THE USE OF DISCRETE COMPUTER SIMULATION MODELS FOR HARBOURS IN DEVELOPING COUNTRIES

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ABSTRACT

In the past usually the queueing theory was used to determine the number of berths and with that the quay length. This analytic method can be applied when it is acceptable to create a very simple model by schematization of the so called real life system. In most cases however it is not possible to schematize to such an extend that the model consists only of a queue (anchorage) and a number of places where service is rendered to ships (berths). Moreover, it is necessary to express the inter-arrival time distribution and the service time distribution in mathematical formulations.

A powerful method that can be used in complicated situations is offered by the discrete computer simulation of harbour systems, provided that enough data are available.

In this paper a review is given of the situations that can be solved in an analytical way by means of the queueing theory.

Next the discrete computer simulation technique will be discussed in the course of which the possibilities and limitations of this technique when applied to harbours in developing countries come up.

The simulation results of the harbour of Beira in Mozambique are discussed to illustrate the possibilities. A generally applicable simulation model, developed by the Delft University of Technology has been used to execute the simulation.

1. INTRODUCTION

Many service systems exist in port engineering examples are harbour systems, terminal systems as container terminals, oil terminals, liquid gas terminals, lock-systems etc. All these systems render service to ships in a specific way. To determine the capacity of a system it is necessary to schematize the reality (the real life system) by leaving out all non relevant aspects.

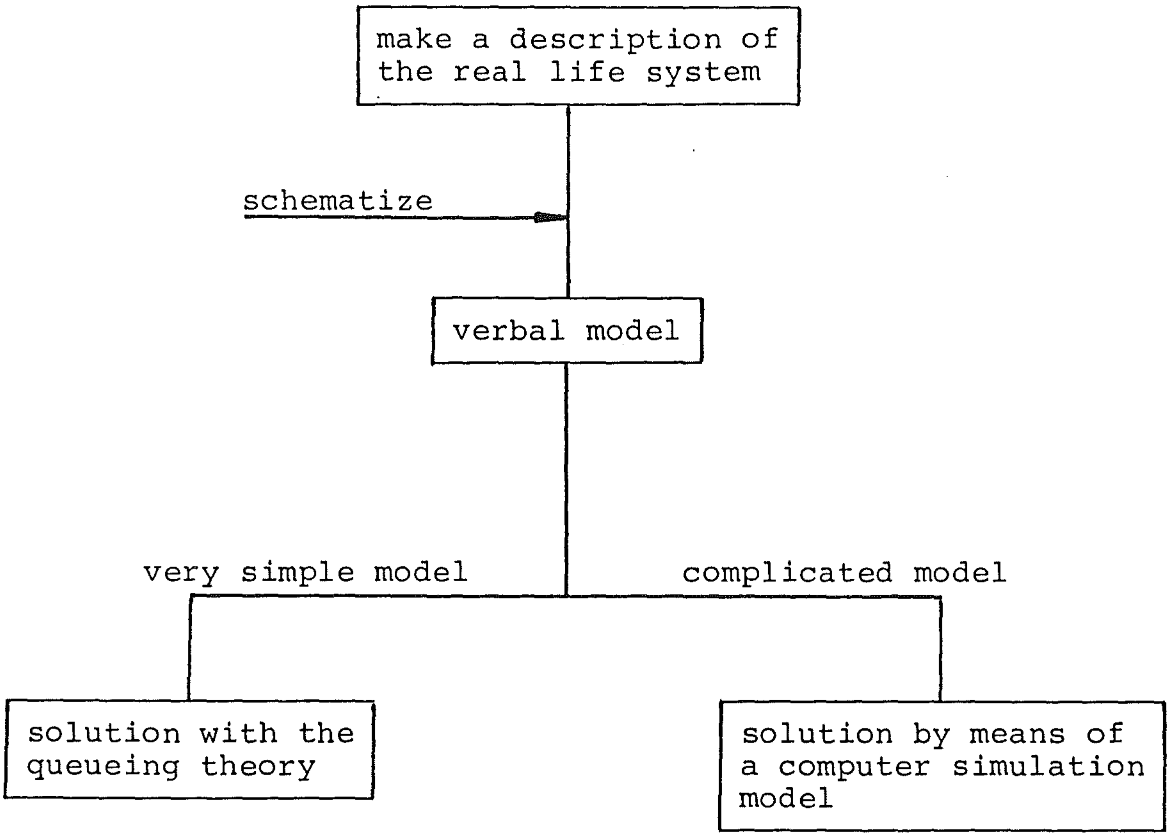
In order to make a description of the real life system it is necessary to define the boundary-conditions. The boundaries have to be chosen in such a way that a change in the functioning of the system does not affect the boundary conditions.

When it is acceptable to create a very simple model, it is possible to determine the capacity on an analytical way with the so called queueing theory. This analytic approach with the queueing theory is no longer possible when for example:

a. the sailing time from the anchorage or arrival point to the quay cannot be neglected in relation to the service time of the ship;
b. the number of berths is dependent on the length of the ships;
c. the tidal conditions, the characteristics of the entrance chan-

nel, the navigation characteristics of the harbour, the availability of tugboats, the availability of pilots, etc. affect the functioning of the system.

Unfortunately the queueing theory is still frequently applied in above mentioned complex situations and in these cases the results have nearly no relation to the actual harbour system concerned.
A powerful method that can be used in these complicated situations is offered by the discrete computer simulation of harbour systems provided that there are enough data.
The procedure is represented below schematically.

