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A Simulation based model for the berth allocation and quay crane assignment problem

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1. Introduction

With the global development of container transport, container terminals have become important nodes in transport networks which serve as hubs for the transshipment of containerized goods from ship to ship or from ship to other transport modes. As the container transport system is capital intensive, the turnaround time of ships at container terminals is an important factor for liner shipping companies to consider in order to decrease their costs. The turnaround time includes berthing, unloading, loading and departure and therefore, berth allocation and quay cranes assignment for unloading and loading operations is critical to the efficiency of container terminal systems. In addition, the rising competition between ports has compelled them to improve their service levels with the efficiency of container terminal operations becoming an important factor for success (Zeng, 2009).

Considerable studies have been done on the berth allocation problem (BAP) and the quay crane assignment problem (QCAP). By definition, the former determines the berthing positions and berthing time for incoming ships, while the latter determines the assignments of quay cranes to each ship). Existing approaches to these problems can be classified into two categories: the independent approach and the integrated approach (Yang et al., 2012).

The literature provides many approaches for the individual and integrated Berth and Quay Crane Assignment Problems (BAQCAP) using mathematical models. On the other hand, few publications have used simultaneous BAQCAP. Simulation modelling techniques are being applied to a wide range of container terminal (CT) planning processes and operational analysis of container handling systems (Park et al. 2012). These models have become extremely valuable as decision support tools during the planning and modelling of CT operations.

The application of Discrete Event Simulation (DES) where there exists queuing and scarcity of the number or availability of resources is viewed as a valid approach in simulating a CT (Bruzone, 1999*).* Discrete event simulation is probably the most widely used simulation technique in Operational Research. As the name suggests it models a process as a series of discrete events. This means that entities (the general name for what is being considered; e.g. "ships") are thought of as moving between different states as time passes. The entities enter the system and visit some of the states (not necessarily only once) before leaving the system. Discrete event simulation is a relatively easy to use tool, but, needs extensive effort in model development and validation, in order to have practical value. Most simulation based container terminal models are general ones examining the general performance of the container terminal. These models are coded in different simulation languages. The different types of simulation languages that have been used include PORTSIM, Modsim III, SIMPLE++, ARENA and SLX, Visual SLAM and AweSim.

In this paper we present a framework for a simulation based model for the BAQCAP that can be used as a decision support tool for the container terminal planner to decide on the allocation that achieves the best solution according to different operational requirements. Given a specific set of vessels to process in a typical week, and the related container loading and unloading requirements, the model helps the decision maker develop a set of operational plans illustrating the different performance parameters associated with each plan. The plan includes the start time and service time for each vessel at the specified berth, and the timed assignments of the different quay cranes to the different vessels.

This paper is organized as follows. In Section 2, a brief review of previous works is given. The framework and procedure of the simulation optimization model is developed in Section 3. The results of the simulation model is presented in Section 4. Conclusions and future work are given in Section 5.

