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WORKING PAPER SERIES

Simulation of Container Ship Arrivals and Quay Occupation

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Abstract. This contribution presents a simulation model that generates arrivals of ships over time at a container terminal. The model includes a quay of limited capacity, a decision module for assigning berths to ships, and a queue for ships for which currently no berth is available. Such models are applied in practice to examine the capacity of the quay and of the quay cranes in scenarios for expected future workloads. We outline the concept for a simple and generic simulation model and present some experimental results based on real data. Subsequently, we discuss various extensions of the model that would be necessary to adapt it to a specific terminal.

1 Introduction

Quay walls are among the most expensive infrastructure investments in container ports. Especially in regions with significant tides quay walls can achieve enormous dimensions and require substantial construction efforts. A typical modern container ship quay wall in a North Sea port has a height of about 40 m from bottom to top (see Grabe 2008). The costs per running meter can be as high as 65,000 Euros (press release, Hamburg Port Authority, November 22, 2008). Requirements like heavier quay cranes and permanent water depths of 16 m and more for the container ships of the next generation pose further requirements on quay walls.

Consequently, building quay walls is associated with enormous investments as well as long time spans needed for planning and construction. Hence, the decision how long a terminal's quay wall should be is of tremendous importance. This holds both for new terminals to be built as well as for existing terminals that consider an extension of their quay wall.

When facing this decision, the main difficulty lies in the estimation what quay wall length would be appropriate for a certain throughput of ships and containers. A static calculation can hardly take into account dynamic effects such as distributions of ship arrivals over time in a realistic way. Therefore, simulation suggests itself as a tool since it allows to capture the dynamic nature of the ship arrivals.

In this contribution, we outline a simple and generic simulation model that generates ships of different classes (i.e., sizes) and their arrivals over time. The model further includes the quay wall along with strategies for assigning berths to arriving vessels. Several months of ship arrivals can be simulated, and resulting figures such as average waiting times of ships for a free berth

are analyzed. Hence, the model is a tool for determining the terminal's service level that can be expected for a given arrival scenario and a given quay wall length.

The remainder is organized as follows. Section 2 provides a brief discussion of terminal capacity and quay wall length. Then Section 3 introduces the simulation model. Section 4 summarizes the results of some experiments that have been conducted using real-world data. Subsequently, Section 5 points out to possible extensions of the model, and some conclusions are drawn in Section 6.

2 Container Terminal Capacity and Quay Wall Length

Terminal capacity is an often mentioned term in container terminal planning. Unfortunately, a precise definition of this term does not exist. While the maximum number of containers that can be stacked on the terminal is often referred to as *stacking capacity*, the term *terminal capacity* usually refers to the maximal waterside throughput per year, i.e. the maximum number of containers (or TEU¹) that can be unloaded from and loaded onto ships per year.

However, a meaningful way to determine the capacity of a terminal does not seem to exist. For example, the terminal capacity of the Port of Hamburg according to its webpage is around 8.8 million TEU per year. However, the actual throughput in 2008 was around 9.7 million TEU.

The main problem when determining the throughput capacity of a terminal is that many factors have to be taken account. This obviously includes the length of the quay wall as well as the quay cranes and resources for transportation and stacking. External factors such as tides and vessel schedules must be considered as well. Some impacts on the terminal capacity are displayed in Figure 1. The number of factors as well as their diversity make a calculation of the capacity a highly complex task.

A measure that puts the total waterside throughput in relation to the length of the quay wall is the throughput per meter. Values for different container terminals can be found in Table 1. The values vary strongly between the terminals. This is due to the various factors mentioned above. Consider especially the types of ships: Terminals with a large fraction of smaller feeder ships are likely to obtain less throughput per meter since large vessels allow for much more efficient operations. When interpreting the data, however, one must be cautious because construction efforts may temporarily have decreased the actual throughput capacity. Nevertheless, Table 1 indicates that the throughput strongly depends on the conditions at the particular terminal.

In what follows, we discuss a simulation model that can help to determine the throughput capacity of a terminal with a focus on the quay wall. Rather than a value for the throughput capacity, it provides service level indicators (such as ship waiting times) for a given quay length and workload scenario. This is because there may not be a capacity in the sense of a fixed upper limit on the throughput—it is often possible to further increase the throughput, but at the cost of deteriorating service quality.

The model is based on the use of empirical distributions which determine ship sizes, interarrival times, and berthing times. While the model itself is basically a simple queueing model, the use of empirical distributions implicitly takes into account many of the factors influencing the terminal performance that are summarized in Figure 1.