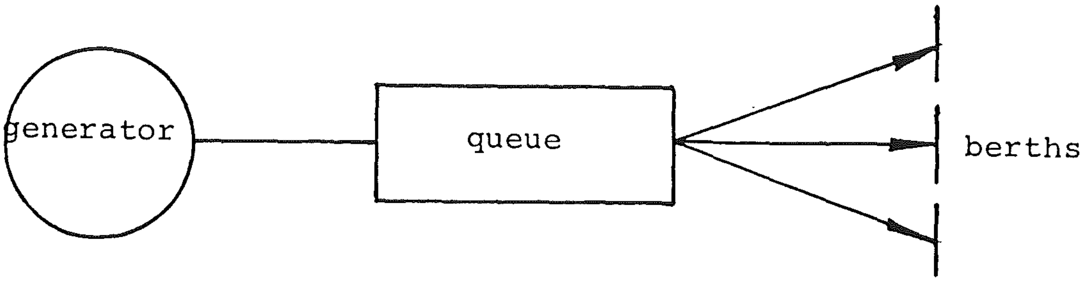


2. QUEUEING THEORY

In the case systems can be represented very simply, consisting only of the elements such as a statistical inter-arrival time distribution, an arrival queue, a discrete number of berths and a statistical service time-distribution (a post office situation) it is possible to calculate:

a. Nw = the average number of ships in the arrival queue (anchorage)
b. Np = the average number of ships present in the system
c. St = change of delay (all berthing points are occupied)
d. W = the mean waiting time in the arrival queue before being served
e. Ψ = the mean quay-utilization
f. T_a = the mean turn around time (waiting time plus servicing time)

Such a delay-system can be represented as under:



generator of demands according a distribution function	queue with the queue discipline first in first out	s berths render service according to a service time distribution

The variables used in these mathematical models are:

a. variables to characterize the statistical inter arrival time distribution as λ = the mean arrival rate of ships in the port;
b. variables to characterize the statistical service time distribution as μ = the mean service rate of ships in the port;
c. the number of berths s.

The time intervals between the arrivals are usually found to fit in a negative exponental distribution and mostly a k-Erlang distribution is used to represent the servicing operation. The mathematical formulation of this negative exponential distribution is

$f(t) = 1-e^{-\lambda t}$ (probability density function) of

$F(t) = 1-e^{-\lambda t}$ (cumulative distribution function).

The servicing operation can be regarded to consist of one or more stages. When the number of stages approaches a large number then a high Erlang number (k) is used to fit in a measured distribution. The mathematical formulation of the Erlang-k distribution is given by

$$f(t) = \frac{(k\mu)^{k}\ t^{(k-1)}}{(k-1)!} \ .\ e^{-k\mu t}$$

Suppose the inter arrival time distribution can be represented by a negative exponental distribution and the servicing operation fits a Erlang-k distribution with k = 1 than:

a. the mean utilization $\Psi = \frac{\lambda}{\mu . s}$ of $\Psi = \frac{a}{s}$ when $\frac{\lambda}{\mu} = a$

b. the chance of delay

$$St(a,s) = \frac{a^{s}/s!\ .\ {}^{s}/s-a}{1+a+a^{2}/2!\ +\ \dots\ a^{s-1}/_{(s-1)!}+(a^{s}/s!).({}^{s}/s-a)}$$

c. the average number of ships in the arrival queue

$$Nw(a,s) = a^{s}/s!\ .\ a.s/(s-a)^{2}.f(0)$$

where $f(0) = 1/(1+a + a^{2}/2! + \dots + a^{s-1}/(s-a)!.({}^{s}/s-a))$

d. the mean waiting time in the arrival queue $W(a,s) = Nw(a,s)/\lambda$

e. the turn around time $Ta = \frac{1}{\mu} + W(a,s)$

f. the average number of ships present in the system $Nw + \frac{\lambda}{\mu}$

Now it is possible to calculate the optimum number of berths or

the necessity of extention according to economic criteria. It is clear that the number of berths has to be extended when $a/s > 1$ because in this case the average capacity of the system is smaller than the arrival rate.
If $a/s < 1$ then the extention of the number of berths is justified when:

$$Nw(a,s) \cdot k_1 \quad + \quad s \cdot k_2 < Nw\,(a,s-1) \cdot k_1 + (s-1) \cdot k_2$$

cost per unit time of the ships waiting in the arrival queue in the case of s berths	costs of s berth per unit time	total costs in the case of s-1 berths

k_1 = costs per ship per unit time waiting in the arrival queue

k_2 = costs per berth per unit time

This in equality is shown in a graph in figure (1). The areas between the curces give the optimal number of berths. Suppose $k_1/k_2 = 0.1$ (in most cases this is an acceptable value) than with $a = 1,5$ 4 berths are necessary.