2. Literature Review

2.1 Introduction

The Berth Allocation Problem can be identified as the problem of allocating ships to berths or to quays. In the berth allocation problem the aim is to plan and assign ships to berthing areas along a quay in order to achieve the maximum utilisation possible. The objective is to minimise the total service time for all ships which is defined as the time elapsed between the arrival in the harbour and completion of handling (Cordeau et al., 2005). There are many constraints and issues when allocating ships to berths. The constraints and issues include the length of ship, depth of berth, time frame, priorities assigned to the ship, and shippers' favourite berthing areas (Imai et al., 2007; Lee & Chen, 2009; Legato & Mazza, 2001; Vacca et al., 2007). An example for the graphical representation of a berth plan with five vessels is shown in Figure 1 (a). Ship 1 spent around 3 hours at berth. Ship 2 spent 9 hours. While, ship 3 spent 3 hours. From the figure, it is clear that the quay can accommodate 3 ships at the same time with maximum ship's length of 200 metres. Berth planning has been shown to be a nondeterministic polynomial time (NP)-hard problem.
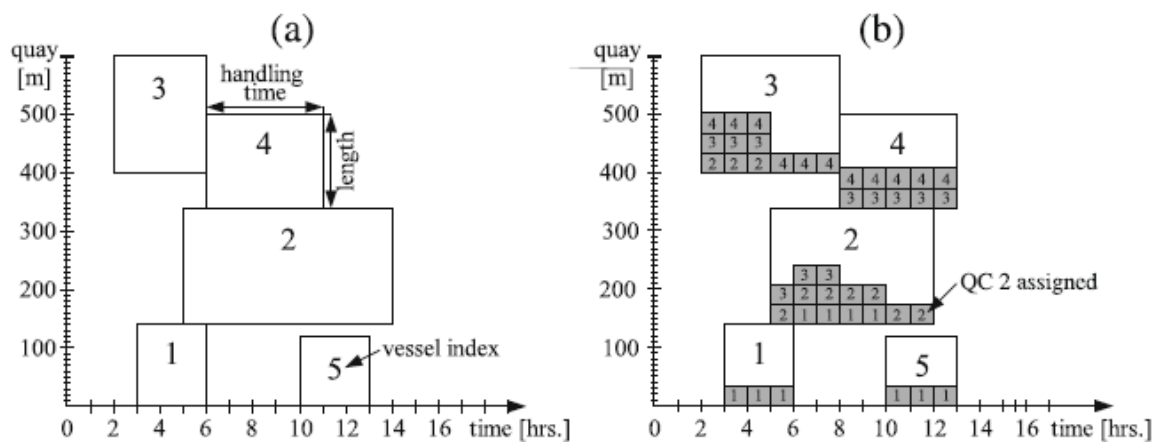

Figure 1: (a) the Berth Allocation Problem, (b) The Quay Crane Assignment Problem
Source: Bierwirth and Meisel (2010)

In the QCAP, a feasible berth plan and a set of identical QCs available for service are provided. For all the vessels included in the berth plan, the volume of containers to be loaded and/or unloaded is known as well as the maximum number of cranes allowed to serve simultaneously. The cranes are supposed to be lined up alongside the quay. They can be moved to each vessel but they are not able to pass each other. The problem is to assign cranes to vessels such that all required transhipments of containers can be fulfilled. In Figure 1 (b), QCs numbers 2, 3 and 4 are assigned to vessel 3. In time period 5, two cranes are moved from vessel 3 to start serving vessel 2. The QCAP and BAP are basically interrelated, because solving the QCAP can have a strong impact on the vessels' handling times. In the case of a discrete berth layout, where each berth holds a set of dedicated cranes, an explicit assignment of cranes to vessels is not necessary.

The studies of efficient terminal operation have become more and more popular. The review of related research can separated into three topics: the BAP, the integrated BAQCAP and the simultaneous BAQCAP. It is noted that the individual QCAP could be solved by rule of thumb in practice. It is not a difficult problem, and has poor academic value and hardly draws any attention in research (Yang et al., 2012). Thus, there is no specific review of the QCAP in this section.

2.2 The Berth Allocation Problem

The berth allocation problem can be modelled either as a discrete or a continuous event. Cordeau et al. (2005) considered two versions of the berth allocation problem in their studies: the discrete case and the continuous case. The discrete case worked with a finite set of berthing points and in the continuous case ships berthed anywhere along the quay. Two formulations and a tabu search

heuristic were presented and tested on realistic traffic and berth allocation data obtained from the port of Gioia Tauro,
Italy. Imai et al. (2005) presented a continuous model of the berth allocation problem to minimise the total service time of ships. The authors presented a heuristic algorithm which solves the problem in two stages, by improving the solution for the discrete case. Lee & Chen (2009) presented an optimisation based approach for the berth scheduling problem. The main purpose of the study was to determine the berthing time and space for incoming ships. The neighbourhood-search based heuristic treats the quay as a continuous space. In addition to the basic physical requirements, the model they presented takes several factors important in practice into consideration, including the first-in-first-out (FIFO) rule, clearance distance between ships, and the possibility of ship shifting. Imai et al. (2007) addressed the berth allocation problem at a multi-user container terminal with indented berths for fast handling of small containerships. The problem is formulated as an integer linear problem and the formulation is then extended to model the berth allocation problem at a terminal with indented berths, where both mega-containerships and feeder ships are to be served for higher berth productivity. The berth allocation problem at the indented berths is solved by genetic algorithms. The solutions are evaluated by comparing the indented terminal with a conventional terminal of the same size. Legato & Mazza (2001) proposed a queuing network model of the logistics activities related to the arrival, berthing and departure process of vessels at container terminals. Wang and Lim (2007) proposed a stochastic beam search scheme for the berth allocation problem. The implemented algorithm is tested on real-life data from the Singapore Port Terminal.

