Capacity Analysis of Container Terminals Using Simulation Techniques

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ABSTRACT

Modeling and simulation are essential tools for the design and analysis of container terminals. A computer model can emulate the activities at various levels of details and capture the essential interactions among the subsystems. Analysis based on the simulation is particularly useful for designing new terminals, making modifications to existing terminals, and evaluating the benefits of new resources or impacts of operation policies.

We present a scalable tool that integrates all the activities of a terminal. The system incorporates methods to generate realistic vessel arrival patterns and can track the moves of millions of containers from their arrival to departure. The simulation system is applied to analyze three container terminals in this region, and it was found to be effective in replicating realistic operations as well as in conducting capacity evaluations.

KEY WORDS
Modelling, simulation, capacity of container terminals.

1. Introduction

A container terminal plays an important role in global trading and international business by serving as a multi-modal interface, usually between the sea and land transports. A container terminal works under multiple operational objectives. Container terminal operations comprise of an intricate set of container-handling processes. Each link in the container handling cycle is of vital importance and the efficacy of the cycle depends on how well this chain is oiled, i.e. how efficiently the different components co-operate with each other. Ultimately what matters is the overall performance of the entire terminal, rather than the behaviors of the individual subsystems. Due to the complexity and scale of operations, it is very difficult if not impossible to build an mathematical model for analytical optimization of the whole terminal operation, even though such models exist for single aspect of one component of a terminal.

Hence computer simulation models, emulating the activities of a terminal to capture the interactions between the individual subsystems, are essential tools. Such a simulation model can be used in the capacity analysis of new terminals, existing terminals, evaluating the benefit-impacts of new resources and operations policies. It is a powerful tool for the decision-makers in making decisions that often involve multi-millions of dollars.

In general the modeling detail of a simulation system should be based upon the required level of accuracy that is in turn closely associated with the particular purpose and utility of the system. Two types of simulation are normally found in the existing literature, namely, strategic simulation and operational simulation.

Strategic simulation is to study and compare alternative layout plans, leasing policies, or handling equipments, and identify the best solution in terms of efficiency and cost-effectiveness. It is mainly used in the design and master-planning phase of a new port or extension of an existing port. For strategic planning purpose, a high level of abstraction is allowed [1-3]. Operational simulation, in contrast, focuses on the issues raised in allocating and planning resource for actual operations. It implements and evaluates, with pre-defined layout and equipment setting, different operating concepts, such as yard allocation [4], berth planning [5], or overall resource sharing and planning [6]. Operational simulation is most valuable in the terminals with high demand on throughput and operation efficiency, where the alternative optimization methods for planning can be tested before implementation [7]. An operational simulation system can be further developed to integrate with container terminal management system for real time decisions. It can assist in pre-alerting “hot spots” where congestion of traffic is identified and proposing possible solutions for the planner to work on. This type of simulation for real time planning is referred to as tactical simulation in [8].

Many simulation models of container terminal operations have been built. Most of the simulation models are developed to study optimization problems in planning and
managing operations for an existing terminal configuration (fixed terminal layout and set of equipment). We can only list a few examples here. Merkuryev et al. [9] used simulation to improve logistics processes at Riga Harbour Container Terminal. Gambardella, Rizzoli, and Zaffalon [10] developed a simulator that provided a test bed for checking the validity and the robustness of the policy computed by the optimisation module for resource allocation. Bruzzone and Signorile [11] employed genetic algorithms and simulation to make strategic decisions about resource allocation and terminal organization.

Some simulation models are created to investigate impact on terminal operations by external factors. For examples, Pope et al. [12] employed simulation to examine the impact of road traffic flows on container terminals located in cities. Thiers and Janssens [13] used a port simulation model to investigate the hindrance of a river quay.

Shabayek and Yeung [14] simulated Kwai Chung container terminals in Hong Kong and their objective was to investigate to what extent a simulation model could predict the actual container terminal operations with a higher order of accuracy. Rensburg, He and Kleywegt [15] reported building a simulation model with an objective to produce a tool for educating and training terminal decision makers.

Little work has been done in container terminal capacity analysis using simulation. Kia, Shayan and Ghotb [3] investigate the impact of ship-to-rail direct loading on the capacity of container terminal using real statistics. The simulation model also identified the congested area of the terminal and compared two operating systems leading to savings in port expansion. In [16], we reported a project which used simulation to evaluate new operation concepts, provably efficient schemes for the design of a high capacity container terminal system for mega vessels.