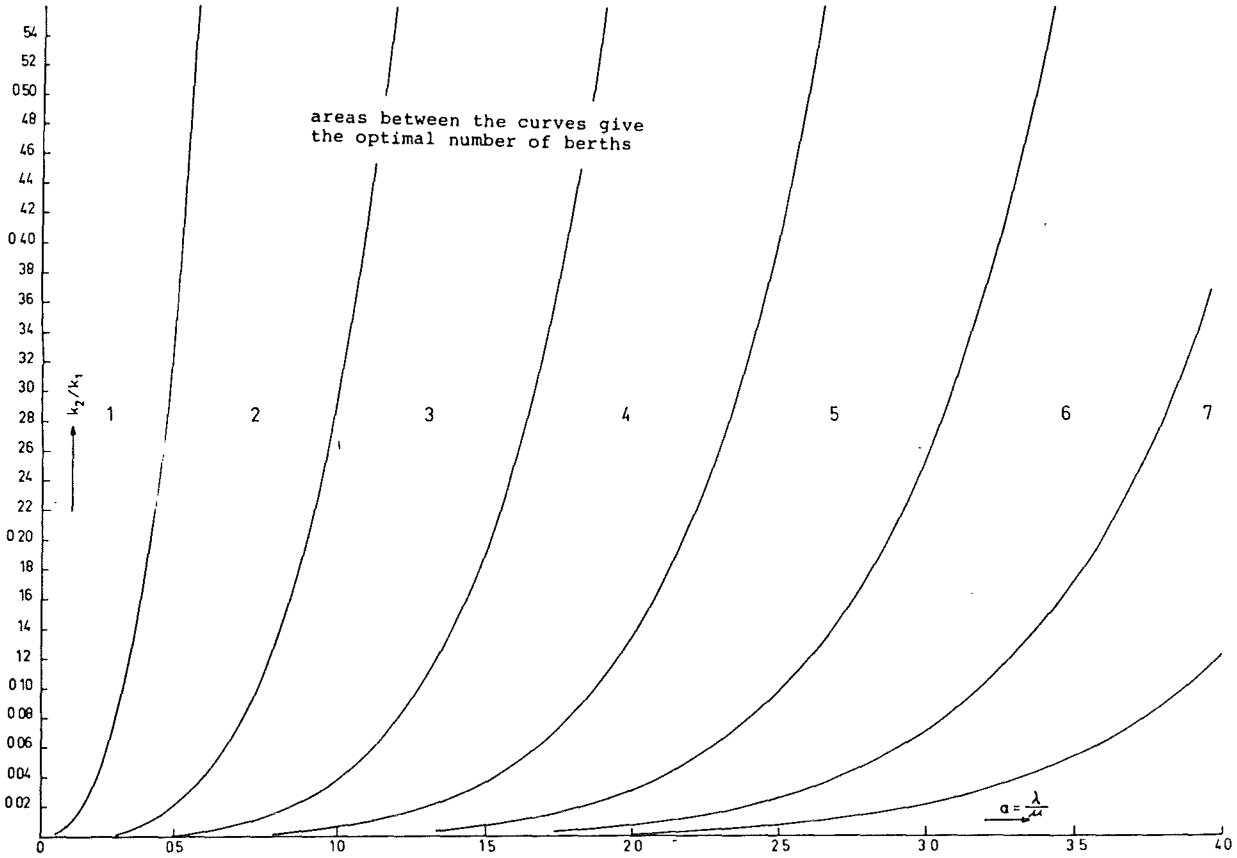


Fig 1.

The same principle can be applied to calculate the optimal transshipment capacity.
Similar formulae and tables have been developed for several combinations of different types of inter arrival time and service time-distribution [1] [2] [3]
As stated before queueing theory is a valuable tool for systems that can be represented very simply and for preliminary studies in behalf of the construction of simulation models.

3. DISCRETE COMPUTER SIMULATION TECHNIQUE

3.1 Introduction

Generally speaking simulation is used to study the dynamic behaviour of a system by means of experimentations with the model of that system. In this way it is possible to obtain data which in statistical sense are relevant to the original system. Computer simulation includes the following points:

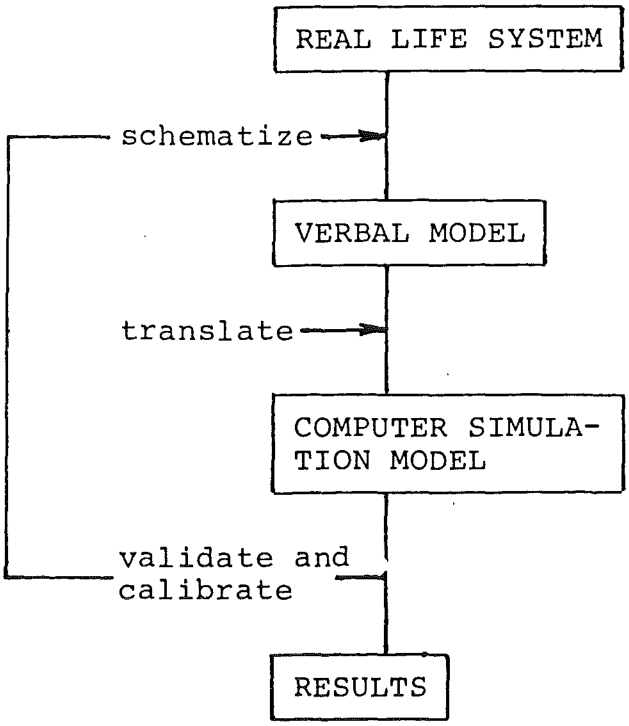
a. Specification of the problem and satisfactory answers to the following questions:
   1. Is it appropriate to execute a simulation. This depends on the availability of data.
   2. Is it possible to carry out the simulation within available time and money.

b. The development of the verbal model.
   The development of the verbal model needs a decision concerning the level of detail of the model.

c. The translation of the verbal model to a computer simulation model. At this stage it is necessary to make a choise concerning the computer simulation language.

d. Validation and calibration of the model.

e. Obtaining forecasts of possible situations in the future to make the correct decisions.
   This can be represented in scheme:



3.2 The objectives of discrete computer simulations

The objectives of discrete computer simulation models are:

a. With a computer simulation model it is possible to determine the results (contemplated results) of an intervention or a number of interventions. The intervention can be of technical nature as enlarging the transshipment capacity, improvement of the nautical conditions, enlarging of the quay length or concern management as changing of priority rules (consequence analysis).
b. With a number of trial interventions a better insight in the functioning of the system can be obtained. It is possible to determine the critical parameters and the parameter which affect the system only slightly (structure analysis).
c. When the boundary conditions of the design of a new harbour are available a simulation model can determine whether the design satisfies the design requirements.

Above mentioned simulations concern discrete simulations and are executed by a digital computer with the variables being discrete functions of the time.
It is manifest that a port authority is able to organize a port to meet any expectable contigency of traffic without waiting times, thus immediate berthing and servicing for any ship entering the harbour is possible. It is clear that this involves large investments. Striving for a minimum of costs it is necessary to find an optimum balance between the minimum number of idle berths on the one hand and a minimum amount of turn around time (servicing and waiting time) in the other.
As stated before the available amount of time and money has to be sufficient to carry out the simulation. Because the complexibility of many harbours in developing countries is rather low it is possible to use a generally applicable simulation model. This means the required amount of time and money is rather small concerning the translation from the verbal model to a computer simulation model. The Hydraulic Engineering Group of Delft University of Technology has developed the general simulation model HARBOURSIM.PRO. Before discussing and employing this model for the port of Beira it is important to explain some notations and description methods.

