OPTIMAL DESIGN OF CONTAINER TERMINAL LAYOUT

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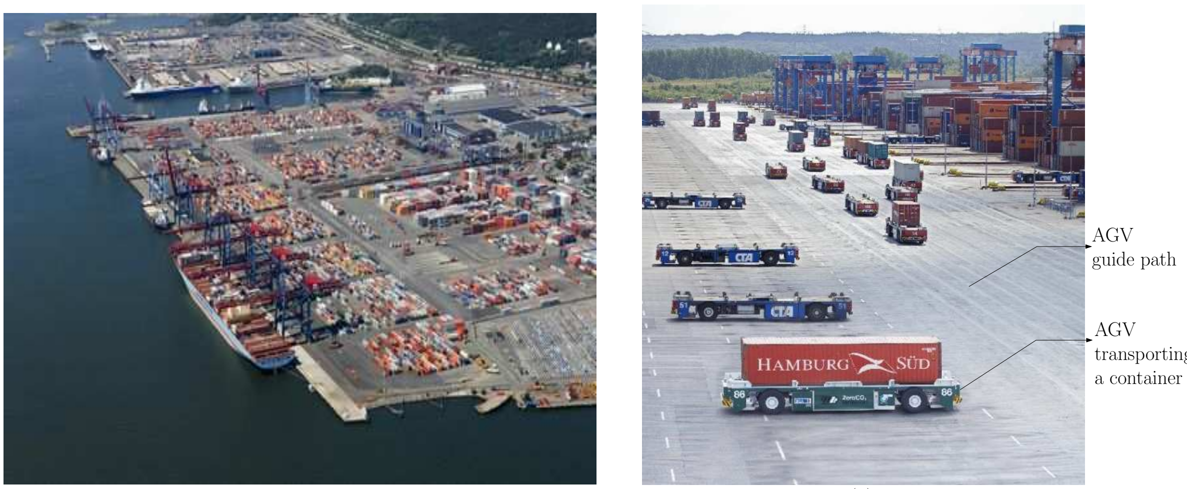
Abstract

Due to rapid growth in foreign trade using sea vessels, there is a growing focus in improving the infrastructure and operational efficiencies at the container terminals. Particularly, the operational responsiveness of loading and unloading of containers, affects the vessel idle times and profitability of the shipping liners. In this research, we determine optimal stack layout design, which minimizes the container unload times using Automated Guided Vehicles (AGVs). To analyze alternate stack layout designs, we develop integrated queuing network models that capture the stochastic interactions among the container terminal processes (quayside, vehicle transport, and stackside), and provides realistic estimates of expected container unload throughput times.

1 Background and Motivation

Due to growth in international trade and better accessibility to the major seaports via deep-sea vessels, containerization has become the preferred mode for maritime shipping and inland transportation. Between 1990 and 2008, container traffic has grown from 28.7 million TEU to 152.0 million TEU, an increase of about 430% ([3]). Currently, several new deep-sea as well as inland container terminals are being designed across continents. Several of the larger ones will be automated.

The design of the container terminal includes strategic design choices such as the terminal layout at the stackside, choice of equipment for handling containers at the seaside and landside, and type of vehicles for container transport between seaside and the landside. However, the process to arrive at an optimal design is extremely complex due to several reasons. They are: 1) physical constraints such as variations in ground conditions and topology of the terminal area, 2) large number of design parameters and corresponding solution search space, and 3) stochastic interactions among the three processes (quayside, vehicle transport, stackside). In this research, we analyze container terminal operations at the seaside using AGVs. Figure 1a shows an aerial view of a container terminal that includes vessels berthing at the quayside and the stackside whereas Figure 1b describes AGVs transporting containers in the yard area.



(a) (b)

Figure 1: (a) Aerial view of a container terminal (Courtesy: marineinsight.com) and (b) AGVs transporting containers in the yard area (Courtesy: porttechnology.org)

Due to significant investments involved in the development of a container terminal, an optimal design of the terminal is crucial. Traditionally, the main research focus has been on building simulation and optimization models to address strategic and tactical issues such as the container stowage problem at ships and in the stack, as well as on operational issues such as vehicle dispatching rules and quay crane scheduling ([2], [5]). Practitioners also develop detailed simulation models to design new terminals or improve the efficiency of existing terminal operations. While simulation provides detailed performance measures, it limits the extent of the design search procedure due to associated model development time and costs. In this research, we develop analytical models, which enable the terminal operator to analyse alternate configurations rapidly.