¹ TEU = twenty foot equivalent unit, i.e. twenty foot standard container

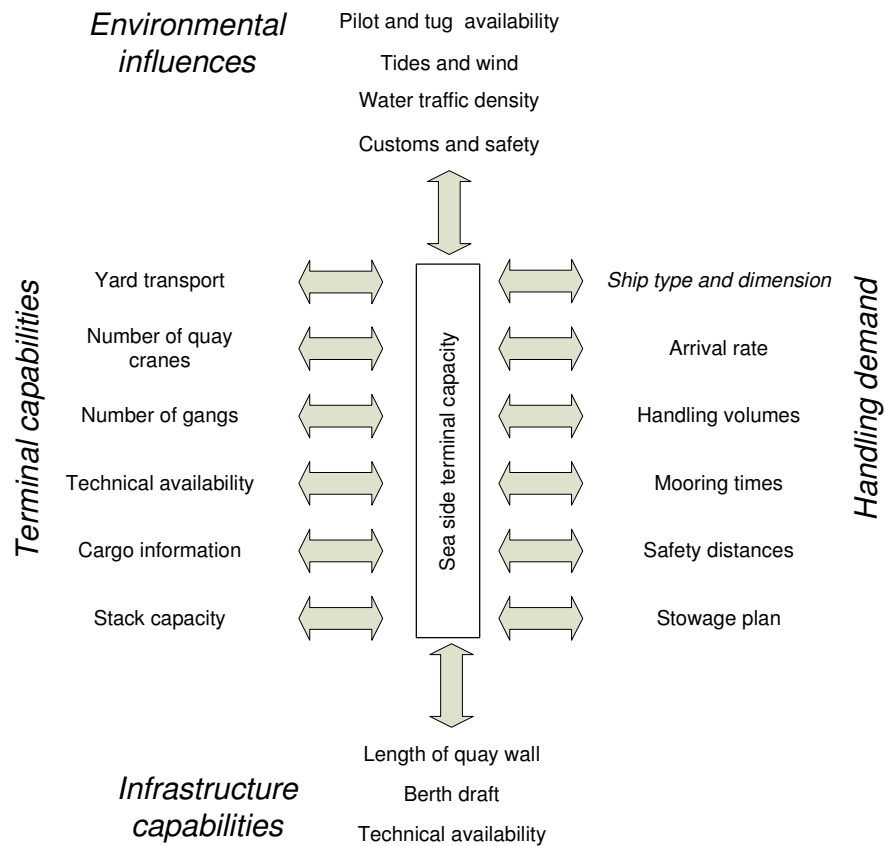


Figure 1: Some impacts on the waterside terminal throughput capacity

Terminal	Quay wall length [m]	Throughput [million TEU]	Throughput per meter [TEU/m/year]
Kwai Chung Hong Kong	2,322 *	5.40 *	2,325
PSA Singapore	16,000 #	23.98 *	1,499
Shinsundae Busan	1,500 *	2.08 *	1,384
MSC Bremerhaven	600 *	0.62 *	1,040
HHLA Burchardkai Hamburg	2,850 *	2.90 §	1,018
La Spezia	1,438 *	1.00 *	693

Sources:

*Fossey (2008) #www.singaporepsa.com §HHLA Annual Report 2006 (www.hhla.de)

Table 1: Comparison of quay wall throughput on different terminals in 2006

3 Simulation Model

This section provides a description of the simulation model. It is rather a generic prototype than a full-fledged model, and it can be adapted to any specific terminal by including further relevant requirements of that terminal. Some guidelines for extending the model will be given in Section 5.

3.1 Overall Structure

Ships of different sizes have different characteristics and are often treated differently when they are allocated to berths. This is taken into account in the simulation model by considering different classes of ships. We have three classes representing small feeders, medium-sized ships and deep-sea vessels, respectively. A description of the three classes is provided in Table 2 (note that the parameter settings can easily be adapted by the user). As in the remainder of Section 3, the data is taken from a major European container terminal.

Ship class	Description	Capacity	percentage of total number of ships	percentage of total TEU throughput
1	small feeder	up to 1500 TEU	87.3%	27.4%
2	medium-sized	1500 – 6000 TEU	7.3%	27.6%
3	deep-sea vessel	more than 6000 TEU	5.4%	45.0%

Table 2: Description of the ship classes used in the simulation model

The simulation model consists of three main stages. The first one generates arriving ships and the ship-related information. We have a separate set of parameters for the generation of each ship class. The second component is the queue for ships. Whenever a ship arrives at the terminal, it is appended to the queue. There is one queue for all ships. The third component is the quay of the terminal. The queue and the quay are managed by a specific logic that decides which ship is next to moor and which berth it is assigned to. The structure of the simulation model is sketched out in Figure 2. The components of the model are described in more detail in the following sections.