3.3 Notations, event, component and attribute

The status of the system is changed by an event. In discrete simulation the status of the system remains unchanged between two successive events. For example the arrival or departure of a ship in a port system is an event and the instant of time or arrival or departure is called eventtime. It is manifest that different events don't cause the same changes in the system and for this reason event classes exist. Every system description method formulates the behaviour and interactions of the components in the system. There are temporary and permanent components in a port system. An example of a temporary component is a ship and the harbourmaster for instance is a permanent component.
Components are specified by a list of attributes.
The attributes of a ship are for instance:

1. the arrival time in the system
2. the length
3. shiptype
4. draught
5. destination in the port etc.

3.4 Description methods

A description method has to be used to translate the verbal model to a computer simulation model. Three description methods can be distinguished viz. the process description, the activity description and the event description.
The process description gives a description of the processes of the components in the system for instance the process of a ship, the process of the harbourmaster, the process of the generator of ships. It is clear interactions exist between the several processes.
The process description method is considered to be a method describing a system in a very natural way. For instance the sequence of states of the ship are simple to describe.
The activity-description describes the activities present in the system. The activity takes place provided a number of conditions are satisfied. For example the activity, moor along the quay, has to satisfy the conditions concerning the free quay length, the tidal circumstances and the channel occupation.
The activity method is considered to be a rather computer time consuming method.
In the event-description the event takes the central place. Dependent on the eventclass the event description formulates the changes in the system. Using the event-description method it is necessary to know the functioning of the system very thoroughly.

4. DESCRIPTION OF THE GENERAL PORT SIMULATION MODEL "HARBOURSIM.PRO"

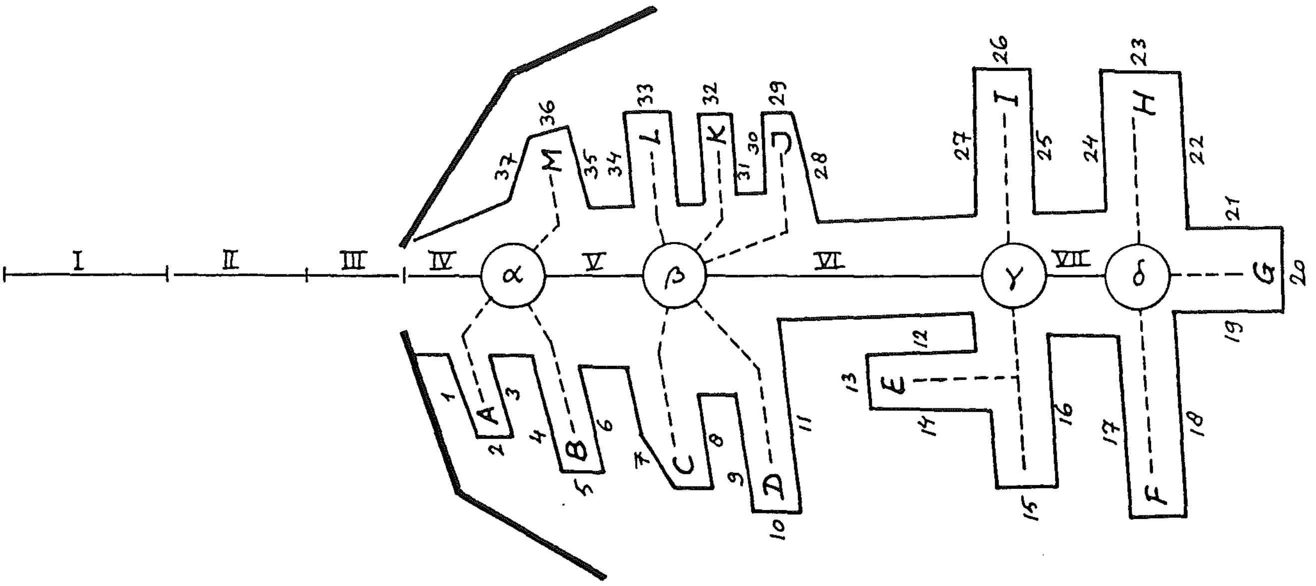
The Hydraulic Engineering Group of the Delft University of Technology has developed the general portsimulation model "HARBOURSIM.PRO". The model has been written in the computer simulation language Prosim (Process Simulation) using the process description method. The general configuration of the model is given in fig.(2)
The model has at its disposal:
a. an access channel consisting of atmost 4 sections
b. maximum 4 turning basins each of which has access to a maximum of 10 basins
c. each basin may consist of a great number of quays

Each channel section in the model Harboursim.pro can be made one of more way traffic for each shiptype. This information has been put in two three-dimensional arrays. This arrays inform whether it is possible that shiptype x overtakes or meets shiptype y in channel section s.

The computer simulation model "Harboursim.pro" consist in broad lines of two sections. The first section is called the definition section and shows how the model is composed.
The second section of the computer model is called the dynamic section and shows the dynamic behaviour of the different components and class of components.
In scheme the computer simulation model is represented below.

COMPONENT	PROCESS DESCRIPTION	
MAIN	defines: components queues histograms takes care of: declarations run control output	definition section
GENERATORS OF SHIPS	generates according to the distribution of the shiptype	dynamic section
SHIP (temporary component)	passes through the process of the ship	
PILOT	determines in conjunction with the harbour master concerning the incoming traffic	
HARBOURMASTER	determines in conjunction with the pilot concerning the leaving traffic	
ADMINISTRATOR 1	takes care of the administration concerning quays	
ADMINISTRATOR 2	takes care of the administration of sailing ships	

POSSIBLE CONFIGURATION OF GENERALLY APPLICABLE
SIMULATION MODEL HARBORSIM.PRO



A - M	SHIP DESTINATION
1 - 37	QUAYS
I - VII	SAIL SECTIONS
α - δ	TURNING BASINS

FIG. 2

Some processes need some explanation.