Analytical models have also been built to analyze specific system design aspects, for instance, Canonaco et al. [1] developed a queuing network model to analyze the container discharge and loading at any given berthing point. Hoshino et al. [4] proposed an optimal design methodology for an Automated Guided Vehicles (AGV) transportation system by using a closed queuing network model. However, in literature, integrated analytical models for analyzing the performance of loading and unloading operations by considering some of the stochastic inputs are scarce ([8], [7]). For instance, Vis et al. [9] assume deterministic AGV travel times while estimating the number of AGVs in a semi-automated container terminal.

New automated terminals typically adopt Automated Guided Vehicles (AGVs) for vehicle transport. AGVs do not have self-lifting capabilities and they need to be synchronized with the quay cranes at the quay side and with the stack cranes at the stackside to pick up or drop off the containers. In this research, we analyze alternate terminal layout configurations by varying the stackside configuration (number of stacks, bays, and height), and vehicle transport configuration (number of AGVs and travel path dimensions and topology) using analytical models. Each configuration may also impact the vehicle guide path and hence the travel times. For instance, by increasing the number of stack blocks, the length of the vehicle guide path also increases (refer Figure 2). Therefore, the stacking time per stack may decrease whereas the vehicle transport time may increase. Therefore, the configuration of an optimal stack layout is not clear.

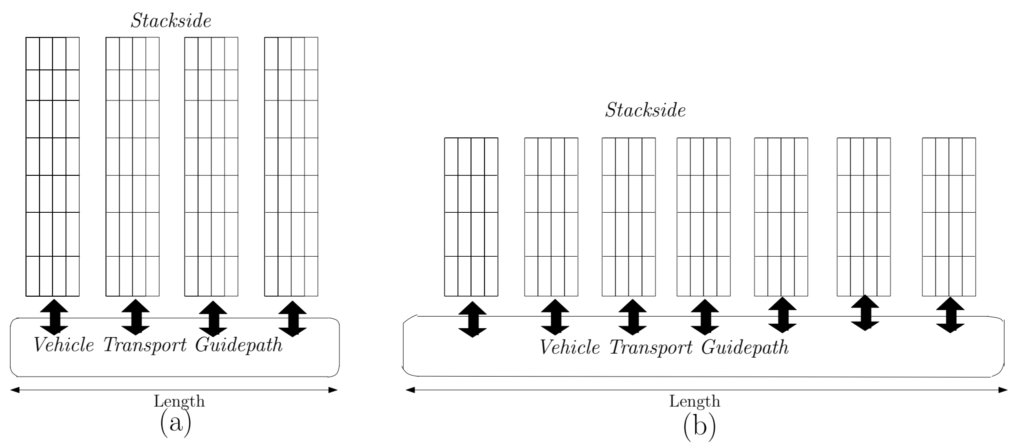


Figure 2: Alternate terminal layout configurations (a) small number of stacks and large number of bays (b) large number of stacks and small number of bays

Our work closely aligns with the analytical model developed by [4]. However our research differs from their work in several aspects:

1. We develop a semi-open queuing network model of the terminal system, which considers the synchronization of the AGVs and the containers waiting at the vessel to be unloaded. In reality, on some occasions, an AGV would be waiting for a container to be unloaded while during other times, a container would be waiting in the vessel for unloading operations. In a closed queuing network (such as in [4]), synchronization effects are not considered.

2. We consider realistic vehicle travel paths with multiple shortcuts that decrease the average travel times and improve vehicle capacity. Previous models do not consider the effects of multiple short cuts.

3. We develop protocols for handling containers at the quayside and the stackside that allows us to model the vehicle synchronization effects at the quay and the stack area.

4. We adopt our model to analyze alternate terminal layouts by varying the number of stacks, bays, and vehicle path dimensions, and arrive at a layout that minimizes throughput times and costs.

In this research, we develop an integrated analytical model for the unloading of containers at the *seaside* by considering the queuing dynamics at the quayside operations, vehicle transport operations, and stackside operations. Each quay crane is modelled as a single server station with general service times. The travel times associated with vehicles are modelled using Infinite server stations with general service times. Similarly, each stack crane is modelled as a single server station with general service times. Containers that wait to be unloaded may wait for an available vehicle, at the quayside. However, due to capacity limitations of the quay crane, a vehicle may also wait for a container arrival. This interaction between vehicles and containers is precisely modelled using a synchronization station and the queuing dynamics in the vehicle transport is modelled using a semi-open queuing network (SOQN) with V vehicles. The performance measures from the analytical model are validated using detailed simulations. Using the analytical tool, which can be evaluated rapidly, we analyze alternate terminal layout configurations and arrive at an optimal configuration. We believe that the stochastic model of the container handling operations can be used for rapid design conceptualization for container port terminals and improve container handling efficiencies.

