MARITIME HIGHWAYS TO A PORT - MODELLING OF MAXIMUM CAPACITY

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ABSTRACT

Maritime ports are a vital link in the national and international cargo transport chain and their efficient functioning is critical for an economy with large volumes of international trade. Queueing theory and related numerical models are used to optimise the port throughput, both for existing ports and for new or extended ports. Several relationships are shown which can fruitfully be employed to investigate components of the port logistics chain. An application for the extension of an ore export port is shown as a case study.

INTRODUCTION

Ports are a vital component of the national and international cargo transport infrastructure. They serve as an important link between national and global trade and tourism systems. At present, sea transport is still the most common and cost effective way to transport large quantities of goods over large distances. The ports form a critical link between land transport and maritime transport, each with different supply intensities and hence buffer storage requirements. The challenge for ports is to maximise cargo throughput.

As the world economy grows, so does the quantity of goods being traded between different continents and countries. This results in larger transport vessels continually being designed and built to handle the growth in quantities. To stay economically competitive, ports are required to expand their capacity to accommodate these large transport vessels. Continuous infrastructure improvements and developments to the ports are therefore needed, such as the construction of new import and export terminals and berths, as well as the deepening of entrance channels and berths. Operational improvements to facilitate the overall logistics chain are also needed as part of such an expansion process.

Before implementing the port expansion modifications, detailed investigations are to be conducted on the effects of the changes in the throughput and various operational aspects and to identify bottle necks in the logistics chain. This is necessary to optimise all components of the transport and buffer systems and to aid decision making in the economic viability and sustainability of such expansion operations. Computer simulations can be used to analyse the terminal performance and predict the effect of changes in the port infrastructure, as well as to optimise the overall cargo throughput capacity of the port.

In this paper an outline is given on port operations and the effect of an increasing demand on export or import volumes on a port. Focus is placed on waiting times of vessels outside a port and berth utilisation. An overview of a planned ore export terminal expansion is presented as a case study.

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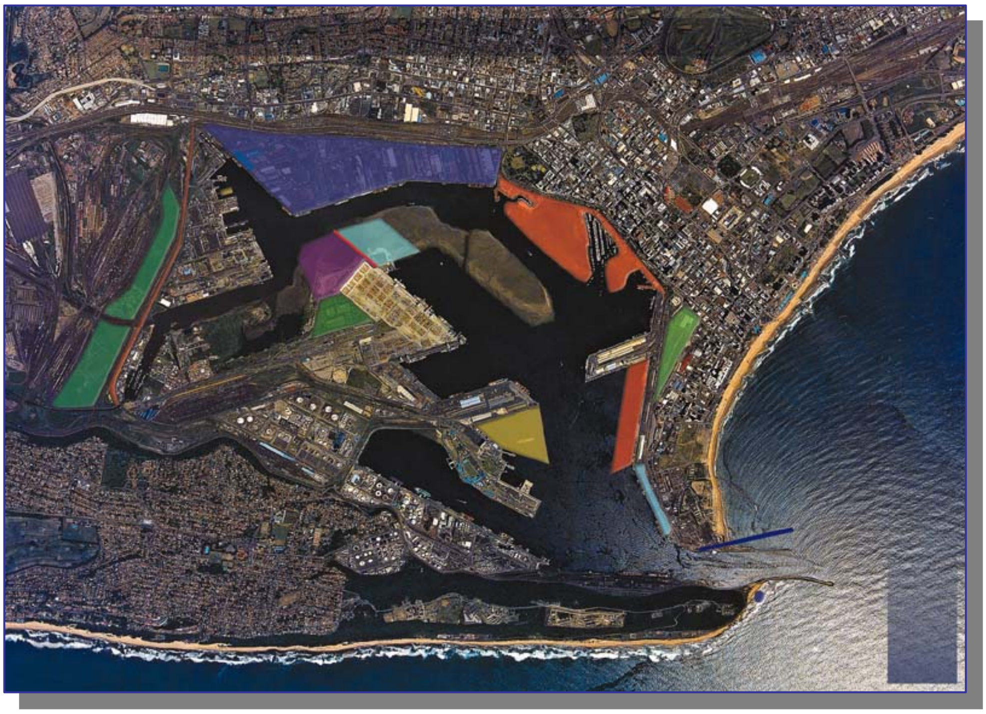

Figure 1: Port of Durban (colours indicate different cargo activities)

Figure 1 shows an areal view of the Port of Durban, which is South Africa's largest multi-purpose port. The colours indicate the terminal facilities for different commodities.