2.3 The Berth allocation and Quay Crane Assignment Problem (BAQCAP)

Because the quay crane assignment has a strong impact on ship handling time and further influences the berth allocation, more and more researchers have shown their extensive interests in studying the BAQCAP.

Meisel and Bierwirth (2006) investigated the integration of berth allocation and quay cranes, focusing on the reduction of QCs idle times, which significantly impact on terminal labour costs. A heuristic scheduling algorithm based on priority-rules methods for the resource-constrained project scheduling is proposed and tested on six instances, based on real data, which considered up to 18 vessels to be served in two days. Preliminary results, compared to the manually generated schedules which have been used in practice, were encouraging. Giallombardo et al. (2008) studied the integration of berth and quay cranes' problems. They presented two formulations for the integrated problem: a mixed integer quadratic program and a linearization which reduces to a mixed integer linear program. The objective function aims, on the one hand, to maximize the total value of chosen QC profiles and, on the other hand, to minimize the housekeeping costs generated by transhipment flows between ships. An economical analysis of the value of QC assignment profiles and of yard-related costs in a transhipment context is provided. Meisel and Bierwirth (2009) studied the integration of BAP and QCAP with a focus on quay crane productivity. An integer linear model was presented and construction heuristic, local refinement procedures and two meta-heuristics were developed to solve the problem. Authors compare their approach to the one proposed by Park and Kim (2003) over the same set of instances and they always provide better solutions. Chang et al. (2010) developed a dynamic allocation model using objective programming for berth allocation and quay crane assignments based on a rolling-horizon approach. Afterwards, a hybrid parallel genetic algorithm (HPGA), which combined parallel genetic algorithm (PGA) and heuristic algorithm, was employed to resolve the proposed model. Furthermore, a simulation was conducted to evaluate the HPGA and to execute relevant gene repair techniques. Eventually, the numerical experiments on a specific container terminal were applied to illustrate the proposed models and algorithms.

The simultaneous berth allocation and quay cranes assignment has received less attention in the scientific literature mainly due to the complexity of the problem. However, a few studies on this specific topic have been published.

Park and Kim (2003) investigated the simultaneous BAP in the continuous case with the QCAP, also considering the scheduling of quay cranes. They determined the optimal start times of ship service and associated mooring locations and at the same time they determined the optimal assignment of quay cranes to those ships. In their study, the handling time of a particular ship is a function of the number of quay cranes engaged in the ship; however, the handling time is independent from the mooring location of the ship. Their solution procedure consisted of two phases: one for berth allocation and the other for crane allocation. In a sense, they solved the berth–crane allocation problem simply

by solving the berth allocation and crane allocation independently. Imai et al. (2008) addressed the simultaneous berth-crane allocation and scheduling problem, taking into account physical constraints of quay cranes, which cannot move freely among berths as they are all mounted on the same track and cannot bypass each other. A mixed integer programming (MIP) formulation which minimizes the total service time is proposed and a genetic algorithm-based heuristic is developed to find an approximate solution. Recently, Vacca et al. (2011) studied the simultaneous optimization of berth allocation and quay crane assignment in seaport container terminals. They proposed a model based on an exponential number of variables that is solved via column generation. An exact branch-and-price algorithm is implemented to produce optimal integer solutions to the problem. Vacca et al. (2011) studied the simultaneous optimization of berth allocation and quay crane assignment in seaport container terminals. They proposed a model based on an exponential number of variables that is solved via column generation. An exact branch-and-price algorithm is implemented to produce optimal integer solutions to the problem.

According to Meisel and Bierwirth (2006) the BAP and QCAP strongly interact. The QCAP determines the ship's time in port which, at the same time, is an input for BAP. Moreover, the BAP determines the ship's time at berth which, again is an input for the QCAP. Therefore, solving of both problems will be presented in this study.

3. <u>The Model</u>

This section presents the framework of a simulation based model for the Berth Allocation and Quay Crane Assignment Problems (BAQCAP) that can be used as a decision support tool for the container terminal planner to decide on the allocation that achieves the best solution according to different operational requirements. A simulation tool, ARENA 14.0, is used for developing the model and integration of berth and quay cranes simulation, as well as for analyzing the results.