In this paper, we present an innovative tool that integrates all the activities of a terminal. The system is flexible and scalable, allowing users to plug in any equipment specification, change resource settings, modify policies, change the size of the container storage yard and change the container vessels arrival patterns. The tool is especially useful for capacity analysis as the user may change the throughput level, i.e. the container handling volume demanded on the terminal to realistically evaluate the terminal’s handling limits. In Section 2 of the paper, we present the architecture and the overview of the simulation system. Section 3 describes how we generate realistic vessel arrivals that drive the simulation process. Section 4 is on simulation accuracy and model scalability. Section 5 is about how we conduct simulation experiments for terminal capacity analysis and Section 6 presents three case studies of determining terminal capacity using simulation. The last section briefly concludes the paper.

2. Simulation System Architecture and Overview

The system consists of 6 modules, named after their functions in the real operations. As shown in Figure 1, these modules include:

- Berth allocation and quay crane assignment, taking care of berthing space allocation to incoming vessels, bearing in mind the availability of quay cranes.
- Quay crane management, coordinating quay crane operations.
- Prime mover management, dispatching prime movers to transfer containers between the quay side and the yard side.
- Yard allocation, taking care of yard space allocation to incoming containers.
- Yard crane management, coordinating yard crane operations.
- Gate operations, determining the arrivals and departures of local hauliers for local containers.

Each module is independent of the others in terms of internal operations and status, yet all are interdependent in terms of information exchange and sharing.

Berth allocation module assigns berths to incoming vessels, based on the real time situation of the berth space occupancy and the quay crane (QC) availability. The allocation aims to achieve a high utilization of berth while still assuring a certain degree of service quality, i.e. satisfactory Berth-On-Arrival (BOA) rate and predefined maximum vessel waiting time. A vessel can berth if a berthing pocket is available that satisfies both the following conditions: (a) the pocket is long enough to accommodate the LOA (length overall) of the vessel and the required safety clearance; (b) the number of QCs available along the pocket is not less than required.

The quay crane management module tries to emulate quay crane operations at today’s existing container terminals. The main aspects involved are allocation and deployment of cranes, scheduling, workload distribution, actual trolley operations for container handling and synchronization with transport system.

Transport is one of the most important aspects in a container terminal. Because of the tight loading sequence constraint and the large number of concurrent activities within the limited space of the quayside, it is a real challenge to achieve the high throughput requirement. Transport operations are associated tightly with quayside operations, yard side operations, and layout design. The critical objective is the efficient handling of the containers, which is equivalent to a reduction of the turnaround time of vessels. Prime movers (PMs) support a quay crane’s (QC’s) operations at the quayside. There are two
modes of deploying PMs: (1) Depending on the QC performance that is required to be sustained, we decide on the number of PMs to be assigned to a QC. PMs are dedicated to the QC they are assigned to, till all operations of the designated QC are completed. (2) PMs are not dedicated to a QC so they are dispatched to any loading/unloading job that is most urgent or the job location is closest to them.

Yard allocation module maintains yard inventory and assigns yard space to incoming containers. A terminal is normally partitioned into export yard, import yard, reefer yard, dangerous cargo yard, and empty container yard. A common practice is that containers belonging to the same connection vessel are stored in a few clusters that are not far away from each other. Yard planning for export containers is done in two phases, namely macro yard planning and micro yard planning. Macro planning estimates the number of clusters needed for a particular vessel and searches suitable yard blocks for placing the clusters. Micro planning assigns a specific yard space to an incoming container.

The objective of yard crane management is, above all, to service the prime movers as quickly as possible. To improve the operation efficiency, the job split to cranes in the same block is based on a “Harmonic Algorithm”, instead of the greedy distance-based or workload-based approaches. The gate operations module generates the arrivals of trucks for import/export containers.

3. Generation of Vessel Arrivals

Here we present the containership arrival modeling methodology applied in our simulation model. The generated patterns are validated and verified against historical data obtained from a real container terminal.

The generation of containership traffic includes assigning characteristics of vessel calls (e.g., vessel mix, TEUs/call, LOA, etc.) to individual vessels, and compiling a schedule for vessel arrivals. The assignment of vessel call characteristics can usually be well forecasted by port operators based on their experience. The simulation system allows the user to specify vessel categorization, vessel mix, and TEUs/call for their simulation study. We used the results from an analysis of 2-week operation data of a real terminal for container mix and the distribution of ports of discharge (POD). The problem of forecasting the arrival schedule is much more challenging as it is due to shipping lines’ planning which is more sensitive to economics fluctuations.