PORT LOGISTICS

A simplified form of the logistics chain of a typical port is illustrated in Figure 2. As shown in the figure, arriving vessels may have to wait in an anchorage area situated at the outside of the port. This would be needed if there are no berths available or if the entrance channel has a tidal draught restriction. The anchorage area itself has, in many instances, restrictions on the number of vessels it can accommodate, due to the available area or due to safety reasons.

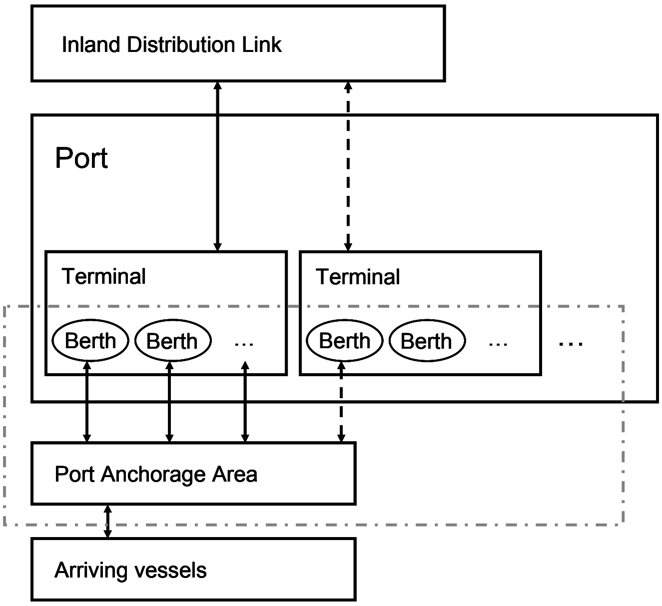

Figure 2: A schematisation of the logistics chain of a typical port

When a berth becomes available at the terminal where the vessel needs to go, the vessel will move from the anchorage area to the berth. Once the vessel is at the berth, loading or unloading of the goods can commence. As depicted in Figures 1 and 2, a port may consist of several terminals that can be used for different kinds of goods and may contain, for example, dry bulk, liquid bulk or container terminals. Each type of terminal has its own type of loading and transport equipment and stockpiles. But a port can also be a dedicated port, e.g. for oil import or coal export and would then only consist of one or more special terminals.

Ports have an agreement with shipping companies to load or unload vessels within a certain time period, usually measured from when the first mooring line is fastened until the last mooring line is loosened. If the service time of the vessel at the terminal exceeds the agreed service time, demurrage fees are paid to the shipping company by the port. If the service time is less than the time agreed on, there may be a bonus scheme in place for the port. The operational cost of large ships is about US$ 2 000 per hour. During the analysis of the port operations it is therefore important to minimise service time to save money.

In the case of import operations, dry cargo on the vessels is usually offloaded by equipment on the berth. The equipment used and the rate of offloading the vessel depends on the type of material imported. In the case of container terminals, ship to shore gantry cranes are mostly used to offload the container vessels. In the case of bulk terminals, bucket elevators or reclaimers are normally used to unload the bulk carrier. After unloading, the cargo is transported to a storage area at the terminal, by means of e.g. straddle carriers (for containers), pipelines, conveyor belt systems or other equipment.

