across the quay, and the length of the quay, if chosen optimally, will definitely make a positive impact on the revenues. Moreover, there are two main time dependent issues to be considered for the revenue and cost structures. The former one is the waiting time of the ship for enough space, and the latter is the berthing time, which is the time a ship spends during loading and unloading. The ship that has arrived to a port can wait for hours or days if sufficient place is not available at the quay. This directly leads to a loss of time, where time means money in the transportation industry. The ship that has lost time could have been loaded for another cargo and have gone to another port to unload that cargo at the mean time, indicating a loss of money. On the other hand, if the discharging is performed in a relatively slow manner at a port, this will also cause a loss of time and money since the ship is supposed to wait more and a new ship waiting for berthing can not enter the quay. As one can easily guess, the quay length design is one of the best remedies for these time dependent problems.

Moreover, during the design and planning stage, port planner has to avoid unnecessary investments and reduce the capital cost. Hence, the determination of optimum capacity of a port becomes a very important issue. This study basically aims to find a tool for the port planner so that he can determine an accurate quay length value at the construction stage.

Besides achieving the optimal value necessary for the construction of the port, the correct and logical forecasting should also be desired and therefore, the expansion potential of the port region should be carefully examined. That is, experiencing several challenging years may enforce the port to meet the needs of many new customers, and the port can be insufficient at that point. Hence, it is crucial to consider the future improvement of the port at the very beginning of the construction and act according to this consideration. Moreover, at the point of insufficiency, some further investments may be performed to serve the ships, which arises another important question, which is *"How much to expand an existing quay?"*

With this research, several models are developed to find out optimal and satisfactory solutions to the questions above. Moreover, an efficient analytical and logical way of attaining the optimal quay length for a port is pursued throughout the work regarding the similarities between the quay length and inventory optimization strategies. In this manner, several assumptions about the cost and the gain (revenue) structures, interarrival and waiting times of the ships are made to obtain an acceptable initial model. First, a recursive deterministic dynamic programming approach is used to find out if the quay length asymptotically reaches an optimum value throughout the periods. All possible conditions of accepting and rejecting the ship regarding the quay length are checked in this model. Finally, a stochastic knapsack approach mainly used in electronics and telecommunication industry is adapted to our case. The model is based on the fact that ships arrive according to a Poisson process, and leave the quay as soon as their load is discharged. The significant issue is the operation of the quay throughout its entire life, which gives us an opportunity to turn the annual revenues and operating costs into their present values easily where they can be compared with the construction cost of the quay. With this approach, profits are obtained for different quay lengths, and the quay length with the best profit is chosen as the optimum one. Besides, blocking probability issue is introduced into the system as a constraint to find out the percentage of ships rejected at the optimum quay length. By this means, it is possible to obtain the optimal quay length with which most of the ships arriving to the port can be accepted at the selected confidence level.

2. LITERATURE REVIEW

As the first model formulation is mainly based on the resemblance between the inventory theory and the quay length utilization in the maritime industry, it is necessary to review the literature related to both different areas of interest. Actually, there are very few studies on the area of quay length optimization, and most studies in the maritime industry are related with simulation types of research, indeed. To be able to represent the cost and revenue structures in the stochastic model, it is also necessary to review the literature including the cost and revenue issues for ports and terminals in the next chapters.

2.1. Quay Length Utilization in the Maritime Industry

To begin with, the research in the shipping industry mostly aims an optimal design of the overall system, e.g. the port itself with the incentives of the cost minimization. Therefore, the majority of the works performed in this area is related with simulation, capacity planning and scheduling-queuing decision models.

Simulation is a technique to describe the behaviour of the system under study. Hence, it can be easily used for port design, capacity planning and productivity issues. The basic method used is to form a simulation model measuring the port performance where the simulator basically gets input data about the port, runs the simulation and provides the statistical output data. The importance of an efficient measurement of port performance is shown by Fourgeaud [1], where the main idea is to carefully identify the problem and to take into account the main characteristics of the commercial activity so that the benchmarks that can be applicable for any port are determined. Besides, the researchers have developed a variety of simulation models for different ports. Henesey, Davidsson, and Person have conducted simulation models in order to evaluate berth allocation at a container terminal [2]. Here, a berth can be defined as *"a place on the quay where a ship anchors"*. This research is very important due to the fact that two simulation models are attained with various quay lengths, berth spacing length, and ship arrival sequences. The main objective in this research is to evaluate which model will give the best policy under various conditions, and the results are given according to different quay length values suggesting the length interval for the related policy.

Other interesting simulation models performed are by Ottjes, Hengst, and Tutuarima [3] for the Port of Rotterdam; Demirci [4] for the Trabzon Port; Veenstra and Long [5] for the Port of Rotterdam; Nom, Kwak, and Yu [6] for the Gamman Container Terminal in Pusan, Korea among many other researches. The basic idea in each of these studies is to create a structure and operation policy so that the expected utilization of the port is maximized.

Jagerman and Altıok [7], on the other hand, deal with the vessel arrival process and the queuing behaviour at the ports. The vessel arrival pattern is another critical component in port performance which is usually measured by how long each ship spends at the port. Regarding this fact, an approximation for the probabilities of delay and the number of vessels at the port is given by this research.

Das and Sapasoviç [8] present a scheduling procedure that can be used by a terminal scheduler to control the movement of material handling vehicles in a container port. This is achieved by driving an assignment algorithm to minimize the delays in material handling and performing a simulation model regarding this algorithm.

Unfortunately, these works are not very much related to obtaining the optimal quay length. However, they rather have a larger point of view in which the quay length is also considered as a significant element. Fernhout [9], on the other hand, has written a program with which one can get an insight about the effect of the quay length for the efficiency of a port. This program offers the users a tool to study the influence of the changes caused by certain variables, including the quay length, on the waiting times of the ships. As a matter of fact, the program is specifically used for quay modelling.

2.2. Inventory Theory

Among many inventory models, the newsboy model (also called the newsvendor model) seems to be very useful and can be used as a starting point for the quay length optimization. The name of the model derives from a newsboy who must purchase newspapers at the beginning of the day before attempting to sell them at a designated corner. That is, an unknown quantity D for the newspapers will be demanded (purchased) during a day (a single period). The decision to make for the newsboy is how many newspapers to order first. Thus, the main objective in this model is trying to obtain the optimal order, y. The decision variable y actually represents the stock level after ordering. The problem arises if the demand D is smaller and bigger than the order, y. If the newsboy can not sell some of the newspapers ($D < y$), he will lose money. On the other hand, if he sells all the newspapers he has, and if there are still people asking for newspapers ($D > y$), he will lose the opportunity of earning more money from $D - y$ amounts sold. Besides, the objective function $v(y)$ is simply the expected contribution. The basic model (2.1) is given by Portheus [10] as,

$$v(y) = E[p \min(D, y) - cy] = \int_0^y (1 - \Phi(\varepsilon))d\varepsilon - cy \tag{2.1}$$

Here, p represents the unit sales price whereas c is the unit cost. Basically, c satisfies the inequality $0 < c < p$. On the other hand, Φ and ϕ are the cumulative distribution function and probability density function of demand, respectively. Actually, this model is formed with a single period basis and the optimal solution is

$$\Phi(y^*) = \frac{p - c}{p}, \tag{2.2}$$

which means that if $p = 2c$, it is optimal to stock the median demand basically.

More generally, Portheus defines $c_o(c_h)$ as the unit overage (holding) cost where $D \leq y$ and $c_u(c_p)$ as the unit underage (shortage) cost where $D \geq y$. Using these parameters, he shows that the expected cost can be written according to

$$c(y) = c_0(y - D)^+ + c_u(D - y)^+ \tag{2.3}$$

Here, the optimal solution gives

$$\Phi(y^*) = \frac{c_u}{c_u + c_o}.$$

Taha states a dynamic version of the newsvendor problem in which the system will be operated over N periods [11]. In this case, the cost function is the addition of three elements, namely the expected cost of raising the inventory level from x to y, c, the expected holding cost, c_p and shortage cost, c_h, and the expected present value of starting period $t + 1$ in state $y - D$. The revenue per unit produced is abbreviated as p. Using these ideas and the one period discount factor, $\alpha\epsilon(0, 1]$, the expected contribution function becomes

$$\begin{aligned} f_t(x) = \max\nolimits_{y \geq x} -c(y - x) + \int_0^y \left[p\varepsilon - c_h(y - \varepsilon)\right] \phi(\varepsilon) d\varepsilon \\ + \int_y^\infty \left[py + \alpha p(\varepsilon - y) - c_p(\varepsilon - y)\right] \phi(\varepsilon) d\varepsilon \ + \alpha \int_0^\infty f_{t+1}(y - \varepsilon)\phi(\varepsilon) d\varepsilon \end{aligned} \tag{2.4}$$

This is a backwards recursion equation where $f_{t+1}(y_{_N} - \varepsilon) = 0$. The quantity $\alpha p(D-y)$ in the second integral is included because $(D-y)$ is the unfilled demand in period t that must be filled in period $t+1$. The optimal value of y can be determined from the following necessary condition (2.5), assuming $f_t(x)$ is concave.

$$\frac{\partial(\cdot)}{\partial(y)} = -c - c_h \int_0^y \phi(\varepsilon)d\varepsilon + \int_y^\infty \left[(1-\alpha)p + c_p\right]\phi(\varepsilon)d\varepsilon + \alpha \int_0^y \frac{\partial f_{t+1}(y-\varepsilon)}{\partial(y)}\phi(\varepsilon)d\varepsilon \quad (2.5)$$

The value

$$\frac{\partial f_{t+1}(y-\varepsilon)}{\partial(y)}$$

can be easily determined to be c, and the optimal solution can be found using the equation

$$\int_0^{y^*} \phi(\varepsilon)d\varepsilon = \frac{c_p + (1-\alpha)(p-c)}{c_p + c_h + (1-\alpha)p} \quad (2.6)$$

The optimal inventory policy for each period given by its entering inventory level x is thus given as

$$\begin{aligned} &If\ x < y^*, \quad order\ y^* - x \\ &If\ x \geq y^*, \quad do\ not\ order \end{aligned}$$

A similar approach is proposed by Bertsekas for successive discrete demands [12]. Bertsekas gives the total expected cost to be minimized, regarding that x_{t+1} is the inventory level after the order, x_t is the inventory level before the order, u_t is the order, w_t is the demand, as,

$$f_t(x) = E\left\{\sum_{t=0}^{N-1}[cu_t + c_p \max(0, -x_{t+1}) + c_h \max(0, x_{t+1})\right\} \tag{2.7}$$

where,

$$x_{t+1} \quad = x_t + u_t - w_t. \qquad t = 0......N-1 \ .$$

A multi-stage stochastic inventory model is given by Chikan which indicates a typical (s,S) periodic review policy [13]. The periodic review policy can be explained as follows. If, at the end of a period, the inventory level is higher than a predetermined reorder level, s, you take no action. If it is less than or equal to that level, an order quantity, q, is placed. The policy is periodic because of the fact that there are specific control periods for the inventory level. If the duration of the control periods goes to zero, then it means a continuous control of the inventories. With this model, Chikan tries to find an answer to the questions, "How much to order?", and "What is the optimal reorder level?". The cost function is again as aforementioned. The expected value of the total cost regarding this approach is given in (2.8).

$$\begin{aligned} c(s,q) = c_h \int_{s}^{s+q}\int_{0}^{Q}(Q-\varepsilon)\phi(\varepsilon)h(Q)d\varepsilon dQ + c_p \int_{s}^{s+q}\int_{Q}^{\infty}\phi(\varepsilon)h(Q)d\varepsilon dQ \\ +c\int_{s}^{s+q}\int_{Q-s}^{\infty}\phi(\varepsilon)h(Q)d\varepsilon dQ \end{aligned} \tag{2.8}$$

Here, it is interesting to observe that the inventory quantity at the beginning of certain periods, Q, is a discrete stochastic variable which has a uniform distribution, and has the possible values of which are in the $(s, s+q)$ interval. The optimal parameters can not be expressed in explicit form due to the difficulty of calculating the partial derivatives; therefore an approximate method is used to find the optimal solution.

For multiple demand classes, the model proposed by Şen and Zhang indicates a solution following the pattern of multiple demand classes with non-increasing prices [14].

Another similar model deals with a simple water reservoir management problem [10]. In this case, a fixed capacity, C units of water and an end reservoir level, y units of water after an amount of water is to be released, are the basic parameters used. The level of water at the beginning of the next period is written as $z(y, D) = \min\{y + D, C\}$ which is independent of the initial water level, interestingly.

3. DETERMINISTIC DYNAMIC PROGRAMMING APPROACH

3.1. Model and Assumptions

This model is based on the following assumptions. First, throughout the analysis, the lengths of the ships arriving during the periods of the planning horizon is given. There is an handling rate, V, which is assumed to be constant. That is, the length of the ship discharged per unit time is assumed to be constant. Moreover, a length of the quay equal to the length of the last served ship becomes available after the waiting time of that ship at the quay. Specifically, the constant discharge rate directly determines the waiting time for a ship.

There are several costs and revenues incurred in the model. First, a net amount of price, p, excluding all the costs incurred during the process, is gained per unit length of the ship served. On the other hand, the operational cost of the quay depends on the unit cost per length, p_2. If the length of the ship arriving is larger than the available quay length, then an opportunity cost per unit length of the ship, p_2, is assumed to be incurred. This might be viewed as losing the opportunity of serving a ship if you had a longer quay. Besides, the construction cost of the quay is obtained as follows:

The area below the quay is calculated using the angle and quay length. Here, q represents the initial quay length at the beginning of the period whereas u is the additional quay length to be constructed. The unit construction cost, p_1, is assumed to be incurred due to quay construction and the quay angle is given as α, *alpha*. The area, which gives the construction cost appears to be

$$Construction\ Cost = p_1 * \tan(alpha) * u * (q + \frac{u}{2}) \tag{3.1}$$

The issue in this approach is to cover every possible instant of conditions in terms

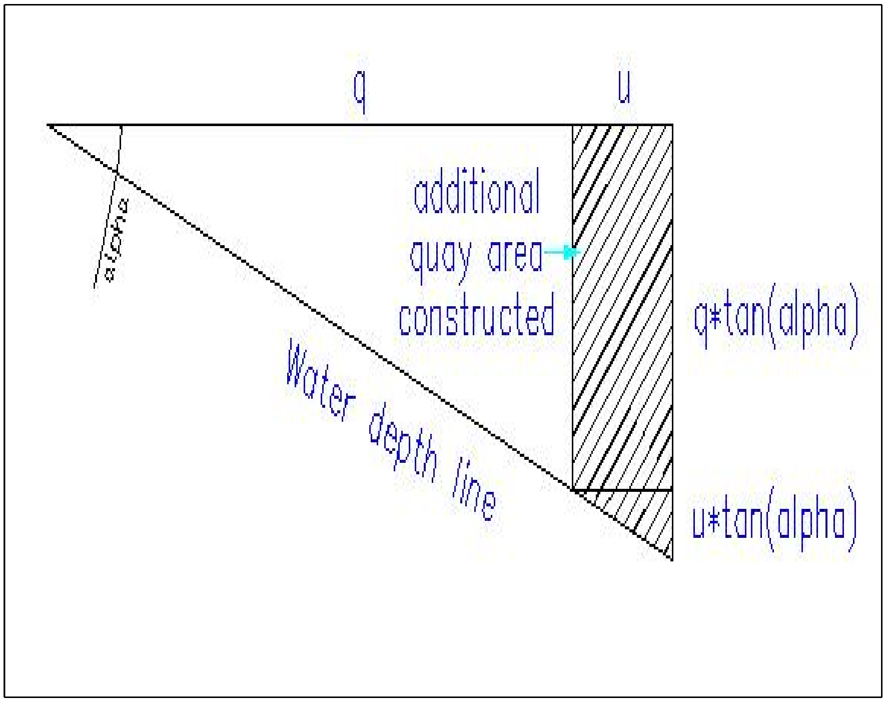

Figure 3.1. Quay Length Construction Scheme

of accepting and rejecting the ships throughout a selected amount of periods. That is, in each period, when a ship arrives to the quay, it is either accepted or rejected. If there are n periods, as there are two alternatives for a ship in each period, the total alternatives amount to 2^n. If the procedure is considered as a network, starting from one node, ending with 2^n nodes, it becomes easier to see the different ways of attaining the last period. In each way, there occurs a different cost and revenue, therefore, every possible instant is to be considered in the model giving the optimal condition. This is performed with the recursive feature of the model. The model calculates the cost for each feasible route, and finds the optimum one.

Given arrivals randomly generated, and using the constant discharge rate, the departures are obtained before the execution procedure. Assuming that in each period a specific amount of length is discharged, the number of periods that is required for a ship to leave the quay after loading its cargo is easily calculated.

L, the available quay length in each period is also very important for the sake of the model. The analysis starts executing with a zero initial value of quay length and unoccupied length. Basically, for a ship there are two choices. Rejection or acceptance. In each period, the quay length, Q and the unoccupied length, L is revised with the chosen alternative. If the ship is rejected, the quay length after the decision, Q_{out}, remains the same as before, Q_{in}. Besides, the unoccupied length after the decision, L_{out}, is basically revised according to both arrivals and departures. Regarding the rejection case, L_{out} is simply the sum of available quay length before the decision, L_{in}, and the departure in that period. If the ship is accepted, on the other hand, the quay length, Q_{out}, increases with that amount, and the occupied length change is done according to arrivals in period n, $A(n)$, and departures in period n, $D(n)$. The cost structure is revised as well.

That is, if a ship is accepted,

$$\begin{aligned} Q_{out} &= Q_{in} + A(n) \\ L_{out} &= L_{in} - A(n) + D(n) \\ Cost_{out} &= Cost_{in} + p_1 * \tan(angle) * (A(n) - D(n) - L_{in}) * (Q_{in} + \tfrac{(A(n)-D(n)-L_{in})}{2}) \\ &+ p_2 * (Q_{in} - L_{in} + A(n) - D(n)) - p * A(n) \end{aligned} \tag{3.2}$$

and if it is rejected,

$$\begin{aligned} Q_{out} &= Q_{in} \\ L_{out} &= L_{in} + D(n) \\ Cost_{out} &= Cost_{in} + p_2 * Q_{in} \end{aligned} \tag{3.3}$$

The total cost after the rejection, $Cost_{out}$, case can be calculated as the sum of the previous cost value, $Cost_{in}$, and the operational cost, p_2, multiplied by the quay length before the decision, Q_{in}. If the ship is accepted, the cost structure is somewhat more difficult to obtain. The cost of additional quay length construction and operational cost are added to the previous cost, $Cost_{in}$, and the revenue per ship, $pA(n)$, is subtracted from that amount. Here, u is obtained as $(A(n) - D(n) - L_{in})/2$.

In each period, the cost is obtained for both alternatives, and the resulting cost for each route is achieved at the last period. With a backward recursion, it is possible to find the optimal path for the least cost alternative. With this optimal path, the structural behaviour is that the quay length tries to reach an optimal value asymptotically. That is, up to a point, the quay length increases as it is mostly optimal to choose the accepting alternative, and after that point, it becomes no longer logical to accept the ship finding an optimum quay length value.

3.2. Numerical Example

The model is executed with $p_1 = 2$; $p_2 = 1$ and $p = 20$. The velocity parameter is changed to see the behaviour given a fixed arrival vector. For the 20 periods considered, the arrival vector chosen randomly is

Table 3.1. Arrivals

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Arrival	285	69	182	146	268	229	137	5	247	133
Period	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Arrival	185	238	277	222	53	122	281	275	123	268

When the velocity is equal to 50, the behaviour occurs as in Figure 3.2.

Here, 20 periods are considered, and throughout these periods, the model finds the optimal path in terms of acceptance and rejection. At the end, the quay length with the least cost happened to be 146. Moreover, the optimum path appeared to be [0 1 0 1 0 0 1 1 0 1 0 0 0 0 0 1 0 0 1 0] . The values of 1 indicate the accepted ships whereas 0 means rejection. The resultant vectors with a velocity of 50 is obtained as in Table 3.2.

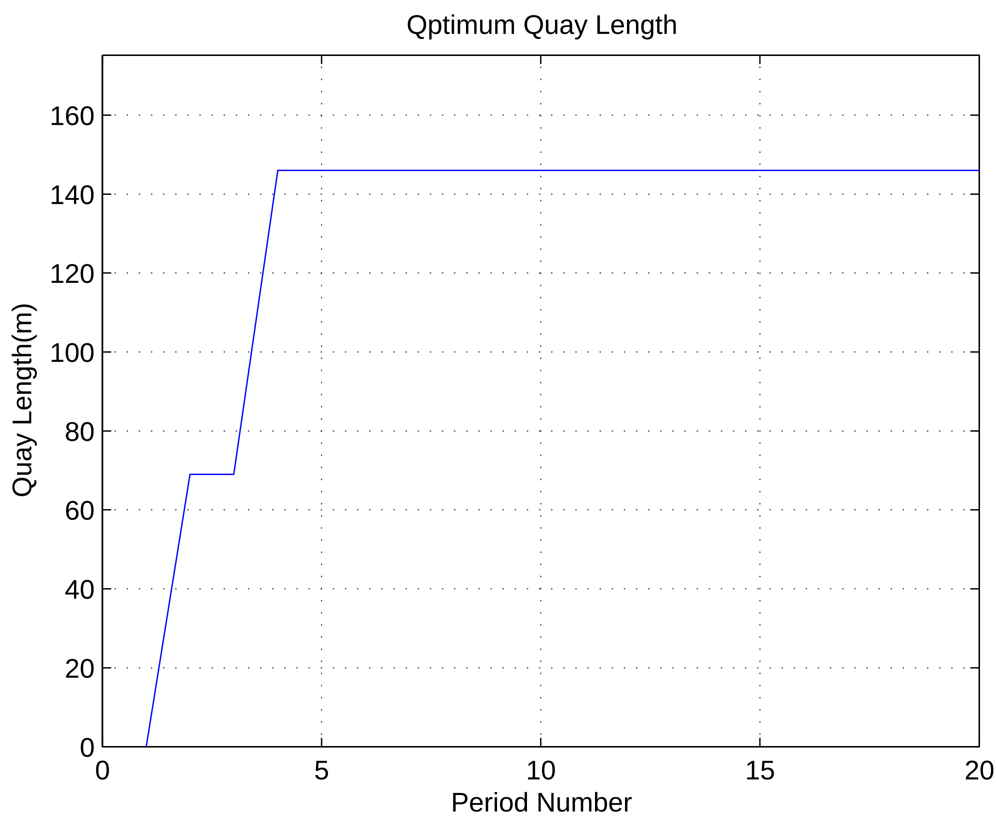

Figure 3.2. Quay Length (V=50)

Table 3.2. Results for V=50

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$A(n)$	285	69	182	146	268	229	137	5	247	133
$D(n)$	0	0	0	69	0	0	146	0	5	137
$L_{available}$	0	0	0	0	0	0	9	4	9	13
Q	0	69	69	146	146	146	146	146	146	146
Period	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
$A(n)$	185	238	277	222	53	122	281	275	123	268
$D(n)$	0	0	133	0	0	0	0	0	122	0
$L_{available}$	13	13	146	146	146	24	24	24	23	23
Q	146	146	146	146	146	146	146	146	146	146

Here, $L_{available}$ represents the available quay length in any period whereas Q is solely the total length of quay for each period. The longer ships are not accepted at the very beginning as seen.

For the velocity of $V = 25$, the behaviour happens to be as in Figure 3.3.

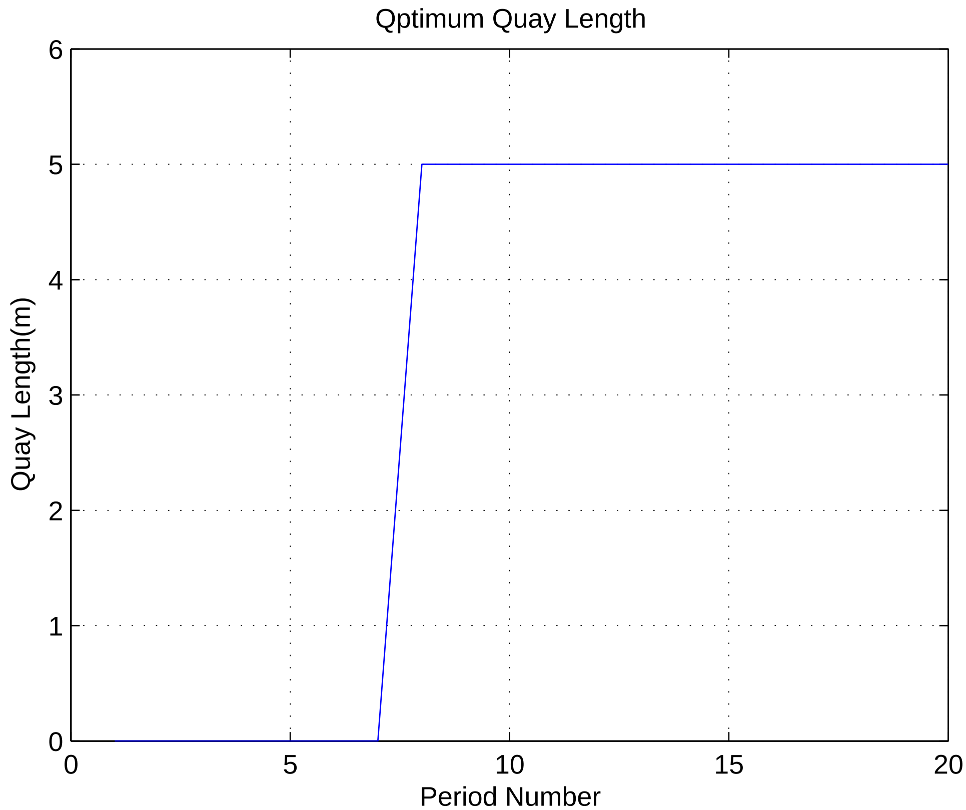

Figure 3.3. Quay Length (V=25)

The optimum path appeared to be [0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0] . The values of 1 indicate the accepted ships whereas 0 means rejection. The departure vector with a velocity of 25 is obtained in Table 3.3.

The only ship accepted with this velocity is 5 in the optimal path.

On the other hand, for velocity $V = 75$, the figure is exactly same with the velocity of 50, thus final quay length value is 146. However, the optimum path has been changed due to acceptance of one more ship in the 14^{th} period. The final quay length does not change just because of that slight change in the optimal path, because the quay has sufficient length for that ship at that period, so there is no need for extra construction. The optimum path appeared to be [0 1 0 1 0 0 1 1 0 1 0 0 0 0 1 1 0 0 1 0]. The values of 1 indicate the accepted ships whereas 0 means rejection. The departure vector with

Table 3.3. Departures for V=25

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$A(n)$	285	69	182	146	268	229	137	5	247	133
$D(n)$	0	0	0	0	0	0	0	0	5	0
$L_{available}$	0	0	0	0	0	0	0	0	5	5
Q	0	0	0	0	0	0	0	5	5	5
Period	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
$A(n)$	185	238	277	222	53	122	281	275	123	268
$D(n)$	0	0	0	0	0	0	0	0	0	0
$L_{available}$	5	5	5	5	5	5	5	5	5	5
Q	5	5	5	5	5	5	5	5	5	5

a velocity of 75 is obtained in Table 3.4.

Table 3.4. Departures for V=75

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$A(n)$	285	69	182	146	268	229	137	5	247	133
$D(n)$	0	0	69	0	0	146	0	0	142	0
$L_{available}$	0	0	69	0	0	146	9	4	146	13
Q	0	69	69	146	146	146	146	146	146	146
Period	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
$A(n)$	185	238	277	222	53	122	281	275	123	268
$D(n)$	0	133	0	0	0	53	0	122	0	0
$L_{available}$	13	146	146	146	93	24	24	146	23	23
Q	146	146	146	146	146	175	175	175	175	175

Of course, this model is very insufficient to represent the real life cases. It is important as the expected asymptotically behaviour occurs. In fact, the one arrival in each period assumption and cost structures are not very acceptable. Therefore, it is logical to pursue a different way where the real life conditions in the ports can be more accurately modelled.