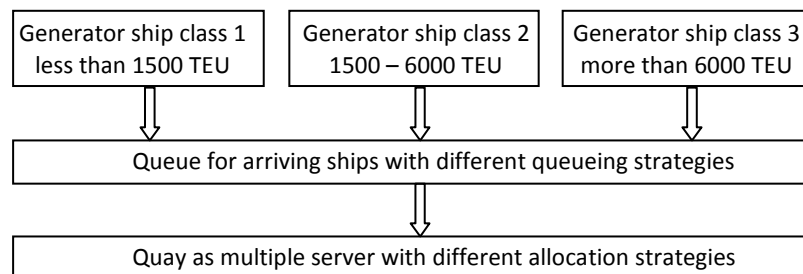


Figure 2: Schematic view of the simulation model

All of the relevant input information such as sizes of ships, times between arrivals etc. can be specified by the user in terms of empirical distributions. The reason for this approach is that it allows the user to adapt the behavior of the simulation model to any terminal by taking statistical data from this terminal. In addition, most real distributions taken from the terminal mentioned above did not match any theoretical distribution type. For example, the interarrival times are approximately exponentially distributed only for small feeders. For medium-sized and large ships the distribution is irregular, which is due to specific vessel schedules and other factors such as tides. Hence, we consider empirical distributions to be more realistic than theoretical distribution types that are often used in simple queueing models.

The distributions are, together with the length of the quay, the main parameters which can be controlled by the user. Each of the three ship classes is associated with an individual set of distributions.

3.2 Generation of Ship Arrivals

Whenever an arrival of a new ship of a particular class is generated, the following information must be determined: the time between the arrival of the previous ship of the same class and the arrival of this ship (interarrival time), the length of the ship (i.e., the portion of the quay it will occupy), and the handling time of the ship (i.e., the time span it will occupy the quay).

As mentioned in Section 3.1, all data is generated randomly based on empirical distributions. In what follows, we give some details on the methodology for ship generation. The explanations are illustrated by means of (shortened) example distributions for the first ship class, i.e. small feeders. The distributions were taken from the major European terminal mentioned above.

The first step is the generation of the **interarrival time**. Table 3 gives an example distribution which has been shortened since the actual table would be too long. Note that interarrival times are not the only possible basis for such a simulation model. For example, Hartmann (2004) uses distributions for ship arrival patterns over a week and during a day. However, the scope of that generator is a more general one, and for rather simple queueing models like the one considered here, interarrival times are a common approach.

Probability	Interarrival time [minutes]
0.155	6.5
0.102	23.1
0.083	38.1
0.071	52.7
0.057	67.7
(...)	(...)

Table 3: Distribution of interarrival times (small feeders)

The second step is the generation of the **ship size**. Based on a distribution a ship is assigned a length and a capacity. An example distribution is displayed in Table 4.

Probability	Length [m]	Capacity [TEU]
0.001	80.8	68.7
0.011	88.8	204.7
0.021	92.4	268.7
0.094	99.3	379.0
0.145	101.3	480.7
(...)	(...)	(...)

Table 4: Distribution of ship length and capacity (small feeders)

The third step is the generation of the **ship handling time** at the terminal, i.e. the time for discharging and loading. The handling time depends on the number of containers that is discharged and loaded. The number of containers is measured here as a percentage of the ship's total TEU capacity. Note that the largest possible percentage is 200% because all containers could be unloaded and then the empty ship could be fully loaded (values above 100% do occur in practice but are very rare). Table 5 gives an example distribution.

Probability	Percentage of capacity
0.043	3.4%
0.131	7.7%
0.139	12.4%
0.139	17.5%
0.119	22.6%
(...)	(...)

Table 5: Distribution of handled containers (small feeders)

The only scarce resource in our model is the quay, that is, the quay cranes are not modeled explicitly. Therefore, we cannot determine the ship handling time using the number of handled containers and the available quay cranes over time (also see Section 5.3 on this issue). Consequently, a different approach is needed. We determine the ship handling speed of the ship as number of TEUs handled per minute per ship. This handling speed can easily be derived from terminal or port statistics. The ship handling time is then obtained from dividing the number of handled containers by the ship handling speed. For example, we may have drawn a ship with a capacity of 1000 TEU, and 25% of the capacity are unloaded and loaded, so 250 TEU are handled. If we have a speed of 0.547 TEU per minute (which could be realistic for a small feeder), we obtain a ship handling time of 457 minutes (7.6 hours).