Next the goods are moved from the storage areas at the terminals to an inland distribution link as illustrated in Figure 2. Distribution to inland destinations is mainly done by trucks or a railway system. The same process applies for the export of goods. The cargo is transported to the port by means of inland supply links and is then distributed to stockpiles at the different terminals, where feeder equipment collects the cargo for loading onto the berthed vessel.

MODELLING

From the overview of port logistics in the previous section it can be seen that detailed modelling of a port supply chain can become a complex task. Each link in the supply chain has its own restrictions and varies according to different factors.

Several commercial process simulation computer packages exist which are mainly used in the industrial engineering sector. These computer packages can be set up for the supply chain of a port and model the different components and their interactions in detail. One such simulation package which is widely used is the GENSIM process simulation model. The GENSIM model structure is customisable to specific processes and can be calibrated using available empirical data and expert knowledge.

In many practical cases it is sufficient to model only a part of the logistics chain of the port. It is, for example, possible to model only the part of the logistics chain contained in the grey dashed rectangle displayed in Figure 2 (Radmilovich, 1992). The selected entities represent the link between the sea transport and land transport and can be modelled as a queueing system with one queue and multiple servers representing the different berths (Page, 1972; Winston 1984). This would be possible under the assumption that the port side of the supply chain and the sea-land transport link can operate independently without affecting one another. In other words it is assumed that the storage area at the terminal always has sufficient stock and sufficient capacity for new stock.

A simple stochastic Monte Carlo simulation can be used to model the queueing system. Certain distributions should then be assumed for the inter arrival times and service times of the vessels. Different arrival rates can be implemented for the different types of transport vessels such as bulk carriers, oil tankers and container vessels. Each of the berths can also be modelled with different service time rates and characteristics.

It has been found that a negative exponential distribution of inter-arrival times best describes the arrival of ships in practice (e.g. Kia *et al*, 2002, Stahlbock and Vob 2008). The probability density function of the exponential distribution is given by :

$$\mathrm{p}(x) = \lambda e^{-\lambda x} \tag{1}$$

This relationship is used to describe a random variable representing inter-arrival times. Both the mean and standard deviation of the distribution are equal to 1/λ, where λ is the so called rate parameter of the distribution. Figure 3 shows the probability density p(x) of the exponential distribution (y-axis) for three different rate parameters λ, as function of x (x-axis). Van Asperen *et al* conducted a study on the effect that different arrival rates have on the queueing system and found that waiting times could be decreased by a stock-controlled arrival process (van Asperen *et al*, 2003).

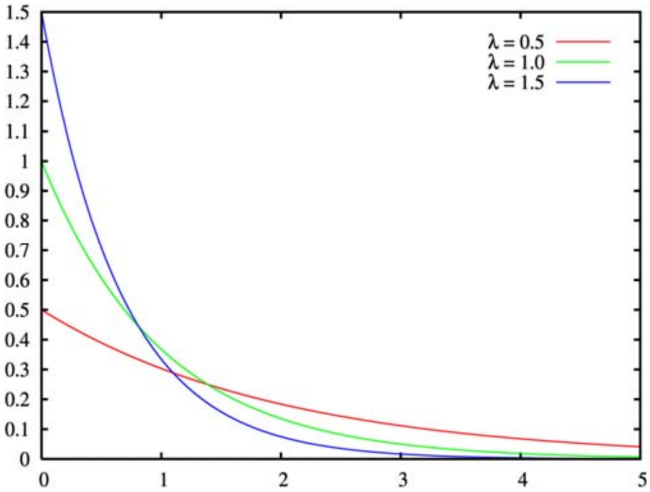

Figure 3: Probability density function of the exponential distribution

It has been found that the distribution of service times of vessels at the berths is best described by the Erlang distribution (Page, 1972). The probability density function of the Erlang distribution is given by :

$$\mathrm{p}(x) = \frac{\mu^k t^{k-1} e^{-\mu x}}{(k-1)!} \tag{2}$$

This function is used to describe a random variable representing the service times of the vessels. The mean of the distribution is given by k/μ, where μ and k are the rate and shape parameters of the distribution, respectively. Figure 4 shows the probability density function p(x) of the Erlang distribution for different rate and shape parameters, as function of x (x-axis). It can be seen from this figure that the limiting cases of the probability density function with respect to the shape parameter is the exponential distribution (k = 1) and the normal distribution (k → ∞).