Berth allocation model: Instead of the existing mathematical methods for the calculation of BAQCAP, this study has built a simulation model for BAQCAP based on the real data, this simulation model can present a more practical way for BAQCAP. Ship operation usually begins when the ship arrives to the port anchorage area. Depending on the state of congestion, or priority of the arriving ship, the latter may have to wait in the anchorage area. After berthing, QCs start unloading/loading containers from/onto the ship. Finally, when containers handling is completed, the ship leaves the port.

QC assignment model: Berth allocation is based on the berthing plan that is linked to the QC operation policy and CY operation strategy. As stated earlier, the berth allocation of a ship has to consider the QC assignment rule. Therefore, the calculations of the total number of containers on board ships are done on the data collected by Alexandria Container Terminal (ACT). Then the ships are categorized in two classes according to the number of unloaded/loaded containers.

3.1 The Structure of the Model

The berth allocation model created is an abstraction of a real world Container Terminal handling over 750,000 TEU per annum. We believe that the BAQCAP model would be a useful tool for such CTs where large numbers of containers are handled and CT managers need assistance in developing berthing decisions. This model represents a container terminal with 530 metre quay for allocating ships, the quay is partitioned into three discrete berths [B1, B2, B3], where only one vessel can be served at each single berth at a time. The terminal has five quay cranes lined up alongside the quay [QC1, QC2, QC3, QC4, and QC5].

3.2 Model assumption

1. The three berths are identical and have the same characteristics (Berth Length, Berth draft).
2. Vessel is allocated to the berth depending on First Come First Serve rule (FCFS).
3. Berth allocation to B1 or B2 or B3 depends on number of containers to be unloaded and loaded, other parameters like Ship Length are not considered.
4. All containers have the same size (20 feet).
5. It's assumed that all containers are located at the same place (stowage plan is not considered)
    Quay crane assignment depends only on the number of unloaded/loaded containers and availability of QCs (at B2 & B3). Quay crane assignment depends also on ship length, location of

containers, and clearance between quay cranes. These parameters are not considered in the model.
6. Number of assigned quay cranes doesn't change during unloading or loading process.

3.3 Input parameters

Distribution estimation and empirical distribution for input parameters are fitted using the Input Analyzer (Fig.2). The Input Analyzer is a standard tool that accompanies Arena and is designed specifically to fit distributions to observed data, provide estimates of their parameters, and measure how well they fit the data (Kelton et al., 2010). Input Analyzer requires text files containing basic data to fit probability distributions to data. These input distributions are used as input variables in the model. Goodness-of-fit test was evaluated, for all tested data, by both Chi-square and Kolmogorov-Smirnov test at a 5% significance level.
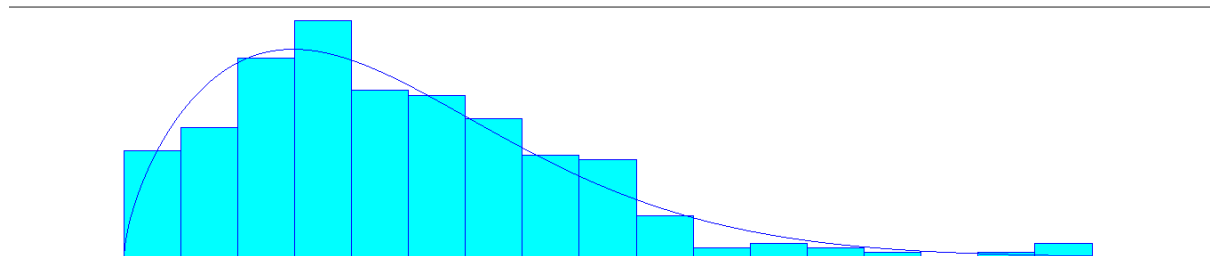

Figure 2: Distribution of data using Input Analyzer

The input data for the simulation model is based on the actual ship arrivals at the ACT for 15 days period from 29/12/2011 to 15/01/2011. This involved approximately 33 ship calls. The ships were categorized into two classes according to the number of containers: first class, unloaded >150 and loaded >150; and second class unloaded or loaded >150. Ship arrival probabilities were as follows: 30.3% for first class, 69.7% for second class of ships. Total throughput during the considering period was 11,493 TEU. Berthing/unberthing time of ships was assumed according to table 1.