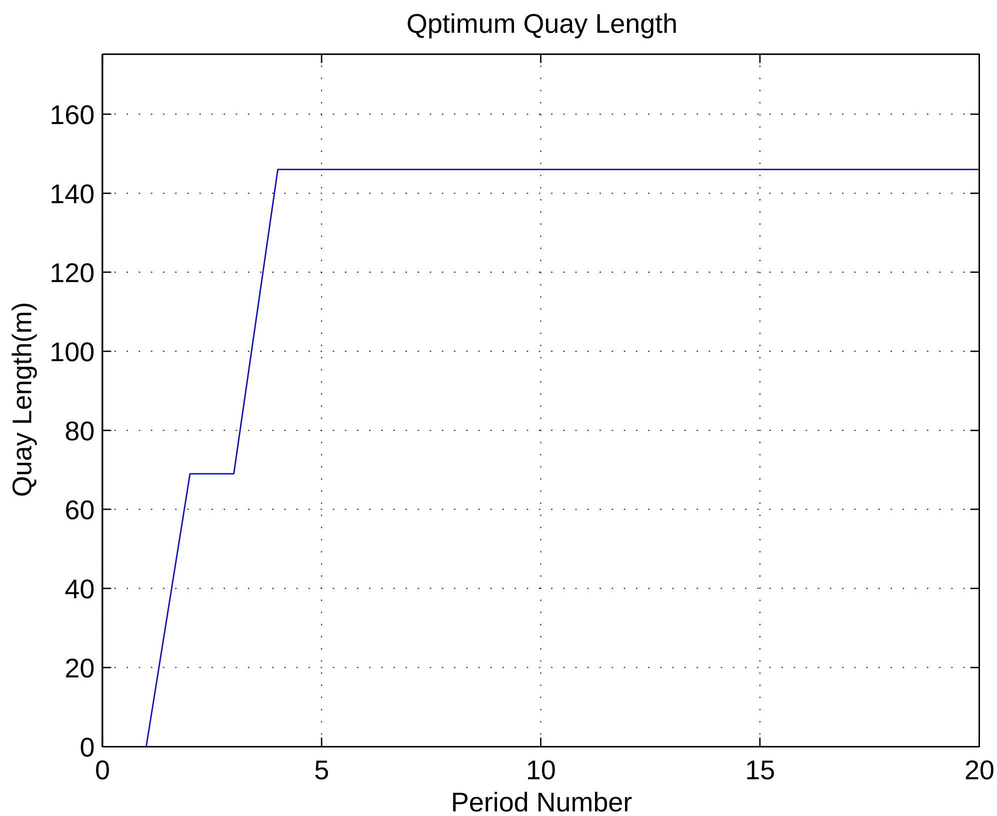

Figure 3.4. Quay Length (V=75)

4. STOCHASTIC KNAPSACK PROBLEM AND QUAY LENGTH DETERMINATION

4.1. Stochastic Knapsack Problem

Knapsack problem can be interpreted as a problem of selecting a best set of items going to a hiker's knapsack, given the value he attaches to these items and an upper limit on the amount of weight he can carry. The problem can be formulated as an integer program where the purpose is to pack a knapsack of volume B with a subset of N different objects so as to maximize the total value of the knapsack's content. Stochastic knapsack can be also defined in a similar manner, but paying attention to the stochastic nature of the problem. Suppose that there are N customers arriving to a system where B resources are available. Customer type i arrives according to a Poisson process with a parameter λ_i. Each customer demands b_i units of resources. The customer of type i are released simultaneously from the system after an exponentially distributed sojourn time with parameter μ_i. Each state in the model defines the number of type i customers in the system, x_i. Therefore, a state vector $x = (x_1, ..., x_N)$ can be obtained for the overall system. A crucial assumption here is that customers that can not find available space in the system are automatically blocked, that is, they are not accepted into the system. This implies that there is an upper limit of resources, $\sum_{i=1}^{N} b_i x_i \leq B$. There is also a reward r_i gained from each customer that enters to the system [15].

To sum up, the problem has some critical issues to be examined carefully. First, the resource has a finite capacity of B units. Customers arrive to this resource according to a Poisson distribution with parameter λ. Each customer i has an arrival rate of $\lambda_i = \lambda q_i$, where $P\{b = b_i\} = q_i, i = 1, ..., N$, where b represents a random variable describing the requirement at an arrival. Each customer requires an amount of b resources (spatial requirement) for τ units of time (temporal requirement). The sojourn time can be used as class dependent.

So, N customer types with spatial and/or temporal requirements arrive, and any customer not accepted by the system immediately departs without affecting the system. This is called blocking, and it will be a critical issue for the sake of the model [16].

There are several policies, involved in this model, where the knapsack partitioning is a matter. If knapsack is partitioned and each customer class has exclusive use of its dedicated portion of the knapsack volume, a complete partitioning (CP) policy is on hand. On the other hand, one can expect complete sharing (CS) policy, if a customer is always offered access whenever sufficient volume is available in the knapsack. The optimization problem with any policy used is to accept/block arriving customers as a function of the current system state in order to maximize the long-run average revenue [17].

The model can be formulated as follows. The state description is, $x = (x_1, x_2, ..., x_k)$ where x_i is the number of type i customers using the resource, as mentioned before. In each state, every type i customer needs b_i units of resources, and these b_i units are simultaneously relinquished when the customer departs. The complete sharing policy is used, so the equation $0 \leq \sum_{i=1}^{N} b_i x_i \leq B$ is satisfied in any state. That is, sum of the amount of resources used by each customer class can be at most the capacity itself. It is possible to obtain the state distribution corresponding to a given sharing policy Ω and it is given by

$$P(n) = \prod_{i=1}^{N} \frac{a_i^{x_i}}{x_i!} G^{-1}(\Omega) \tag{4.1}$$

where the normalization constant $G(\Omega)$ is defined as,

$$G(\Omega) = G(B, N) = \sum_{x \in \Omega} (\prod_{i=1}^{N} \frac{a_i^{x_i}}{x_i!}).$$

Here, a_i is simply the offered load of type i customer and can be written as $a_i = \lambda_i \tau_i$ where $\lambda_i = \lambda q_i$ and τ_i is the mean residency of type i customers in the system. Using this state distribution, one can obtain the blocking probability, P_{b_i}, for each customer type. To recall, blocking directly comes from the rejection of that class type customers given the amount of resources. So, in the case of complete sharing, blocking probability can be written as,

$$P_{b_i} = 1 - \frac{G(B - b_i, N)}{G(B, N)} \tag{4.2}$$

There are easier ways to obtain these probabilities, and they can be calculated with the one-dimensional recursion suggested by Kaufman [16]. Here, the key idea is to consider the random variable $j = xb$ which is the total number of resource units occupied. j can be considered as the total amount of resources used by all the customers present at each state. Hence, any mathematically possible amount of volume smaller than the capacity can be obtained by this approach. The distribution of j is given by,

$$q(j) = \sum_{\{x:x*b=j\}} \prod_{i=1}^{N} \frac{a_i^{x_i}}{x_i!} G^{-1}(B, N) \tag{4.3}$$

As observed, $q(j)$ includes all the states satisfying the equation $xb = j$. This distribution, $q(j)$, for the complete sharing policy satisfies the equation:

$$\sum_{i=1}^{N} a_i b_i q(j - b_i) = j q(j) \qquad j = 0, 1, ..., B \tag{4.4}$$

where $q(y) = 0$ for $y < 0$ and $\sum_{j=0}^{B} q(j) = 1$.

Trivially generating the distribution recursively, blocking probabilities of each class can be attained as follows:

$$P_{b_i} = \sum_{\{x : x*b > B - b_i\}} P(n) = \sum_{i=0}^{b_i - 1} q(B - i) \qquad i = 1, ..., N \tag{4.5}$$

We also see that $q(0) = P(x = 0)$, so we obtain the normalization constant as

$$G^{-1}(B, N) = q(0) \tag{4.6}$$

Kaufman also states that if $q(j)$ can be defined as

$$q(j) = q'(j) q(0) \tag{4.7}$$

Then $q'(0) = 1$ and

$$q'(j) = \frac{1}{j} \left\{ \sum_{i=1}^{N} a_i b_i q'(j - b_i) \right\} \tag{4.8}$$

As $\sum_{j=0}^{B} q(j) = 1$, it is trivial to see that $q(0) = \left\{ \sum_{j=0}^{B} q'(j) \right\}^{-1}$. So, $q(j)$ values can be obtained recursively via (4.7).

As a result, the one-dimensional recursion allows us to analyze the complete sharing policy simply and efficiently.

4.2. A Stochastic Knapsack Model for Optimal Quay Length Determination

4.2.1. Basic Assumptions

The stochastic knapsack application to our case is performed as follows. Basically, the quay length, Q, is considered as the resource volume. As existing ports are studied during the research, real data are used throughout the analysis for both arrivals and departures. Here, the arrival data includes the ship lengths and the daily number of ships coming to a port. The arrivals of the customers, which are in our case, the number of ships arriving each day are assumed to behave according to Poisson distribution. This assumption happens to be valid as the data is checked for goodness of fit. On the other hand, the departures of the customers are modeled according to the velocity, or handling rate assumption as before. The ship data is carefully examined to obtain an acceptable value of velocity for each port studied.

The model is executed for different quay length values to determine the one which gives the best profit results. To begin with, the execution of the analysis starts after the daily received ship length data for the selected ports are sorted according to their lengths and daily amounts. The ship lengths are arranged so that each ship belongs to one ship class as defined above. Moreover, the number of ships that arrive daily at the port deserves great significance since it defines the load of each ship class. Hence, the daily number of ships in the selected length range for each class are obtained throughout all the periods.

One of the most important issue considered in the model, the blocking criteria, is used as explained before. If the available quay length is not sufficient for a ship, it immediately departs and becomes a lost order. It is important to search for the reasonable amount of each ship class that should be accepted by the quay length constructed. Blocking probability is introduced into the model as an independent constraint. With the selected level of confidence, the acceptance of each ship class is ensured. It is appropriate to use a level of confidence %95. Actually, the optimum length is obtained for both including the blocking probability constraint and not considering blocking at all. The key idea is that it will be necessary to choose a larger value of quay length to satisfy the blocking probability constraint. In fact, when the blocking is not used in the model, the resulting quay length will always have a tendency to reject longer ship classes.

4.2.2. Model Structure

It is assumed that ships arrive according to a Poisson distribution with arrival rate λ and each ship of class i has an arrival rate of $\lambda_i = \lambda q_i$, where $P\left\{b = b_i\right\} = q_i, i = 1, ..., N$. As one can guess, the average amount of daily arrivals gives the parameter λ. The probability of occurrence for each ship class throughout all periods, q_i, on the other hand, can be calculated simply by dividing the number of ships falling into class i by the total number of ships. Now, the arrival rate for each class is on hand. It is the time to find the departure rate of each ship class, τ_i using velocities. The velocities, or the handling rates, are calculated on a daily basis for each port. The velocity of a ship that stays in the port is simply the ratio of ship length by the amount of time spent. A ship of length $200 meters$ that stays two days in a port has a velocity of $100 m/day$, as for example. The average discharge rate value ($meter/day$) of all the ships that has arrived to the ports is used as the velocity component in the model. For the data having hour by hour arrivals and departures, ships that depart in less than 24 $hours$ are assumed to have a velocity of their length per day. The other data is handled in the same manner. On the other hand, for daily based data, the amount of days stayed in the port is directly used to attain the velocities. With this information, departure rate, τ_i, for ship class i is calculated by dividing the ship length of class i to the velocity.

Using these rates, it is possible to achieve a_i, the load offered by each ship class i. As mentioned before, $a_i = \lambda_i \tau_i$. This load is the main determinant of the revenue by means of making it possible to determine the occupied length distribution, $q(j)$, where j is the amount of space that can be occupied in the quay by any combination of ship lengths. That is, j is any integer number between zero and the quay length itself. So, the distribution $q(j)$ gives the probabilities for any length occupied in the quay. The ship data is simplified by creating ship classes of multiples of $5 meters$, so j becomes any number that can be divided by 5 with a remainder zero up-to the quay length, and as a result, the probability distribution only has the values for the lengths that can be divided by 5. This fact indicates the existence of zero probabilities for other lengths as well.

The occupied length distribution is obtained by means of (4.7). Moreover, using this distribution, it will be possible to obtain annual revenues using (4.10). The revenue function has a concave like shape reaching an asymptotic value, which indicates that there is an economies of scale in the ship length. This is obvious as the ships arriving does not indicate a fluctuating behaviour. If the demand of ships increases, then the revenue function starts increasing again. As mentioned before, the construction cost is a linear function of quay length, having a slope of cost per length. The annual revenue, then, is turned into the present value with an appropriate interest rate to find out if the length chosen is able to make profit or not.

Executing the program with different quay lengths from smaller to bigger values, the concave shape of the function can also be plotted. Hence, the optimum value is achieved for given ship arrival and length data of the relevant port. While defining the optimal quay length, blocking probability comes into the picture. The model can be checked for a given level of confidence with the blocking probability constraint. As for example, if the level of confidence is chosen as 95%, blocking probability constraint can be stated as $\Pr(Blocking) = \beta_i \leq 0.05$. Here, β_i is the blocking probability of ship class i. The analysis stops executing when the first quay length that satisfies this equation for each ship class is attained. However, this value need not to be optimum. That is, the optimum length does not have to satisfy the blocking constraint. Indeed, the profit obtained with the constraint can be negative. To satisfy this constraint, the quay length may have to be increased up-to an amount that is not desired. Therefore, the model should be carefully examined while checking the results with and without the constraint.

Furthermore, ships are divided into length classes for the sake of simplicity. The model is also checked by considering each ship as an independent customer not belonging to any class and the results are found similar. Therefore, it is logical to create ship classes. Each class of ship lengths is defined as the intervals of increment 10 *meters*. The average length of each ship class, b_i, is used in the model. For instance, if a ship has a length 18 *meters*, then it is in the range of 10 to 20 *meters*, therefore it belongs to the Class 2. A length of 15*meters* is used for all Class 2 ships. There are 35 classes, indicating that there are up to 350*meter* length ships, which can be normally considered as maximum ship length navigating between ports. Ship classes are tabulated in Table 4.1 and Table 4.2.

4.2.3. Construction Cost and Revenue

The cost and revenue criteria is performed according to Drewry studies. First, construction cost is obtained via multiplying the cost per unit length by the quay length to be constructed, namely

$$Construction\ Cost = Cost\ per\ Length * Quay\ Length \tag{4.9}$$

The annual revenue, on the other hand, is obtained as follows. All the possible $q(j)$ values are calculated, and multiplied by the j values, achieving all the quay length utilization possible given the ship classes. Hence, the objective is to achieve all possible states, that is all possible combinations of ship classes from the given data. Actually, it is expected to use the state distribution so as to obtain the annual revenues at

Table 4.1. Ship Classes

Class No	**Ship Length Range (m)**	**Average Ship Length, b_i (m)**
1	0-10	5
2	10-20	15
3	20-30	25
4	30-40	35
5	40-50	45
6	50-60	55
7	60-70	65
8	70-80	75
9	80-90	85
10	90-100	95
11	100-110	105
12	110-120	115
13	120-130	125
14	130-140	135
15	140-150	145
16	150-160	155
17	160-170	165
18	170-180	175
19	180-190	185
20	190-200	195

the very beginning. However, if examined carefully, it can be seen that the occupied length distribution can be used for the same purpose. To recall, the state description is, $x = (x_1, x_2, ..., x_k)$ where x_i denoting the number of type i customers using the resource and $q(j)$ is the distribution of any occupied length that is possible with the class of ships on hand. Therefore, each occupied length will cover all its possible states, states that are constituting the occupied length at the end. For instance, suppose $j = 200$ given that quay length is 1000. $q(j)$ can be attained with many different combinations

Table 4.2. Ship Classes (continued)

Class No	**Ship Length Range (m)**	**Average Ship Length, b_i (m)**
21	200-210	205
22	210-220	215
23	220-230	225
24	230-240	235
25	240-250	245
26	250-260	255
27	260-270	265
28	270-280	275
29	280-290	285
30	290-300	295
31	300-310	305
32	310-320	315
33	320-330	325
34	330-340	335
35	340-350	345

of the state vector and ship lengths. One 200$meter$ length ship can give that j, twenty of ships having length 5$meter$ length can sum up to 200, or one 45$meter$, one 105$meter$ and two 25$meter$ ships can make this up. This indicates that sum of all $q(j)'s$ will actually include the sum of all probabilities for the possible states. The annual revenue is calculated by introducing the revenue per length as

$$Annual\ Revenue = (Revenue\ per\ Length)\sum_{j=0}^{Q} jq(j). \tag{4.10}$$

Other costs may also be used as well throughout the analysis. For instance, the blocking costs (costs that are incurred when a ship is rejected), and operational costs (costs due to the unoccupied part of the quay, and can be considered as holding cost) can be added to the model if needed as below. Here p_2 represents a cost of punishment per length for any available length of the quay.

$$Operational\ Cost = p_2 \sum_{QuayLength>j} q(j)(Quay\ Length - j) \tag{4.11}$$

$$Blocking\ Cost = \sum_{j} \sum_{for\ each\ class} \lambda_i ShipLength(i)(Revenue\ per\ Length)q(j) \tag{4.12}$$

Finally, the profit is attained by calculating the present value of the revenues using the appropriate interest rate, i, and subtracting the construction cost. It can be calculated as

$$Profit = \frac{Annual\ Revenue}{i} - Construction\ Cost. \tag{4.13}$$

Here, the formula below is used to obtain the present value of annual revenues throughout the operation of the quay for his entire life recalling the principles of economics: $\sum_{n=1}^{\infty} \frac{1}{(1+i)^n} = \frac{1}{i}$

Since a dollar based revenue and cost structure is used in the model, an appropriate interest rate of 5% is employed in the structure. However, the calculations are repeated for a standard interest rate of 10%.

4.2.4. Multi-Purpose Functionality

The multi-purpose functionality of the terminals is also important, which is not considered in this study. First, for different cargo types, there are different terminals in a port. These terminals include structurally different quays to serve specifically that type of cargo. Terminal modules are developed for Container, Neo-Bulk, Break-Bulk, Dry-Bulk and Liquid-Bulk facilities. Container cargo, loaded into the hold of a ship by crane (specialized rail-mounted crane located on the quay for the purpose of loading and unloading containers), in substantial-sized containers that are, customarily used for such shipments, and designed for use in and transfer between 2 or more modes of transportation.

Here, it will be appropriate to define a twenty-foot-equivalent unit, TEU. It represents a standard unit for counting containers of various capacities and for describing the capacities of container ships or terminals. These ships carry cargo in standard metal boxes, called containers, which can be transferred easily to trains or trucks. TEU is an abbreviation for "twenty-foot equivalent unit." One TEU represents the cargo capacity of a standard container 20 $feet$ long, 8 $feet$ wide, and (usually) a little over 8 $feet$ high. There are also 48-$foot$ containers which are equal to 2.4 $TEUs$. The revenue in the container terminals are mainly defined and obtained per twenty-foot equivalent unit loaded or unloaded.

On the other hand, bulk cargo means cargo that is unpacked, unsegregated or non-unitized, carried loose, and loaded directly into the hold of a ship by pouring, pumping, scooping, shoveling, or other similar means.

Break-Bulk cargo is simply the non-container packaging. The cargo loaded into the hold of a ship piece-by-piece like cartons, pallets, boxes and barrels, and separate units of cargo, including steel coils, metal bars, lumber, logs and machinery.

Dry-Bulk cargo represents the bulk other than liquid bulk, such as grain and fertilizer, iron ore, coal, sand and gravel, and scrap metal, whereas, Liquid-Bulk cargo includes the ones other than dry bulk, such as oil and propane, petroleum products, liquefied natural gas (LNG), and chemicals. Neo-bulk commodities are generally handled like bulk commodities, except they move in small quantities per shipment. For example, steel, paper, lumber, wood, oranges, and forest products could all be shipped in the same vessel with cargo separation maintained during loading, transportation, and unloading. Automobiles can also be handled as Neo-Bulk cargo [18].

For these different cargo types, different features should be considered for quay construction. For example, cranes will be needed only for the container terminals, so there is no use to consider them in a bulk-cargo module. The critical point is, different quay lengths will be attained as optimum regarding different cargo types.

The ports working mostly on containerized cargo are selected, and the study regarding the cost and revenue issues are conducted with this selection. In fact, we can attain the port conceptual development estimates for different type of terminals from Latin American Trade & Transportation Study, 2004. The key idea here is to develop the conceptual construction cost estimates for the five marine terminal modules, container, break-bulk, neo-bulk, dry bulk and liquid bulk. Of course, this study is performed under several assumptions, and it represents the cases in America. However, it can be viewed as a critical study as it directly gives the cost estimate ratios of different cargo modules with each other. Basically, the container terminals are the most expensive ones, and the conceptual cost estimate results for five different marine modules that are to be constructed at the same location with different demand of cargo can be seen in Table 4.3. The quay lengths differ in a range of $700 meters$ to $1000 meters$ for different modules.

These figures make it possible to make a rough comparison between the construction costs for different type of terminals.

One last point to consider is that the bulk cargo and container cargo have different units of measures. It is apparent that all bulk cargo is measured in tons. Besides the metric tons, the register ton used in the maritime industry is a unit of volume used

Table 4.3. Construction Costs for different modules

Module Type	**Conceptual Development Cost**
Container	\$32000000
Break-bulk	\$20600000
Neo-bulk	\$14600000
Dry-bulk	\$17600000
Liquid-bulk	\$19300000

for the cargo capacity of a ship, defined as 100 $cubic\ feet$ (roughly 2.83 $cubic\ metres$). It is often abbreviated as GRT referring to gross registered ton. Therefore, for the revenues, it may be appropriate to change tons into $TEUs$ for the sake of the proposed model. On the other hand, short tons are also used in the U.S. ports where 1 $short\ ton$ is equal to 0.9 $metric\ tons$. The average weight of cargo per TEU can vary from 5 to 18 $tons$ according to the nature of the commodity handled. To illustrate, the internal volume of a TEU can be taken as 29 $cubic\ metres$. This volume can be filled at the maximum allowable cargo weight 18 $tons$ only when the cargo stowage factor is 57 $cubic\ feet\ per\ ton$. Commodities of this density are, for example, flour or potatoes. Therefore, when $TEU\ per\ ton$ comparison values are given for each port, that value is used. However, if that data is not available 1 TEU is taken as approximately equal to 5 $metric\ tons$, and 12.8 $register\ tons$. These are accurate estimates to transform tons into $TEUs$.

5. MODEL PERFORMANCE ON REAL DATA

In this chapter, the comparison between the results of the model and actual port data is performed. Indeed, the model is applied mostly for container ports. The critical issue is to determine the cost and revenues carefully and accurately. The main cost component is the construction cost of the quay, which is the main determinant for the model. It is modeled as a linear function of the quay length itself, however it is necessary to determine a unit cost per quay length. The aim is to make a profit regarding this construction cost by the use of ship revenues. As the quay considered is to be operated for its entire life, the long-run revenue is obtained and turned into the present value to make the cost-revenue comparison available. Besides the construction cost, two other cost components, blocking cost and operating cost can be introduced into the model. Both costs may be viewed as penalties. Blocking cost penalizes the loss profit due to the shortage in the quay length, whereas the operating cost penalizes an unnecessarily long quay by introducing a cost for free quay length. Basically, when a short quay is preferred, the blocking probabilities of each ship class becomes very high, that is, most of the ships arriving is not accepted, and therefore there is a loss of profit. Using these blocking probabilities, blocking cost is derived. On the other hand, redundant quay length can lead to smaller blocking probabilities, but if the quay is too long for the arriving ships, then there will be free quay space most of the time. This can be used as another kind of penalty by creating the operating cost of this free space. Both of these costs become dominant at the boundaries, either for short, or long quay lengths. These costs are not considered in the final model where the construction cost is used as the only cost component. Now, the next question is how to achieve a correct representation of port construction costs.

The revenues, on contrary, are much more difficult to obtain. Mostly, the revenues are gained per cargo carried, so this makes it difficult to find the revenue per length than as it is for the construction cost. A relation between the amount of cargo and the corresponding quay length is used to make use of revenue per length. Therefore, to achieve the relations of quay length between cost and revenues, Drewry reports, which are the most creditable studies in the maritime industry, are used in this work. They are normally prepared with the years' experience and incredible amount of data received from all around the world, hence they give accurate measures for maritime studies [19].

5.1. Construction Cost

First, the construction cost per unit length has to be determined. The construction costs for several ports all around the world are given as a source document in Drewry Reports [19]. Using the average value of this costs, a value of $\$200619/m$ is calculated. The relevant table is given in Appendix A. Drewry also suggests a way to calculate construction costs for container terminals. The summary of key cost and operating benchmarks for terminals with annual throughputs 210000 TEU and 600000 TEU are as follows:

Table 5.1. Key Cost and Operating Benchmarks

Terminal **TEU/year**	**Medium** **(210000)**	**Large** **(600000)**
Key Features		
Quay Length	$250m$	$550m$
Terminal Area	$8 hectares$	$16 hectares$
Number of quay cranes	2	5
Cost Benchmarks		
Land, civil works, buildings	\$21000000	\$47500000
Equipment costs	\$19000000	\$60800000
Total Initial Capital Outlay	\$40000000	\$108300000

Using this table, construction cost per unit length can be calculated as cost per length, as $(\$108300000 - \$40000000)/(550m - 200m) = \$225000/meter$. This cost is abbreviated as p_1.

Considering the value obtained from Drewry calculations and data attained from several ports all around the world, the unit construction cost per length is taken as

$\$200000/m$. So, the cost function is linear with a slope of unit construction cost per length.

5.2. Revenue

The break-even probability for a 210000 TEU Capacity Terminal for both emerging and developed economy scenarios are given by Drewry. According to this information, the gross revenue is $\$120/TEU$ for countries with an emerging economy, whereas it is $\$150/TEU$ for developed economies. Excluding the port authority charges, total annual fixed and variable (operating) costs, the net profit can be obtained as $\$70/TEU$ for emerging economies and approximately $\$60/TEU$ for developed economies from Drewry. The difference is due to the annual operating cost increase for developed economy scenario.

Table 5.2. Revenues for a 210000 TEU Capacity Terminal

Benchmarks	**Revenue (Emerg. Ec.) (\$/TEU)**	**Revenue (Devel. Ec.) (\$/TEU)**
Gross Revenue	\$120	\$150
Port Auth. Charges	\$10.83	\$21.31
Fixed Cost	\$25.76	\$50.32
Variable Cost	\$13.79	\$21.30
Net Revenue	\$69.61	\$57.07

Moreover, as normally the revenues are gained per $TEUs$ discharged or loaded, it is convenient to pursue a way to turn this revenue into a length-based structure. The accurate conversion scheme can be achieved at Drewry reports. According to the Drewry data, the throughputs per metre of quay length in $TEUs$ can be attained for various ports all around the world, and the average value is given as 528 $TEU/m/year$. The relevant data is given in Appendix B [19]. As the net profit is $\$70/TEU$ for developing economies, which are mostly studied in this research, then $Revenue\ per\ length = \$70/TEUx528TEU/m = \$37000/m/year$.

Throughout the overall analysis, the revenue per length is taken as $\$40000/m$ per year.

5.3. Fitting Poisson Distribution for Ship Arrivals

As mentioned before, the analysis is carried out with the assumption of Poisson arrival of ships. The daily Poisson arrival data is converted into probabilities and used in the analysis based on an annual scheme. Our data represents the occurrences of each number of ships. For instance, among the periods studied, only in 2 of them, 9 ships may have arrived and we just concentrate on the value 2 for the test. In this section, chi-square goodness of fit test results of ship arrival data obtained from the ports considered are given. The chi-square test is used to test if a sample of data comes from a population with a specific distribution. Actually, it is an approximate test of the probability of getting the frequencies one has actually observed if the null hypothesis is true.

5.3.1. Kumport, Türkiye

Histogram given in Figure 5.1 depicts the observed frequencies for Kumport arrival data, whereas the piecewise linear curve gives the expected frequencies under the null hypothesis.

There is clearly a bit discrepancy. There are two peak values that have much more arrivals compared with the Poisson distribution. However, the significant point is whether the discrepancy between the observed and expected distributions is statistically significant. The Chi-square goodness of fit test is used to determine this.