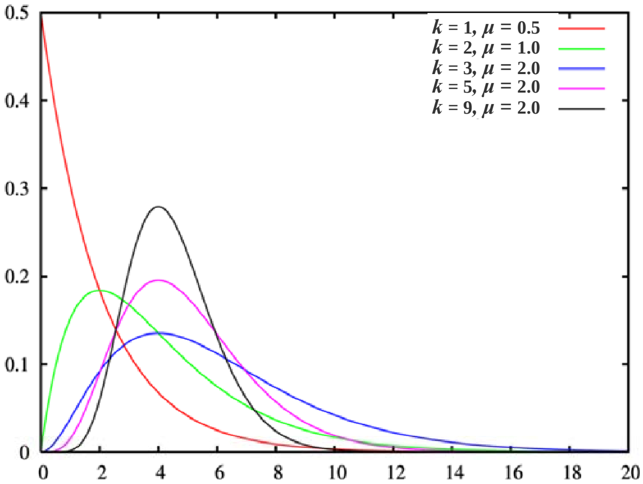

Figure 4: Probability density function of the Erlang distribution

Although the probability density functions described here are recommended for inter arrival times and service times by literature, other distribution functions can also be used in the simulation if they fit the observed data better. Goodness of fit statistics, such as the Chi-squared test, can be applied to the observed data and distribution function to determine whether the distribution function is a good representation of the observed data.

An event-driven stochastic Monte Carlo simulation can be used to simulate the queueing system. In such a simulation, stochastic arrival events are generated on time intervals taken from the inter arrival time distribution. Figure 5 outlines the procedure on how to generate stochastic data. Each arrival event joins a *first in first out* queue. If a berth is empty, the arrival event in the front of the queue is taken out to be serviced, at which time a service time is sampled from the berth's service time distribution. When one of the berths' service time elapses, the next arrival is taken from the front of the queue if there is a queue. The duration of the simulation can be based on a certain number of arrival events or on a predefined time span.

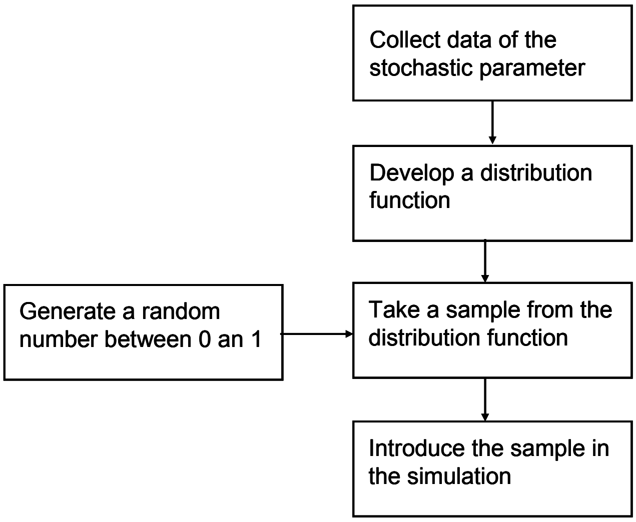

Figure 5: Flow chart on how to include stochastic parameters into a simulation

The exponential distribution has an explicit expression for its quantile function. An explicit quantile function for the Erlang distribution can not be obtained. A sample from the distribution must therefore be generated numerically. There are different techniques on how to generate samples from such a distribution with various levels of efficiency and accuracy. A widely accepted method is an iterative method called the Acceptance Rejection Method.