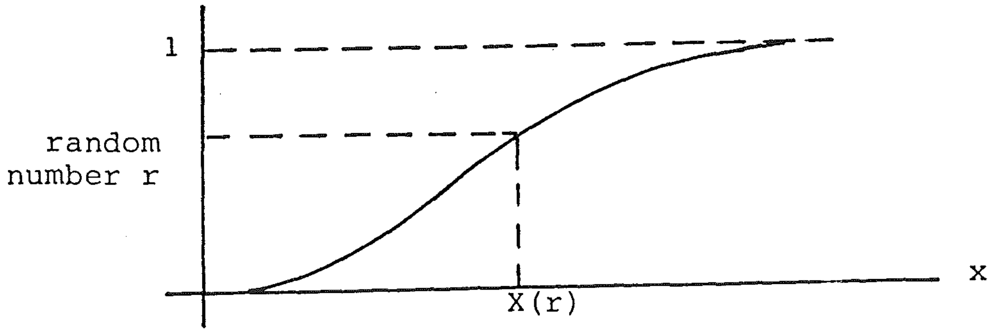
- The component Main.

The model is written in the simulation language Prosim; this simulation language has been developed by the Delft University of Technology. Using Prosim it is not necessary to define the component Main. Main exists already before the simulation starts.

- The generators of ships.

Each shiptype has the disposal of an own generator. This means that the inter arrival times of each shiptype can be generated according to its own inter arrival time distribution as for instance a negative exponentional distribution (Poisson), k-Erlang distribution, a uniform distribution, normal distribution etc. Uncertainties exist about arrival times and servicing times of ships. They are usually subject to random fluctuations. On the basis of a great number of observations or theoretical considerations it is possible to construct a distribution function of inter arrival times or servicing times. Using random numbers it is possible to draw samples from the given distribution. Suppose r is a random number and $F(t) = 1-e^{-\lambda t}$ is a cumulative distribution function (with t = the inter arrival time and λ = mean arrival rate). Then $r = 1-e^{-\lambda t}$ or $t = \frac{-1}{\lambda}\ln(1-r)$.

In this way it is also possible to draw samples from a cumulative distribution given in the form of a table. When the arrival time of a ship has been generated at the same time, the attributes will be determined:
1. sailing times, 2. the stay in the turning circle, 3. sailing



Distribution function

list, 4. quay destination, 5. draught (for incoming and leaving ships), 6. keel clearance, 7. length, 8. servicing times, 9. critical water velocities, 10. priority of the ship etc.
It is necessary to simulate several runs (with the same boundary conditions but with different random numbers) of may be one year to get in statistical sense significant figures.
The length of the run has to be sufficient to registrate independent figures.
The model Harboursim.pro gives per run the following output:

1. The status of the system with data about the queues (number of entries, length, maximum and minimum length during the run, the mean and maximum waiting time), the status of the components in the model (current, passive or suspended).
2. The number of generated ships per shiptype.
3. Histograms concerning waiting times per shiptype at the arrival buoy, in the harbour and the total waiting times per shiptype (with the number of entries, mean, standard deviation and the maximum and minimum waiting time).
4. Histograms concerning the utilization per quay.

With this registration of the different runs significant figures with the confidence intervals can be determined.

5. APPLICATION TO THE PORT OF BEIRA

5.1 Introduction and input data

To show the possibilities of discrete simulation models the model Harboursim.pro has been applied to the port of Beira.
The configuration and schematization of the port of Beira is given in fig. (3). The access channel consists of 6 sections. The sections 1, 2 and 5 are more way and the sections 3, 4 and 6 are only one way while section 3 reduces the passages by its confined depth. Channel section 6 connects the turning circle in front of the quays (fig. (4)).
The port of Beira is called by several shiptypes such as roro-vessels, molasses-vessels, coal-carriers, gasoline-carriers, general cargo ships and coasters. The fishing boats have been left out

of the consideration because these boats do not affect the system. Tidal conditions are important because of the confined water depth of the Macuti Channel (section 3) and when critical velocities are exceeded berthing and unberthing is not possible. This means that a fully loaded ship with a draught of 9.5 m has to wait for a suitable tide to pass the Macuti Channel while berthing and unberthing is subject to restrictions. The input data of the tidal conditions are given in fig. (4) and table (1).