The observed and expected frequencies are calculated and calculations are tabulated. There are 8 categories to be taken, which normally provides us with $df = k-1 = 7$ degrees of freedom. However, when we compute our expected frequencies, we have to use the data to estimate $\mu = 4.41$ since μ is not provided to us by the null hypothesis. This step costs us one more degree of freedom, leaving 6. The critical value for χ^2 with 6 degrees of freedom and $\alpha = 0.05$ is 12.59. Our χ^2 statistic, on the other hand,

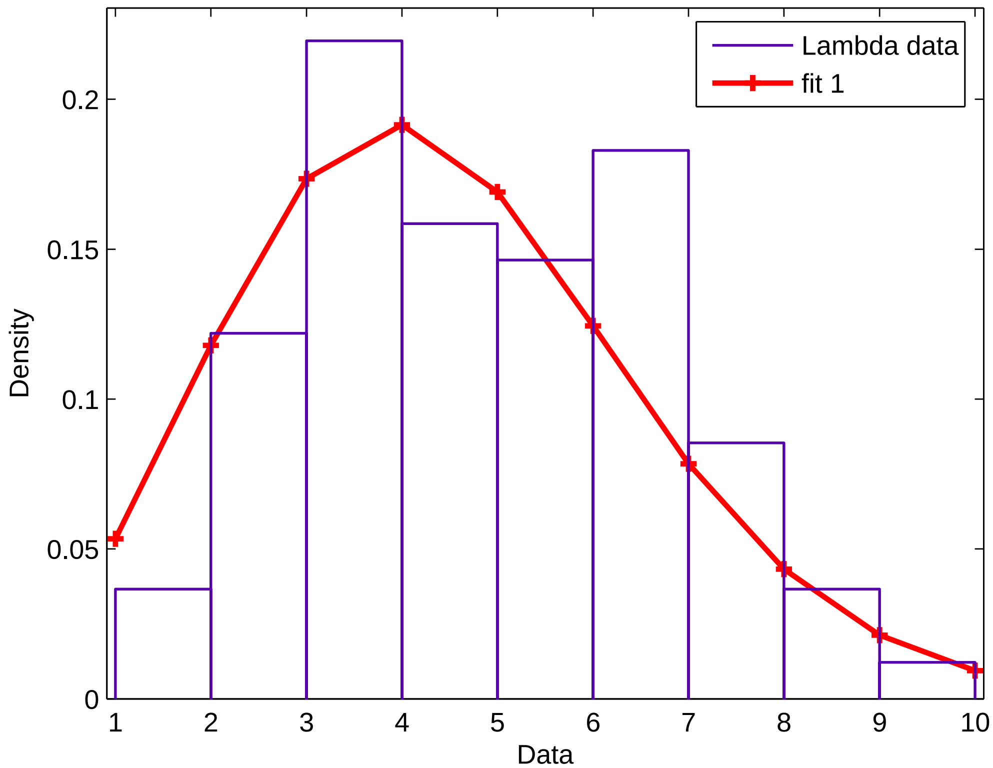

Figure 5.1. Poisson fit for Kumport Data

is calculated as 6.07, therefore we can not reject the null hypothesis of ship arrivals following Poisson distribution.

A final useful comparison is between the sample mean number of arrivals, 4.41, and the sample variance for the number of arrivals which is computed as 3.58. As the figure shows, the sample mean and variance are close to each other.

5.3.2. Port Qasim, Pakistan

Histogram of Figure 5.2 depicts the observed frequencies for Port Qasim arrival data, whereas the piecewise linear curve gives the expected frequencies under the null hypothesis.

The peak value that have much more arrivals do not seem to be complying with

Table 5.3. Poisson Test Table for Kumport

# of ships	**Periods**	**Probability**	**Expected # of Arrivals**	**Chi-square Value**
0	0	0.012	0.99	
1	3	0.053	4.38	
≤1	3	0.066	5.37	1.05
2	10	0.118	9.67	0.01
3	18	0.173	14.23	1.00
4	13	0.191	15.70	0.46
5	12	0.169	13.86	0.25
6	15	0.124	10.20	2.26
7	7	0.078	6.43	0.05
≥ 8	4	0.080	6.54	0.98
8	3	0.043	3.55	
9	0	0.021	1.74	
10	1	0.009	0.77	
11	0	0.004	0.31	
12	0	0.001	0.11	
13	0	0.000	0.04	
14	0	0.000	0.01	
15	0	0.000	0.00	
χ^2 statistic				**6.07**

the Poisson distribution. However, the significant point is that if the discrepancy between the observed and expected distributions are statistically significant. The Chi-square goodness of fit test is used to determine this.

There are 5 categories to be taken to satisfy the minimum frequency assumption, which normally gives $df = k - 1 = 4$ degrees of freedom. However, when expected frequencies are computed, we have to use the data to estimate $\mu = 1.91$ since μ is not provided to us by the null hypothesis. This step leaves us with $df = 3$. The critical

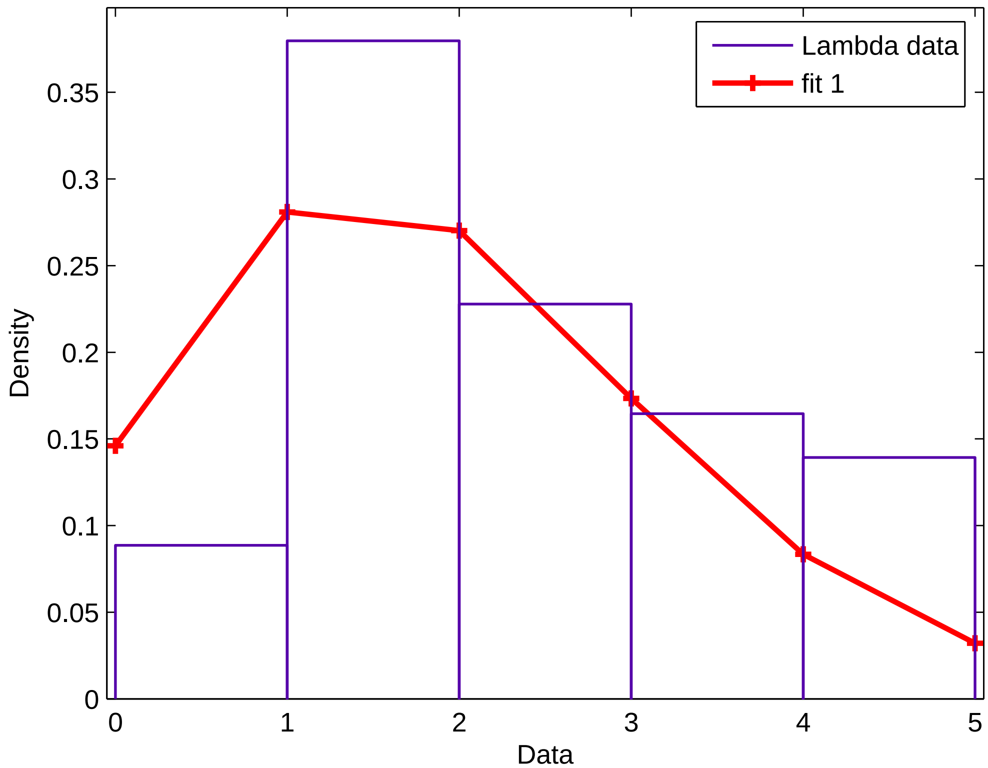

Figure 5.2. Poisson fit for Port Qasim Data

value for χ^2 with 3 degrees of freedom and $\alpha = 0.05$ is 9.49. Our χ^2 statistic, on the other hand, is calculated as 6.59, therefore we can not reject the null hypothesis.

A final useful comparison is between the sample mean number of arrivals, 1.91, and the sample variance for number of arrivals which is computed as 1.67. The sample mean and variance are close to each other.

5.3.3. Port Tuticorin, India

The observed frequencies for Port Tuticorin arrival data result in the histogram given in Figure 5.3. Again the piecewise linear curve gives the expected frequencies under the null hypothesis.

The peak values that have much more arrivals do not seem to be complying

Table 5.4. Poisson Test Table for Port Qasim

# of ships	**Periods**	**Probability**	**Expected # of Arrivals**	**Chi-square Value**
0	7	0.148	11.68	1.88
1	31	0.283	22.33	3.37
2	17	0.270	21.34	0.88
3	13	0.172	13.60	0.03
4	8	0.082	6.50	0.35
$\geq$ **5**	3	0.045	3.56	0.09
5	3	0.031	2.48	
6	0	0.010	0.79	
7	0	0.003	0.22	
8	0	0.001	0.05	
9	0	0.000	0.01	
10	0	0.000	0.00	
		χ^2 statistic		**6.59**

with the Poisson distribution. The lower values also have less arrivals. However, the significant point is that if the discrepancy between the observed and expected distributions are statistically significant. The Chi-square goodness of fit test is used to determine this.

8 categories are chosen, which normally gives $df = k - 1 = 7$ degrees of freedom. However, when expected frequencies are computed, we have to use the data to estimate $\mu = 3.96$. This step leaves us with $df = 6$. The critical value for χ^2 with 6 degrees of freedom and $\alpha = 0.05$ is 12.59. Our χ^2 statistic is calculated as 6.80, therefore we can not reject the null hypothesis.

A final useful comparison is between the sample mean number of arrivals, 3.96, and the sample variance for number of arrivals which is computed as 4.01. It is obvious that he sample mean and variance are approximately equal to each other.

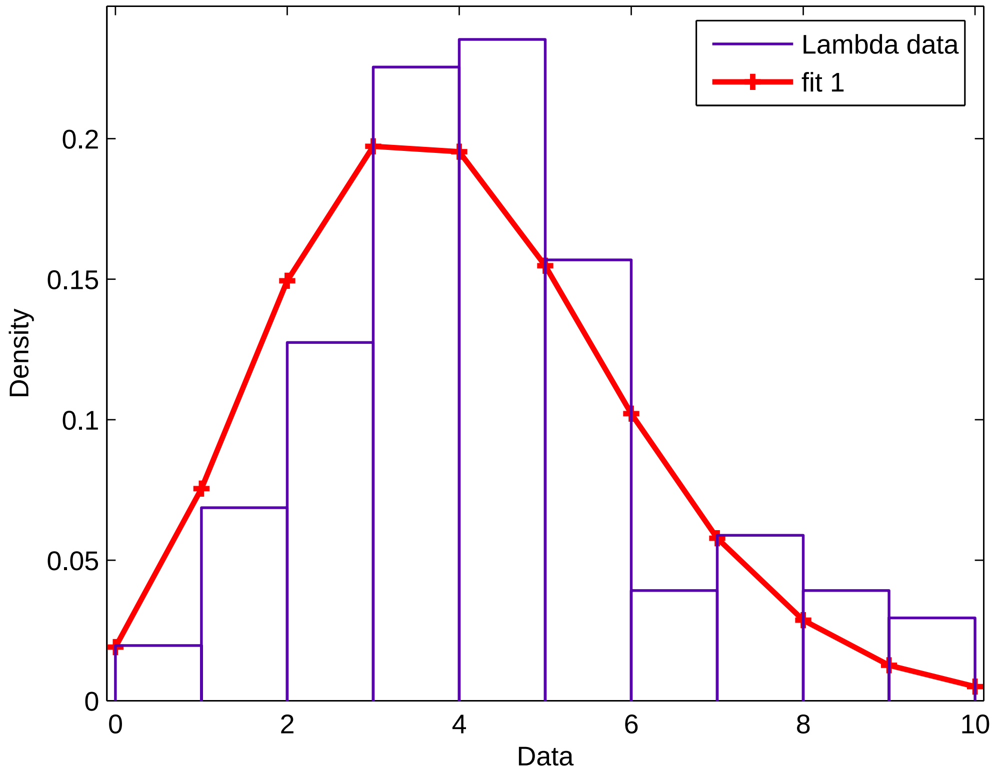

Figure 5.3. Poission fit for Port Tuticorin Data

5.3.4. Port Honolulu, USA

Figure 5.4 shows the histogram for Port Honolulu arrival data on the piecewise linear curve for the expected frequencies under the null hypothesis.

The significant point here is that if the discrepancy between the observed and expected distributions are statistically significant. The Chi-square goodness of fit test is used to determine this.

There are 10 categories chosen, which normally gives $df = k - 1 = 9$ degrees of freedom. However, when expected frequencies are computed, we have to use the data to estimate $\mu = 7.52$. Then, we have $df = 8$. The critical value for χ^2 with 8 degrees of freedom and $\alpha = 0.05$ is 15.51. Our χ^2 statistic is calculated as 9.29, therefore we can not reject the null hypothesis.

Table 5.5. Poisson Test Table for Tuticorin

# of ships	**Periods**	**Probability**	**Expected # of Arrivals**	**Chi-square Value**
0	2	0.019	1.94	
1	7	0.075	7.70	
$\leq$**1**	9	0.094	9.64	0.04
2	13	0.149	15.24	0.33
3	23	0.197	20.12	0.41
4	24	0.195	19.92	0.83
5	16	0.155	15.78	0.00
6	4	0.102	10.42	3.95
7	6	0.058	5.90	0.00
$\geq$ **8**	7	0.049	4.98	0.40
8	4	0.029	2.92	
9	2	0.013	1.28	
10	1	0.005	0.51	
11	0	0.002	0.18	
12	0	0.001	0.06	
13	0	0.000	0.02	
14	0	0.000	0.01	
15	0	0.000	0.00	
χ^2 statistic				**6.80**

A final useful comparison is between the sample mean number of arrivals, 7.52, and the sample variance for number of arrivals which is computed as 8.98. It is apparent that both values are close to each other.

5.4. Data Analysis

It is very important to validate the model with the real data. The desire is to end up with good estimates of optimal quay lengths for existing ports. Thus, the ship data

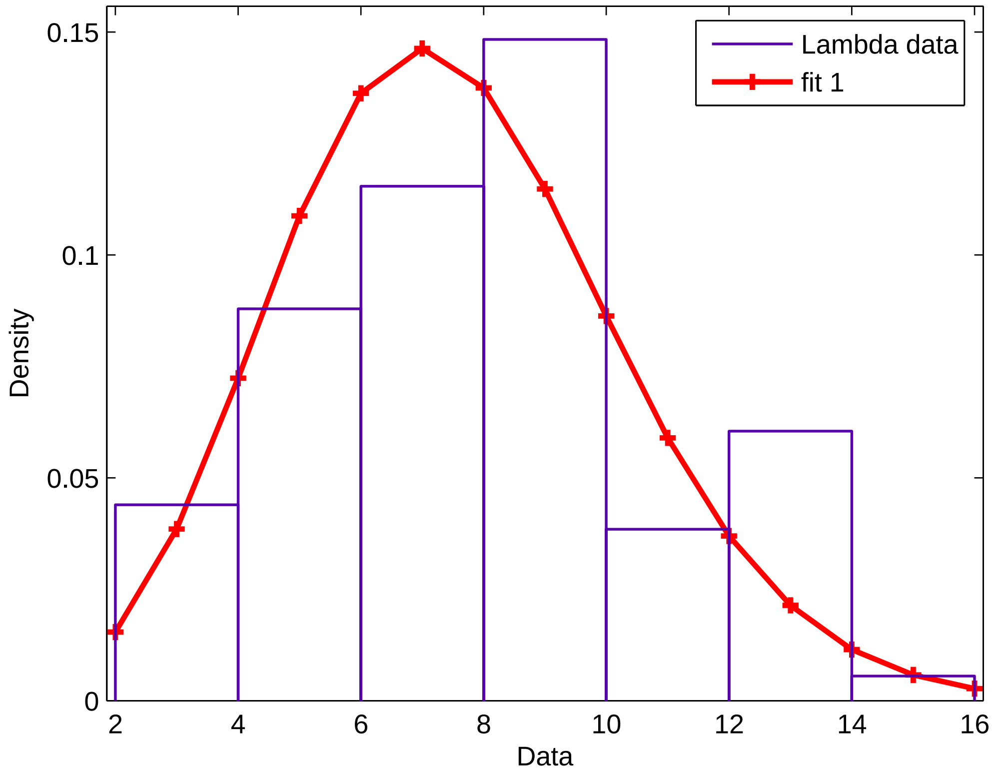

Figure 5.4. Poisson fit for Port Honolulu Data

is obtained for several ports, including Kumport, Türkiye; Port Qasim, Pakistan; Port Tuticorin, India; Port Bilbao, Spain; Port İzmit, Türkiye and Port Honolulu, U.S.A. This daily ship arrival and length data is used for the validation of the model. In fact, the model can be used to validate the existing quay length of an existing port. The velocities obtained from the data are reported in Table 5.7.

The information and analysis results for the ports studied follows in the proceeding subsections. The analyses are conducted with the parameters as follows. The arrival rates and velocities are obtained from the real data. Interest rate is taken as 5% whereas the level of confidence for blocking probabilities is 95%.

Table 5.6. Poisson Test Table for Honolulu

# of ships	**Periods**	**Probability**	**Expected # of Arrivals**	**Chi-square Value**
0	0	0.001	0.05	
1	0	0.004	0.37	
2	4	0.015	1.40	
3	4	0.039	3.50	
≤ 3	8	0.059	5.32	1.34
4	7	0.072	6.58	0.03
5	9	0.109	9.90	0.08
6	10	0.136	12.40	0.46
7	11	0.146	13.32	0.40
8	16	0.137	12.51	0.97
9	11	0.115	10.45	0.03
10	4	0.086	7.85	1.89
11	3	0.059	5.37	1.04
≥ 12	12	0.080	7.30	3.03
12	4	0.037	3.36	
13	7	0.021	1.94	
14	0	0.011	1.04	
15	1	0.006	0.52	
16	0	0.003	0.25	
17	0	0.001	0.11	
18	0	0.000	0.05	
19	0	0.000	0.02	
20	0	0.000	0.01	
χ^2 statistic				**9.29**

5.4.1. Kumport, Türkiye

Kumport, having a total length of 2380$meters$, has been established in 1994 in İstanbul/Türkiye, and started giving active services as a multi purpose port for

Table 5.7. Port Velocities

Port	**Velocity (Handling Rate)**
Kumport	$77m/day$
Qasim	$83m/day$
Tuticorin	$47m/day$
Honolulu	$68m/day$

handling containers, general and bulk cargoes, RoRo services for 24 *hours* a day and 365 *days* a year. In 2004, 483831 TEU and 660120 *metric tons* of cargo was handled. This represents a %10 increase in container cargo and %60 increase in bulk cargo. Considering that 1 TEU is approximately equal to 5 *metric tons*, the total amount of $TEUs$ handled can be calculated as $483831 + (660120/5) = 615855$ TEU.

The port plan can be seen from Figure 5.5. It is divided into 5 approximately equal basic pieces as observed. The first quay has a total length of $600meters$, whereas the other four quays are $520meter$ long. This division is performed due to lack of sufficient place and it is studied in the last chapter.

Kumport consists of 13 berths and their lengths are given in Table 5.8.

An arrival data of 82 *days* is obtained for this port, and the velocity component calculated for the analysis is $77m/day$. The analysis is carried out with this demand and velocity. The results are very encouraging in terms of attaining acceptable values of quay length. When the blocking probability constraint is considered, a quay length of $2000meters$ is achieved at the end of the analysis. On the other hand, if the constraint is not applied, the result appears to be $1500meters$. The revenue and profit functions and summary of the results are given in Table 5.9.

The economies of scale of the profit and revenue functions against the quay length values become very important. From the graphs, it is obvious that the functions seem to be concave. The first issue to be considered is the relatively constant number of ship arrivals. That is, the amount of ships arriving to the ports does not indicate a

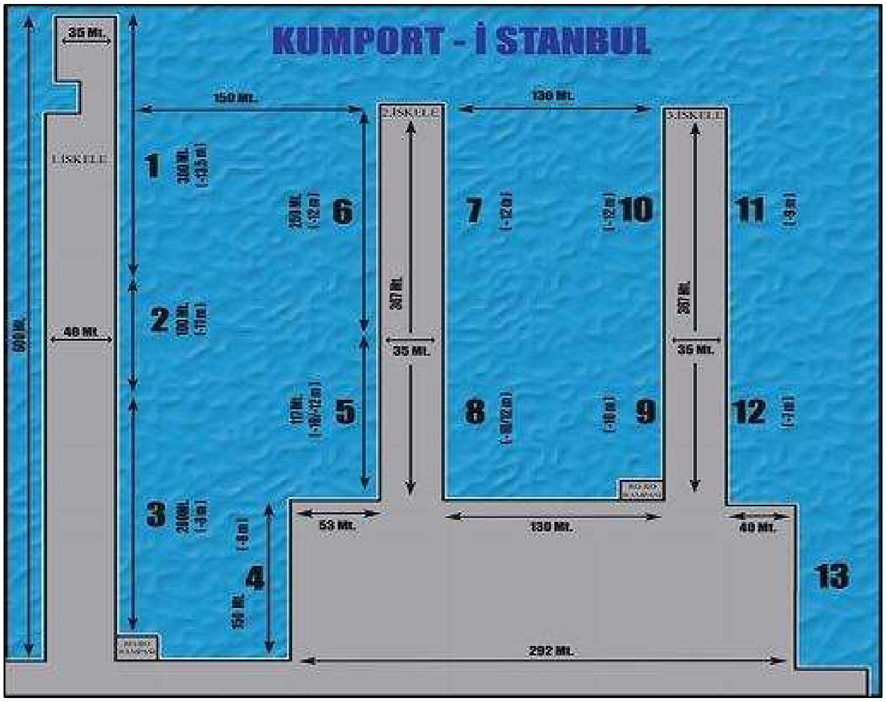

Figure 5.5. Kumport Layout

fluctuating behaviour. Besides, the variance of the daily number of ships for each port is very close to the mean as considered before. Therefore, the revenue does not increase infinitely even if you increase the quay length more and more. The $q(j)$ values, which are the probabilities of occupied lengths given the quay length, indicate an increase in the very last digits after the optimal point. Hence, the sum of $jq(j)$ values come to a point of optimality and the increase in the revenue after that point has no significance for the analysis as it is minor. Besides, as the cost function is simply linear, the profit function happens to be concave when costs are added to the revenues.

Using the $528TEU/m$ value from Drewry reports, the total number of $TEUs$ can be calculated as $(1500x528) = 792\,000$, and $(2000x528) = 1056\,000$. These results show a great deal of resemblance with the original values obtained from Kumport datas. Of course, the data is obtained for 2005 and as the structure is container based, slight differences are supposed to occur.

Table 5.8. Berth Lengths of Kumport

Berth 1	$300m$
Berth 2	$100m$
Berth 3	$200m$
Berth 4	$150m$
Berth 5	$120m$
Berth 6	$250m$
Berth 7	$250m$
Berth 8	$120m$
Berth 9	$120m$
Berth 10	$250m$
Berth 11	$250m$
Berth 12	$120m$
Berth 13	$150m$

Table 5.9. Optimal Quay Lengths for Kumport

With	$\mathbf{Q_{opt}}$	**Cost (\$)**	**Annual Revenue (\$)**	**Profit (\$)**
Constraint	$2000m$	4.0×10^8	3.97×10^7	3.93×10^8
Without	$\mathbf{Q_{opt}}$	**Cost (\$)**	**Annual Revenue (\$)**	**Profit (\$)**
Constraint	$1500m$	3.0×10^8	3.66×10^7	4.33×10^8

It is very important to see the blocking probability behaviour for two cases. If the constraint is not considered, the longer ships will have very high blocking probabilities and they will not be accepted most of the time to the quay whose optimal length is $1500meters$. The results with and without the constraint are given in Table 5.10 and Table 5.11, consecutively.

Clearly, the satisfaction of the blocking probability constraint is a very valuable asset. Consider the quay length of $1500meters$, where the class of ships 35 has an acceptance probability of 75%. In other words, 25% of that class ships are rejected when they arrive at the quay. Actually, the confidence level 5% is satisfied only before class 10 ships representing a length range of 100 to 110, which indicates that many

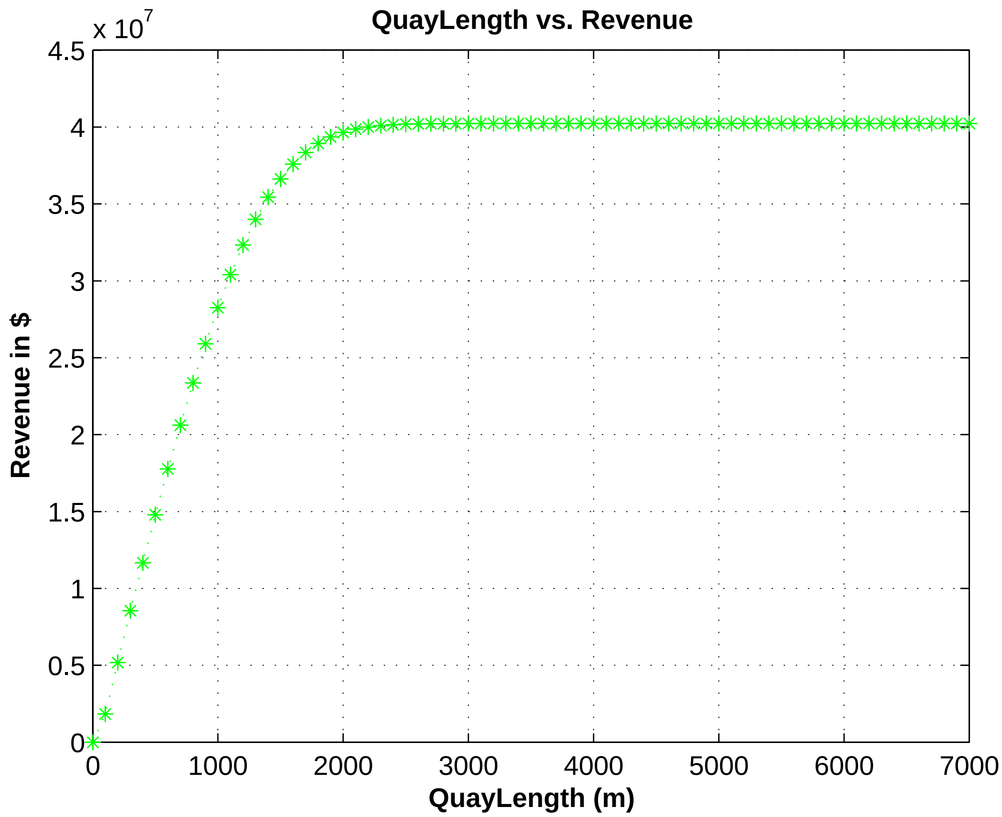

Figure 5.6. Kumport Annual Revenue

of the ships having a length larger than 110*meters* are not accepted. This is why a blocking probability constraint is introduced to the system. Although the objective is the maximization of the profit, it is not logical and accurate for a port to reject and lose many ships in such a competitive environment. Therefore, the quay length without the blocking probability constraint should be carefully examined for the blocking probabilities of ship classes.

The model results indicate that the port is constructed in an accurate manner to satisfy the daily ship arrivals in that region. A sensitivity analysis with respect to the model parameters are given in the next chapter.