There is a strong correlation between the number of TEU handled and the handling speed; the correlation coefficient is 0.88 when ships of all classes are considered. This is due to the fact that the smaller a ship and the smaller the number of containers handled, quay cranes must change the ship bay more often, which is time consuming and slows down the discharging and loading process. Even within a ship class, there is still a dependency. As a consequence, we cannot simply draw the handling speed from a distribution, because we might get a slow speed for a ship with many containers and hence an unrealistically long ship handling time.

Therefore, the handling speed is modeled as a function of the number of TEU to be loaded and unloaded. For each ship class, a separate function is defined. For the first two classes (small feeders and medium-sized ships), a functions of the type $y = a \cdot x^b$ are estimated using nonlinear regression. For the third class (deep-sea vessels) a function of the type $y = a \cdot x + b$ was estimated using linear regression. As an example, the ship handling time function (as well as the observations used for the estimation) for small feeders is shown in Figure 3.

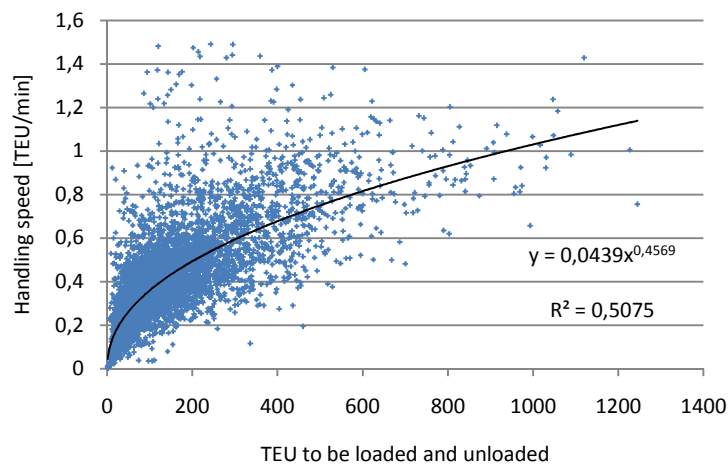


Figure 3: Relationship between handled containers and handling speed (small feeders)

3.3 Berth Allocation

The simulation model captures one continuous quay, and the conditions such as quay crane types, water depth etc. are the same everywhere along the quay wall. That is, any ship can berth anywhere. Specific conditions that might have an influence on arrival or departure such as tide or traffic conditions are not taken into account. For modeling purposes, the quay is discretized, that is, it is divided into segments of constant length (50 m). A segment cannot be shared by two ships. Thus, a ship will always be assigned to the smallest possible number of quay segments that covers its length plus a required minimum distance that must always be kept between two ships. For example, a ship with a length of 160 m and a safety distance of 25 m requires 185 m of space, which translates to four consecutive segments occupied by this ship.

Berth allocation is triggered by arrival and departure events, that is, whenever a ship arrives or a ship leaves the terminal (and at least one other ship is waiting in the queue), the berth allocation component is called. It is responsible for two decisions, namely which ship in the queue will be next to obtain a berth at the quay and at which position this ship will berth.

The first step of the berth allocation process is to select the next ship from the queue. The simulation model currently offers two alternative selection rules. The first one is first-come-first-serve (FCFS), that is, the ship with the earliest arrival time is selected. The second one is the earliest due date (EDD) rule. Here a due date for the completion of a ship is defined as the arrival time plus the ship handling time plus a buffer time that reflects the urgency of the ship. We have an individual buffer time for each ship class (6 hours for small feeders, 4 hours for medium-sized ships, and 2 hours for deep-sea vessels).

An additional option is to give priority to deep sea vessels. If this is done, a small or medium-sized vessel can only be assigned to a berth if no deep sea vessel is in the queue, and the FCFS or EDD rule is only used for selecting among large vessels or among medium sized and small ships. Notice that when a deep sea vessel is waiting for a free berth then a small feeder is not assigned a berth even there would be sufficient space for it.

The second step of the berth allocation process is to find a berth at the quay with sufficient space for the ship. Again, there are two alternatives: The first fit method scans the quay from left to right and assigns the ship to the first position that is large enough. The best fit method scans the entire quay and selects the smallest available space that is large enough for the ship. Obviously, the idea behind the best fit method is to save large spaces for larger vessels that might arrive later.

3.4 Performance Measures

The main goal of the simulation model is to determine whether the quay capacity is sufficient in a certain scenario or not. That is, we need measures that describe the utilization of the quay as well as the impact of possible insufficient capacity for the ships and for the terminal. In its current state, the simulation model writes detailed information on ships and events into files that can then be analyzed using MS Excel. For this study, we determined the following measures.

The **container throughput** is the number of containers discharged and loaded within the horizon of the simulation. Note that this measure is given in TEU (and not boxes).