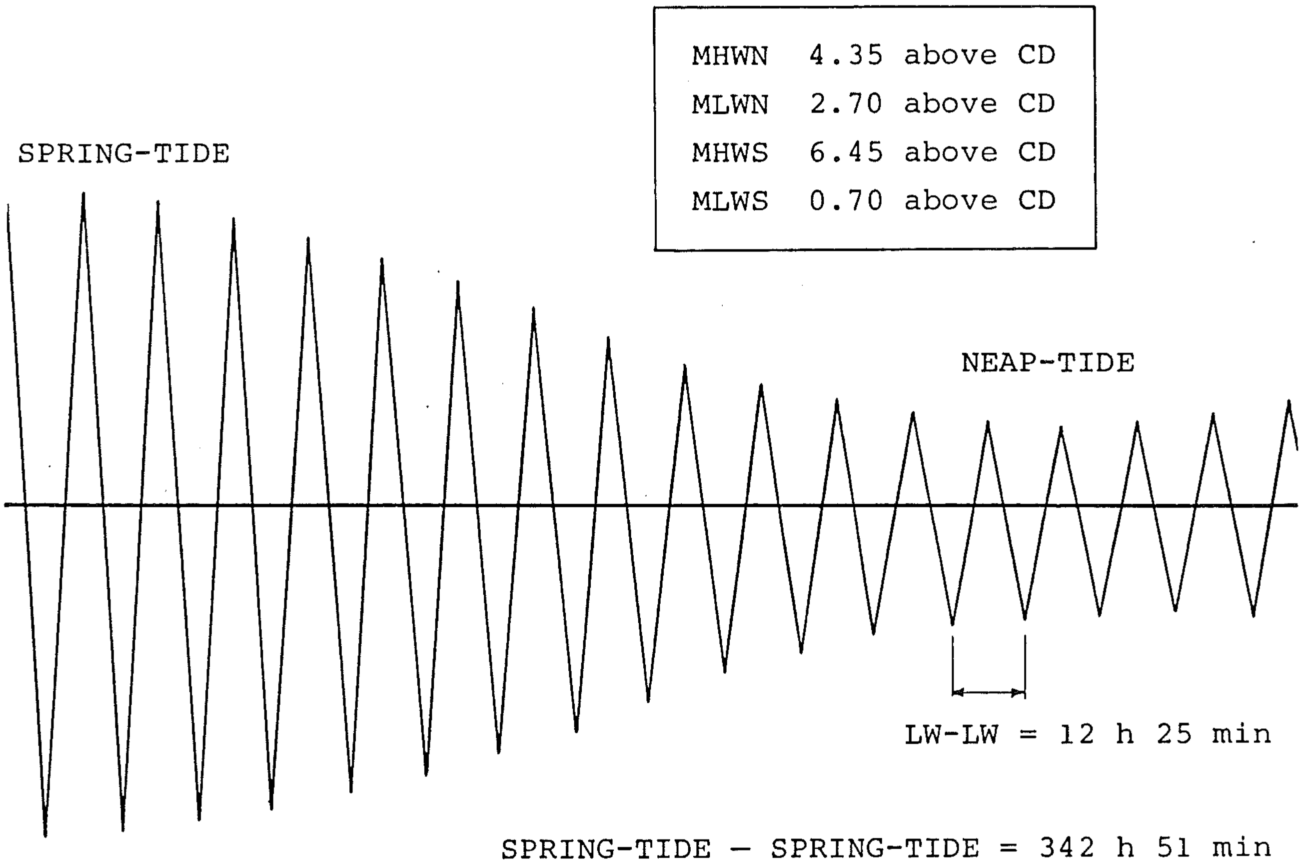

MHWN 4.35 above CD
MLWN 2.70 above CD
MHWS 6.45 above CD
MLWS 0.70 above CD

FIG.4 TIDAL CONDITIONS BEIRA

	from	to
Berthing:	LW	HW + 3 hrs
Unberthing		
Length < 130	LW + 1 hr	HW + 3 hrs
130 < Length < 160	LW + 1 hr	HW + 2 hrs
Length > 160	LW + 1 hr	HW

table (1)

A number of simulation runs each with a length of 1 year have been carried out to know the influence of the depth of the Macuti Channel and the influence of the navigation restrictions during the night on the waiting times of the ships:
a. With the traffic volume of 1980, navigation restrictions during the night while the nautical depth of the Macuti Channel has been varied from 5.50 to 5.90 m. The input data of the ships are given in table (2).
b. The same conditions as given under a. but without navigation restrictions during the night.
c. The same conditions as given under a. but with a larger draught distribution of the ships.
The nautical depth of the Macuti Channel has been varied from 5.50 to 7.20 m. The input data of the ships are given in table (3).

5.2 Validation and calibration

The Beira port study of Nedeco mentions that in 1980 200 shipdays of delay were recorded due to waiting for tides and daylight. The simulation results show a good resemblance to this figure. The simulation model registrates 209 shipdays of delay if the Macuti Channel has a nautical depth of 5.50 m. More data for validation and calibration were not available.

5.3 Simulation results and conclusions

The simulation results are given in fig. (5) and fig. (6). It is clear that with the boundary conditions given under a. of par. 5.1 (the present situation) the optimal depth comes to 5.80 m. (fig. (5)). Further decrease of the depth gives a strong increase of the waiting times. The simulation model registrates 170 shipdays of delay with a nautical depth of 5.80 m. A sharp improvement proceeds when navigation during the night is possible (conditions given under b. of par. 5.1).
With a nautical depth of 5.80 the model registrates 60 shipdays of delay.
Simulating with a larger draught distribution (conditions under c. of par. 5.1) the optimal nautical depth comes to 6.20 m. This depth gives 130 shipdays of delay while with no restrictions concerning night navigation this figure decreases to 85 days.
Enlarging of the existing quay length is not appropriate in the view of the rather low utilizations.
Widening of the one way channel sections is probably appropriate with larger traffic volumes.
It is the intention to simulate the future situation with the new coal terminal of the port of Beira.