The above simulation method can be effectively used to model the queueing system of ships in ports. If a sufficient amount of observed data is collected on ship arrivals and services at a port, distributions can be fitted to the data to obtain the rate and shape parameters that best describe the arrivals of certain types of ships and the service potential of specific berths. The distribution parameters can then be used to simulate the queueing process and perform "what if" analyses by adjusting the rate and shape parameters. This type of computer simulation can also be used to design terminals with the optimum number of berths (Ergin and Yalciner, 1991).

Statistical analyses can be performed on the simulation outcomes to determine important parameters such as average waiting times, berth occupancy, etc. A large amount of repetitive Monte Carlo simulations can be performed to obtain reliable confidence levels from the statistical simulation output.

CASE STUDY

In this section a practical example of a port operations problem is presented. The port under consideration is used for the export of ore. The ore terminal presently consists of two berths serviced by two loading cranes. The proposed port expansion would roughly double the export capacity by constructing two new berths with two new loading cranes. As part of the first phase in the expansion process, only one additional loading crane would be set up to service the two new berths. The inclusion of the fourth loading crane would form part of the second phase. The necessary improvements also need to be made to the terminal and inland infrastructure to accommodate the increased throughput of ore.

The increase in export volume will lead to an increase in shipping to the port. A consequence may be that more ships will have to wait for a berth and may need to anchor until a suitable berth becomes available. This means that waiting times and demurrage, as well as the number of anchored ships may increase. The anchorage capacity of the port is limited to three vessels and may be exceeded. Ore carriers will then have to anchor at a nearby sheltered location.

If the expanded navigation and mooring facilities would be kept the same as the existing navigation and mooring facilities, it would be expected from theory that the number of anchored ore carriers would decrease with the number of berths. However, the two new berths that will be constructed are designed for smaller class ships than those calling at the existing berths. Due to such differences and the complexity of the logistics chain, the effect of an increase in shipping on waiting times and anchoring can not be predicted accurately by analytical methods. The most effective way of handling such investigations is by means of computer simulations.

The port has, as part of the engineering design studies, undertaken numerical simulations of the entire logistics chain from the ore mine to the port. The detailed simulation model was set up and executed with the GENSIM software package. Figure 6 shows a schematic of the GENSIM model setup that was used to model the logistics chain of the port. The main purpose was to undertake a capacity study and identify critical components of the logistics chain such as the required capacity of the stockpile area, the tipplers, the stacker reclaimers and the ship loaders. The simulation model was later extended to include the ship arrivals and berthing components to determine waiting and demurrage times of ships. Demurrage times form an important component of the assessment of the economic viability of the proposed port expansions.