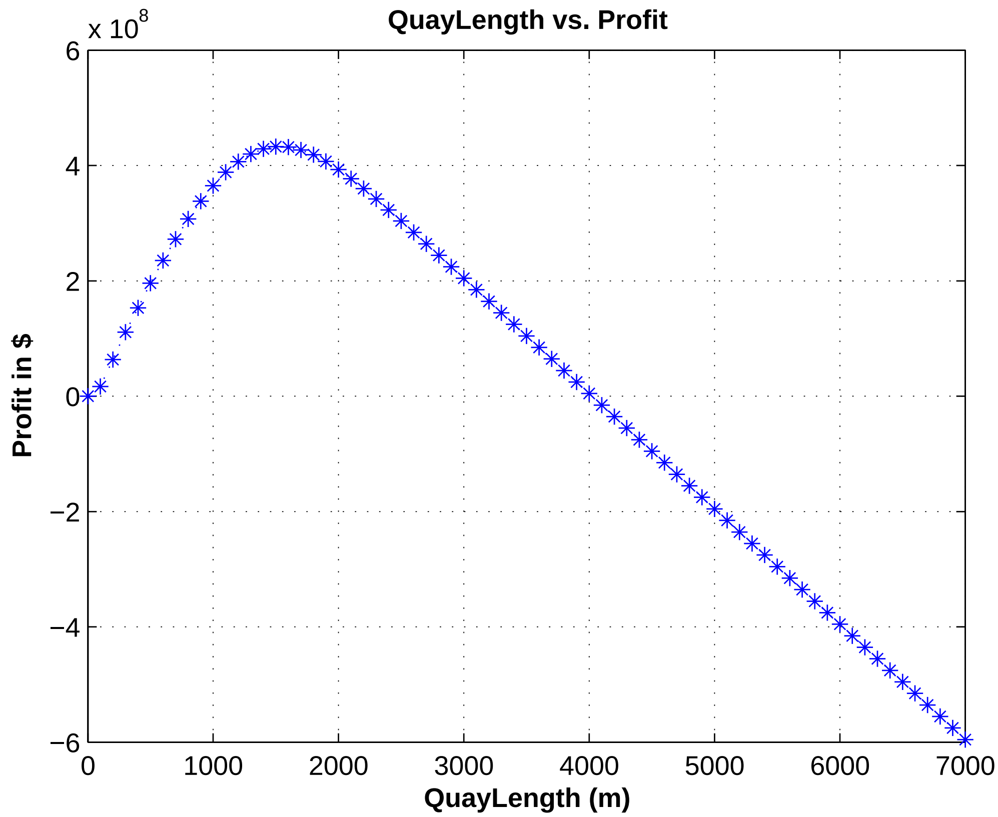

Figure 5.7. Kumport Profit

5.4.2. Port Qasim, Pakistan

Port Qasim is Pakistan's first industrial and multi-purpose deep-sea port. The port has been developed on the coastal line of Arabian Sea where once the sand dunes of Bin Qasim desert could be seen. Located in Indus delta region at a distance of $50km$ South East of Karachi, the port is well connected to all over the country through modern modes of transportation. The total length of the port is about $2150meters$, comprising three multi-functional berths, three container terminals, a chemical terminal, an oil terminal, and an ore and coal terminal. 18183303 $tons$ of bulk cargo and 518805 TEU of containerized cargo is handled. The conversion between $tons$ and $TEUs$ can be performed using a value of 16 regarding the port data. Therefore, this value is used to turn tons into $TEUs$ for this port. Then the total handled cargo becomes $518805 + (18183303/16) = 1655260$. The berth lengths are given in Table 5.12.

Table 5.10. Blocking Probabilities for Kumport

Class No	b_i (**m**)	Pr (**Blocking**) (**with constraint**)	Pr (**Blocking**) (**without constraint**)
1	5	0.0003	0.0023
2	15	0.0010	0.0071
3	25	0.0016	0.0119
4	35	0.0024	0.0169
5	45	0.0031	0.0221
6	55	0.0039	0.0273
7	65	0.0047	0.0326
8	75	0.0055	0.0383
9	85	0.0064	0.0440
10	95	0.0073	0.0499
11	105	0.0083	0.0559
12	115	0.0093	0.0621
13	125	0.0104	0.0683
14	135	0.0115	0.0748
15	145	0.0126	0.0814
16	155	0.0138	0.0882
17	165	0.0151	0.0951
18	175	0.0164	0.1022
19	185	0.0177	0.1095
20	195	0.0191	0.1168

An arrival data of 79 *days* is present for this port, and the velocity component calculated for the analysis is $83m/day$. Optimal quay length results indicate that when the blocking probability is considered, the output length value is $2000meters$, which is very close to the original quay length. On the other hand, if the model is employed without considering blocking, the result happens to be $1500meters$. Here, it will be useful to examine the resulting blocking probabilities carefully so as to the fact that longer ship classes have a higher tendency to be rejected. The revenue and profit

Table 5.11. Blocking Probabilities for Kumport (continued)

Class No	b_i (**m**)	Pr (**Blocking**) (**with constraint**)	Pr (**Blocking**) (**without constraint**)
21	205	0.0206	0.1244
22	215	0.0221	0.1321
23	225	0.0238	0.1400
24	235	0.0253	0.1480
25	245	0.0270	0.1562
26	255	0.0288	0.1646
27	265	0.0307	0.1731
28	275	0.0326	0.1817
29	285	0.0346	0.1905
30	295	0.0366	0.1995
31	305	0.0388	0.2086
32	315	0.0410	0.2178
33	325	0.0433	0.2272
34	335	0.0457	0.2367
35	345	0.0481	0.2463

Table 5.12. Berth Lengths of Port Qasim

Berths 1-4	$800m$(total)
Berths 5-7	$600m$(total)
Engro Vopak Chemical Terminal	$225m$
Fotco Oil Terminal	$245m$
Iron Ore&Coal Terminal	$279m$

functions and the summary of the results are reported in Table 5.13.

Using the 528 TEU/m value from Drewry reports, the total number of $TEUs$ can be calculated as $(1500x528) = 792\,000$, and $(2000x528) = 1056\,000$, which are well below the $TEUs$ calculated above given the port statistics. The parameter checks should be performed carefully for this port in order to attain logical results.

Table 5.13. Optimal Quay Lengths for Port Qasim

With	$\mathbf{Q_{opt}}$	**Cost ($)**	**Annual Revenue ($)**	**Profit ($)**
Constraint	$2000m$	4.0×10^8	3.59×10^7	3.17×10^8
Without	$\mathbf{Q_{opt}}$	**Cost ($)**	**Annual Revenue ($)**	**Profit ($)**
Constraint	$1500m$	3.0×10^8	3.28×10^7	3.56×10^8

Table 5.14. Blocking Probabilities for Port Qasim

Class No	b_i (**m**)	Pr (**Blocking**) (**with constraint**)	Pr (**Blocking**) (**without constraint**)
1	5	0.0003	0.0008
2	15	0.0009	0.0046
3	25	0.0017	0.0084
4	35	0.0024	0.0123
5	45	0.0032	0.0163
6	55	0.0040	0.0205
7	65	0.0048	0.0247
8	75	0.0056	0.0291
9	85	0.0065	0.0336
10	95	0.0074	0.0382
11	105	0.0084	0.0430
12	115	0.0094	0.0479
13	125	0.0104	0.0530
14	135	0.0115	0.0583
15	145	0.0126	0.0638
16	155	0.0138	0.0694
17	165	0.0150	0.0752
18	175	0.0162	0.0811
19	185	0.0175	0.0871
20	195	0.0189	0.0932

As illustrated in Table 5.14 and Table 5.15 consecutively, blocking probability

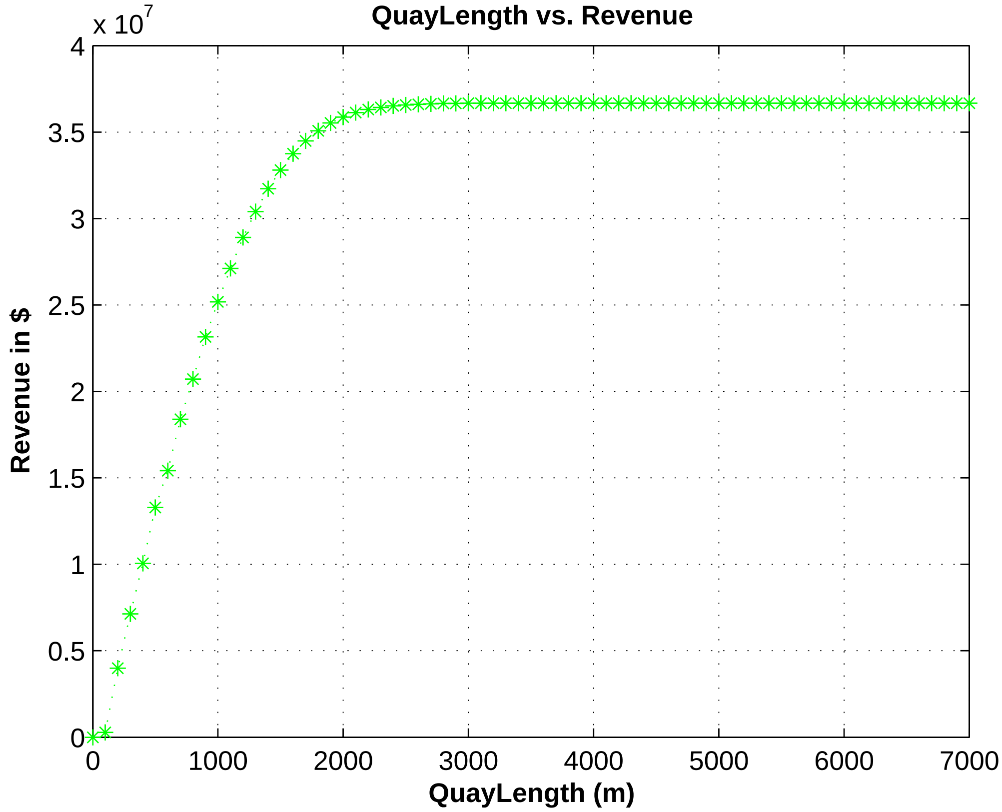

Figure 5.8. Port Qasim Annual Revenue

has a direct effect on satisfying the ship demand. With a quay length of $1500 meters$, the class of ships 35 has an acceptance probability of 80%. That means 20% of that class ships are rejected. Actually, the confidence level 5% is satisfied only before class 12 ships representing a length range of 120 to 130, showing that many of the ships having a length larger than $130 meters$ are not accepted. As suggested before, the quay length without the blocking probability constraint should be carefully examined for the blocking probabilities of the ship classes.

The model results indicate that the port is constructed in an accurate manner to serve the ships in that region. The results obtained via changes in the parameters are given in the next chapter.

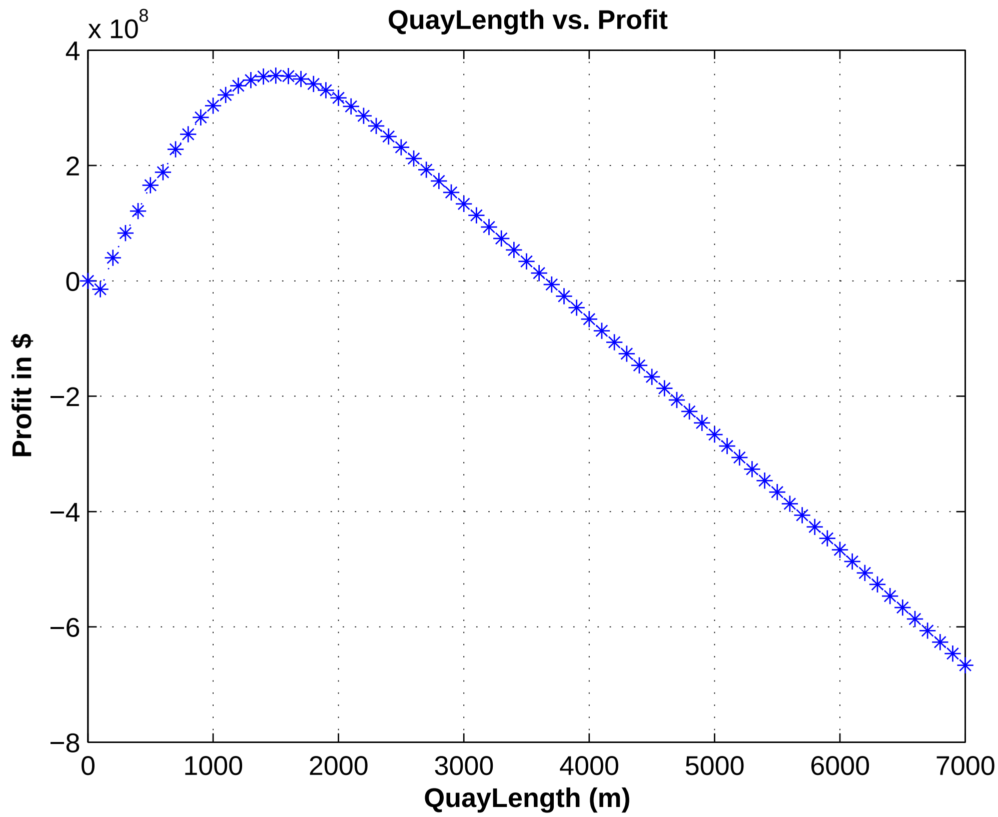

Figure 5.9. Port Qasim Profit

5.4.3. Port Tuticorin, India

Tuticorin Port is an artificial deep-sea harbour formed with rubble mound type parallel breakwaters projecting into the sea for about $4km$. Tuticorin was declared as a minor anchorage port in 1868. Since then there have been various developments over the years. It is the only Port in Southern India to offer a direct weekly container service to U.S.A. Tuticorin Port is located strategically close to the East-West International sea routes on the South Eastern coast of India, having good road/rail connectivity. Port consists of 13 berths, making a total quay length of approximately $2610 meters$. The cargo handled is given as 12605696 $tons$ of bulk cargo and 307310 TEU of containerized cargo. The conversion between $tons$ and $TEUs$ is performed with a factor of 12.8 regarding the port data. Therefore, this value is used to turn tons into $TEUs$ for this port. Then the total handled cargo becomes $307310 + (12605696/12.8) = 1292130$. The layout of the port is given in Figure 5.10. The berth lengths, on the other hand, are

Table 5.15. Blocking Probabilities for Port Qasim (continued)

Class No	b_i **(m)**	Pr (**Blocking**) **(with constraint)**	Pr (**Blocking**) **(without constraint)**
21	205	0.0203	0.0994
22	215	0.0218	0.1056
23	225	0.0233	0.1119
24	235	0.0249	0.1181
25	245	0.0265	0.1243
26	255	0.0281	0.1305
27	265	0.0298	0.1367
28	275	0.0315	0.1431
29	285	0.0333	0.1495
30	295	0.0352	0.1562
31	305	0.0370	0.1629
32	315	0.0390	0.1698
33	325	0.0409	0.1769
34	335	0.0430	0.1840
35	345	0.0451	0.1914

tabulated and given in Table 5.16.

Data for 102 *days* is achieved for this port, and the velocity component calculated for the analysis is $47m/day$. When the blocking probability is considered, the output length value is $2900meters$, whereas the result happens to be $2500meters$ without considering blocking. The revenue and profit functions and the summary of the results are given in Table 5.17.

Using the 528 TEU/m value from Drewry reports, the total number of $TEUs$ can be calculated as $(2500x528) = 1320\,000$, and $(2900x528) = 1531200$, which very well fits the results obtained via the port statistics.

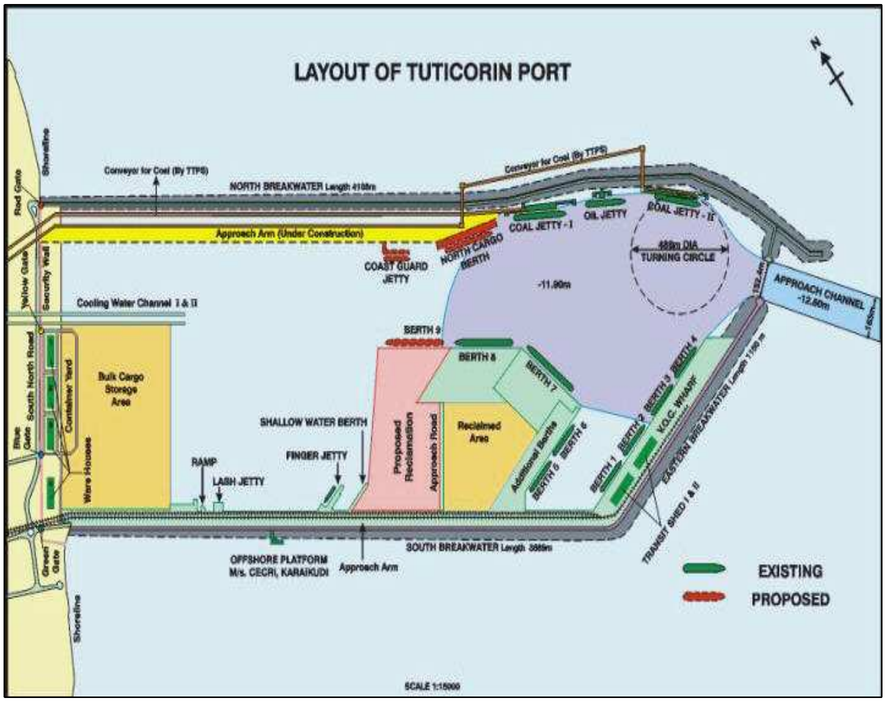

Figure 5.10. Tuticorin Layout

Table 5.16. Berth Lengths of Port Tuticorin

Berth I	168m
Berth II	168m
Berth III	192m
Berth IV	192m
Berth V	168m
Berth VI	168m
Berth VII	370m
Berth VIII	275.5m
Shallow Draught Berth	140m
Passenger Jetty	121m
Oil Jetty	228m
Coal Jetty I-II	210m(each)

Table 5.17. Optimal Quay Lengths for Port Tuticorin

With	$\mathbf{Q_{opt}}$	**Cost (\$)**	**Annual Revenue (\$)**	**Profit (\$)**
Constraint	$2900m$	5.8×10^8	6.80×10^7	7.80×10^8
Without	$\mathbf{Q_{opt}}$	**Cost (\$)**	**Annual Revenue (\$)**	**Profit (\$)**
Constraint	$2500m$	5.0×10^8	6.54×10^7	8.09×10^8

Table 5.18. Blocking Probabilities for Port Tuticorin

Class No	b_i **(m)**	Pr (**Blocking**) **(with constraint)**	Pr (**Blocking**) **(without constraint)**
1	5	0.0004	0.0013
2	15	0.0013	0.0041
3	25	0.0021	0.0069
4	35	0.0030	0.0098
5	45	0.0040	0.0128
6	55	0.0049	0.0158
7	65	0.0059	0.0189
8	75	0.0069	0.0221
9	85	0.0080	0.0253
10	95	0.0090	0.0287
11	105	0.0102	0.0321
12	115	0.0113	0.0355
13	125	0.0125	0.0391
14	135	0.0137	0.0427
15	145	0.0150	0.0464
16	155	0.0163	0.0501
17	165	0.0176	0.0540
18	175	0.0190	0.0579
19	185	0.0204	0.0619
20	195	0.0219	0.0660

As seen from Table 5.18 and 5.19, with a quay length of $2500meters$, the class

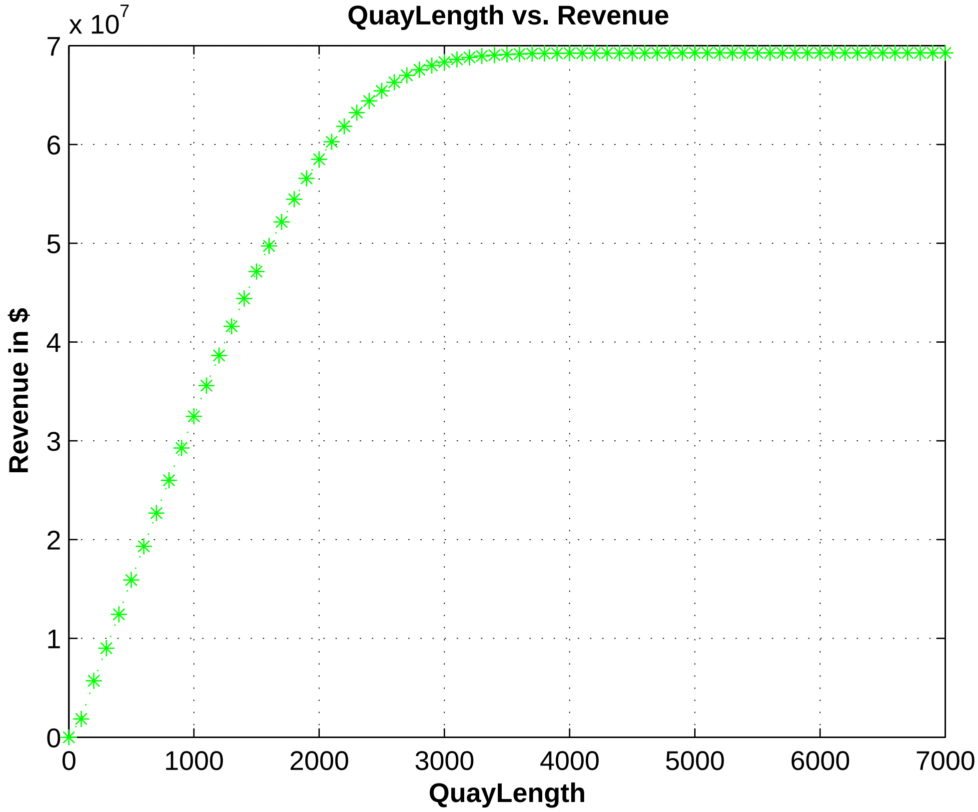

Figure 5.11. Tuticorin Annual Revenue

of ships 35 has an acceptance probability of 76%. That means only 76% of that class ships are accepted. Actually, the confidence level 5% is satisfied only before class 16 ships representing a length range of 160 to 170, showing that some of the ships having a length larger than 170*meters* are not accepted. As suggested before, the quay length without the blocking probability constraint should be carefully examined for the blocking probabilities of the ship classes.

The model results indicate that the port has an efficient length to serve the ships in that region. The results obtained via changes in the parameters are given in the next chapter.

For the ports considered up to now, it can be concluded that the model is validated by means of comparing the actual quay lengths with the calculated ones with and without blocking probability constraint. The key issue here is that these ports are

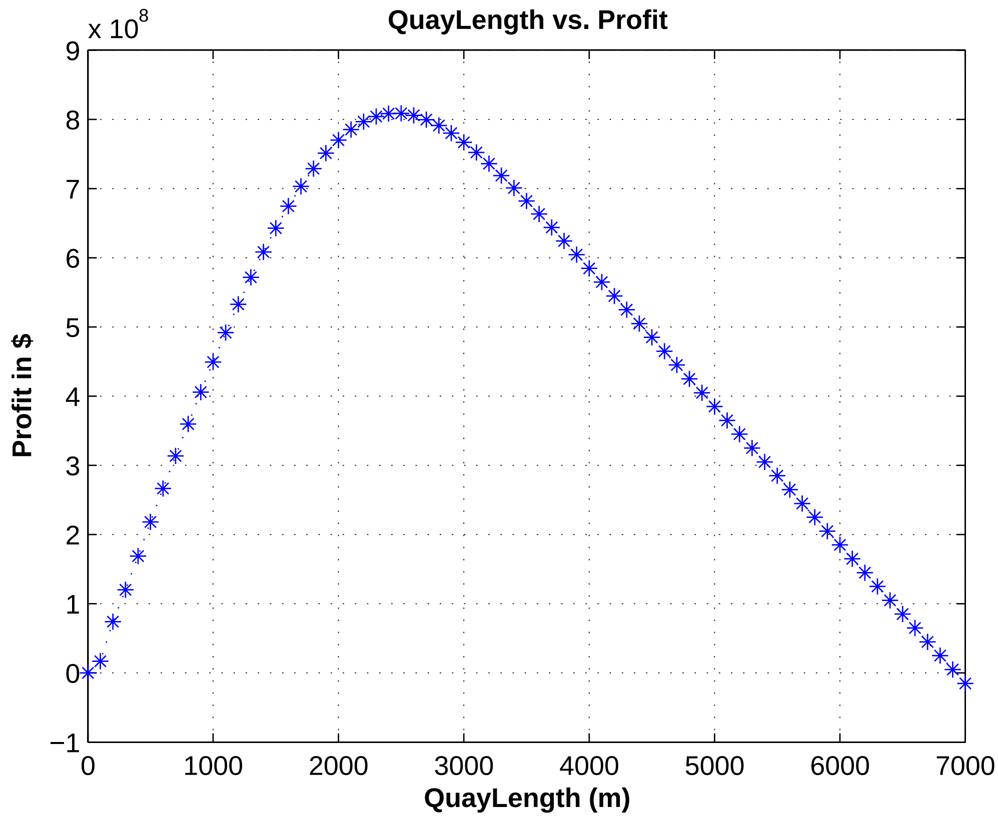

Figure 5.12. Tuticorin Profit

considered as efficient enough to make it able to perform a validation for the model. Figure 5.13 gives a brief summary of the quay length comparison and validation for these ports. The results obtained from the model is given with the star markers for each port. On the other hand, the actual port lengths can be seen as the circled ones. For Kumport and Port Qasim, the resulting quay length range is lower than the original one. However, for Port Tuticorin, the actual quay length happens to be just in between the range of values obtained from the analysis.

5.4.4. Port Honolulu, USA

The Island of Oahu in Hawai is distinguished by three of the State's nine commercial harbors - Barbers Point, Kewalo Basin and Honolulu Harbor. Honolulu Harbor, with a length of approximately $9250 meters$, is the largest and most singularly important of Oahu's and the State's commercial harbors. Its success as a world-renowned

Table 5.19. Blocking Probabilities for Port Tuticorin(continued)

Class No	b_i (**m**)	Pr (**Blocking**) **(with constraint)**	Pr (**Blocking**) **(without constraint)**
21	205	0.0234	0.0702
22	215	0.0249	0.0744
23	225	0.0265	0.0787
24	235	0.0281	0.0831
25	245	0.0298	0.0876
26	255	0.0315	0.0922
27	265	0.0333	0.0968
28	275	0.0351	0.1016
29	285	0.0370	0.1064
30	295	0.0389	0.1113
31	305	0.0409	0.1162
32	315	0.0429	0.1213
33	325	0.0450	0.1264
34	335	0.0471	0.1317
35	345	0.0493	0.1370

port is responsible for the evolution of an ancient Hawaiian village into the State's capitol city. Honolulu Harbor bears a crucial responsibility as the State's port-of-entry for nearly all imported goods - a figurative umbilical cord sustaining Hawaii's modern life. Honolulu Harbor not only continues to function as the hub of Port Hawaii, receiving, consolidating and distributing practically all overseas cargo shipments, but finds itself catering to passenger and fishing operations and distraught with countless requests for additional accommodations. More than 11 *million short tons* of cargo is handled in Port Honolulu every year. This makes an amount of about 10 *million metric tons*. This value makes approximately 2000000 $TEUs$ handled annually. The port consists of about 60 piers and their lengths are given in Table 5.20.

The ship data of 91 *days* is attained for the Honolulu, and the velocity calculated

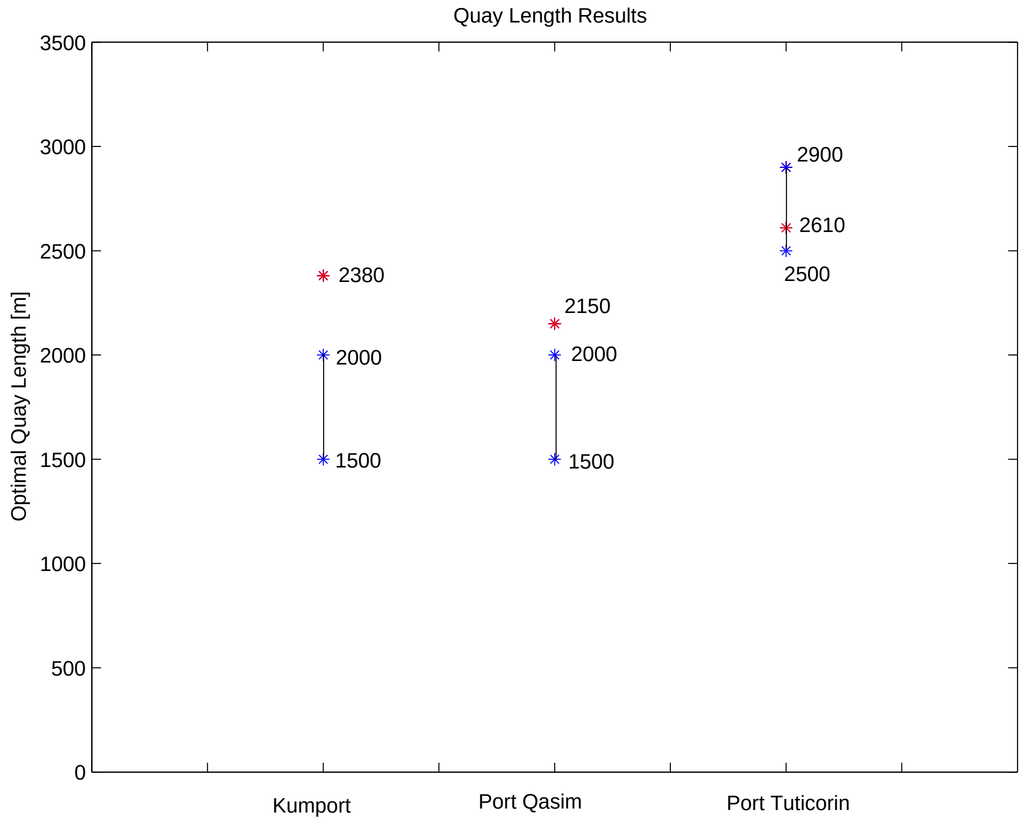

Figure 5.13. Quay Length Comparison Figure

for the analysis is $68m/day$. Optimal quay length results show that with the blocking probability constraint, the output length value is $4100meters$. On the other hand, not considering the constraint, the resultant value is $3700meters$. For this case, it will be useful to examine the resulting blocking probabilities carefully so as to the fact that longer ship classes have a higher tendency to be rejected. Using the 528 TEU/m value from Drewry reports, the total number of $TEUs$ can be calculated as $(3700x528) = 1953600$, and $(4100x528) = 2164800$, which are well below the $TEUs$ calculated above given the port statistics. The parameter check should be performed carefully for this port in order to attain logical results. The revenue and profit functions and the summary of the results are given in Table 5.21.