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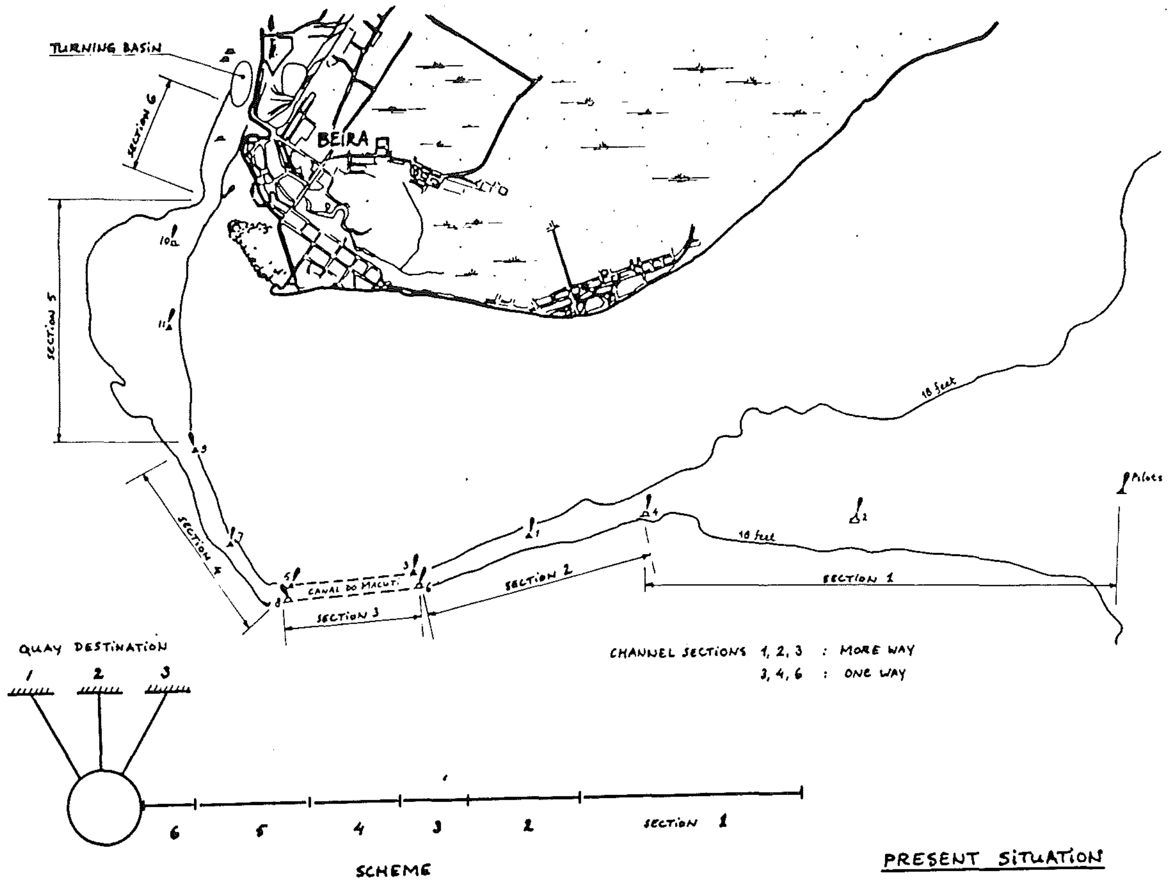


FIG. 3

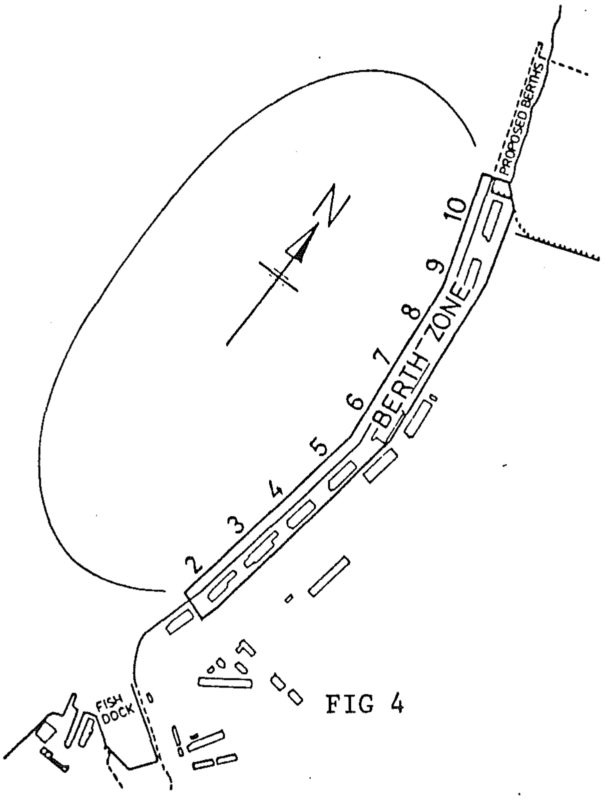
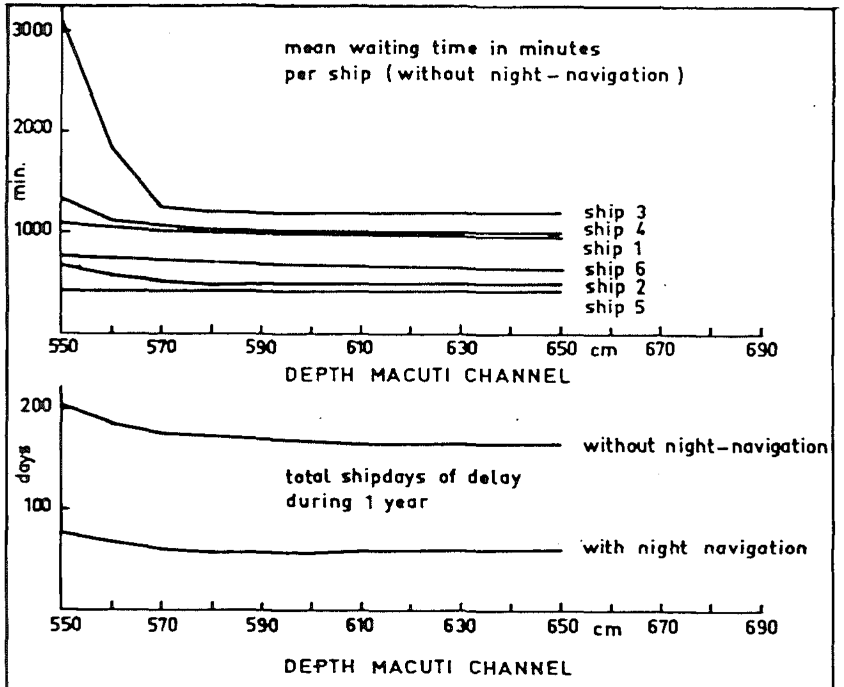