The **throughput of ships** is the number of ships the handling of which could be completed within the horizon of the simulation. This measure is given separately for each ship class.

The **average** and **maximum ship waiting time** for a free berth is the average difference between ship arrival and berthing time of the ship. Also these measures are determined separately for each ship class. Note that the average is calculated over all ships and not just those ships that do not immediately get a berth upon their arrival.

The **percentage of waiting ships** is the number of ships that have to wait for a berth divided by the total number of ships. Like the two previous measures, also this one is determined separately for each ship class.

The **quay utilization** gives the average percentage of the quay that is occupied over time. This percentage quay utilization is determined at every event (i.e. ship arrival or departure) during the simulation time, at the end the average value of these observations is calculated. Note that also the safety distance between ships is counted as occupied.

4 Experiments

In this section, we present the results of several experiments that were carried out with the simulation model from the previous section. The purpose is to illustrate typical applications of such a berth simulation and to demonstrate the power of this rather simple model as well as its limitations.

The model was coded in the simulation framework Flexsim (see, e.g., Garrido 2009). The experiments were done on a PC with Intel Pentium M processor with 2.13 MHz clockpulse and 2 GB RAM running under Windows XP.

4.1 Basic Settings

For the experiments to be presented below, we have derived distributions concerning interarrival time, ship size and handling time (cf. Section 3.2) from real data provided by a major European container terminal. The year from which the data has been taken was a very busy one for this terminal, hence the distributions lead to a considerable but realistic workload. For all experiments the length of the quay has been set to 2000 m.

The standard setting of the berth allocation strategy consists of the best fit method for finding a berth along the quay, the first-come-first-serve strategy for selecting waiting ships from the queue, and no priority for deep-sea vessels (cf. Section 3.3). These settings have been varied systematically in order to analyze their impact.

Each simulation run covered 90 days, which took on average 110 seconds of CPU time. For each scenario (i.e., parameter configuration), several simulation runs (replications) were carried out. In what follows, the reported results are averages of the replications of a scenario.

4.2 Impact of Workload

The first experiment was to simulate a scenario that is characterized by an increased workload. Such simulations are of high practical relevance for terminals that want to know if the current quay is sufficient for an expected growth in container throughput caused by one or more additional services. For this contribution, the purpose is to demonstrate how the simulation model can help to analyze such future scenarios.

We have compared two scenarios, one with the original workload according to Section 4.1 and one with an increased workload. All other distributions and strategy setting were kept unchanged. The increase in the workload was achieved by dividing all interarrival times by a constant factor. Hence, the ship sizes and loads remain the same but the number of ships arriving per week increased, as would be the case when additional services are considered. The simulation results are displayed in Table 6. For both scenarios, five simulation runs were carried out.

	ship class	normal workload	high workload
no. of ships	feeder	1084	1342
	medium	88	114
	deep-sea	62	80
average waiting time per ship [h]	feeder	4.0	15.5
	medium	4.8	15.1
	deep-sea	6.2	17.1
maximum waiting time per ship [h]	feeder	40.0	62.1
	medium	36.1	58.2
	deep-sea	36.0	60.8
ships that have to wait in queue	feeder	31%	73%
	medium	34%	74%
	deep-sea	41%	79%
total throughput [TEU]	all	695,996	897,812
quay wall occupation over time	–	64%	80%

Table 6: Simulation results for normal and high workload

The table shows that the TEU throughput increased by about 25%. The number of ships increased accordingly. This led to longer waiting times; they increase from about 5 h per ship to about 16 h per ship. Also maximum waiting times and the percentage of ships that had to wait for a free berth increased substantially. Note that these measures reflect the terminal's service quality, and one can see that the workload is too high to allow for an acceptable service quality.

One should take into account that ship waiting times for these scenarios would be lower in reality. While the model contains only a simple berth assignment strategy, in practice better decisions could be made considering the upcoming ship arrivals. Moreover, ships would slow down if they expect that they would have to wait for a berth. This leads to a later arrival and hence to a shorter waiting time.

It is interesting to note that both the average waiting time and the percentage of waiting ships are highest for deep-sea vessels. This is probably because these are the longest ships – hence it takes a longer time until a berth of sufficient length has become free.

The results for the quay wall occupation show that in case of the normal workload only 64% of the quay wall are occupied. Considering that this scenario corresponds to a very busy terminal, it might be surprising that the occupation is not higher. However, the result is in line with the real-world terminal (which indicates that our model shows realistic behavior with regard to quay wall occupation). For the second scenario with substantially higher workload, the occupation of the quay climbs to 80%.