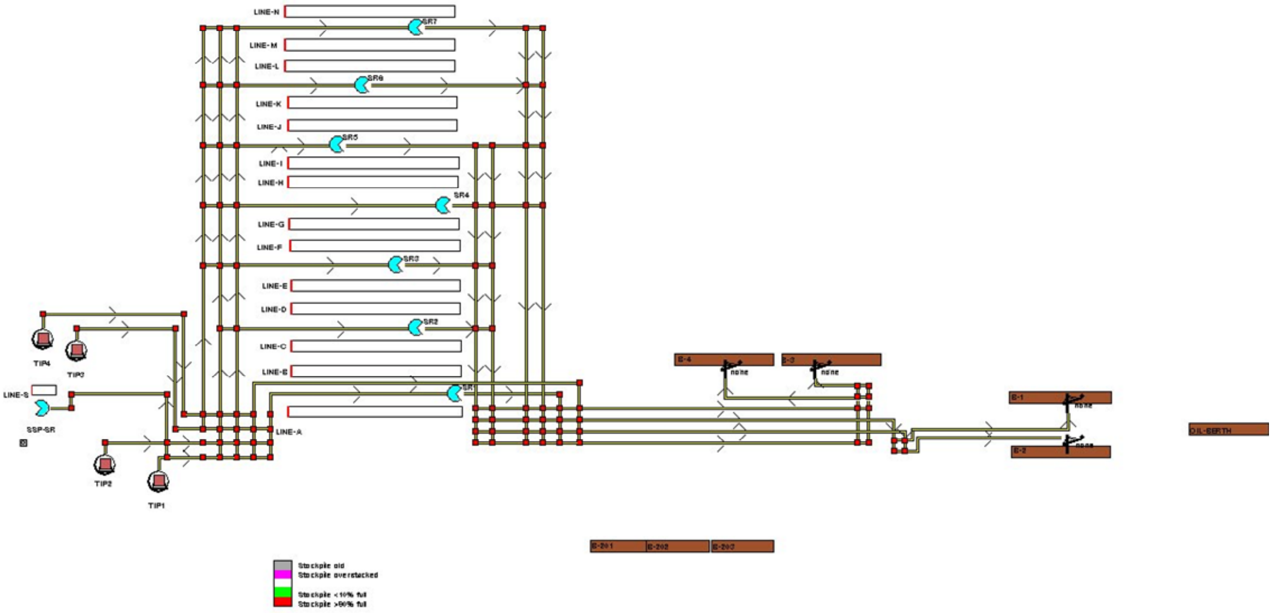

Figure 6: A model schematic of the logistics chain of the iron ore export port (ITE)

The simulation period was thirteen months. The first month was used as the simulation start-up and has not been incorporated in the analyses. The arrival rates and ship size distribution as well as the service times were chosen according to typical observed shipping at the port. Simulation results were produced in the form of tables which included the simulated loading times of each ship and the berth occupancy. The total time that a ship was in the port, from arrival to departure, was compared with the maximum berth time associated with the agreed minimum loading rate. If the simulated time that the ship was in the port exceeded this maximum time, the excess time was demurrage time. Separate tables were produced for the arrival times of the different ships and the queue lengths. An example of the simulation results consisting of queue time, berth time and demurrage time are given in Table 1 for the different phases of the port extension.

From Table 1 the increase in the export capacity of the port is evident from the number of ore carriers calling at the port. Just less than double the amount of ore carriers will visit the port in the extension phases. The number of ore carriers that will have to wait for a berth in Phase 1 is predicted to be more than double the number of ore carriers waiting for a berth in the current scenario. The number of ore carriers predicted to be waiting for a berth in Phase 2 is however significantly less than double the current amount.

A decrease in the percentage of queued vessels can be seen from the current scenario to Phase 2. The increase in the percentage of queued vessel in Phase 1 is because only one loading crane is servicing both of the new berths. The average number of ore carriers waiting in the queue for the current scenario is 1.3 but will double to a value of 2.6 for Phase 1. The value reduces to 1.6 in Phase 2. Special interest is shown in the event when there are more than three vessels in the queue.

Table 1: Summary of the results of the vessel simulation runs

Port Extension Phase		**Current**	**Phase 1**	**Phase 2**
Number of Ore Carriers in Simulation	[-]	269	492	518
Number of Ore Carriers having to wait for Berth	[-]	182	405	307
Percentage of Queued Ore Carriers	[%]	67.7	82.3	59.3
Average No. of Ore Carriers waiting	[-]	1.3	2.6	1.6
Percentage Time with > 3 Ore Carriers in Queue	[%]	0.9	24.0	8.6
Average No. of Ore Carriers > 3	[-]	1.1	1.5	1.3
Average No. of Ore Carriers in Queue over Time	[-]	0.9	2.6	1.6
Standard Deviation of Queue Size	[-]	0.9	2.0	1.5
Mean Queue Time for Queued Ore Carriers	[h]	41.7	54.5	44.9
Queue Time Standard Deviation	[h]	49	50.6	54.2
Average Time at Berth	[h]	41.0	61.7	47.7
Berth Time Standard Deviation	[h]	15.2	24.7	18.4
Number of Demurraged Vessels	[-]	13	140	26
Percentage of Demurraged Vessels	[%]	4.8	28.5	5.0
Mean Demurrage Time	[h]	25.5	32.5	49.0
Demurrage Time Standard Deviation	[h]	24.6	34.3	61.9

Figures 7, 8 and 9 show typical graphs of queue length (y-axis) over time (x-axis) for the simulations. The increase in queue sizes and queueing times are visible in the graphs for the case of Phase 1 (Figure 8). It is also evident that, in terms of queue sizes and queueing times, there is no significant deterioration from the current scenario to Phase 2, although the new berths have a smaller capacity.