FIG 4

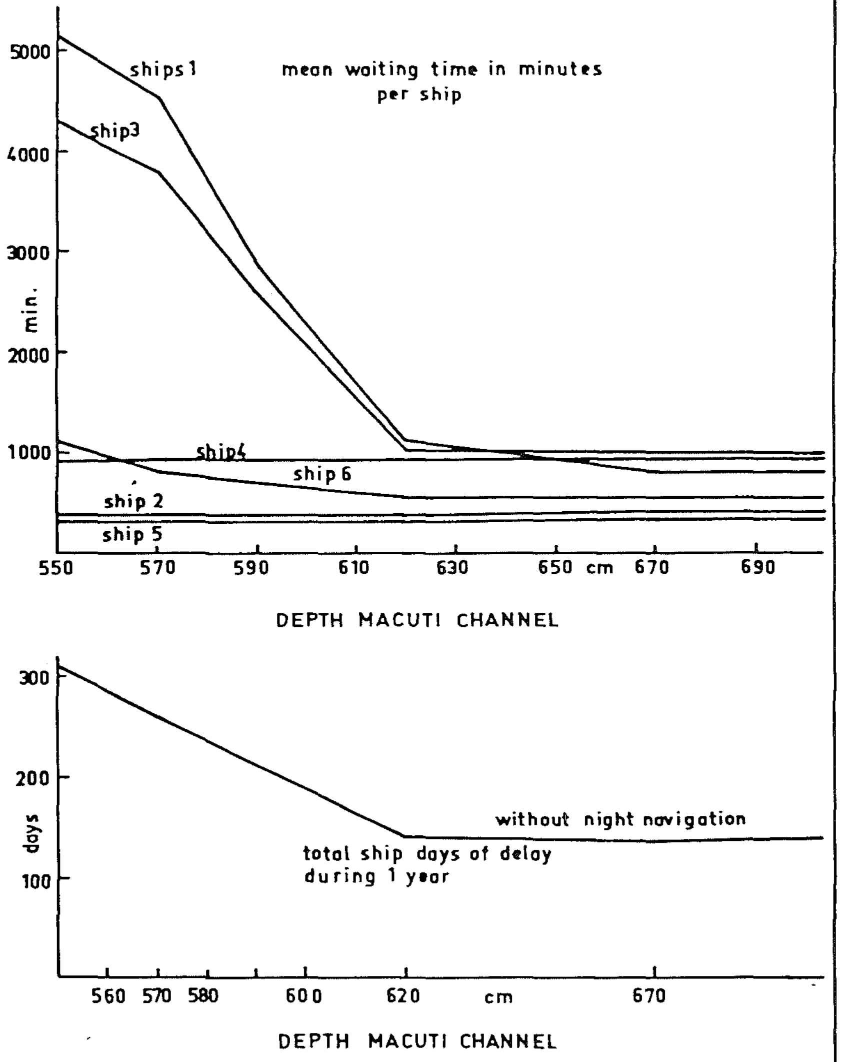
roro vessels : quay 7
molasses vessels: quay 8-9
crude carriers : quay 10
coal carriers : quay 8
coasters : quay 2-7
gen. cargo : quay 2-7



WAITING TIMES SHIPS WITH THE CONTINGENCY
OF TRAFFIC IN 1980

Fig. 5

Ship 1: Roro
Ship 2: Molasses
Ship 3: Gasoline carriers
Ship 4: Coal carriers
Ship 5: Coaster
Ship 6: Gen. cargo



WAITING TIMES SHIPS WITH THE CONTINGENCY
OF TRAFFIC IN 1980 WITH A LARGER
DRAUGHT DISTRIBUTION.

Fig. 6

	roro vessels	molasses vessels	gasoline carriers	coal carriers	coasters	gen. cargo 6000 d.w.t.	gen. cargo 10000 d.w.t.	gen. cargo 16000 d.w.t.
Type	1	2	3	4	5	6	6	6
Quay destination	9	9/8	10	8	2/7	2/7	2/7	2/7
Arrival distribution	E6*	E2	E2	E2	P*	P	P	P
Arrivals per year	16	19	22	7	90	89	88	48
Mean service time (hrs)	35	50	36	150	40	91	139	196
Mean ship-length (m)	190	120	160	170	67	110	125	145
Mean draught incoming ships (m)	6,9	6,5	9	6,5	5,5	6,5	7,5	8,5
Mean draught leaving ships	7,5	7,5	4,5	8,5	5,5	6,5	7,5	8,5
Mean keel-clearance	0,85	0,85	1,00	1,00	0,6	0,7	0,85	0,95
Critical velocity (knots)	1	2	1	1	3	2	2	2
Priority	high	-	-	-	-	-	-	-

table (2)

* E6 = Erlang distr. k = 6

* P = Poisson distr.

	roro vessels	molasses vessels	gasoline carriers	coal carriers	coasters	gen. cargo 6000 d.w.t.	gen. cargo 10000 d.w.t.	gen. cargo 16000 d.w.t.
Type	1	2	3	4	5	6	6	6
Quay destination	9	9/8	10	8	2/7	2/7	2/7	2/7
Arrival distribution	E6	E2	E2	E2	P	P	P	P
Arrivals per year	16	19	22	7	90	89	88	48
Mean service time (hrs)	35	50	36	150	40	91	139	196
Mean ship-length (m)	190	120	160	170	67	110	125	145
Mean draught incoming ships (m)	9,5	6,5	9,5	6,5	5,5	7	8,5	9,5
Mean draught leaving ships	9,5	7,5	4,5	8,5	5,5	7	8,5	9,5
Mean keel-clearance	0,95	0,8	1,00	1,00	0,6	0,7	0,85	0,95
Critical velocity (knots)	1	2	1	1	3	2	2	2
Priority	high	-	-	-	-	-	-	-

table (3)