The rest of this paper is organized as follows. The terminal layout adopted for this study is described in Section 2. The queuing network model for terminal operations with AGVs along with the solution approach is provided in Section 3. The results obtained from numerical experimentation and model insights are included in Section 4. The conclusions of this study are drawn in Section 5.

2 Description of Terminal Layout

Figure 3 depicts the top view of a part of a container terminal, which includes the quayside, transport and the stack side area (stack blocks with cranes, transport area with vehicles, QCs). The design of this layout is motivated from practice (see [2]). We focus on the space allowing berthing of one jumbo vessel with a drop size of several thousands of containers. A large container terminal may contain several of such identical berthing positions. The number of stacks is denoted by N_s and each stack crane is referred as SC_i where $i \in \{1, \ldots, N_s\}$. Similarly, the number of QCs is denoted by N_q and each crane is referred as QC_j where $j \in \{1, \ldots, N_q\}$. There is one shortcut path after each QC (referred as SP_j where $j \in \{1, \ldots, N_q\}$) that connects the quayside and the stackside areas. Both stacks and QCs have a set of buffer lanes, which are used by the vehicles to park during loading or unloading containers. The number of buffer locations at each QC and SC are denoted by N_{qb} and N_{sb} respectively. The other notations present in Figure 3 indicate path dimensions, which are used later to estimate the vehicle travel times.