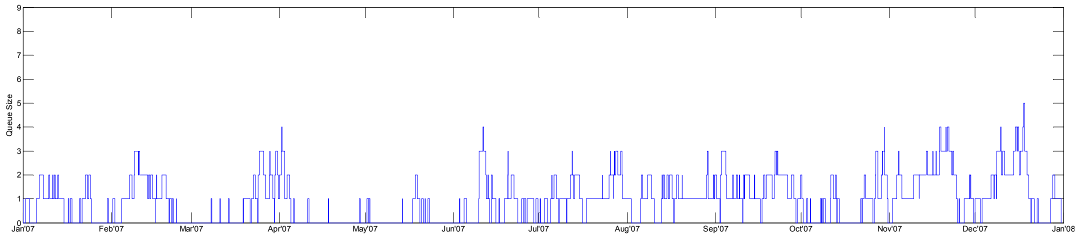

Figure 7: Current Phase queue length versus time

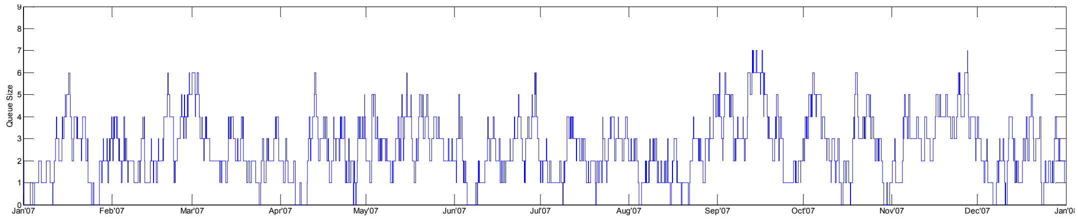

Figure 8: Phase 1 queue length versus time

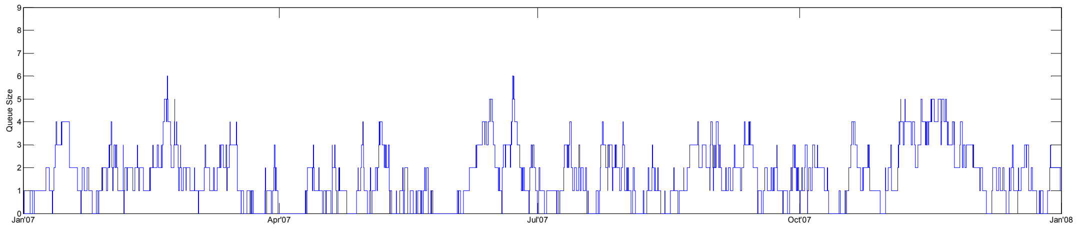

Figure 9: Phase 2 queue length versus time

Additional simulations were carried out by simulating only the interaction of vessel arrivals and service times. This was done by simulation of a M/Ek/2 queue for the current scenario and a M/Ek/4 queue for Phase 1 and Phase 2. Here the first symbol denotes the inter-arrival time distribution, M, which is an exponential distribution. The second symbol denotes the service time distribution, Ek, which is an Erlang distribution with shape parameter k. The last symbol indicates the number of identical berths in the queueing system, which is 2 in the case of the current scenario and 4 in Phase 1 and 2. The parameters used to quantify the arrival rates and service time distributions were obtained by fitting the exponential and Erlang distributions to the data from the GENSIM simulation. A Chi-squared goodness of fit statistic was used to determine applicability of the fits.

The same inter-arrival time distribution was used for Phase 1 and Phase 2 and these are illustrated in Figure 10. The y-axis represents the number of events per minute and the x-axis is time. The mean values of the different distributions are indicated by a dashed line.