As seen from Table 5.23 and Table 5.24, with a quay length of $3700meters$, the class of ships 35 has an acceptance probability of 90%. That means only 10% of that class ships are rejected. Actually, the confidence level 5% is satisfied before class 22 ships representing a length range of 220 to 230, showing that some of the ships having

Table 5.20. Pier Lengths of Port Honolulu

Piers 1&2	2967m(total)	**Piers 28&29**	1290m(total)
Pier 4	325m	**Pier 30**	270m
Pier 5	100m	**Piers 31A,31,32&33**	1440m(total)
Pier 6	250m	**Pier 34**	550m
Pier 7	535m	**Pier 35**	705m
Pier 8	595m	**Pier 36**	1046m
Piers 9,10&11	1564m(total)	**Pier 37**	405m
Piers 13&14	770m(total)	**Pier 38**	165m
Pier 15	535m	**Pier 39**	2143m
Pier 16	660m	**Pier 40**	2260m
Pier 17	803m	**Pier 41**	400m
Pier 18	212m	**Pier 42A**	200m
Piers 19&20	1060m	**Pier 45**	678m
Pier 21	495m	**Pier 51A**	556m
Piers 22&23	800m(total)	**Piers 51B&51C**	1346m(total)
Piers 24&25	575m(total)	**Piers 52A,52B&53**	3000m(total)
Pier 26	695m	**Pier 60**	250m
Pier 27	815m		

Table 5.21. Optimal Quay Lengths for Port Honolulu

With Constraint	$\mathbf{Q_{opt}}$	**Cost ($)**	**Annual Revenue ($)**	**Profit ($)**
	4100m	8.2×10^8	1.03×10^8	1.24×10^9
Without Constraint	$\mathbf{Q_{opt}}$	**Cost ($)**	**Annual Revenue ($)**	**Profit ($)**
	4100m	7.4×10^8	9.99×10^7	1.26×10^9

a length larger than 230$meters$ are not accepted. If a confidence level of 10% is used, a quay length 3700$meters$ will also satisfy the blocking probability constraint.

The model results are lower than the original quay length. However, checking carefully relevant parameters, more logical explanations can be attained. The results obtained via changes in the parameters are given in the next chapter. Actually, Port

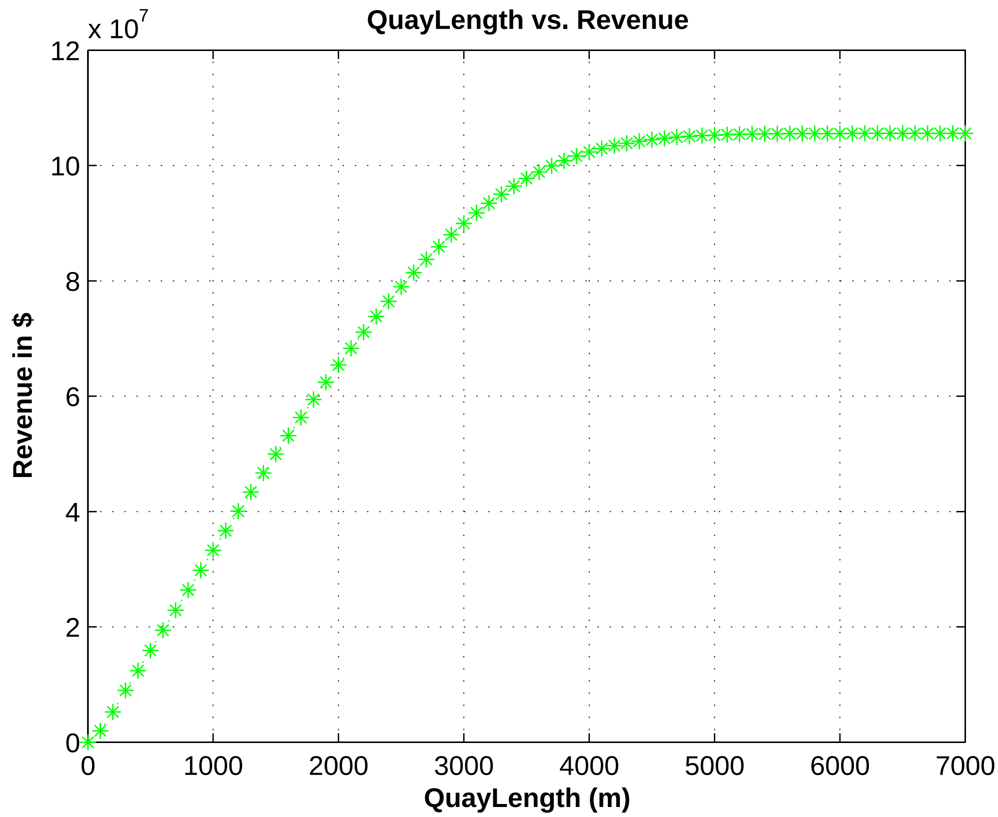

Figure 5.14. Honolulu Annual Revenue

Honolulu, with 60 piers, is a port consisting of many subterminals handling many different cargos, and that's why the results obtained at the end of the analysis are not very good. This is also the case for the other ports studied in this work, Port Bilbao, Spain and Port İzmit, Türkiye. They consist of many subports, including many different terminals, which make it very difficult to observe and model the existing structure. The ship data is achieved for the overall port, nevertheless the data for each subport should be used in the model to obtain satisfactory results, which is not available. Besides, different subports will have different structures, and they must be examined separately. The arrival rates and velocities will be different for each subport. This facts result in unsatisfactory outcomes in the model when the overall port is considered.

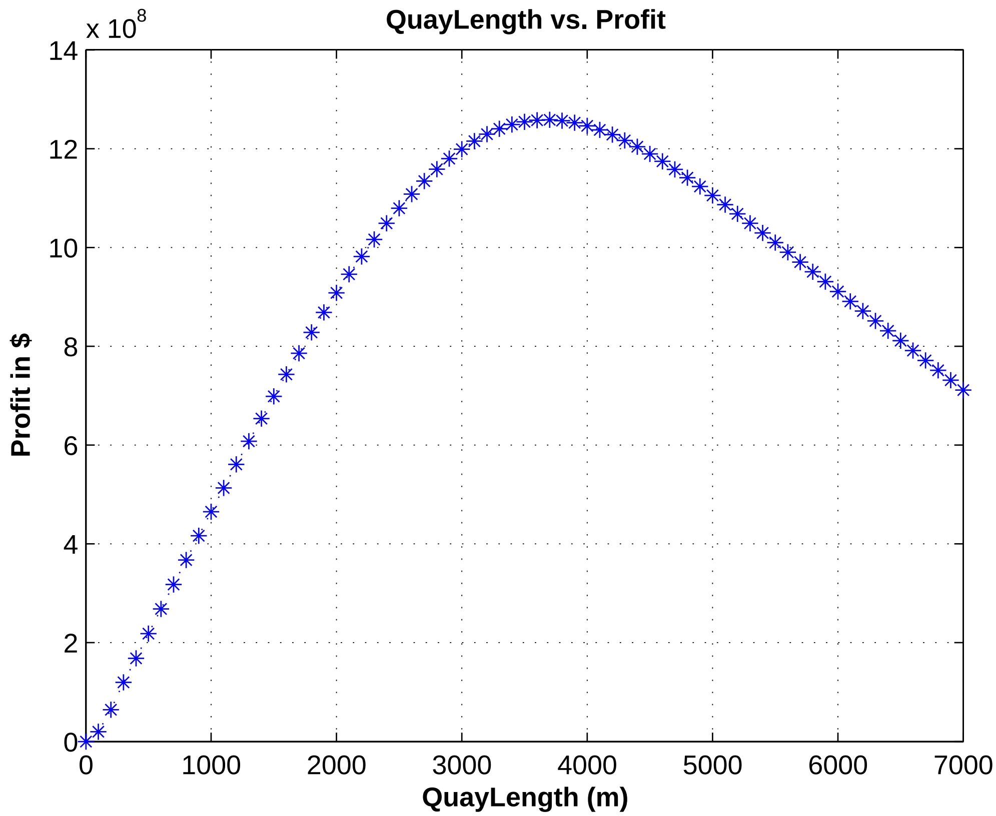

Figure 5.15. Honolulu Profit

Table 5.22. Blocking Probabilities for Port Honolulu

Class No	b_i (**m**)	Pr (**Blocking**) **(with constraint)**	Pr (**Blocking**) **(without constraint)**
1	5	0.0005	0.0010
2	15	0.0014	0.0031
3	25	0.0023	0.0052
4	35	0.0033	0.0073
5	45	0.0042	0.0094
6	55	0.0052	0.0116
7	65	0.0062	0.0138
8	75	0.0073	0.0161
9	85	0.0083	0.0184
10	95	0.0094	0.0207
11	105	0.0105	0.0231
12	115	0.0116	0.0255
13	125	0.0128	0.0279
14	135	0.0139	0.0304
15	145	0.0151	0.0329
16	155	0.0163	0.0355
17	165	0.0176	0.0381
18	175	0.0188	0.0407
19	185	0.0201	0.0434
20	195	0.0214	0.0461

Table 5.23. Blocking Probabilities for Port Honolulu(continued)

Class No	b_i (**m**)	Pr (**Blocking**) **(with constraint)**	Pr (**Blocking**) **(without constraint)**
21	205	0.0227	0.0489
22	215	0.0241	0.0516
23	225	0.0255	0.0545
24	235	0.0269	0.0573
25	245	0.0283	0.0603
26	255	0.0298	0.0632
27	265	0.0313	0.0662
28	275	0.0328	0.0692
29	285	0.0344	0.0723
30	295	0.0359	0.0754
31	305	0.0375	0.0786
32	315	0.0392	0.0818
33	325	0.0408	0.0850
34	335	0.0425	0.0883
35	345	0.0443	0.0916

6. SCENARIO ANALYSIS AND EXTENSIONS

6.1. Sensitivity Analysis

It will be logical to check the structure according to different parameter values to ensure that the behaviour occurs as expected. To illustrate, suppose that the daily number of ships arriving at a port is actually more than the one used in the model. If the arrival rate is increased, then the optimum quay length is expected to be more as other parameters are kept constant. Another example may be the increase in the velocity. If the discharge rate of the port increases, then the quay length obtained at the end should be lower than the former one. If the ships are served faster, the quay should be smaller in length given that every other parameter is constant. It will be convenient to study these parameters and the model's behaviour according to changes in the parameters.

6.1.1. Arrival Rate

The model is run for three different arrival rates, namely, λ, the arrival rate obtained from the original data, 1.1λ, 10% increased arrival rate, and 0.9λ, 10% decreased arrival rate.

The expected behaviour is that the length should react directly proportional to any change in the arrival rates. The model is verified by attaining expected behaviour. Indeed, this arrival rate issue is very critical. For instance, the amount of additional quay that has to be constructed owing to an increase in the daily number of ships can be achieved by the results of this model according to arrival rate changes.

6.1.2. Velocity (Handling Rate)

The model is verified for three cases, high, normal and low velocities. The normal velocity is the one obtained from the original port and ship data. This velocity is increased and decreased about 30%, to attain the high and low velocity values. The quay is expected to response the velocity change in an inversely proportional manner. The velocities obtained from the data differs from $47m/day$ to $83m/day$. Hence, it is appropriate to use $100m/day$ as the high velocity and $50m/day$ as the low velocity parameters for the ports, except for Port Tuticorin which has a velocity of $47m/day$. The analysis is also carried out with velocities $100m/day$ and $75m/day$ for Port Tuticorin.

6.1.3. Interest Rate

Interest rate is very important due to the fact it is the only parameter used to turn the annual revenues into present value for the comparison with the construction cost. The 5% rate used is an appropriate value as the currency used is dollars for both revenues and costs. However, there are many considerations in selecting the interest rate for public selections. A 10% discount rate was specified in March 1972 by the U.S. Office of Management and Budget (OMB) Circular A-94, for use in federal government investments. The model is also employed with this interest rate. Actually, the lower the interest rate, the more the present value. To illustrate, suppose you have some money to invest. With a lower interest value, your annual returns will be low. This is directly opposite case of the case in our model. If you have a constant annual return, then to obtain it, you have to have more present value of money with a lower interest rate.

6.1.4. Blocking Probability

The level of confidence to be chosen takes great interest. One may consider 90% or 95% of the ships coming are to be accepted at the quay when there is enough space. Any other value will not be efficient for the structure of the model. Of course, to satisfy a larger probability value, the model will pursue a way to increase the quay length even if the profit happens to be less than zero at the end. Therefore, if negative profits are attained for the optimal quay length, a negative sign is placed near the length value in the tables. The results are given in the proceeding sections as tabulated.

6.1.5. Experiments with Real Cases

The worse and better cases are studied in this section for the given ports.

Table 6.1. Sensitivity Results for Kumport

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	$\mathbf{Q_{opt}}$ **(with constraint)**	$\mathbf{Q_{opt}}$ **(without constraint)**
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1700(−)	900
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1800(−)	900
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1700	1300
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1800	1300
$1.1 * \lambda$	$V = 77$	$i = 0.10$	$\alpha_1 = 0.90$	2000	1200
$1.1 * \lambda$	$V = 77$	$i = 0.10$	$\alpha_2 = 0.95$	2200(−)	1200
$1.1 * \lambda$	$V = 77$	$i = 0.05$	$\alpha_1 = 0.90$	2000	1700
$1.1 * \lambda$	$V = 77$	$i = 0.05$	$\alpha_2 = 0.95$	2200	1700
$1.1 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	2600	1900
$1.1 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	2900	1900
$1.1 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	2600	2400
$1.1 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	2900	2400

6.1.5.1. Kumport. From Table 6.1, Table 6.2 and Table 6.3, it can be concluded that the model behaves and reacts accurately according to the parameter changes. Especially the increase in arrival rate is significant because this can happen any time in the future. This sensitivity analysis gives a clue for the question how much to extend the quay length to satisfy the increase in the daily number of ships. It is also apparent that the confidence level has no influence on the case without the blocking probability constraint. The lower interest rate gives higher revenue and this leads to larger quay length values whereas slow velocities directly make an increase in the length values. It can be concluded that the original quay length for Kumport is in the optimal range. The negative sign near the quay length value indicates that the profit at that length is less than zero indicating that the blocking constraint is satisfied only when the profit

Table 6.2. Sensitivity Results for Kumport (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	$\mathbf{Q_{opt}}$ **(with constraint)**	$\mathbf{Q_{opt}}$ **(without constraint)**
λ	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1600(−)	900
λ	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1700(−)	900
λ	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1600	1200
λ	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1700	1200
λ	$V = 77$	$i = 0.10$	$\alpha_1 = 0.90$	1900	1100
λ	$V = 77$	$i = 0.10$	$\alpha_2 = 0.95$	2000(−)	1100
λ	$V = 77$	$i = 0.05$	$\alpha_1 = 0.90$	1900	1500
λ	$V = 77$	$i = 0.05$	$\alpha_2 = 0.95$	2000	1500
λ	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	2500	1700
λ	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	2700	1700
λ	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	2500	2200
λ	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	2700	2200

is negative.

6.1.5.2. Port Qasim. From the Table 6.4, Table 6.5 and Table 6.6, it is obvious that the model behaves and reacts accurately according to the parameter changes. This sensitivity analysis tries to give an answer for the question how much to extend the quay length to satisfy the increase in the daily number of ships. Besides, the confidence level has no influence on the case without the blocking probability constraint. The lower interest rate gives higher revenue and this leads to larger quay length values whereas slow velocities directly cause an increase in the length values. It can be concluded that the original quay length for Port Qasim is in the optimal range. The negative sign near the quay length value indicates that the profit at that length is less than zero. That is, the blocking constraint is satisfied only when the profit is negative.

Table 6.3. Sensitivity Results for Kumport (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	**Q_{opt} (with constraint)**	**Q_{opt} (without constraint)**
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1500(−)	800
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1600(−)	800
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1500	1100
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1600	1100
$0.9 * \lambda$	$V = 77$	$i = 0.10$	$\alpha_1 = 0.90$	1700	1000
$0.9 * \lambda$	$V = 77$	$i = 0.10$	$\alpha_2 = 0.95$	1900(−)	1000
$0.9 * \lambda$	$V = 77$	$i = 0.05$	$\alpha_1 = 0.90$	1700	1400
$0.9 * \lambda$	$V = 77$	$i = 0.05$	$\alpha_2 = 0.95$	1900	1400
$0.9 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	2300	1500
$0.9 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	2500	1500
$0.9 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	2300	2000
$0.9 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	2500	2000

6.1.5.3. Port Tuticorin. From Table 6.7, Table 6.8 and Table 6.9, it can be seen that the model behaves and reacts accurately according to changes in the parameter values. A possible change in number of ship arrivals in the future makes the arrival rate change very important. This parameter study tries to find a way how much to extend the quay length to satisfy the increase in the daily number of ships. It is obvious that the confidence level has no influence on the case without the blocking probability constraint. The lower interest rate gives higher revenue and this leads to larger quay length values whereas slow velocities directly make an increase in the length values. It can be concluded that the quay length for Port Tuticorin can be considered as optimal although the resulting length value is a bit higher than the original quay length. The negative sign near the quay length value indicates that the profit at that length is less than zero indicating that the blocking constraint is satisfied only when the profit is negative.

Table 6.4. Sensitivity Results for Port Qasim

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	$\mathbf{Q_{opt}}$ **(with constraint)**	$\mathbf{Q_{opt}}$ **(without constraint)**
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1700(-)	900
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1900(-)	900
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1700	1400
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1900	1400
$1.1 * \lambda$	$V = 83$	$i = 0.10$	$\alpha_1 = 0.90$	1900	1200
$1.1 * \lambda$	$V = 83$	$i = 0.10$	$\alpha_2 = 0.95$	2100(-)	1200
$1.1 * \lambda$	$V = 83$	$i = 0.05$	$\alpha_1 = 0.90$	1900	1600
$1.1 * \lambda$	$V = 83$	$i = 0.05$	$\alpha_2 = 0.95$	2100	1600
$1.1 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	2700	1900
$1.1 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	3000	1900
$1.1 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	2700	2500
$1.1 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	3000	2500

<u>6.1.5.4. Port Honolulu.</u> From the Table 6.10, Table 6.11 and Table 6.12, it is apparent that the model behaves and reacts accurately according to the parameter changes. The most important point is the change in arrival rates as obvious. Actually, comparing the model results and the original quay length of $9250 meters$, it can be concluded that the port is somewhat overdesigned given the demand. However, there may be various reasons for the longer quay length. First of all, the port consists of several subterminals each handling different cargos. This directly influences the results, and therefore a model improvement for this purpose is suggested in the conclusion part. Moreover, the model results may be owing to a forecasting manner of construction. That is, future extensions or future increase in ship demand may have been considered just at the very beginning, or the demand at the time of construction may have been more than the one today. Another reason may be the velocity. Using an optimizing manner such as improving the port with cranes or fastening modules, the discharge rate may have been decreased throughout the years.

Table 6.5. Sensitivity Results for Port Qasim (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	$\mathbf{Q_{opt}}$ **(with constraint)**	$\mathbf{Q_{opt}}$ **(without constraint)**
λ	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1600(-)	900
λ	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1800(-)	900
λ	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1600	1300
λ	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1800	1300
λ	$V = 83$	$i = 0.10$	$\alpha_1 = 0.90$	1800(-)	1000
λ	$V = 83$	$i = 0.10$	$\alpha_2 = 0.95$	2000(-)	1000
λ	$V = 83$	$i = 0.05$	$\alpha_1 = 0.90$	1800	1500
λ	$V = 83$	$i = 0.05$	$\alpha_2 = 0.95$	2000	1500
λ	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	2500	1700
λ	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	2800	1700
λ	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	2500	2300
λ	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	2800	2300

Besides, the confidence level has no influence on the case without the blocking probability constraint. The higher interest rate gives lower revenue and this leads to smaller quay length values whereas fast velocities directly make an decrease in the length values. The negative sign near the quay length value indicates that the profit at that length is less than zero indicating that the blocking constraint is satisfied only when the profit is negative.

6.2. An Approximation for Handling Multi-Quay Situations

The model developed determines the optimum length of a single quay. However, in real life, some of the ports may have multi-quay structure because of the space considerations. That is, the quay may have to be divided into several parts like the one in Kumport. This mostly represents the case in Türkiye. Due to the inadequacy of land, the quays may have to be constructed perpendicular to the shore, longing into

Table 6.6. Sensitivity Results for Port Qasim (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	$\mathbf{Q_{opt}}$ **(with constraint)**	$\mathbf{Q_{opt}}$ **(without constraint)**
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1500(-)	700
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1700(-)	700
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1500	1200
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1700	1200
$0.9 * \lambda$	$V = 83$	$i = 0.10$	$\alpha_1 = 0.90$	1700(-)	900
$0.9 * \lambda$	$V = 83$	$i = 0.10$	$\alpha_2 = 0.95$	1900(-)	900
$0.9 * \lambda$	$V = 83$	$i = 0.05$	$\alpha_1 = 0.90$	1700	1400
$0.9 * \lambda$	$V = 83$	$i = 0.05$	$\alpha_2 = 0.95$	1900	1400
$0.9 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	2300	1600
$0.9 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	2600	1600
$0.9 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	2300	2100
$0.9 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	2600	2100

the sea. Nevertheless, as there is also a limit of protruding into the sea, the entire structure can not be built in terms of a single, very long quay. The answer lies on dividing the original quay length into parts and constructing more than one quay with smaller lengths. On account of this issue, the model is revised to check the optimality condition for divided quay lengths. After obtaining the optimal value, the length is split into pieces of two, three, four and five equal pieces, and profit obtained from these calculations are checked with the original profit obtained from the entire quay length. The analysis is carried out for both including and excluding the blocking probability constraint. With this quay splitting approach, a lower bound for revenues is achieved, whereas the one obtained from the analysis with the original quay length forms an upper bound. It can also be possible to find out the optimal way of splitting the original quay regarding this study. For the sake of simplicity, equal quay pieces are considered in the model.

Table 6.7. Sensitivity Results for Port Tuticorin

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	**$\mathbf{Q_{opt}}$ (with constraint)**	**$\mathbf{Q_{opt}}$ (without constraint)**
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1700	1000
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1900(-)	1000
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1700	1400
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1900	1400
$1.1 * \lambda$	$V = 75$	$i = 0.10$	$\alpha_1 = 0.90$	2100	1300
$1.1 * \lambda$	$V = 75$	$i = 0.10$	$\alpha_2 = 0.95$	2300	1300
$1.1 * \lambda$	$V = 75$	$i = 0.05$	$\alpha_1 = 0.90$	2100	1800
$1.1 * \lambda$	$V = 75$	$i = 0.05$	$\alpha_2 = 0.95$	2300	1800
$1.1 * \lambda$	$V = 47$	$i = 0.10$	$\alpha_1 = 0.90$	2900	2100
$1.1 * \lambda$	$V = 47$	$i = 0.10$	$\alpha_2 = 0.95$	3100	2100
$1.1 * \lambda$	$V = 47$	$i = 0.05$	$\alpha_1 = 0.90$	2900	2700
$1.1 * \lambda$	$V = 47$	$i = 0.05$	$\alpha_2 = 0.95$	3100	2700

The division is handled in a manner that the arrival rate is kept constant in every division state. For example, consider that it is desired to build an initial optimal quay length of Q working with a ship arrival rate of λ. However, suppose that there happens to be not enough space to construct this amount of length as a whole. Therefore, the quay has to be split into parallel pieces. Now, again suppose that quay will be divided into two equal sections of length $Q/2$ each. The arrival rate for two pieces are calculated with the help of blocking probabilities. To recall, blocking probability gives the percentage of the ships rejected for each class. So, the model is executed for a divided length of quay and the blocking probabilities, β_i, of the length $Q/2$ for each class is calculated. Then, the analysis is carried out as if one of the pieces is given an arrival rate of $\lambda(1 - \beta_i)$ for each class. This indicates that the ships that are to be rejected does not enter the first quay. Then the model is executed with the same quay length of $Q/2$, but this time each class has an arrival rate of $\lambda\beta_i$. These are exactly the ships that are supposed to be lost at the former quay as they are not accepted.

Table 6.8. Sensitivity Results for Port Tuticorin (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	**Q_{opt} (with constraint)**	**Q_{opt} (without constraint)**
λ	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1600(-)	900
λ	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1800(-)	900
λ	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1600	1300
λ	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1800	1300
λ	$V = 75$	$i = 0.10$	$\alpha_1 = 0.90$	2000	1200
λ	$V = 75$	$i = 0.10$	$\alpha_2 = 0.95$	2200(-)	1200
λ	$V = 75$	$i = 0.05$	$\alpha_1 = 0.90$	2000	1700
λ	$V = 75$	$i = 0.05$	$\alpha_2 = 0.95$	2200	1700
λ	$V = 47$	$i = 0.10$	$\alpha_1 = 0.90$	2700	1900
λ	$V = 47$	$i = 0.10$	$\alpha_2 = 0.95$	2900	1900
λ	$V = 47$	$i = 0.05$	$\alpha_1 = 0.90$	2700	2500
λ	$V = 47$	$i = 0.05$	$\alpha_2 = 0.95$	2900	2500

But, they are not lost as they are transferred to the second quay. Apparently, the total rate sums up to λ, the arrival rate at the very beginning. So, the daily number of ship rate is kept constant, however the quay is divided into two parts, the former with the accepted ships, the latter with the rejected ships. The acceptance and rejection criteria are to be obtained from originally executed model for a quay length of $Q/2$. In order to produce an approximation for the case where there are three parallel quay pieces, the model with a quay length of $Q/3$ is executed again to obtain the blocking probabilities for each class. Then, the analysis for the first piece is carried out given the class arrival rate of $\lambda(1-\beta_i)$. Next, the blocking probability for each class, say δ_i, are calculated from the model with a length of $Q/3$ and a class arrival rate of $\lambda\beta_i$. Finally, the analysis is performed for the last two quay lengths with arrival rates of $\lambda\beta_i\delta_i$ and $\lambda\beta_i(1-\delta_i)$ consecutively where the rejected ships from the quay of length $Q/3$ are distributed into the remaining pieces. The sum of each arrival rate again gives the original one, as $\lambda\beta_i\delta_i + \lambda\beta_i(1-\delta_i) + \lambda(1-\beta_i)$ is equal to λ. The idea is kept

Table 6.9. Sensitivity Results for Port Tuticorin (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	$\mathbf{Q_{opt}}$ **(with constraint)**	$\mathbf{Q_{opt}}$ **(without constraint)**
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	1500(-)	800
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	1700(-)	800
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	1500	1200
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	1700	1200
$0.9 * \lambda$	$V = 75$	$i = 0.10$	$\alpha_1 = 0.90$	1800	1100
$0.9 * \lambda$	$V = 75$	$i = 0.10$	$\alpha_2 = 0.95$	2000(-)	1100
$0.9 * \lambda$	$V = 75$	$i = 0.05$	$\alpha_1 = 0.90$	1800	1500
$0.9 * \lambda$	$V = 75$	$i = 0.05$	$\alpha_2 = 0.95$	2000	1500
$0.9 * \lambda$	$V = 47$	$i = 0.10$	$\alpha_1 = 0.90$	2500	1700
$0.9 * \lambda$	$V = 47$	$i = 0.10$	$\alpha_2 = 0.95$	2700	1700
$0.9 * \lambda$	$V = 47$	$i = 0.05$	$\alpha_1 = 0.90$	2500	2300
$0.9 * \lambda$	$V = 47$	$i = 0.05$	$\alpha_2 = 0.95$	2700	2300

similar and the analysis is carried out up-to 5 pieces of the quay, as it is in the case of Kumport.