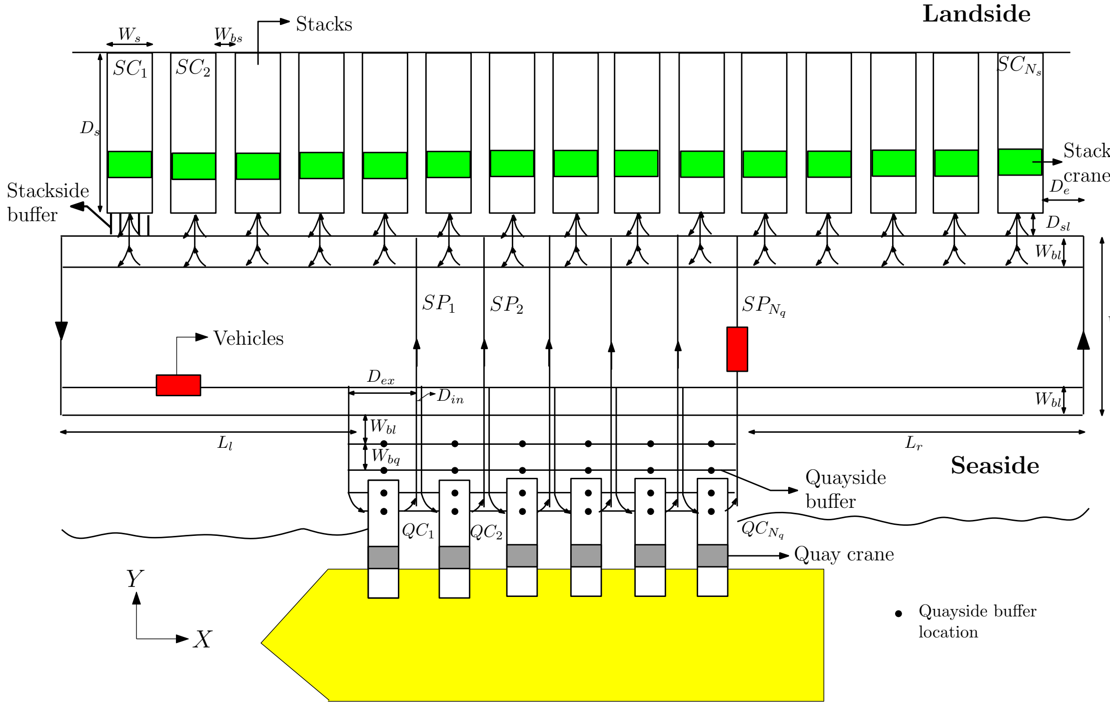


Figure 3: Layout of the container terminal used in this research

The container unload operation using an AGV is explained now. Due to hard coupling between the AGVs and the QCs, the containers that are waiting to be unloaded need to first wait for an AGV availability (waiting time denoted by W_v). When an AGV is available and the container needs unloading, it travels to the quayside (travel time denoted by T_{v_1}). Then the AGV may wait for the QC to be available after which the QC repositions the container from the vessel to the AGV (the waiting time and repositioning time denoted by W_q and T_q respectively). Then the AGV, loaded with a container, travels to the stackside, may wait for the SC availability. Once a SC is available, the crane travels to the stack buffer lane and picks the container from the AGV. The container is then stored in the stack area. The AGV travel time to the stackside, waiting time for the SC, and the crane travel times are denoted by T_{v_2}, W_s, and T_s respectively. Using these travel and wait time components, the throughput time for the unload operations with the AGVs is expressed using Equation 1.

$$CT_u = W_v + T_{v_1} + W_q + T_q + T_{v_2} + W_s + T_s \tag{1}$$

To determine the optimal layout of the terminal, the number of storage locations, number of vehicles (V), and the number of quay cranes (N_q) are fixed; we vary the number of stacks (N_s), number of rows per stack (N_r), bays per stack (N_b), and tiers per stack (N_t). By varying the four parameters, N_s, N_r, N_b, and N_t, the length of the vehicle guide path is also altered (Figure 2), which affects the unload throughput time, CT_u. The optimization formulation to determine the optimal combination of the four design variables is presented in Equation 2. The objective function is to minimize $E[CT_u]$, subject to the network throughput ($X(V)$) stability constraint with V vehicles, fixed locations constraint (C), vehicle utilization constraint ($U(V)$), and upper and lower bound constraints for the decision variables. To determine the optimal terminal layout configuration for unloading operations with AGVs, we analyze alternate configurations for different combinations of design parameter settings using the integrated queuing network model (described in the following section).

$$\begin{aligned}
\underset{N_t, N_s, N_r, N_b}{\text{minimize}} \quad & E[CT_u]\,(N_q, N_t, N_s, N_r, N_b, V) \\
\text{subject to} \quad & X(V) \geq \lambda_u \\
& N_t N_s N_r N_b = C \\
& U(V) \geq U_{min} \\
& N_{t_{min}} \leq N_t \leq N_{t_{max}} \\
& N_{r_{min}} \leq N_r \leq N_{r_{max}} \\
& N_{b_{min}} \leq N_b \leq N_{b_{max}} \\
& N_{s_{min}} \leq N_s \leq N_{s_{max}} \\
& N_t, N_s, N_r, N_b \in \mathbb{Z}^+
\end{aligned} \tag{2}$$

3 Queuing Network Model for Terminal Operations with AGVs

In this section, we develop the model of the unloading operations at a container terminal using AGVs. In an AGV-based system, both the QC and the SC drops-off (picks-up) the container on (from) the top of the vehicle. Therefore there is a hard coupling between the vehicle and the QC/SC. We first discuss the protocols that we develop to model the AGV-based terminal operations.

1. **Synchronization protocol at the quayside:** For the unloading operation, the QCs begin their operation only when an empty AGV has arrived at the buffer lane to transport the container. Similarly, for the loading operation, the QCs begin their operation only when a AGV loaded with a container has arrived at the quay buffer lane from the stackside.

2. **Synchronization protocol at the stackside:** For the unloading operation, the SCs begin their operation only when an AGV loaded with a container has arrived at the stack buffer lane to store the container. Similarly, for the loading operation, the SCs begin their operation only when an empty AGV has arrived at the stack buffer lane to transport the container to the quayside.

We now list the modeling assumptions for the three processes.

Quayside process: We assume that there is one trolley/QC. Further, there is infinite buffer space for parking vehicles at the QC location. The dwell point of QCs is the point of service completion. Containers arrive in single units with exponential interarrival times. Further, containers are randomly assigned to a QC.

Vehicle transport process: Each AGV can transport only one container at a time. The dwell point of the vehicles is the point of service completion. The vehicle dispatching policy is FCFS and the blocking among vehicles at path intersections is not considered. Further, vehicle acceleration and deceleration effects are ignored.

Stackside process: We assume that the stack layout is perpendicular to the quay and there is one crane per stack. The dwell point of cranes is the point of service completion. Similar to the quayside, we also assume infinite buffer space for parking vehicles at the SC location. Containers are randomly assigned to a SC.

3.1 Model Description

The inputs to the queuing network model are the first and second moment of the container inter arrival times (λ_a^{-1}, c_a^2), and the service time information at the resources. Each QC is modeled as a single server FCFS station with general service times. Likewise each SC is modeled as a single server FCFS station with general service times. The components of the AGV travel times are modeled as IS stations (VT_1 and VT_2). The AGVs circulate in the network processing container movements.