Data	Expression type	Expression value		Unit
Interarrival time of ships	According to schedule			
No. of Unloaded Containers	Real data from ACT			TEU
No. of loaded Containers				
Ship Route Time from Entrance to B1 [R1]	*Exponential	EXPO (45)		Minutes
Ship Route Time from Entrance to B2 [R2]		EXPO (55)		
Ship Route Time from Entrance to B3 [R3]		EXPO (60)		
Delay Time for the following processes • Pickup cont. from ship by QC • Place cont. on truck by QC • Pickup cont. from truck by QC • Place cont. into the ship by QC	*Exponential	EXPO (1)		Minutes
QC Velocity	Constant	50		m/min
Distance covered by spreader from Ship to Berth	Constant	120		meter
Distance covered by spreader from Berth to Ship				
Distance between QC4 station at B2 and QC4 station at B3	Constant	200		meter
Ship Route Time from B1to Departure [R4]	*Exponential	EXPO (30)		Minutes
Ship Route Time from B2 to Departure [R5]		EXPO (35)		
Ship Route Time from B3 to Departure [R6]		EXPO (40)		
Unloading/loading time for one container = Delay Time x 2 + $\frac{Distance}{QC\ Velocity}$ (Constant)				

*Expression values are estimated

Table 1: Summary of all input parameters used in the model.

3.4 Modeling BAQCAP

The BAQCAP simulation model is proposed in figure 3 for representing the berth allocation and quay crane assignment inside a CT. This model developed using block diagrams from ARENA discrete event simulation package. The model is developed by defining the CT entities and by describing the sequences of activities to be performed by the transient entities included in the simulation model.
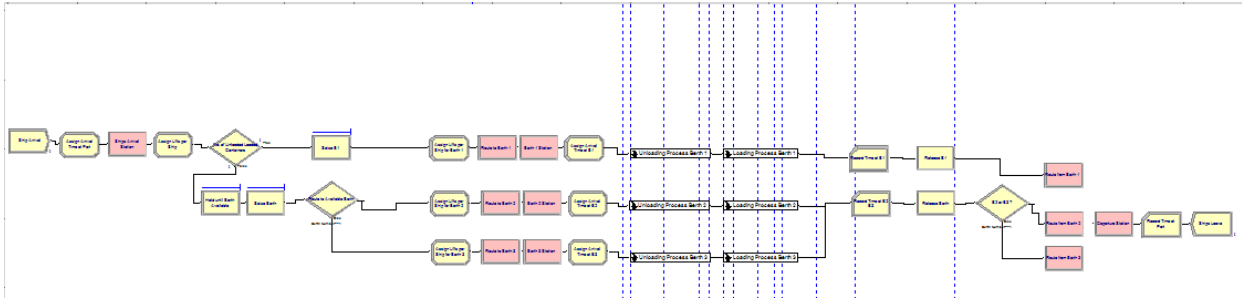

Figure 3: The Top level simulation model using Arena

To develop the simulation model, the logic of ACT is divided into different levels. The first level involves general processes, for example ship arrives, unload import containers, load export containers, ship leaves terminal, to more detailed processes such as loading and discharging of each single container. The general processes are represented by a top-level model and more detailed ones are represented with sub-models.

3.4.1 Top level Model

When a ship arrives to the terminal, it will need to be assigned a berth along the quay. After the input parameter is read, the simulation model starts by generating the ship arrivals in the container terminal according to the schedule. Next, the ship class is determined from the empirical distribution. Then, the ship priority is assigned depending of its class. For the given number of lifts per ship to be processed, the number of QCs to be requested is chosen from empirical distribution. If there is no ship in the queue, the assigned berths are allocated to each arriving ship. In other cases ships are put in queue. The first come first served strategy is employed for the ships without priority and ships from the same class with priority. After berthing, ship is assigned the requested number of QCs. In the case when all QCs are employed the ship is put in queue for QCs. Finally, after completion of loading and unloading process the ship leaves the terminal as illustrated in figure 3.