The quay splitting analysis results for selected quay lengths are given in the proceeding tables for each port with an interest rate of 5%, and the original velocities and arrival rates obtained from the data. The length ranges are taken to be $1000-3000$ for Kumport and Port Qasim, and the results are given for the lengths in differences of 500. For Port Tuticorin, the range of quay length values are increased from $1000-3000$ to $2000-4000$, because the optimal quay length is at that range. For Port Honolulu, on the other hand, the range of quay length values are $3000-5000$, including the optimal quay length for Port Honolulu.

As expected, the results obtained from the multi-quay approximations give a lower bound for the revenues and profits. The upper bound, on the other hand, is

Table 6.10. Sensitivity Results for Port Honolulu

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	**Q_{opt} (with constraint)**	**Q_{opt} (without constraint)**
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	3000	2200
$1.1 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	3300	2200
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	3000	2900
$1.1 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	3300	2900
$1.1 * \lambda$	$V = 68$	$i = 0.10$	$\alpha_1 = 0.90$	4000	3200
$1.1 * \lambda$	$V = 68$	$i = 0.10$	$\alpha_2 = 0.95$	4400	3200
$1.1 * \lambda$	$V = 68$	$i = 0.05$	$\alpha_1 = 0.90$	4000	4000
$1.1 * \lambda$	$V = 68$	$i = 0.05$	$\alpha_2 = 0.95$	4400	4000
$1.1 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	5100	4300
$1.1 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	5500	4300
$1.1 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	5100	5100
$1.1 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	5500	5500

given by the values obtained with the original, not divided quay length. Hence, this information can be used to check the efficiency of resulting quay pieces. To illustrate, consider the split quay length calculations for $Q = 2000 meters$ with $i = \%10$ for Kumport. This is an extreme case where the profit value happens to be -3476000\$, a negative value and the revenue is 39700000\$. The optimality of that quay length in spite of a negative profit value is achieved regarding the blocking probability constraint. Revealing the fact that the optimal quay length is $1100 meters$ for those parameters chosen, the scheme seems interesting. $Q = 2000 meters$ is simply in the decreasing part of the quay length versus profit graph with a negative profit value. Moreover, let us concentrate on the multi-quay with 2 parallel pieces. Here, it seems that the first length is working optimally with a positive profit, and there is no need for the second quay piece. That is just because of the fact that the optimal quay length is around that range. The chosen illustration is taken for one of the worst cases just to see the the multi-quay approximation given by the model. As the first quay length

Table 6.11. Sensitivity Results for Port Honolulu (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	**Q_{opt} (with constraint)**	**Q_{opt} (without constraint)**
λ	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	2800	2000
λ	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	3100	2000
λ	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	2800	2600
λ	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	3100	2600
λ	$V = 68$	$i = 0.10$	$\alpha_1 = 0.90$	3700	2900
λ	$V = 68$	$i = 0.10$	$\alpha_2 = 0.95$	4100	2900
λ	$V = 68$	$i = 0.05$	$\alpha_1 = 0.90$	3700	3700
λ	$V = 68$	$i = 0.05$	$\alpha_2 = 0.95$	4100	3700
λ	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	4700	3900
λ	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	5200	3900
λ	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	4700	4700
λ	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	5200	4700

is already optimum for the aforementioned case, there is no need for the construction of the second quay length. This extreme example gives a clue about how to use and interpret the quay splitting model.

6.3. A Generalization for Obtaining Optimal Quay Lengths

It is crucial to obtain a design scheme for optimal quay lengths regardless of the daily ship arrival and length data. That is, the idea is to achieve a scheme where the port planner can determine the optimum quay length with just knowing or forecasting the daily number and mean length of ships at that region, and the average handling rate per day. In the preceding chapters, the model is validated using the data obtained from actual ports and the results are found to be accurate. Now, in this section, the model will be refined in order to calculate the optimum quay length values in a general manner. With this purpose, load is decomposed into its components.

Table 6.12. Sensitivity Results for Port Honolulu (continued)

Arrival Rate (λ)	**Velocity (m/day)** (V)	**Interest Rate** (i)	**Confidence Level** (α)	**$\mathbf{Q_{opt}}$ (with constraint)**	**$\mathbf{Q_{opt}}$ (without constraint)**
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_1 = 0.90$	2600	1800
$0.9 * \lambda$	$V = 100$	$i = 0.10$	$\alpha_2 = 0.95$	2900	1800
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_1 = 0.90$	2600	2400
$0.9 * \lambda$	$V = 100$	$i = 0.05$	$\alpha_2 = 0.95$	2900	2400
$0.9 * \lambda$	$V = 68$	$i = 0.10$	$\alpha_1 = 0.90$	3400	2600
$0.9 * \lambda$	$V = 68$	$i = 0.10$	$\alpha_2 = 0.95$	3800	2600
$0.9 * \lambda$	$V = 68$	$i = 0.05$	$\alpha_1 = 0.90$	3400	3400
$0.9 * \lambda$	$V = 68$	$i = 0.05$	$\alpha_2 = 0.95$	3800	3400
$0.9 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_1 = 0.90$	4300	3500
$0.9 * \lambda$	$V = 50$	$i = 0.10$	$\alpha_2 = 0.95$	4800	3500
$0.9 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_1 = 0.90$	4300	4300
$0.9 * \lambda$	$V = 50$	$i = 0.05$	$\alpha_2 = 0.95$	4800	4300

$$a_i = \lambda_i \tau_i = \lambda q_i \left(\frac{Ship\ Length\ of\ Class\ i}{Velocity}\right) \tag{6.1}$$

$$a_i == \lambda\left(\frac{Number\ of\ Ships\ for\ each\ class}{Total\ Number\ of\ Ships}\right)\left(\frac{Ship\ Length\ of\ Class\ i}{Velocity}\right)$$

Therefore, abbreviating velocity as V,

Table 6.13. Quay Division Results for Kumport

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	1000	3.72×10^8	2.86×10^7
	2	500	2.72×10^8	2.36×10^7
$Q = 1000$	3	340	1.97×10^8	1.98×10^7
	4	250	1.41×10^8	1.71×10^7
	5	200	9.39×10^7	1.47×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	1500	4.33×10^8	3.66×10^7
	2	750	3.60×10^8	3.30×10^7
$Q = 1500$	3	500	2.91×10^8	2.96×10^7
	4	380	2.36×10^8	2.70×10^7
	5	300	1.88×10^8	2.44×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	2000	3.93×10^8	3.97×10^7
	2	1000	3.65×10^8	3.65×10^7
$Q = 2000$	3	670	2.75×10^8	3.38×10^7
	4	500	2.32×10^8	3.16×10^7
	5	400	1.92×10^8	2.96×10^7

$$a_i == \frac{\lambda}{V}\left(\frac{Number\ of\ Ships\ for\ each\ class}{Total\ Number\ of\ Ships}\right)(Ship\ Length\ of\ Class\ i)$$

Now, the significant issue is to represent the actual system with a load and mean ship length value. That is, the aim is to obtain the optimal quay length regardless of anything else, but only considering the load and mean ship length values. As any

Table 6.14. Quay Division Results for Kumport (continued)

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	2500	3.25×10^8	4.13×10^7
	2	1250	2.52×10^8	3.76×10^7
$Q = 2500$	3	840	2.08×10^8	3.53×10^7
	4	630	1.65×10^8	3.34×10^7
	5	500	1.33×10^8	3.16×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	3000	2.26×10^8	4.13×10^7
	2	1500	1.76×10^8	3.86×10^7
$Q = 3000$	3	1000	1.31×10^8	3.66×10^7
	4	750	9.23×10^7	3.46×10^7
	5	600	6.11×10^7	3.31×10^7

given ship demand can be represented by its mean ship length and total load of all ship classes,

$$\sum_{i=1}^{35} a_i == \frac{\lambda}{V}\left(\sum_{i=1}^{35}\left(\frac{Number\ of\ Ships\ for\ each\ class}{Total\ Number\ of\ Ships}\right)(Ship\ Length\ of\ Class\ i)\right)$$

The second part of the equation on the right hand side is simply the mean ship length itself. Then,

$$\sum_{i=1}^{35} a_i == \frac{\lambda}{Velocity}(Mean\ Ship\ Length) \tag{6.2}$$

Table 6.15. Quay Division Results for Port Qasim

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	1000	3.04×10^8	2.52×10^7
	2	500	2.10×10^8	2.05×10^7
$Q = 1000$	3	340	1.04×10^8	1.52×10^7
	4	250	9.90×10^7	1.49×10^7
	5	200	-5.12×10^7	7.44×10^6
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	1500	3.56×10^8	3.28×10^7
	2	750	2.69×10^8	2.84×10^7
$Q = 1500$	3	500	2.11×10^8	2.55×10^7
	4	380	9.82×10^7	2.01×10^7
	5	300	9.21×10^7	1.96×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	2000	3.17×10^8	3.59×10^7
	2	1000	2.36×10^8	3.18×10^7
$Q = 2000$	3	670	1.74×10^8	2.88×10^7
	4	500	1.41×10^8	2.71×10^7
	5	400	6.54×10^7	2.33×10^7

Hence, the model can be easily executed by just this total load and mean length value which are used to obtain the occupied length distribution, $q(j)$. To recall,

$$q(j) = q'(j)q(0) = \frac{1}{j}\left\{\sum_{i=1}^{N} a_i b_i q'(j - b_i)\right\} q(0).$$

It is obvious that $q(j)$ directly depends on the loads and ship lengths for each class.

Table 6.16. Quay Division Results for Port Qasim (continued)

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** ($)	**Annual Revenue** ($)
	1	2500	2.31×10^8	3.66×10^7
	2	1250	1.61×10^8	3.30×10^7
$Q = 2500$	3	840	1.12×10^8	3.04×10^7
	4	630	6.32×10^7	2.85×10^7
	5	500	4.18×10^7	2.71×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** ($)	**Annual Revenue** ($)
	1	3000	1.33×10^8	3.67×10^7
	2	1500	8.28×10^7	3.41×10^7
$Q = 3000$	3	1000	3.73×10^7	3.19×10^7
	4	750	-1.65×10^6	2.99×10^7
	5	600	-4.05×10^6	2.80×10^7

Of course, representing the system with one load and one ship length value, which is simply the mean, the distribution will be obtained via the multiplication of the load and the mean ship length. The analysis is carried out without the blocking probability constraint and with an interest rate of $i = 0.05$. At the end of this analysis, the optimal quay lengths versus different $\lambda/Velocity$ values and mean ship lengths are given in a graphical manner. From these figures, one can easily find out how long to build a quay just knowing the daily number of ships (mean arrival rate) in the region, the discharge rate (velocity) per day and the mean of the ship lengths arriving. To illustrate, consider Kumport. The mean arrival rate for Kumport is 4.41 whereas the mean time is $77m/day$. So, the mean rate/mean time value 4.41/77 is equal to 0.057. Since the average ship length for Kumport is $126meters$, the optimal quay length is around $1500meters$, which is aforementioned in the Data Analysis Chapter. A similar example can also be given for Port Qasim. The mean arrival rate and mean velocity values for Port Qasim are 1.91 and $83m/day$, respectively. Then, the mean rate/mean time value 1.91/83 gives 0.023 leading to quay length of $1500meters$ approximately.

Table 6.17. Quay Division Results for Port Tuticorin

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	2000	7.70×10^8	5.85×10^7
	2	1000	6.41×10^8	5.20×10^7
$Q = 2000$	3	670	5.41×10^8	4.71×10^7
	4	500	4.47×10^8	4.22×10^7
	5	400	3.95×10^8	3.91×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	2500	8.09×10^8	6.54×10^7
	2	1250	6.89×10^8	5.95×10^7
$Q = 2500$	3	840	6.00×10^8	5.49×10^7
	4	630	5.29×10^8	5.17×10^7
	5	500	4.50×10^8	4.75×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	3000	7.67×10^8	6.83×10^7
	2	1500	6.41×10^8	6.20×10^7
$Q = 3000$	3	1000	5.60×10^8	5.80×10^7
	4	750	4.97×10^8	5.49×10^7
	5	600	4.44×10^8	5.22×10^7

Interestingly, the optimal quay length values for Kumport and Port Qasim appear to be the same. The reason for this similarity can be easily explained. First, although the mean rate/mean time value for Kumport is much more larger, the mean ship length for Port Qasim is $193 meters$ which is more than the one for Kumport. Hence, as the ships arriving to Port Qasim have bigger lengths and less ship arrival rates, the optimal quay length values for both ports approximately appears to be the same as $1500 meters$. Actually, to calculate $q(j)$, the total load value is once more multiplied by the mean ship length. Therefore, it can be concluded that the structure is mainly controlled by

Table 6.18. Quay Division Results for Port Tuticorin (continued)

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	3500	6.82×10^8	6.91×10^7
	2	1750	5.58×10^8	6.29×10^7
$Q = 3500$	3	1170	4.88×10^8	5.95×10^7
	4	880	4.29×10^8	5.67×10^7
	5	700	3.81×10^8	5.40×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	4000	5.85×10^8	6.92×10^7
	2	2000	4.79×10^8	6.39×10^7
$Q = 4000$	3	1330	4.22×10^8	6.10×10^7
	4	1000	3.60×10^8	5.80×10^7
	5	800	3.11×10^8	5.55×10^7

the function $\lambda(Mean\ Ship\ Length^2)/Velocity$. That value is $0.057x126^2 = 905$ for Kumport whereas it is calculated as $0.023x193^2 = 857$ for Port Qasim.

Moreover, as the optimum quay length is attained regardless of ship demand data, a new approach considering the cost and revenue per unit length as relevant parameters can be used. The cost and revenue per length values are decreased and increased in an amount of 25% and the proceeding figures giving the optimal quay length values regardless of ship demand data are obtained. The cost per unit length is taken as \$200000/m originally. However, here, the model is also employed with \$150000/m and \$250000/m. The revenue per unit length, on the other hand, is normally given as \$40000/m regarding Drewry studies. In this section, \$30000/m and \$50000/m are also used in the analysis. From the figures, the quay length values can be achieved for many different schemes, and it is possible to use interpolation in that means. It is very encouraging and interesting that the relationship appears to be almost linear.

Table 6.19. Quay Division Results for Port Tuticorin

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	3000	1.20×10^9	8.99×10^7
	2	1500	1.01×10^9	8.07×10^7
$Q = 3000$	3	1000	8.74×10^8	7.37×10^7
	4	750	7.54×10^8	6.77×10^7
	5	600	6.42×10^8	6.21×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	3500	1.25×10^9	9.77×10^7
	2	1750	1.08×10^9	8.91×10^7
$Q = 3500$	3	1170	9.49×10^8	8.25×10^7
	4	880	8.40×10^8	7.72×10^7
	5	700	7.22×10^8	7.11×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	4000	1.25×10^9	1.02×10^8
	2	2000	1.07×10^9	9.29×10^7
$Q = 4000$	3	1330	9.51×10^8	8.68×10^7
	4	1000	8.52×10^8	8.19×10^7
	5	800	7.72×10^8	7.76×10^7

Table 6.20. Quay Division Results for Port Tuticorin (continued)

Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	4500	1.19×10^9	1.04×10^8
	2	2250	1.00×10^9	9.52×10^7
$Q = 4500$	3	1500	8.87×10^8	8.94×10^7
	4	1130	7.95×10^8	8.49×10^7
	5	900	7.20×10^8	8.10×10^7
Total Quay Length (m)	**# of Quays**	**Quay Length** (m)	**Profit** (\$)	**Annual Revenue** (\$)
	1	5000	1.11×10^9	1.05×10^8
	2	2500	9.18×10^8	9.59×10^7
$Q = 5000$	3	1670	8.13×10^8	9.07×10^7
	4	1250	7.32×10^7	8.66×10^7
	5	1000	6.59×10^7	8.30×10^7

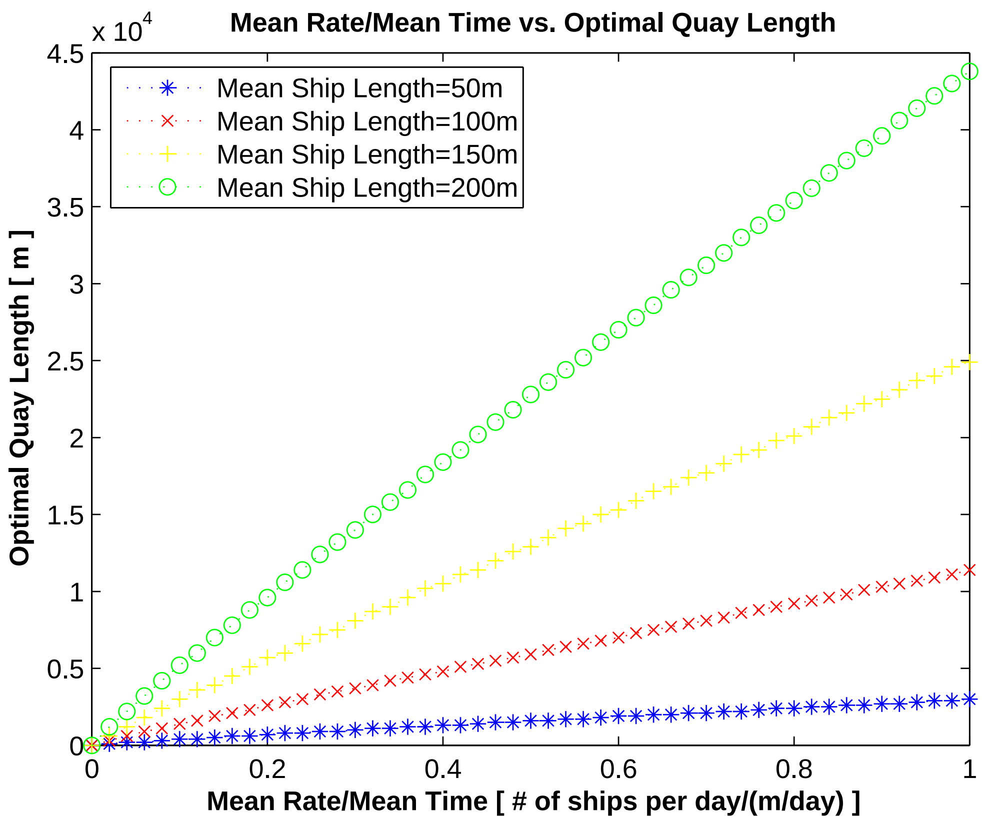

Figure 6.1. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$30000 / p1=$150000)

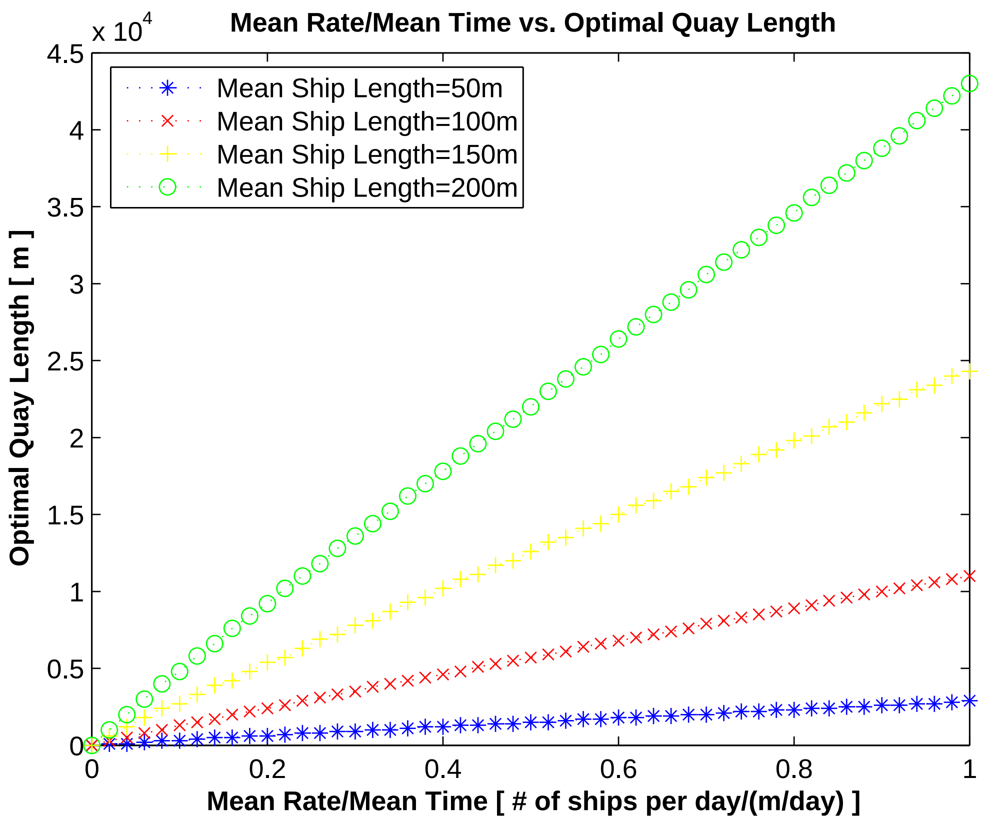

Figure 6.2. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$30000 / p1=$200000)

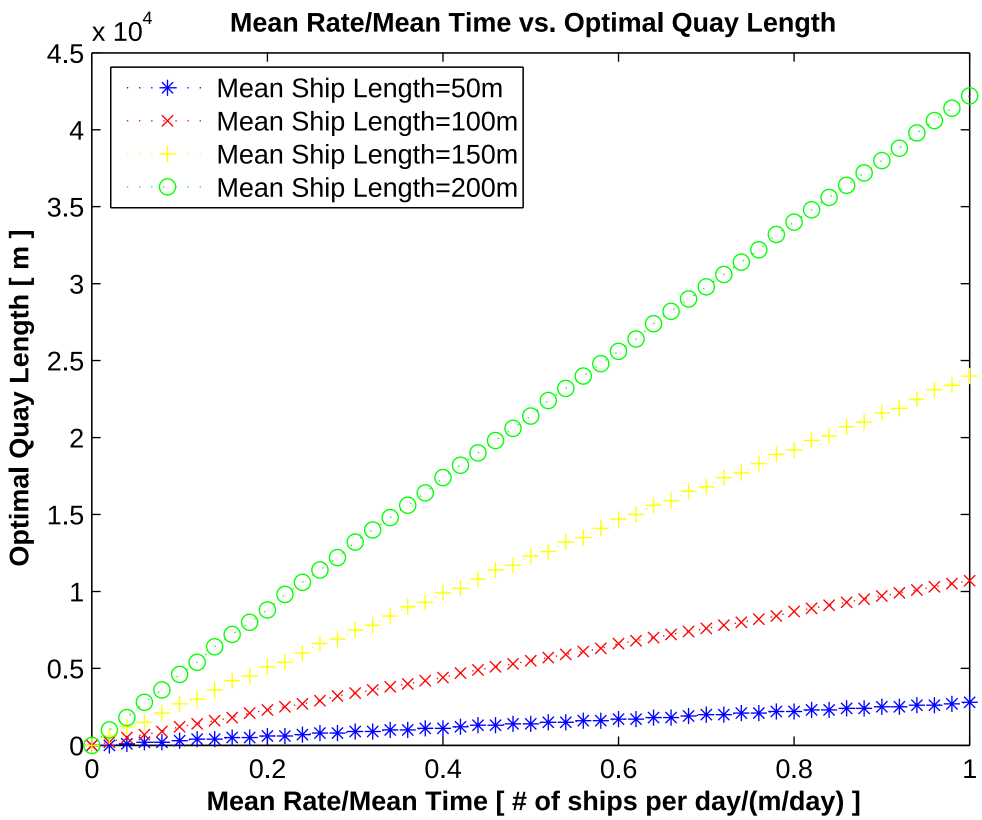

Figure 6.3. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$30000 / p1=$250000)

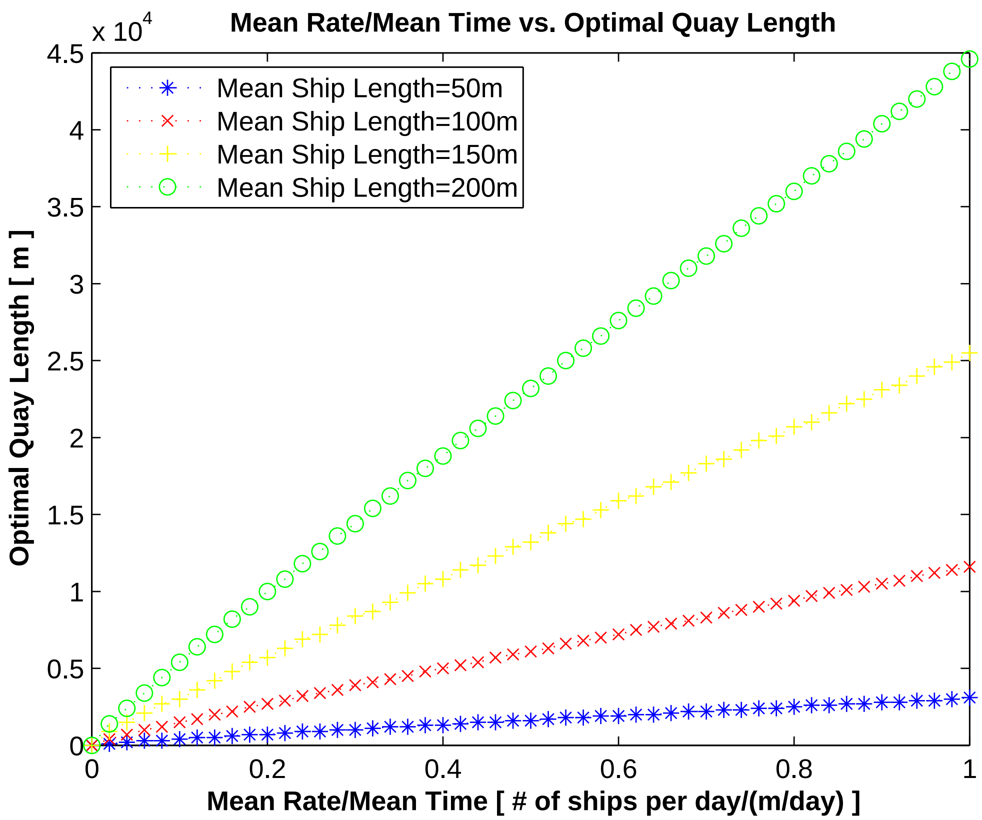

Figure 6.4. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$40000 / p1=$150000)