There are several reasons for quay wall occupation rates well below 100% even in cases of very high workload. Of course, when several ships are mooring along the quay, it is very likely that there are spaces between the ships that are too small for arriving ships. Another effect is that even for the second scenario with the increased workload, there are times when the queue is empty and thus no ship arrives to make use of available quay capacity. Finally, a large vessel may wait for a berth while there is some free quay capacity that is not yet sufficient, but due to the FCFS strategy smaller ships that are also waiting do not get a berth.

Summing up, the simulation model allows to analyze different workload scenarios with regard to important performance measures that reflect both quay utilization and terminal service quality. This makes it a valuable tool for examining future developments. In practice, of course, also other factors could be incorporated when defining future scenarios. This could be an additional berth or an increased handling speed.

4.3 Impact of Strategy Parameters

Another important application of the simulation model is the analysis of the impact of different berthing strategies (see Section 3.3). In a first step, we have a look at the prioritization of deep-sea vessels. Terminals usually prioritize these vessels such that they can be processed within a certain time window.

We compare the case without priority for deep-sea vessel (hence a pure FCFS strategy) with the case where each deep-sea vessel has a higher priority than medium-sized and small vessels. Table 7 shows the simulation results. To keep things short, we restrict ourselves to the high workload case here because this scenario shows the impact of prioritization more clearly. It should be mentioned that the purpose of this experiment is to demonstrate the capability of our model to appropriately capture the impact of the strategy, but the scenario itself is not very realistic because of the high workload.

We observe that both the average and the maximum waiting times decrease for deep-sea vessels but increase for the two classes of smaller ships. This is, of course, the effect that could be expected. The percentage of ships that have to wait does not change much. It does not decrease for deep-sea vessels because the high workload implies that most arriving vessels have to wait for a berth. Also the quay occupation remains the same.

	ship class	without prioritization	with prioritization
no. of ships	feeder	1342	1301
	medium	114	112
	deep-sea	80	86
average waiting time per ship [h]	feeder	15.5	26.6
	medium	15.1	27.7
	deep-sea	17.1	3.4
maximum waiting time per ship [h]	feeder	62.1	90.4
	medium	58.2	89.2
	deep-sea	60.8	21.7
ships that have to wait in queue	feeder	73%	76%
	medium	74%	79%
	deep-sea	79%	79%
total throughput [TEU]	all	897,812	900,044
quay wall occupation over time	–	80%	80%

Table 7: Simulation results for deep-sea vessel prioritization (high workload case)

Next, we examined the impact of the rule that is used to select ships from the queue. We compared the standard setting (FCFS, no vessel priority, best fit for berth selection) with a setting in which the FCFS rule was replaced by the earliest due date rule (EDD) described in Section 3.3. However, we could not find a significant difference between these two rules.

In the final experiment we tested the influence of the method to determine a berth, i.e. a position along the quay. We compared the standard setting with a setting in which the best fit strategy was replaced by the first fit strategy, see Section 3.3. But again we did not find a significant difference.

The results of the last two experiments could have two different interpretations: Either replacing the strategy does not have an impact (i.e., the strategies are very similar with regard to their behavior), or there are certain limitations in the model that prevent us from detecting actual differences. The latter point will be discussed in the next section.

4.4 Limitations of the Model

As outlined in the previous section, some of the experiments did not lead to different results for different strategies. One possible cause for this could be that the replications of the same scenario are often remarkably different which can lead to a substantial variation in the simulation results for the same scenario.

Consider as an example the five replications of the “normal workload” scenario of Table 6. The number of containers to be handled is largely responsible for the workload. According to Table 6, the average throughput was 695,996 TEU in these five simulation runs. But the range of the values was 627,591 TEU to 793,627 TEU. The standard deviation was 56,595 TEU, which leads to a coefficient of variation of 8.1% (cf. Bluman 2008).

This variation is caused by the distributions, especially the interarrival times for the deep-sea vessels. Both very small and very large interarrival times have rather small probabilities. But it may happen that in one simulation run an interarrival time of, say, one week is drawn once or twice while such extreme values do not appear in another simulation run. Consequently, the second run will have several vessels more than the first one during same simulation time. Because the deep-sea vessels are associated with a large number of containers to be handled, this has a big impact on the total workload. Given that the number of large vessels in one simulation run is rather small, such effects are not unlikely. In fact, in the five simulation runs mentioned above, the number of deep-sea vessels was between 54 and 73 during the same period of 90 days, although one might argue that one scenario should be related to (more or less) a fixed number of deep-sea vessel arrivals. Note that this problem does not occur for small feeders because they carry less containers, they arrive much more often, and their interarrival time distribution contains less extreme values.

This issue can be overcome in two ways. The first approach would be to carry out a very large number of simulation runs for each scenario. This would lead to a large sample, which might allow to detect significant differences by means of statistical tests.