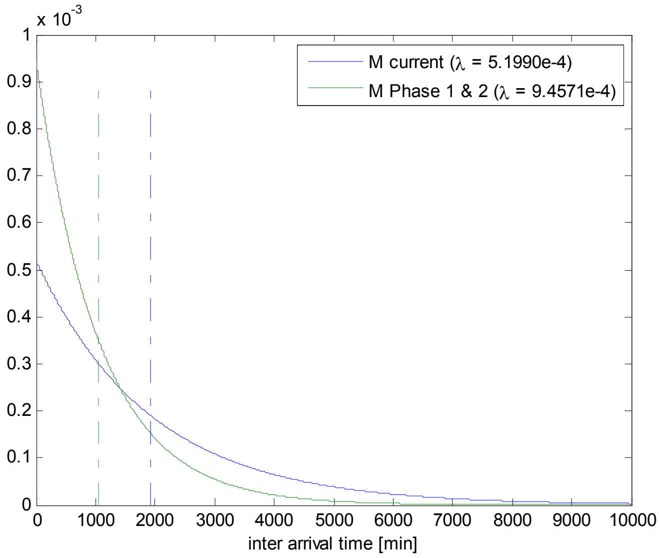

Figure 10: Inter-arrival time distribution used for the queue simulation

The same service time distribution was used for the current scenario and Phase 2. This assumes four identical berths for Phase 2 with similar capacity as that of the current berths. In reality the two new berths have a restriction on the size of the vessels serviced at the berth, which influences the service time distribution.

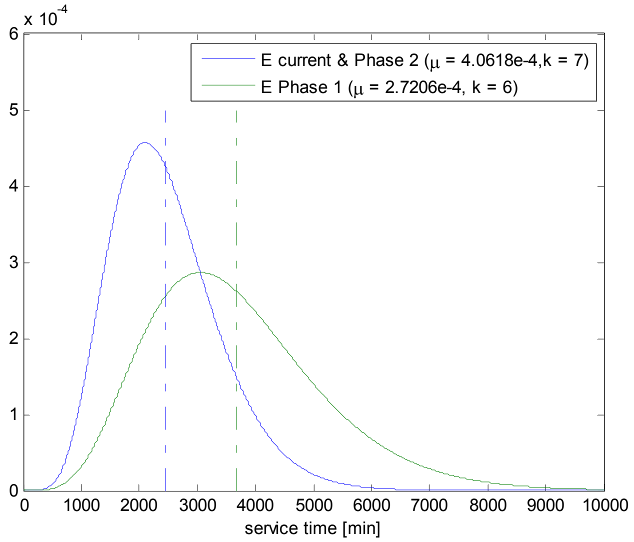

Figure 11: Service time distribution used for the queue simulation

A different distribution for service times has been used for Phase 1 and was constructed from the data. Four identical berths are also assumed for this model, but with a reduced service capacity. The distributions are displayed in Figure 11 with the mean service times indicated by dashed lines. Again, the y-axis represents the number of events per minute and the x-axis is time.

The results of the queue simulations compare very well to queueing tables found in literature (Hillier and Yu, 1981) in terms of queue lengths and waiting times. No vessel size distributions were incorporated in the queue simulation and as a result the demurrage times could not be predicted accurately.

CONCLUSIONS

A general description of the significant components of port operations and logistics was provided. The importance of sea transport and the effective operation of ports to the economy in general were highlighted.

Some background was given on the modelling of port logistics with the focus on the modelling of ship arrivals and service times. A case study of such a port expansion was presented as an example. Simulation results from a process simulator have been analysed and discussed. Simplified simulations have been done using queueing theory and the results have been compared to the full process simulations.

A simplified queueing theory simulation can be used to model relative changes in port infrastructures. These simulations can be used to perform "what-if" studies and determine if a port would have sufficient capacity when expansions in infrastructure are planned. The final optimised conditions could then be verified in a more detailed model like GENSIM.

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