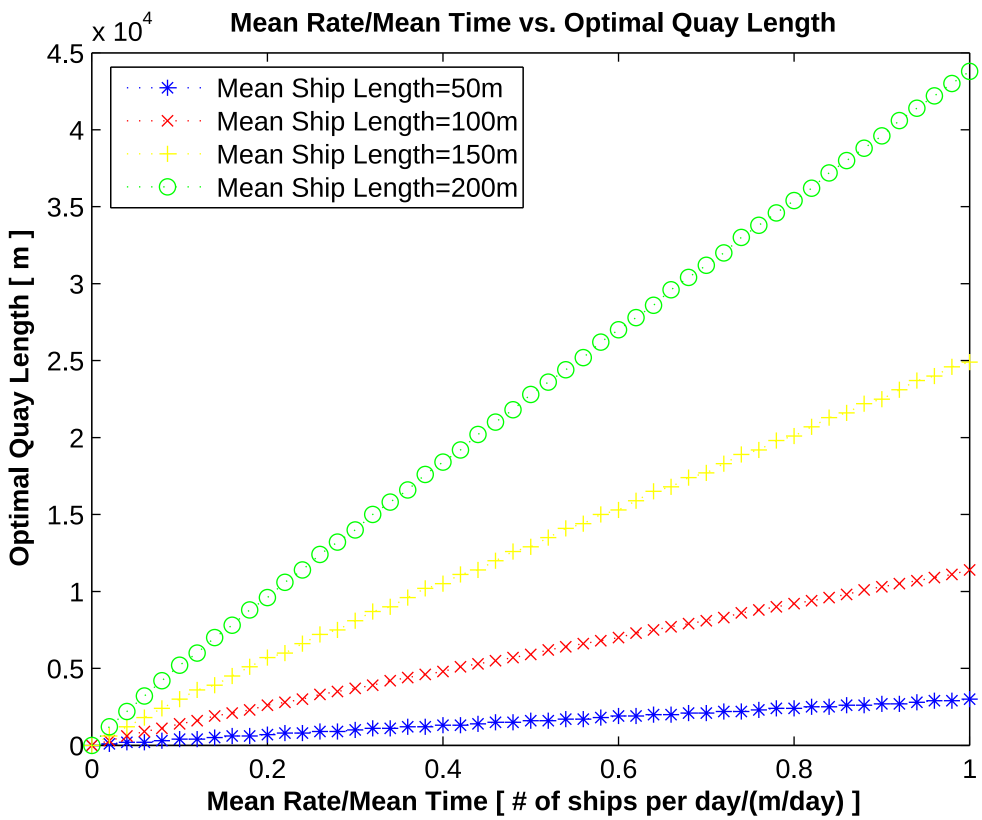

Figure 6.5. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$40000 / p1=$200000)

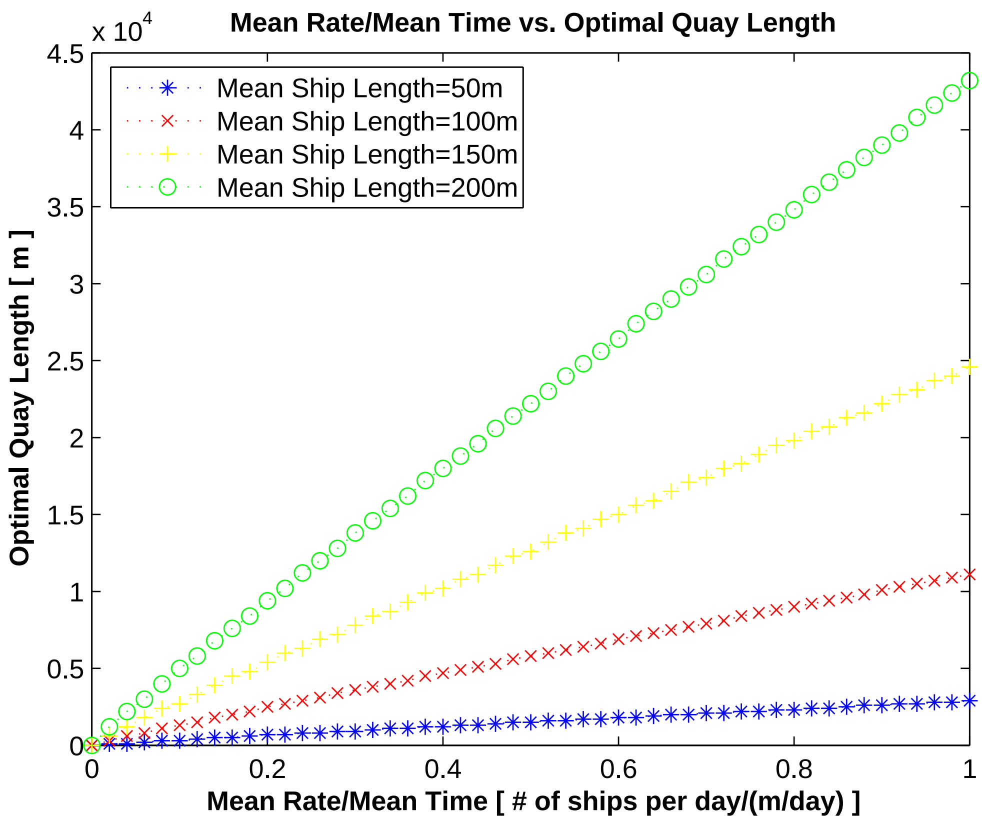

Figure 6.6. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$40000 / p1=$250000)

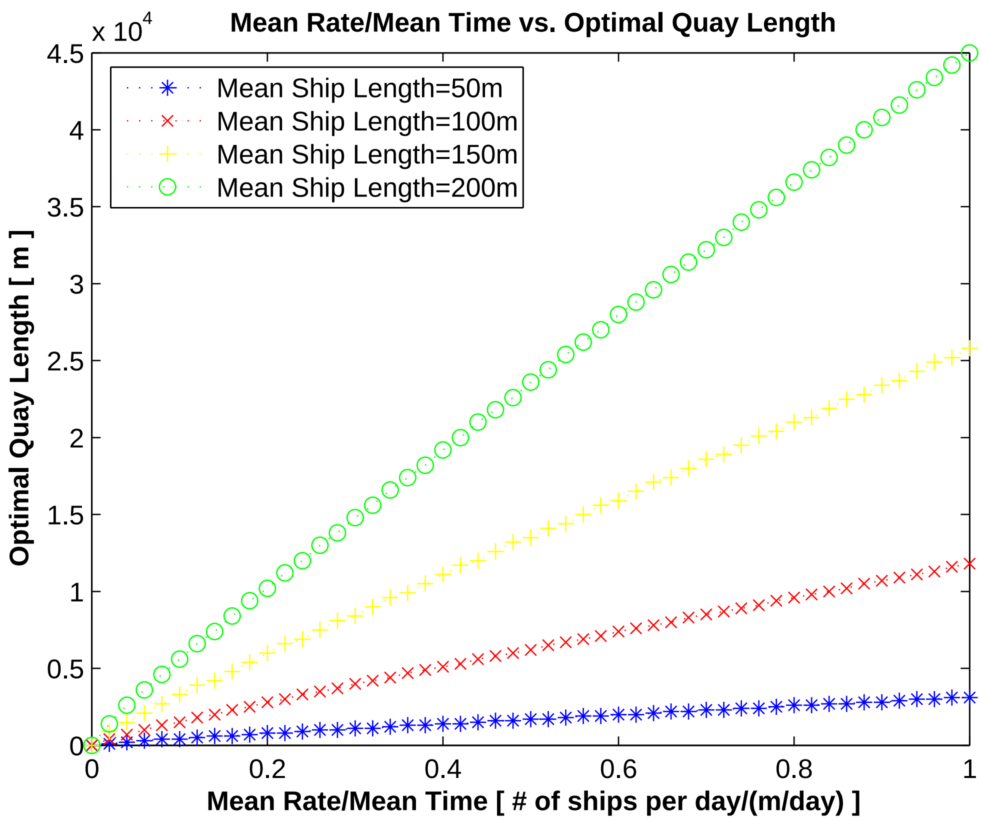

Figure 6.7. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=\$50000 / p1=\$150000)

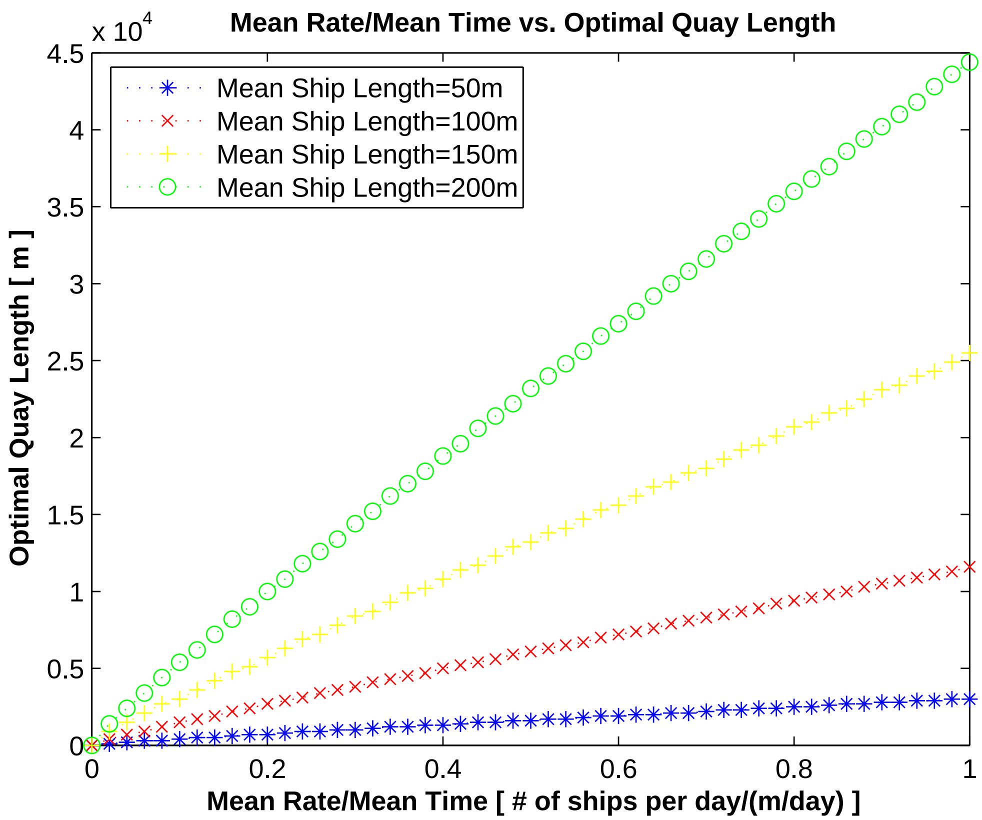

Figure 6.8. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$50000 / p1=$200000)

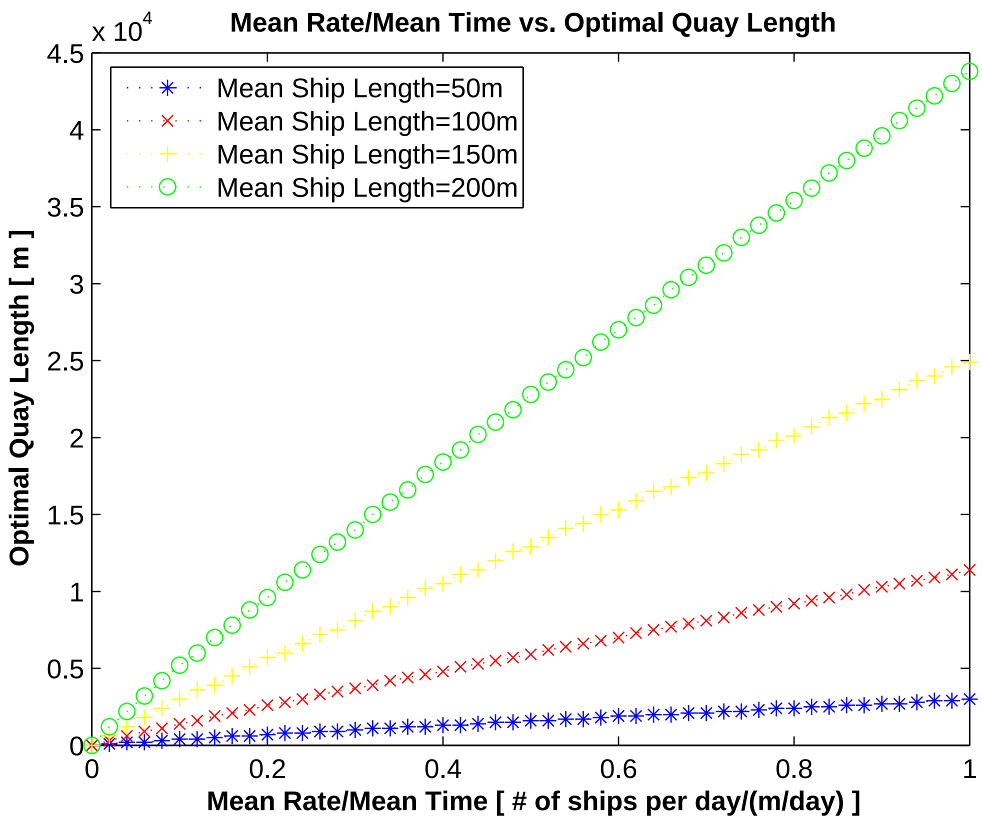

Figure 6.9. Optimal Quay Length vs. Mean Rate/Mean Time for Different Mean Ship Lengths (p=$50000 / p1=$250000)

7. CONCLUSIONS

The major point of interest within this research was to attain an optimal range of quay length values in an efficient manner at the best profit. With this point of view, the purpose is fulfilled and several ports throughout the world, including Kumport of Türkiye, Port Qasim of Pakistan, Port Tuticorin of India are analyzed with the model by carefully selecting and applying relevant parameters. The results appear to be valuable and significant owing to the fact that the analysis based on the stochastic knapsack methodology gives accurate values for quay lengths when compared with the actual ports. So, the model can be used to check the optimality and efficiency of existing ports. Moreover, new quay constructions or extensions of existing quays can be verified easily when the existing quay is found to be insufficient. The ports mentioned above are mostly comprising up-to 20 berths, where container type cargo is dominant. This cargo similarity makes it more efficient to use the model for the ports regarding both velocities (handling rates), cost and revenue structures. Besides, it is very difficult to examine big ports including many subports and terminals such as Port Honolulu of USA, Port Bilbao of Spain and Port İzmit of Türkiye, therefore each subport or terminal should be checked one by one to attain an accurate outcome for these big ports. Since the data for each subport is not available, the analysis results happen to be insignificant.

The arrival structure, where ships arrive according to a Poisson distribution, is acceptable in terms of mathematical modelling. However, the departure structure is based on some assumptions. The departure scheme can be improved by means of not taking the average of all discharge rates, but rather obtaining the real velocity distribution for every port from the data and defining different velocities for each type of cargo. With this approach, a more logical way of modelling the departures can be achieved.

The revenue structure can be changed in a way that it no longer depends on the quay length. Using several reports and studies, a logical comparison between the container cargo units and quay length is found. However, revising and executing the model by obtaining the revenues per unit cargo, not length, shall improve the credibility of the research.

It would be interesting to create a multi-quay model directly working for multi-quay port design. This study may give better estimates for the real life case in a port rather than giving a lower bound for revenues. For this purpose, the analysis can be executed considering the stochastic multi-knapsack problem. The purpose is to make the maximum profit regarding the divided quays as knapsacks having different capacities.

Moreover, a complete partitioning policy (CP) can be applied for the port studied, each partition representing a terminal module for different cargos. To recall, if a knapsack is partitioned and each customer class has exclusive use of its dedicated portion of the knapsack volume, a complete partitioning (CP) policy is being applied. Therefore, every ship should be classified according to the cargo it carries and each ship with a specific cargo should be accepted by the relevant module only. To illustrate, a dry bulk terminal module will accept the ships having a dry bulk cargo, however, on the other hand, it will reject the ships with container cargo.

Another important point is that every ship has its own berthing place in most of the efficient ports. That is, the ship berths at the same part of the quay whenever it arrives at the port. Therefore, a scheduling and queueing model can be developed to handle such a case.

By using the stochastic knapsack method proposed in this study, the functional relationship obtained between the optimal quay length and the arrival rate, the average handling rate (velocity) and the mean ship length is found to be very encouraging. Indeed, the relevant function appears to be almost linear. This behaviour should be studied and examined carefully to attain a logical and accurate relation.

APPENDIX A: DREWRY COST DATA

Table A.1. Drewry Cost Data

Quay Length (m)	**Investment (m)**	**TEU (in million $)**	**Investment/m (in million $)**
1100	110	800000	100000
400	55	300000	137500
234	32	175000	136752
600	60	450000	100000
700	266	500000	380000
350	48	260000	137143
1400	194	1000000	138571
2600	1600	1950000	615385
450	16	335000	35556
25	4	20000	160000
800	110	600000	137500
2000	370	2000000	185000
100	12	150000	120000
700	110	600000	157143
500	37	200000	74000
1900	500	1425000	263158
500	110	600000	220000
1400	185	1000000	132143
1200	170	1000000	141667
1200	77	400000	64167

Table A.2. Drewry Cost Data (continued)

Quay Length (m)	**Investment (m)**	**TEU (in million $)**	**Investment/m (in million $)**
500	50	375000	100000
2000	236	1275000	118000
625	130	750000	208000
2800	820	2100000	292857
2500	350	1875000	140000
600	600	1200000	1000000
700	700	2400000	1000000
1500	500	1000000	333333
550	90	500000	163636
1290	180	970000	139535
250	35	190000	140000
298	37	200000	124161
300	55	300000	183333
1800	250	1350000	138889
800	110	600000	137500
360	37	200000	102778
2500	500	500000	200000
600	130	750000	216667
1000	200	750000	200000
350	50	260000	142857

Table A.3. Drewry Cost Data (continued)

Quay Length (m)	**Investment (m)**	**TEU (in million $)**	**Investment/m (in million $)**
310	20	230000	64516
320	30	160000	93750
1200	100	900000	83333
2300	320	1725000	139130
610	60	460000	98361
280	65	350000	232143
Average Investment per metre of quay			200619

APPENDIX B: DREWRY THROUGHPUT-LENGTH COMPARISON DATA

Table B.1. Drewry Throughput-Length Comparison Data, 1996

Region	**Port** *(Terminal)*	**Throughput (TEU)**	**Quay Length (m)**	**Throughput per m. of quay p.a.**
				(TEU)
N.Europe	Antwerp *(Hessenatie)*	1655341	3234	512
	Bremerhaven	1490819	3946	378
	Hamburg *(Burchardkai)*	1420000	2790	509
	Hamburg *(Eurokai)*	803103	1700	472
	Rotterdam *(Home)*	1044000	1700	614
	Rotterdam *(Mertens)*	350000	310	1129
	Felixstowe	2042424	3197	639
	Southampton	849000	1357	626
	Thamesport	350000	650	538
	Le Havre	1020040	5250	194
Average				*457*
S.Europe	Genoa *(SECH)*	267943	520	515
	Genoa *(Voltri)*	433388	1200	361
	Gioia Tauro	571951	3144	182
	La Spezia *(LSCT)*	594186	987	602
	Malta *(Marsaxlokk)*	593013	1000	593
	Lisbon *(Santa Apolonia)*	119715	870	138
	Lisbon *(Alcantara-Sul)*	114736	630	182
	Algeciras *(Maersk)*	877075	644	1362
	Barcelona *(TCB)*	509899	1390	367
	Limassol	398600	1100	362
Average				*390*

Table B.2. Drewry Throughput-Length Comparison Data, 1996 (continued)

Region	**Port** *(Terminal)*	**Throughput (TEU)**	**Quay Length (m)**	**Throughput per m. of quay p.a.**
				(TEU)
Asia/	Hong Kong *(Sea-Land)*	1015286	305	3329
Indian	Hong Kong *(HIT)*	4498759	3292	1367
	Yantian	353509	700	505
	Jawaharlal Nehru	339136	680	499
	Yokohama (Honmuku)	638618	1620	394
	Busan *(Jasungdae)*	1696665	1262	1344
	Busan *(Shinsundae)*	1313344	1200	1094
	Port Klang *(KCT)*	946788	1079	877
	Port Klang *(KPCT)*	442698	1066	415
	Manila *(MICT)*	848017	1300	652
	Colombo	1356301	2071	655
Average				*941*
Australia	Brisbane *(Berths 1/2/3)*	105475	700	151
	Brisbane *(Berths 4/5/6)*	149085	700	213
	Melbourne *(E. Swanson)*	317130	885	358
	Melbourne *(W. Swanson)*	326020	980	333
	Port Botany *(Northern)*	252863	1005	252
	Port Botany *(Southern)*	370076	980	378
Average				*290*

Table B.3. Drewry Throughput-Length Comparison Data, 1996 (continued)

Region	**Port** *(Terminal)*	**Throughput (TEU)**	**Quay Length (m)**	**Throughput per m. of quay p.a.**
				(TEU)
N. America	Vancouver *(Vanterm)*	422675	800	528
	Hampton Roads *(NIT)*	517514	1290	401
	Long Beach *(LBCT)*	417100	884	472
	Oakland *(Sea-Land)*	223912	699	320
	Oakland *(Yusen)*	130203	274	475
	Seattle *(SIT)*	378400	1600	237
	NY *(Global Marine)*	278000	548	507
	Portland	302171	1616	187
	Savannah	650253	1978	329
	Montreal *(Racine)*	439000	1651	266
Average				*332*
Central/	Kingston	477246	1262	378
S. America	Port of Spain	161113	410	393
	Buones Aries *(Term. 5)*	175830	965	182
	Buones Aries *(Exolgan)*	345540	700	494
	Santos *(Tecon)*	254688	510	499
	Rio de Janeiro *(Tecon)*	144919	480	302
	San Antonio	308782	383	806
	Montevideo	160000	574	279
Average				*384*

Table B.4. Drewry Throughput-Length Comparison Data, 1996 (continued)

Region	**Port** *(Terminal)*	**Throughput (TEU)**	**Quay Length (m)**	**Throughput per m. of quay p.a.**
				(TEU)
Middle East	Dammam	237357	960	247
	Dubai	2247024	2938	765
	Fujairah	403259	780	517
	Khor Fakkan	655046	710	923
	Damietta	808608	1050	770
	Jeddah	748182	681	1099
Average				*716*
Africa	Cape Town	355400	1371	259
	Durban	928566	1583	587
Average				*435*
Overall Average				**528**

APPENDIX C: DAILY SHIP DATA FOR KUMPORT

Table C.1. Ship Data for Kumport

	AUGUST 2005								**SEPTEMBER 2005**				
	23	**24**	**25**	**26**	**27**	**29**	**30**	**31**	**1**	**2**	**3**	**4**	**5**
Ship	122	88	151	115	76	116	79	117	115	137	137	136	60
Lengths	157	77	158	172	149	180	239	140	77	104	138	162	76
(m)	122	239	127	85	84		90	92	72	72	154	122	202
	138	76	149					91	84	157	115	149	122
		60						84		122	79	76	161
		132						114			137	76	138
		92						149			138		76
											154		84
Daily #													
of ships	**4**	**7**	**4**	**3**	**3**	**2**	**3**	**7**	**4**	**5**	**8**	**6**	**8**

Table C.2. Ship Data for Kumport (continued)

	SEPTEMBER 2005												
	6	**7**	**8**	**9**	**14**	**15**	**16**	**17**	**19**	**20**	**21**	**22**	**23**
Ship	116	121	90	149	163	117	126	137	115	122	149	117	156
Lengths	79	156	117	85	137	158	104	116	149	136	77	122	
(m)	111	76	77	78	140	122	137	149	138	60	149		
	156		92	115		114	162	184	91	95	239		
	117		126			79	157	89	202	147	85		
	115					76	114	77	147	118	79		
	126									114	151		
	149												
	239												
	92												
Daily #													
of ships	**10**	**3**	**5**	**4**	**3**	**6**	**6**	**6**	**6**	**7**	**7**	**2**	**1**

Table C.3. Ship Data for Kumport (continued)

	SEPTEMBER 2005							**OCTOBER 2005**					
	24	**25**	**26**	**27**	**28**	**29**	**30**	**1**	**2**	**3**	**4**	**5**	**6**
Ship	137	122	122	92	91	60	116	138	149	157	136	77	60
Lengths	149	260	117	140	76	216	59	91	202	117	239	76	149
(m)	149	149	104	239	240	122	122	172	158	149	115	84	76
	154	202	118	70	184		114		172	126	117		82
	116		76		162		75						
	115				161		79						
							104						
							149						
Daily #													
of ships	**6**	**4**	**5**	**4**	**6**	**3**	**8**	**3**	**4**	**4**	**4**	**3**	**4**

Table C.4. Ship Data for Kumport (continued)

	OCTOBER 2005												
	7	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Ship	48	79	179	157	113	105	115	118	151	138	202	77	157
Lengths	122	149	122	122	239	79	76	151	75	149	122	91	60
(m)	137	184	156	200	114	149	137		104		161	122	158
	85			75	140				122			239	136
	98			162	95				149				115
					117				149				79
									154				60
Daily #													
of ships	**5**	**3**	**3**	**5**	**6**	**3**	**3**	**2**	**7**	**2**	**3**	**4**	**7**

Table C.5. Ship Data for Kumport (continued)

	OCTOBER 2005											
	20	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Ship	79	92	95	149	163	137	115	75	116	82	137	82
Lengths	149	116	240	202	138	95	79	122	151	157	149	
(m)		162	149		95	148		156	104	184	138	
		149	172		79	239		30	48		202	
		137	77		118	85		76			60	
		85	114		126	117		91				
		75										
Daily #												
of ships	**2**	**7**	**6**	**2**	**6**	**6**	**2**	**6**	**4**	**3**	**5**	**1**

Table C.6. Ship Data for Kumport (continued)

	NOVEMBER 2005												
	1	**2**	**6**	**7**	**8**	**9**	**10**	**18**	**19**	**20**	**21**	**22**	**23**
Ship	60	182	157	122	149	79	70	149	77	202	149	240	157
Lengths	114	122	116	78	239	161	85	59	85	151	132	60	76
(m)	115	78	202	158	151	149		122	184		84	149	122
	138	149	137	115					76		122	239	
	76	239	149	91					114		179	137	
				122					116				
Daily #													
of ships	**5**	**5**	**5**	**6**	**3**	**3**	**2**	**3**	**6**	**2**	**5**	**5**	**3**

Table C.7. Ship Data for Kumport (continued)

	NOVEMBER 2005			
	24	**25**	**26**	**27**
Ship	117	149	149	202
Lengths		91	104	156
(m)			137	62
			115	59
			138	
			154	
Daily #				
of ships	**1**	**2**	**6**	**4**

Table C.8. Velocity Data for Kumport

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
ADMIRAL DE RIBAS	90	2	45
ADMIRAL MARS	85	2	42
ADMIRAL RAINBOW	104	2	52
AJAX 2	79	1	79
ALCIONE	117	2	59
ALEKSANDRA ARZHAVKIN	92	2	46
ALHANI AKDENIZ	76	3	25
ALKIN KALKAVAN	149	2	75
ALKOR	79	1	79
AMIRAL AKDENIZ	95	2	48
ANKARA	239	3	80
ANTARES 1	127	1	127
AREL	59	2	29
ATLAS	79	1	79
AURA	76	1	76
BERKAY N	78	2	39
BESIRE KALKAVAN	149	2	75
BLACK SEA	240	3	80
BS EXPRESS	114	2	57
CEC PASIFIC	89	2	45
CLAIRE A	122	1	122
CONTAZ CARRIER	149	2	74
CONTAZ PIONEER	149	2	74
CSCL FUZHOU	207	3	69
DIANE A	122	2	61

Table C.9. Velocity Data for Kumport (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
EDOUGH	119	2	60
ELBSTROM	158	2	79
ERKUT A	122	1	122
ETNA	77	2	38
FROST	88	3	29
HUA YUN HE	180	2	90
INGA LENA	121	1	121
IVAN PROKHOROV	85	2	42
KANLAR 2	75	2	38
KAPTAN ERGUN	149	3	50
KAPTAN IBRAHIM	60	5	12
KASIF KALKAVAN	149	2	75
KIRSTEN	118	2	59
KIYAMOGLU-1	48	1	48
LEVENT HASLAMAN	72	1	72
LEYLA KALKAVAN	149	2	75
LIAN YUN GANG	200	1	200
LIDYA	105	1	105
LIGURIA	157	2	79
LT BIANCA	162	2	81
LT VERDE	151	2	76
MAERSK BARCELONA	239	2	120
MAERSK BELEWAN	239	2	120
MAERSK BRISBANE	239	2	120
MAERSK DOROTHEA RICKMERS	184	2	92