The second approach would be to adapt the input data and the model such that the replications of each scenario lead to much less variation. The input data of the model could be improved by thoroughly eliminating outliers before deriving the distributions. The model itself could be improved by replacing the interarrival times for large vessels with actual vessel schedules. Some comments on the incorporation of a vessel schedule can be found in Section 5.1.

5 Extensions

As pointed out above, the simulation model of Section 3 is a generic one that needs to be adapted to a specific terminal. In what follows, we outline the most important generalizations of the model. We discuss the incorporation of vessel schedules, more general quay restrictions, ship handling times based on quay crane availability, and more realistic approaches to berth allocation.

5.1 Vessel Schedules

The model introduced in Section 3 contains interarrival times for all ship classes. In practice, this is appropriate for smaller ships. Large ships, however, arrive according to a fixed schedule. Typically each vessel service has a fixed planned arrival time that is the same each week. Hence, to model a specific terminal in a realistic way, the vessel schedule should be incorporated.

Schedules are usually not met accurately. Due to weather conditions or unexpected ship handling times in previous ports, delays and also early arrivals may occur. In the case of the major European container terminal mentioned above, deviations from the planned arrival times are prevalent. An analysis revealed that about 61% of the ships arrive within a time window of ± 12 hours around the scheduled time. Larger delays are common, with about 10% of the ships having delays of more than 48 hours.

Deviations in this magnitude have a substantial impact on the quay wall occupation over time and must therefore be considered in the simulation: While the schedule may imply a more or less even distribution of vessel arrivals, delays might lead to arrivals of several ships during a short time window, such that there might not be sufficient berths during such peak times.

Including vessel schedules and distributions of the deviations from planned arrival times allows for simulation studies concerning vessel services. The terminal management might, for example, consider an additional service which would be scheduled to arrive on a certain day. Then two scenarios could be simulated, one with the current schedule and one which also includes the additional service. The results would indicate whether the terminal capacities (quay and handling equipment) would be sufficient to handle the additional service or not.

Also recall that incorporating vessel schedules is advisable from a more theoretical point of view. As outlined in Section 4.4, drawing interarrival times does not guarantee a realistic arrival pattern for large vessels, and it may lead to large variations in the workload. If vessel schedules are used, this effect cannot occur because the arrival pattern will be the same in every week, and the impact of delays on the total workload is rather small. Hence, including vessel schedules makes the model more realistic and easier to use in practice, and it helps to create more reliable simulation runs.

5.2 Shape and Structure of the Quay

The model described above contains one quay wall along which the berthing conditions are everywhere the same. That is, any vessel can moor anywhere. This assumption holds on many real terminals.

However, there are also many terminals with more than one quay wall, and the quay walls are often different. That is, a quay wall might be equipped with large quay cranes which can serve any vessel whereas another quay wall might have only smaller quay cranes which cannot work on large vessels. Also, the water depth along one quay wall might be limited such that only ships with smaller draft can moor there.

Such restrictions can easily be incorporated into the simulation model. Each of the quay walls can be modeled separately, together with the restrictions concerning the ship types which are allowed to be assigned a berth there.

5.3 Quay Crane Allocation to Ships

One assumption in the modeling approach of Section 3 was that the handling time of a ship is derived from the number of containers discharged and loaded and handling time per container for the related ship type. This implies that the handling time of a ship is fixed in the model, that is, the number of ships at the terminal and the number of quay cranes assigned to the ship are not taken into account. This assumption leads to a simple model which contains the quay as the only explicitly modeled resource.

While this may be sufficient for rough simulation studies, it will be important for many studies to extend the model by considering quay cranes as scarce resources. This is, of course, inevitable for studies which examine not only the quay capacity in future scenarios but also the number and types of quay cranes.

Quay cranes can be incorporated as follows. When an arriving ship has been assigned a berth, the simulation model has to decide how many quay cranes are assigned to this ship. Each ship should be associated with a maximal number of quay cranes (typically between one for small feeders and five for large deep-sea vessels). The system tries to assign to the ship the largest possible number of quay cranes up to this limit. Whenever another event (ship arrival or departure) occurs during the simulation, the system has to check and possibly reassign the quay cranes to the ships currently at the quay. This step must reflect the terminal's policy which usually includes decision rules for situations when less quay cranes are available than would be required to serve all ships optimally.

If quay cranes are modeled explicitly, the user has to adjust their productivities (i.e., containers handled per hour per quay crane), probably in terms of distributions related to the ship classes. Quay crane productivities are more intuitive to use than the parameters needed to calculate the ship handling time as described in Section 3.2. The simulation model also becomes more realistic since the actual handling time then depends on the availability of quay crane resources over time and hence also the other ships at the quay.