3.4.2 Unloading/loading containers (submodels)

These models simulate the unloading/loading operations for a single container ship. The number of QCs assigned for unloading/loading operation depends on the ship's class and the availability of QCs as illustrated in figure 4.
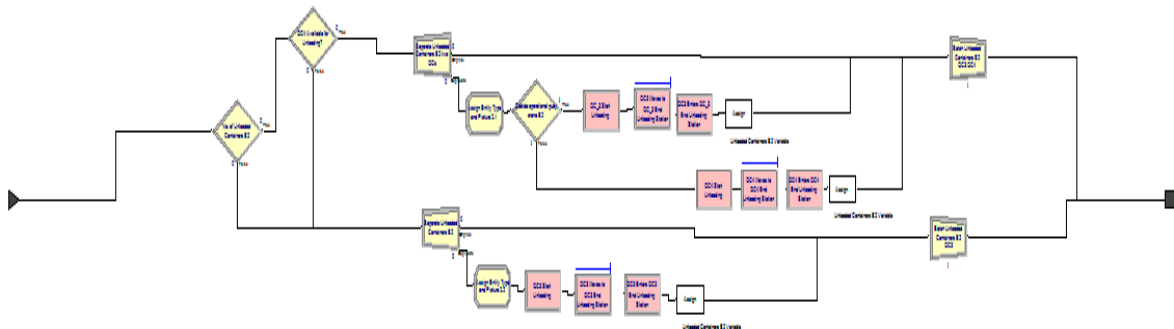
Figure 4: Unloading of containers at B2 (submodel)

4. Results

We have carried out a large number of replications by the model presented in the previous section. For the purpose of the simulation model validation and verification, the results of the summation model compared with the actual measurement. Several statistics and parameters were used as a comparison between simulation output and real data. The values in figure 5 represents berth utilization at ACT and SM with different berth allocation and quay crane assignment scenarios. The results obtained using BAQCAP model with corresponding values of real parameters could also use for CT performance evaluation. In case of ACT, current berth occupancy ratio is estimated to be 25%. However, this is not an appropriate result. As well as ACT consists of three berths, the occupancy ratio could increase up to 65% within permissible ship's waiting ratio. The SM results for considered ACT are as follows: the throughput per berth is 11,493 TEU (15 days). Furthermore, the level of waiting ratio is between 0.75 and 1.3 and average number of QC per ship is 1.6 Thus, the main result is the average total time that ship spends in port and varies from 10.76 to 33.65 hours, respectively. This means that the BAQCAP model can be used as a decision support tool for the container terminal planner to decide on the allocation that achieves the best performance according to different operational requirements.
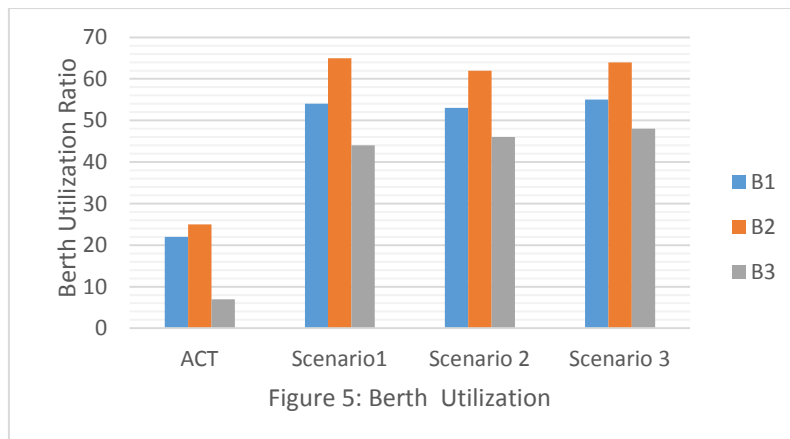

Figure 5: Berth Utilization

5. Conclusion and future work

This paper focuses on efficient scheduling and use of the berths and quay cranes to increase the performance of container terminals. Mathematical solutions are restricted to the integrated/hierarchical approach to solve the problem and make too many assumptions to simplify the problem for solution tractability. In this study, we proposed a simulation framework that can be used to solve the BAQCAP considering a realistic situation that provides the decision maker with a tool can be used to minimize ship's turn-around time and improve the performance of CT. For the future work, different dispatching rules, length of the ships, different types of containers and stowage plan of ships will be considered.

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