Most popularly adopted for modeling vessel arrivals is Poisson process [17-18]. This is based on the facts that: (1) even though the arrivals of individual vessels are scheduled, when the vessel traffic to the whole port is considered, the distribution of the inter-arrival times
(1) becomes random and fits well the exponential distribution; (2) the unpredictable weather conditions and possible delays in service by other ports of call further randomize the arrivals.

To determine whether the Poisson distribution for the arrival process is suitable to container ports in our study, 11-month data have been collected from a real terminal for analysis. As can be seen in Figure 2, the historical data agree reasonably well (less than 3% difference) with the exponential approximation. In other words, the assumption of Poisson arrivals of vessels is justified. Looking into the monthly data on a further level of detail, the inter-arrival times of vessels in one month also demonstrate exponential-like distributions (Figure 3). From another angle, when focusing on the inter-arrival times of individual categories of vessels, they also appear to follow exponential distributions (Figure 4).

We also noted that, like other service industries, container terminals also have their peak and lull demand periods over a year. The number of vessel arrivals has a seasonal pattern, where February appears to be the lowest season (February is the month in which the Chinese New Year falls). The analysis of historical data shows that the vessel arrivals can be adequately modeled by a Non-stationary Poisson process, with a different arrival rate applying to each month. In the model, a Non-stationary Poisson process (NSPP) is therefore used to adequately model the vessel arrival patterns, with piece-wise constant arrival rates that are varied by month to cater to the seasonality. Note that in modeling a Non-stationary Poisson process, simply changing the arrival rate in the generating algorithm would create inconsistencies in the arrivals if the differences in rates are large (Law and Kelton 2000). A “thinning” method was therefore applied in the algorithm to smooth the transitions from heavy to less heavy traffic and vice versa (Law and Kelton 2000).

Figure 2. Comparison of historical data and theoretical approximation.

Figure 3. Comparison of one month historical data and theoretical approximation.

Figure 4. Comparison of one category of vessels historical data and theoretical approximation. Vessels are grouped into different categories according to their lengths.
Figure 5. Comparison between historical and generated arrivals.

Suppose the arrival rate of month $i$ is $\lambda_i$ ($i = 1, 2, \ldots, 12$), and the maximum arrival rate is $\lambda_{\text{max}} = \max(\lambda_i)$. In the simulation, vessel arrivals are generated using an exponential inter-arrival time with a mean of $\frac{1}{\lambda_{\text{max}}}$ and then thinned by the acceptance probability:

$$\rho_i = \frac{\lambda_i}{\lambda_{\text{max}}}$$

The vessel traffic modeling methodology was used to generate vessel arrivals and historical data were used for verification. Figures 4 and 5 illustrate the distribution of the number of arrivals and that of the inter-arrival times over the 11 months, compiled from 5 generated sets of data. Both distributions agree reasonably well (with maximum modeling error of 4.5% and 1.7%, respectively) with the historical data.

Figure 6. Comparison between historical and generated inter-arrivals.

4. Simulation Accuracy and Model Scalability

When simulating large-scale models, the size of the terminal layout and the number of vehicles in the system is considerably huge. A 10-berth model may have a stretch of about 3.3km and a depth of 0.5km which is crisscrossed by a path network for the vehicles to travel and work at the quayside and yardside. During peak periods, there could be hundreds of vehicles (prime movers and local vehicles) in the terminal at one time. The simulation of a large number of vehicles running in the system is a big computational overhead that leads to a running time of about 48 hours to simulate a period of 1 year (for 10-berths with 1M TEUs per berth traffic).

Table 1 Accuracy of abstract model

<table>
<thead>
<tr>
<th>KPI</th>
<th>% variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOA Rate</td>
<td>1.81%</td>
</tr>
<tr>
<td>QC Rate</td>
<td>0.39%</td>
</tr>
<tr>
<td>Berth Utilization</td>
<td>1.39%</td>
</tr>
<tr>
<td>QC Utilization</td>
<td>1.00%</td>
</tr>
<tr>
<td>PM Unloading cycle time</td>
<td>0.32%</td>
</tr>
<tr>
<td>PM Loading cycle time</td>
<td>0.87%</td>
</tr>
<tr>
<td>PM Unloading waiting at yard</td>
<td>1.68%</td>
</tr>
<tr>
<td>PM Loading waiting at yard</td>
<td>3.65%</td>
</tr>
</tbody>
</table>