A typical effect on many terminals is that the productivity per quay crane decreases when more quay cranes are working. This is due to the limited size of the transport vehicle fleet (terminal trucks, straddle carriers, automated guided vehicles): If more quay cranes are active, less vehicles can serve a quay crane. This could be covered by a workload-dependent productivity of the quay cranes.

A further extension would be to consider different quay crane types in certain segments of the quay. This leads to restrictions concerning the ship types that are allowed to moor in these segments, see also Section 5.2.

5.4 Berth Allocation

The methods for berth allocation described in Section 3 are straightforward and intuitive, but also very simple. In practice, more detailed methods are necessary. Generally speaking, the simulation model has to capture the actual berthing policy of the terminal under consideration even if this might not be "optimal" in some theoretical sense.

Typical practical requirements and processes include the following. Berths might be kept free for vessels which are expected to arrive soon even if there are ships waiting in the queue. Equally important, large vessels have a planned berth. Containers for such a vessel will then be stacked close to the berth, and it is essential for an efficient loading operation that the vessel will be assigned to this berth. Some terminals divide the quay into logical berths, and vessels are not berthed across two such sections even if it would be possible. Finally, there may be individual priorities for vessels, services, and shipping companies which influence the berthing decisions.

Berth planning and related problem settings have become increasingly popular in the scientific literature. Lim (1998) demonstrates that the basic berth planning problem can be modeled as a two-dimensional strip packing problem as well as captured using a graph representation. Park and Kim (2003) introduce a more detailed and realistic model that includes, among other features, the impact of quay crane capacity on the mooring time of the ships and a preference for a berth close to the location of the containers to be loaded. Since a comprehensive literature survey is beyond the scope of this contribution, we refer the reader to the excellent surveys of Steenken et al. (2004) and Stahlbock and Voß (2008). In fact, simulation models like the one introduced here require a good method for berth optimization, but focusing on the solution quality is quite useless if practical requirements are not included. Also short run times are essential since the berth optimization routine is called many times during a simulation time of several months.

6 Conclusions and Impact on Terminal Planning

The simulation model presented in this contribution is a simple tool for evaluating the quay wall occupation at container terminals and the achievable service level for given ship arrival scenarios. Various measures for the service level can be derived from the simulation output, with average and maximum ship waiting time for a free berth and percentage of waiting ships being the most important.

Realistic results can only be obtained if appropriate distributions of ship sizes, arrival times and handling times are used. These distributions differ considerably between the regions of the world. Consider as an example the main container terminals in the North Sea area. These terminals have a substantial share of feeder vessels which are small enough to transit the Kiel Canal. Since these feeder vessels are associated with a specific arrival behavior and handling speed, they have a significant impact on the terminal throughput. By allowing for the definition of several ship classes, our model can easily be adapted to such specific regional conditions.

An important application of the model is an analysis of future workload scenarios, in particular additional vessel services. A simulation based on such future scenarios can help to determine the service level that can be expected as well as the benefit of a possible extension of the quay wall.

The model can also be used to investigate the impact of an increased average handling speed on the terminal's service level. In the current model, scenarios for the ship-related handling speed distributions would have to be developed. If quay cranes are modeled explicitly, quay crane productivities would have to be adapted, which might be more straightforward for practitioners.

Furthermore, the influence of limited water depth and tides can be examined. Tides lead to a special arrival patterns for large vessels which cannot enter the port during low tide due to their draft. This is of particular interest for terminals which expect to serve more vessels with large draft in the future.

The applications discussed above are important for terminal planning in practice. The list shows that both strategic decisions (such as quay wall extension) and tactical decisions (such as additional vessel services) can be supported by our simulation model.

In addition, the simulation model may also serve as a testbed for optimization models and methods for berth planning, which is a more theoretical application. Berth planning is done in a dynamic environment which is characterized by uncertain information, in particular delays of ship arrivals as well as more or less unpredictable berthing times. Hence, rather than just running a berth planning method using fixed input information, the method should be incorporated into a simulation model which permanently updates the data.

Future research can be done in two steps. Firstly, the model's behavior could be improved in order to achieve more reliable and realistic output. A starting point would be to replace the interarrival times by schedules and distributions of delays for large vessels. Another important extension would be to explicitly incorporate quay cranes with productivities as parameters. This would not only provide the user with intuitive control parameters (i.e., quay crane productivities), it would also allow to derive berthing times in a more realistic way. Secondly, the model could be adapted to specific terminals by incorporating restrictions such as different quays or special berthing strategies. These extensions would then allow for detailed studies concerning a particular terminal.

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