Table C.10. Velocity Data for Kumport (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
MAERSK FALSTERBO	138	1	138
MAERSK ROSTOCK	154	2	77
MAERSK VAASA	172	3	57
MARMARA SEA	240	2	120
MEHMET KALKAVAN	138	1	138
MSC ARABIA	184	2	92
MSC FLORIANNA	188	3	63
MSC FRIBURG	260	2	130
MSC MIA SUMMER	216	2	108
MUKADDES KALKAVAN	149	3	50
NAVIGIA	76	2	38
OCEAN	157	2	79
ORKUN KALKAVAN	149	3	50
PHILIPOS	126	1	126
PLOVDIV	156	2	78
PRASKOVIYA	78	1	78
REGINA EBERHARD	136	1	136
ROERBORG	140	1	140
ROUSSE	157	2	79
SAMI A	116	2	58
SAMUR 7	90	2	45
SEA LEADER	202	2	101
SENA KALKAVAN	149	2	75
SUN RAYS	91	2	45
SUN SOPHIA	121	6	20

Table C.11. Velocity Data for Kumport (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
TARAMA 1	70	1	70
TRAMOLA 2	92	2	46
URAL	113	1	113
VILKOVO	98	3	33
WANDA A	122	2	61
WEST WIND 1	79	1	79
XIANG KUN	137	1	137
XIANG QIAN	137	2	69
YM EARTH	172	1	172
YM IZMIR	163	2	82
YM PEOPLE	161	2	80
YM SKY	161	2	80
YUNUS	91	3	30
ZERAN	147	2	74
ZERRAN A	115	2	58
Average Velocity			**77**

APPENDIX D: DAILY SHIP DATA FOR PORT QASIM

Table D.1. Ship Data for Port Qasim

	AUGUST 2005												
	14	**15**	**16**	**17**	**18**	**19**	**21**	**22**	**25**	**26**	**27**	**28**	**29**
Ship	170	258	241	175	211	196	190	107	211	155	255	98	196
Lengths	239		159	168		98		258	185				
(m)	236			260				120	113				
	139												
Daily #													
of ships	**4**	**1**	**2**	**3**	**1**	**2**	**1**	**3**	**3**	**1**	**1**	**1**	**1**

Table D.2. Ship Data for Port Qasim (continued)

	AUG 05		**SEPTEMBER 2005**										
	30	**31**	**1**	**2**	**4**	**5**	**6**	**8**	**11**	**12**	**13**	**18**	**19**
Ship	114	112	169	228	244	240	171	225	177	258	184	150	258
Lengths	260			220		258	153				241	225	249
(m)	260					244	198				139	231	139
	148					115						241	
Daily #													
of ships	**4**	**1**	**1**	**2**	**1**	**4**	**3**	**1**	**1**	**1**	**3**	**4**	**3**

Table D.3. Ship Data for Port Qasim (continued)

	SEPTEMBER 2005							**OCTOBER 2005**					
	22	**25**	**26**	**27**	**28**	**29**	**30**	**1**	**2**	**3**	**4**	**5**	**6**
Ship	113	171	258	186	174	123	239	115	177	170	244	153	249
Lengths	225		245		241	216	195	241	225				211
(m)	261		146			260							98
	160												
Daily #													
of ships	**4**	**1**	**3**	**1**	**2**	**3**	**2**	**2**	**2**	**1**	**1**	**1**	**3**

Table D.4. Ship Data for Port Qasim (continued)

	OCTOBER 2005												
	7	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Ship	225	117	171	258	241	172	206	220	166	166		225	
Lengths			224		114		247		146				
(m)			245				241						
							225						
							114						
Daily #													
of ships	**1**	**1**	**3**	**1**	**2**	**1**	**5**	**1**	**2**	**1**	**0**	**1**	**0**

Table D.5. Ship Data for Port Qasim (continued)

	OCTOBER 2005											
	20	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Ship	141	208		229	176		115	69	175		139	170
Lengths				96	258		228	211	248		146	
(m)					183		160	241	242			
								241				
Daily #												
of ships	**1**	**1**	**0**	**2**	**3**	**0**	**3**	**4**	**3**	**0**	**2**	**1**

Table D.6. Ship Data for Port Qasim (continued)

	NOVEMBER 2005											
	5	**7**	**9**	**10**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Ship	183	258	154	169	171	173	224	224		241	235	225
Lengths	225	237	260	211	190	260	151	211			225	
(m)			162					195				
			241					228				
			145					145				
Daily #												
of ships	**2**	**2**	**5**	**2**	**2**	**2**	**2**	**5**	**0**	**1**	**2**	**1**

Table D.7. Ship Data for Port Qasim (continued)

	NOV 2005		
	23	**24**	**25**
Ship		114	157
Lengths		153	225
(m)		211	175
		98	220
Daily #			
of ships	**0**	**4**	**4**

Table D.8. Velocity Data for Port Qasim

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
ACE-7	123	2	62
AL-IHSAA	211	1	211
AL-MANAKH	190	1	190
AL-MAQVA	241	3	80
AL-MARWAH	239	2	119
AL-MIRQAB	211	2	106
AMANAT	69	2	35
AMASIS	196	1	196
ANETTE KOSAN	98	2	49
AONOBAL	166	11	15
ASIAN GYRO	162	2	81
ASIAN TRADER	185	1	185
BAGI	244	4	61
BAY BRIDGE	228	4	57
BOTA FOGO	224	10	22
BOW PETROS	174	2	87
BOW PRIDE	176	2	88
BUMMO	115	2	58
C.P. INDIGO	260	2	130
C.P. TAMARIND	260	2	130
CAROLINE 7	107	3	36
CGM KINGSTON	260	2	130
CGM NILGAI	260	2	130
CHEM STAR BELLE	141	2	71
CHEMBULK	145	3	48

Table D.9. Velocity Data for Port Qasim (continued)

Ship Name	Ship Length	Days Stayed	Velocity (m/day)
CONTSHIP INDIGO	260	2	130
DIFKO HANNE	229	2	114
DOCOMO	171	4	43
DUBAI	211	2	106
DYMPHNA	241	2	121
EBURNA	170	4	43
ENERGY STAR	225	5	45
ENTALINA	169	4	42
GAS FORTUNE	96	1	96
GEMINI	175	1	175
GENCO SUCCESS	186	2	93
GINGA TIGER	159	3	53
GOLDEN OCEANIA	115	2	57
GREEN PARK	145	2	73
HANNIBAL-2	172	3	57
HYDERABAD	153	9	17
JIAN SHE-31	115	2	58
KINUGAWA	160	2	80
LION PRINCESS	146	12	12
MAERSK ALASKA	239	3	80
MAERSK ALE BAMA	155	2	78
MAERSK ARIZONA	239	2	120
MAPLE GALAXY	148	2	74
MARE GALLICUM	195	2	98
MATUMBA	190	4	48

Table D.10. Velocity Data for Port Qasim (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
MEGAS ALEXANDROS	196	3	65
MINNON FLAME	224	8	28
MSC AURORA	175	2	87
MSC AUSTRIA	240	2	120
MSC HAILEY	235	2	118
MSC JORDEN	237	2	119
NORASIA EVEREST	220	2	110
NUEVA UNION	224	6	37
OOCL AUTHORITY	183	3	61
PACIFIC SENATOR	206	2	103
PACIFIC SOUND	151	3	50
PINIOR SPIRIT	112	2	56
PRECIOUS	168	5	34
S.L. INDEPENDENCE	258	3	86
S.L. MARINER	258	3	86
SEA LAND EXPRESS	257	3	86
SEA LAND MARINER	258	3	86
SEA LAND VOYAGER	260	2	130
SINAR SABANG	113	2	57
THAN SONG FENG	225	10	22
VILLE DE MARS	242	2	121
WARBAH	241	2	121
WASHINGTON READER	225	11	20
WEST MOOR	208	2	104
YANASENI	114	2	57
Average Velocity			**83**

APPENDIX E: DAILY SHIP DATA FOR PORT TUTICORIN

Table E.1. Ship Data for Port Tuticorin

	AUGUST 2005												
	6	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Ship	157	190	190	85	169	168	182	126	107	75	137	237	154
Lengths	129		105	190	56	77	172	137	105	178	192	149	126
(m)	200		187	60	20	117	112	50	165	117	87	126	190
			190	222			62	75	102		176	210	192
				126			75	146			116		77
							54						162
							210						239
							225						
							155						
Daily #													
of ships	**3**	**1**	**4**	**5**	**3**	**3**	**9**	**5**	**4**	**3**	**5**	**4**	**7**

Table E.2. Ship Data for Port Tuticorin (continued)

	AUGUST 2005												
	19	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Ship	178	200	75	56	137	117	65	66	62	133		159	223
Lengths	70	186	91		190	116	185	178	60	77		91	193
(m)	65	210	93		93		84	183	116	70		56	190
	100	52	178					146		103		210	178
	159		85					149		126		155	192
										225		133	
												116	
Daily #													
of ships	**5**	**4**	**5**	**1**	**3**	**2**	**3**	**5**	**3**	**6**	**0**	**7**	**5**

Table E.3. Ship Data for Port Tuticorin (continued)

	SEPTEMBER 2005												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**11**	**12**	**13**	**14**
Ship	105	106	116	147	190	157	112	239	133	54	156	153	150
Lengths	126	190	86	65	187	210	116	70	163	169	154	179	188
(m)	155	117	106	105	87	133	223	56			72	120	85
	162	165	145	36			170	225			162	165	192
		85	190				86					163	
		75	57				126					186	
		210	117				77					120	
			165				163					66	
			133									116	
												133	
Daily #													
of ships	**4**	**7**	**9**	**4**	**3**	**3**	**8**	**4**	**2**	**2**	**4**	**10**	**4**

Table E.4. Ship Data for Port Tuticorin (continued)

	SEPTEMBER 2005												
	15	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Ship	179	75	57	91	65	78	161	168	81	210	85	172	57
Lengths	114	210	161	83	70	165	130	210	178	160	66	160	75
(m)	62	195	93	200	179	152	237	190	87		159		116
	133		147	56		54	154	159	75		105		
	168		161	210		116	50	184	159				
			83	186			190						
			133	152			159						
			116										
Daily #													
of ships	**5**	**3**	**8**	**7**	**3**	**5**	**7**	**5**	**5**	**2**	**4**	**2**	**3**

Table E.5. Ship Data for Port Tuticorin (continued)

	SEP 2005			OCTOBER 2005									
	28	**29**	**30**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ship	173	56	105	189	133	121	182	146	168	170	75	190	210
Lengths	147	168	109	50	200	97	130	210	159	210	54	159	165
(m)	114		133		75		176	160	114	160	56	176	146
	70		65				62	36			85	170	187
	222		192				159	54				75	163
								186				54	124
								213					
Daily #													
of ships	**5**	**2**	**5**	**2**	**3**	**2**	**5**	**7**	**3**	**3**	**4**	**6**	**6**

Table E.6. Ship Data for Port Tuticorin (continued)

	OCTOBER 2005												
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Ship	154	172	70	92	94	101	90		177	121	92	166	159
Lengths	154	107	114	133	159	133			112	87	62	102	210
(m)	93	168	173	156	116					210	190	56	102
	163		225	200							50	116	153
											190	186	
											105		
Daily #													
of ships	**4**	**3**	**4**	**4**	**3**	**2**	**1**	**0**	**2**	**3**	**6**	**5**	**4**

Table E.7. Ship Data for Port Tuticorin (continued)

	OCTOBER 2005								**NOVEMBER 2005**				
	24	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**1**	**2**	**3**	**4**	**15**
Ship	178	57	221	190	89	75	145	200	146	98	187	110	139
Lengths	165	116	210	153	156	116	141		108	192	133		167
(m)	85	133	169	156	70	56	159		149	114	65		200
		124	54	133	61	54			116	193			193
			20	168	116								
			85		171								
			66		195								
			114		114								
Daily #													
of ships	**3**	**4**	**8**	**5**	**8**	**4**	**3**	**1**	**4**	**4**	**3**	**1**	**4**

Table E.8. Ship Data for Port Tuticorin (continued)

	NOVEMBER 2005										
	17	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Ship	70	85	170	178	50	172	113	75	156	180	210
Lengths	160	61	165	97	190	186	156		86	193	
(m)	225		192	210	46				210	65	
				159	56				162	168	
Daily #											
of ships	**3**	**2**	**3**	**4**	**4**	**2**	**2**	**1**	**4**	**4**	**1**

Table E.9. Velocity Data for Port Tuticorin

Ship Name	Ship Length	Days Stayed	Velocity (m/day)
ABG KESHAVA	200	3	67
AFRICAN LEOPARD	169	3	56
AFRICAN PROTEA	161	5	32
AGIA EIRINI	188	6	31
ALEXANDROS S	106	9	12
ALMARONA	165	3	55
ANAKURI	57	3	19
ANNEMIEKE	152	3	51
APJ AKHIL	210	4	53
ARKAAN	160	6	27
ASIAN QUEEN	81	4	20
AZZURA	190	4	48
BADULU VALLEY	89	4	22
BELGIAN EXPRESS	168	2	84
BENGAL SEA	237	3	79
BRAND	129	9	14
BUDI AMAN	156	1	156
BUDI TEGUH	156	2	78
C. BRAVE	165	3	55
CALYPSO N	184	8	23
CAN GIO	72	4	18
CARAKA JAYA NIAGA - III	93	2	47
CATTERICK	105	2	53
CEC VISION	97	1	97
CEILO DE VAIANO	172	4	43

Table E.10. Velocity Data for Port Tuticorin (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
CHEMBULK YOKOHAMA	150	3	50
CIMBRIA	222	3	74
CITY OF DUBLIN	77	3	26
COASTLINE EXPRESS	70	1	70
CONTI ESPERANCE	192	3	64
CORALI	146	7	21
CORDELIA	223	3	74
DA FA	130	2	65
DA FU	126	3	42
DA HUA	153	6	26
DELMAS KENYA	157	2	79
DHUVAAFARU GALAXY	65	6	11
DILER 4	185	6	31
DUCKY SAPPHIRE	156	5	31
DUCKY SPLENDID	154	5	31
ELEONORA	91	5	18
FABIAN SCHULTE	168	2	84
FAIR ENERGY	179	3	60
FEDERAL RIDEAU	200	3	67
FEEDER 4	116	3	39
FORTUNA	62	3	21
GEBE OLDENDORFF	154	3	51
GECON I	190	8	24
GEM OF ENNORE	225	7	32
GEM OF HALDIA	192	5	38

Table E.11. Velocity Data for Port Tuticorin (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
GEM OF PARADIP	186	4	47
GLOBAL SATURN	112	3	37
GOLD FRIDAY	170	1	170
GOOD DAY	182	9	20
GWENDOLEN	190	5	38
HATSU PRIMA	182	3	61
HAZASH PRIDE	56	4	14
HIYA BUILDER	147	4	37
IIDA	60	3	20
INDURUWA VALLEY	75	3	25
J.FRIEND	178	9	20
JADE C	146	2	73
JAG PALAK	170	2	85
JAG PREETI	162	3	54
JAG RANI	183	5	37
JAG VIDYA	169	3	56
JIA QIANG	186	3	62
JOINT GRACE	120	6	20
JUPITER	105	6	18
KAMRUP	36	1	36
KAPITAN GRISHIN	114	3	38
LEPTA GALAXY	190	5	38
LUCKY 7	112	3	37
MAA FARU	65	5	13
MAERSK ANTWERP	155	2	78

Table E.12. Velocity Data for Port Tuticorin (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
MAERSK ARIZONA	239	3	80
MAERSK HUMBER	159	3	53
MARY LISA V	190	6	32
MEGA CROWN NO.1	75	3	25
MERCS HENDALA	75	4	19
MERCS KIRINDA	83	9	9
MERCS SAJINDA	75	4	19
MERCS YALA	91	2	46
MOL AMBITION	146	2	73
MONGLA	92	1	92
NAND KISHORE	149	2	75
NAUTICA SEGAMAT	94	3	31
NEDROMA	172	4	43
NEW VEGA	159	4	40
NICEA	126	8	16
NIUMATH	46	2	23
NOORA	178	9	20
NORASIA ALYA	213	2	107
NORASIA RIGEL	222	2	111
NORASIA SILS	223	3	74
NORASIA TEGESOS	210	3	70
NORTH SEA	237	3	79
OCEAN ACE	107	4	27
OCEAN VENTURE	121	5	24
OEL EXPRESS	159	2	80

Table E.13. Velocity Data for Port Tuticorin (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
OEL VICTORY	124	2	62
OEL VISION	102	2	51
PALESSA	118	1	118
PAUL OLDENDORFF	179	6	30
PRATIBA CHANDRABHAGA	176	3	59
PRATIBHA CAUVERY	163	3	54
PREM PRANSHU	189	6	32
PUNITA	195	3	65
QING ANN	130	4	33
RICKMERS MUMBAI	178	7	25
SAFMARINE PAKISTAN	168	2	84
SAN REMO	177	4	44
SEA CHART 1	85	4	21
SEA EMPEROR	153	9	17
SIAM BHAVAS	103	4	26
SILVER STAR	145	5	29
SINDBAD DREAM	174	1	174
SUMIYOSHI	160	2	80
SUNVAZS	147	9	16
SUTHATHIP NAREE	161	7	23
TAMIL KAMARAJ	210	4	53
TAMIL PERIYAR	210	4	53
TAN BINH 10	97	9	11
TCI ARJUN	92	2	46
TEEN	190	6	32

Table E.14. Velocity Data for Port Tuticorin (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
THAI ROSE	100	4	25
THEKKADY	50	4	13
TIGER ARROW	117	2	59
UMMEEDH	78	5	16
VILA	52	2	26
WAADHEE STAR	54	2	27
WAADHEE VENUS	54	3	18
WAVE RULER	112	3	57
WELL PESCADORES	154	5	31
WILHELM SCHULTE	155	2	78
WINNER	105	5	21
X-PRESS MAKALU	137	2	69
X-PRESS PUMORI	133	2	67
YAAD-E-MOHAMMED	156	5	31
YAAD-E-MOSTAFA	163	10	16
Average Velocity			**47**

APPENDIX F: DAILY SHIP DATA FOR PORT HONOLULU

Table F.1. Ship Data for Port Honolulu

	AUGUST 2005												
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**24**	**25**	**27**
Ship	230	179	15	60	41	247	188	34	258	217	34	34	185
Lengths	283	260	34	50	107	38	12	105	217	129	107	105	83
(m)	181	34	64	252	38	34	50	283	248	56	230	55	58
	41	105	63	267	116	105	34	107	34	54	220	50	103
	107	241	34		34	41	107	41	105	104	50	17	41
	219	34	105		107	107	12	107	259	63	217	50	34
		107	176		50	50	182	218	267	34	117	244	105
		217			232	138	259	148		105	241	138	283
		172			274					60			107
										244			200
													17
													219
													145
Daily #													
of ships	**6**	**9**	**7**	**4**	**9**	**8**	**8**	**8**	**7**	**10**	**8**	**8**	**13**

Table F.2. Ship Data for Port Honolulu (continued)

	AUG 2005			**SEPTEMBER 2005**									
	28	**29**	**31**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**13**
Ship	258	15	41	252	129	230	178	41	44	55	241	185	176
Lengths	17	55	107	34	12	107	258	105	116	34	34	98	38
(m)	217	100	15	105	182	283	217		37	107	107	68	116
	248	37	83	34	41	34	272		39	220	165	50	23
	34	116	247	55	105	107	178		231	217	38	12	181
	105	63	232		232	218			57	180	105	229	50
	246	34			182	160			181		172	250	50
		105			183	183					242		252
		129				200							86
						245							
Daily #													
of ships	**7**	**9**	**6**	**5**	**8**	**10**	**5**	**2**	**7**	**6**	**8**	**7**	**9**

Table F.3. Ship Data for Port Honolulu (continued)

	SEPTEMBER 2005												
	14	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Ship	34	38	12	283	139	15	240	34	148	200	219	258	248
Lengths	107	105	50	107	159	64	245	107	38	12	23	38	56
(m)	138	34	34	34	258	97	187	34	105	34	230	105	56
	34	107	107	218	38	63	15	107	165	50	283	34	63
	107	50	38		105	97	50	220	50	34	34	107	185
	230	232	105		34	50	63	50	241	107	107	193	176
	55				107	38		217	248	38	86	11	
	54				217	105		187	171	105	219	217	
	58				172			74	175	69	245	180	
	50									245	269		
	247									245	175		
	232										248		
	250												
Daily #													
of ships	**13**	**6**	**6**	**4**	**9**	**8**	**6**	**9**	**9**	**11**	**12**	**9**	**6**

Table F.4. Ship Data for Port Honolulu (continued)

	SEP 2005				**OCTOBER 2005**								
	27	**28**	**29**	**30**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Ship	176	34	252	12	200	293	114	160	34	220	58	283	219
Lengths	217	107	34	38	283	258	63	41	107	293	38	180	258
(m)	8	53	105	8	294	34	41	118	38	34	107	103	34
		38	8	107	34	105	116	240	107	105	34	34	105
		107	98	34	107	55	248	183	293	69	105	107	38
		247		105	53	68			230	241	259	54	107
		8		259	218	54			217			86	217
		232			159	38						219	241
					183	107							272
					245	217							
						204							
						294							
Daily #													
of ships	**3**	**8**	**5**	**7**	**10**	**12**	**5**	**5**	**7**	**6**	**6**	**8**	**9**

Table F.5. Ship Data for Port Honolulu (continued)

	OCTOBER 2005												
	10	**11**	**13**	**14**	**15**	**16**	**17**	**22**	**23**	**24**	**25**	**27**	**28**
Ship	63	184	34	294	181	283	50	55	35	55	148	38	190
Lengths	176	38	105	34	230	38	69	283	258	64	15	105	15
(m)		116	15	49	283	107	63	191	38	55	219		55
			104	34	294	217	242	34	105	55	66		58
			69	37	34	248		107	34	30	56		64
			34	69	107	34		200	107	63	37		20
			273	12	218	105		219	217	176	116		182
				69	242	225		269	272		252		12
				38		239			129				34
				107									107
				54									38
				185									105
				34									182
				105									
				225									
Daily #													
of ships	**2**	**3**	**7**	**15**	**8**	**9**	**4**	**8**	**9**	**7**	**8**	**2**	**13**

Table F.6. Ship Data for Port Honolulu (continued)

	OCT 2005			**NOVEMBER 2005**									
	29	**30**	**31**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**9**	**11**	**12**
Ship	283	258	294	41	34	38	55	230	258	248	252	38	34
Lengths	185	51	294	116	107	105	34	283	34	54	180	107	105
(m)	57	68	68	64	34	200	107	55	107	64	34	200	258
	97	38	69	240	107	241	170	56	217	54	107		56
	86	105	57		159	116	232	38	38	63	34		56
	57	128	56		68			105	105		107		184
	34	34	103		56			160	232		38		34
	107	107	63		220			69	207		116		107
	218	217			217			34			55		56
	207	247			180			107			247		218
	100	244			207			49			232		274
	88				154			219			207		207
					248			248			56		
Daily #													
of ships	**12**	**11**	**8**	**4**	**13**	**5**	**5**	**13**	**8**	**5**	**13**	**3**	**12**

Table F.7. Ship Data for Port Honolulu (continued)

	NOVEMBER 2005												
	13	**14**	**15**	**18**	**19**	**20**	**21**	**23**	**24**	**25**	**26**	**27**	**28**
Ship	258	34	68	259	283	258	56	34	129	172	193	258	272
Lengths	44	105	181	38	57	34	63	107	104	188	200	34	294
(m)	56	294	240	107	34	105		38	55	34	230	105	55
	39	294	195	228	107	59		107		105	283	69	63
	38	55			159	217		55			294	217	243
	107	56			86	248		34			38		228
	217	63			60	274		105			107		
	272				220			34			34		
					117			116			107		
					225			34			218		
					259			247					
								232					
								228					
Daily #													
of ships	**8**	**7**	**4**	**4**	**11**	**7**	**2**	**13**	**3**	**4**	**10**	**5**	**6**

Table F.8. Velocity Data for Port Honolulu

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
AHI	8	2	4
ALAM SENANG	178	2	90
ALTAIR VOYAGER	259	2	130
AORNOI MARU	66	1	66
CARNIVAL SPIRIT	293	2	147
CLEAN ISLANDS	34	1	34
DA OPAILOLO	15	1	15
DA OPAILOLO II	15	1	15
E. R. CAPETOWN	185	3	62
EHIME MARU	56	3	19
EUROPEAN HIGHWAY	180	2	91
FREEBIRD	39	2	20
FREEDOM ACE	200	2	101
FUJI	191	1	191
FUKISHIMA MARU	57	2	29
FUKUEL MARU	56	2	28
FUNAKAWA MARU	57	3	19
GENYO MARU	57	2	29
GONEL MARU	54	2	27
GREAT LAND	241	2	121
GREEN DALE	179	2	90
HALEAKALA	107	2	54
HAWAI RESPONDER	63	2	32
HAWAI TRADER	116	2	58
HENRY SR.	34	1	34

Table F.9. Velocity Data for Port Honolulu (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
HIIALAKAI	69	2	35
HORIZON CONSUMER	220	2	111
HORIZON FAIRBANKS	204	3	68
HORIZON PACIFIC	217	3	73
HORIZON RELIANCE	272	4	68
HORIZON SPIRIT	272	3	91
HUME HIGHWAY	200	2	101
IBUKI	180	2	91
INFINITY	294	2	148
ISLAND PRINCESS	294	2	148
IZUMO	193	2	97
JAPON TUNA NO. 3	103	2	52
JEAN ANNE	176	2	89
KAIGATO MARU	56	2	28
KALMIKAI O KANOLA	60	4	15
KALYO MARU	54	2	27
KAPITAN MASLOV	185	2	93
KASHIMA MARU	58	2	29
KEKOA	38	1	38
KILO MOANA	55	2	28
KLAUS WRTYKI	17	1	17
KOKUA	41	2	21
KOSLAM	97	2	49
KOTOSHIRO MARU	54	2	27
KULAMANU	87	1	87

Table F.10. Velocity Data for Port Honolulu (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
LE GRAND BLEU	114	2	57
LIBERTY ACE	193	2	97
LIHUE	240	2	121
LURLINE	252	2	127
LYRA LEADER	200	2	100
MAERSK NOVAZZANO	188	2	95
MAKANI OLU	23	2	12
MANULANI	217	3	73
MARY CATHERINE	129	2	65
MATSONIA	129	4	32
MAUL	219	3	74
MAUNA LOA	107	2	54
MAUNAWILL	217	3	73
MICRONESIAN NAVIGATOR	129	2	65
MIRAI	129	4	32
NECHES	182	3	61
NEW KOPEX	103	3	35
NEWMARKET	117	2	59
NORWEGIAN WIND	230	2	116
ONNURI	64	2	32
OOPUULANI	12	1	12
OSCAR ELTON SETTE	68	2	34
P&O NEDLLOYD HORIZON	188	2	95
PACIFIC TRADER	116	2	58
PALMELA	200	1	200

Table F.11. Velocity Data for Port Honolulu (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
PHYLLIS DUNLAP	37	2	19
PRIDE OF ALOHA	260	1	260
PRIDE OF AMERICA	284	1	284
R. J. PFEIFFER	218	3	73
RADIANCE OF THE SEAS	295	1	295
RITA DEL MAR	165	2	83
ROGER REVEILE	113	2	57
RYOFUKU MARU	54	2	27
SAAM PUREPECHA	35	2	17
SATSUMASELUN MARU	64	2	32
SEA VIKING	38	2	19
SEA WAVE	165	2	83
SEAFLYER	50	1	50
SEIHA MARU NO. 2	69	2	35
SERENADE OF THE SEAS	293	2	147
SETTSU	159	2	80
SETUBAL	140	1	140
SHIMA	160	2	80
SHIN CO-OP MARU	98	2	49
SHIN OITA MARU	56	2	28
SHINYO MARU	64	2	32
SHION	148	2	74
SOGA	159	3	53
SOYANG	104	3	35
STATENDAM	219	2	110

Table F.12. Velocity Data for Port Honolulu (continued)

Ship Name	**Ship Length**	**Days Stayed**	**Velocity (m/day)**
TENYU MARU	55	1	55
TOPLESS	182	3	61
UNRYU MARU	56	3	19
USCGC KUKUL	82	2	41
USCGC MAPLE	69	2	35
USCGC WALNUT	69	2	35
WALALEALE	105	2	53
WHITE HOLLY	41	2	20
YUKO MARU	58	2	29
Average Velocity			**68**

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