So we need to improve on the running speed of the model by abstraction with minimum sacrifice in modeling accuracy. To achieve this, the vehicles were removed from the model and their effect was simulated. The traveling time of vehicles between two locations in the terminal is calculated using the path distance between the two points and the actual vehicle speed, acceleration and deceleration specifications. Queuing effect of vehicles at the yard and quayside is simulated, with vehicles being handled in the order of their arrivals. It is therefore expected that the accuracy of modeling will not significantly drop as the essentials of prime mover system are emulated. Experiments were conducted where otherwise identical models were run under two different scenarios – one with the vehicles included and the other with the effect of vehicles simulated. Table 1 lists the variance between the key statistics recorded for the two cases under scrutiny, at the throughput level of 0.7M TEUs/berth/year. It was found, as can be seen from the Table, that the abstraction led to results that were very close to results obtained with the vehicles included. Additionally, the simulation was about 5 times faster. Using this model, we were able to simulate terminals with 10 berths, 20 berths and so on.
Another important fact in simulation studies is that a certain number of simulation runs, rather than a single run, are needed to estimate the “true” characteristics of the model. The number of runs required is closely related to the desired level of accuracy. In practice, a limited number of runs are conducted to estimate the mean value of a performance indicator and the corresponding variance. Based on the preliminary results, statistics formula can be applied to find out the number of replications required.

Taking again the berth utilization as an indicator, and targeting to estimate the expected utilization with a relative error of 0.01 at a confidence level of 95 percent; 5 replications (with different randomness) were conducted for the 0.75MTEU/berth/year throughput level as preliminary testing. The mean and the variance of the utilization results from the 5 runs are as follows:

Mean = 43.14%, Var = 3.98E-7

Based upon t-distribution estimation, we would need the following number of replications to get the desired level of accuracy:

\[
N(0.01) = \min \left\{ i \geq 5 : t_{t_{-1},0.975} \cdot \frac{\text{Var}}{\text{Mean}} \leq \frac{0.01}{1 + 0.01} \right\} = 5
\]

As BOA rate is also an important statistic used in evaluating terminal capacity, we take it as another indicator:

Mean = 93.02%, Var = 1.22E-6

This gives the number of replications as:

\[
N(0.01) = \min \left\{ i \geq 5 : t_{t_{-1},0.975} \cdot \frac{\text{Var}}{\text{Mean}} \leq \frac{0.01}{1 + 0.01} \right\} = 8
\]

Therefore 8 replications are required to achieve a relative error of not more than 0.01 with a confidence level of 95 percent, for both berth utilization and BOA rate. This should be applied to all experiments.

5. Capacity Analysis

The validation of the model was done by generating Key Performance Indicators (KPIs) from the model at a certain throughput level and making comparisons with actual statistics of real terminals.

The capacity is defined as the throughput level beyond which the terminal cannot sustain operations because of either of the following:

- The overflow of containers at the yard exceeds certain acceptable levels, or
- The BOA rate drops below the target percentage.

To determine the capacity of a terminal, the simulation experiments take a lower bound and an upper bound on the capacity and do binary search. The current throughput of a similarly sized terminal is the lower bound and the capacity of a subsystem of the terminal is the upper bound. For example, the quayside standalone capacity is the upper bound. The simulation runs for estimating quayside capacity are designed such that in the experiments, smooth feeding from the yard to the quay cranes is always assured. This means that whenever a quay crane is ready to offload a container to a prime mover or to pick up a container from a prime mover, the prime mover is always ready under the quay crane, so that the quay cranes will encounter zero waiting time for prime movers. This gives us the maximum throughput the quayside can handle; it also gives us the maximum throughput the terminal can handle.

The technique of binary search is applied to guide the search step and direction: the simulation starts with a throughput level at the midpoint of the two bounds, which is \((L + U) / 2\). The process of divide and conquer stops when the divided interval is no bigger than 0.01M. Capacity indicators and performance indicators are collected for each simulation run.

6. Examples of applications of the simulation model

We present three applications of the use of our simulation model in terminal capacity study.

6.1 Case I: A Local Terminal

Our simulation system was applied to model a specific terminal design locally in Singapore, including all major aspects of container operations. Terminal layout, traffic lanes, yard setup, quayside setup were replicated in the simulation model. In addition, resource allocation and operation scheduling policies incorporated into the simulation system were approximations to those used in the day-to-day activities. The objectives were to carry out terminal capacity estimation and resource requirement estimation. The simulation study was to find answers to the questions (1) what is the maximum throughput the current terminal resources can achieve? (2) if we were to try and achieve a specific throughput with the existing resources, what would be the impact on vessel waiting time and other performance indicators? (3) what is the resource requirement to achieve a specified level of terminal throughput?

The model was tested and then validated by the container terminal representatives. Simulations by the model with varied input parameters were run and statistics were
collected to assess the capacity of the terminal. The various input parameters that the user can change include:

1) equipment type: different types of quay cranes.
2) equipment number: number of quay cranes, yard crane, prime movers.
3) equipment settings: Productivity influencing timing parameters like crane trolley speed, aiming time of crane, gantry speed, prime mover travelling speed.
4) number of ground slots in yard: Number and position of ground slots in the yard that can be used for container storage.
5) maximum yard stack height: How high containers can be stacked in the yard.
6) incoming vessel traffic: Based on user pre-specified vessel mix and throughput requirements, corresponding sets of vessel traffic are accordingly generated for the simulation runs. The relevant traffic can then be chosen by the user for each simulation run.

The inputs to the system can be varied so as to create different scenarios for capacity estimation.

6.2 Case II: A Regional Terminal

This study aimed to evaluate the capacity of a container terminal in the region with its current resource settings and operating policies. The study also examined the efficiency of current operations and identified the bottlenecks that limited the capacity of the terminal. This was to see how operations could be improved to achieve higher terminal throughput without additional investment. Moreover, the study served to provide guidelines for the construction of additional area in terms of capacity needed for empty containers and capacity needed for laden containers. A variant of the model evaluated the quayside operations and suggested whether construction of a new berth was necessary. Finally the study will discuss some recommendations and suggestions for improving the terminal capacity.

It should be mentioned that for validation purpose, the model was driven by detailed historical input data of a certain year from the terminal. However the available statistics from real terminal operations were collected in another period, when the input data had noticeably changed. Due to this discrepancy, for comparison purpose we generated a set of benchmark statistics that was the result of proportional change of real statistics according to the change in the input data.

6.3 Case III: A Major Terminal on the Drawing Board

The main objective of the project was to estimate the capacity of a particular terminal setup, under a few different scenarios; namely 20-berth, 10-berth, 6-berth and 4-berth. Using the 10-berth operating scenario, the simulation model was also used to determine the corresponding yard-depth needed to support a specific terminal capacity.

To study the capacity of a new terminal, it is critical to start with realistic forecasts of the key factors such as expected traffic volumes, vessel mix and arrival patterns, and container mix. The planner then has to determine the type of equipment and operational policies that will be used at the terminal to adequately sustain the expected traffic. Once the above are known, the planner can go about determining the capacity of the terminal in question.

A comprehensive simulation model was created for the setup under consideration with the vessel arrivals, quayside container handling, prime mover, yard storage and retrieval and gate operations being simulated in detail. The equipments and facilities used at the terminal, and the operational policies applied, were assumed to be the same as a typical terminal today. Traffic composition and vessel-mix forecasts, as obtained from MPA, were applied to the model. Vessel arrival schedules, being unknown for the future port, were approximated using regulated Poisson arrivals as described in Section 3.

Simulation results showed that the capacities in terms of throughput per berth increases with the number of berths in the terminal, highlighting the positive impact of economies of scale. The capacity of the terminals, in all cases, was found to be constrained by the BOA (Berth On Arrival) target, rather than the yard space. The terminal’s service level, in terms of QC (Quay Crane) rate, vessel turnaround times etc. was found to be very reasonable even beyond the capacity levels. By varying the vessel arrivals favorably, a significant increase in BOA was observed, indicating a higher capacity. This implies that for future ports, with unknown vessel arrival schedules, BOA should not be used as a strict criterion to determine capacity, but should be used in conjunction with other quayside indicators like vessels rates, QC rates and berth utilization.

7. Conclusion

We have built a simulation model that can be used to simulate the complex container terminal operations for the purpose of terminal design, capacity planning and operations planning. It can simulate the entire multitude of terminal operations down to the box level and being modular and flexible. The simulation system has been applied to container terminals in Singapore and in the region, and it was found to be effective in replicating real-world operations as well as in evaluating the handling capacities.

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References