We now describe the routing of the AGVs and containers in the queuing network model with respect to the unloading operations. Figure 4 describes the queuing network model of the container unloading process with AGVs. The containers that need to be unloaded, wait for an available vehicle at buffer B_1 of the synchronization station J. Idle vehicles wait at buffer B_2. The physical location of the vehicles waiting in buffer B_2 would correspond to the stackside buffer lanes. Once a vehicle and a container is available to be unloaded, then the vehicle queues at the IS station (VT_1). The expected service time at VT_1, $\mu_{t_1}^{-1}$, denotes the expected travel time from its dwell point (point of previous service completion) to the QC buffer lane. After completion of service, the vehicle queues at the QC station ($QC_i, i = 1, \ldots, N_q$) to pick up the container. The expected service time at QC_i, $\mu_{q_i}^{-1}$, denotes the expected movement time of the QC to reach the container in the vessel, container pickup time, movement time to reach the AGV, and container dropoff time. Then, the vehicle queues at the IS station: VT_2. The expected service time at VT_2, $\mu_{t_2}^{-1}$, denotes the expected travel time from the QC buffer lane to the SC buffer lane. After completion of service at VT_2, the vehicle queues at the SC station ($SC_i, i = 1, \ldots, N_s$) to dropoff the container. The expected service time at SC_j, $\hat{\mu}_{s_i}^{-1}$, denotes the expected travel time of the SC from its dwell point to the stack buffer lane and the container pickup time. Once the container is picked up from the AGV, the AGV is now idle and available to transport the containers that are waiting to be unloaded at the quayside.

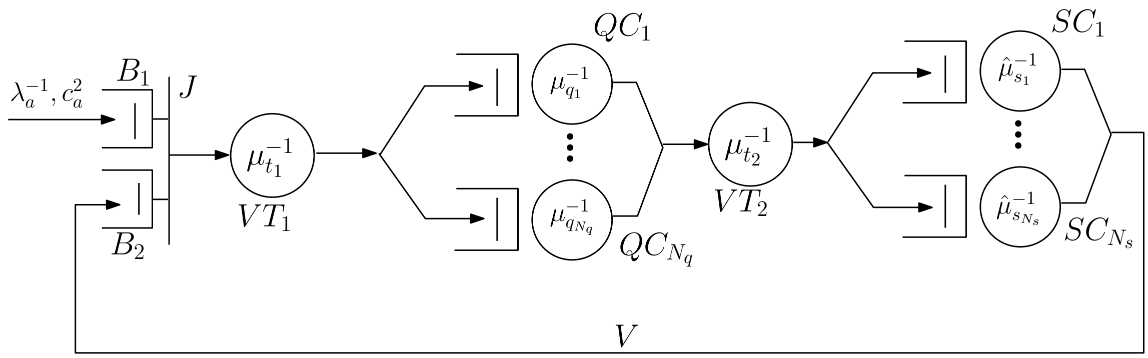


Figure 4: Queuing network model of the container unloading process with AGVs

Note that due to random assignment of containers to a QC and random storage of a container at a stack block, the routing probabilities from station VT_1 to QC_i ($i = 1, \ldots, N_q$) and from VT_2 to SC_i ($i = 1, \ldots, N_s$) are $\frac{1}{N_q}$ and $\frac{1}{N_s}$ respectively. The queuing network in Figure 4 is a semi-open network model because the model possesses the characteristics of both open as well as closed queuing networks. The model is open with respect to the transactions and closed with respect to the vehicles in the network. Due to non-product form nature of the integrated network, an approximate procedure is developed to evaluate the network. First, a sub-network of the original network is replaced by a load-dependent server. The service rates correspond to the throughput of a closed queuing network (sub-network). The reduced model is evaluated using a continuous time Markov chain (CTMC). This approximate procedure provides substantial computational advantage in evaluating the integrated queuing network and estimating performance measures. By accounting for the stochastic interactions among quay cranes, vehicles, and stacking cranes, realistic estimates of system performance measures such as throughput capacity, resource utilization, the container waiting times for resources, and the expected cycle times are obtained. The expressions for the service times at various nodes and detailed description of the solution methodology are included in our working paper ([6]).

4 Numerical Experiments and Insights

We considered a container terminal scenario with a quay crane capacity of 30 cycles/hr, 40 AGVs, each stack has 6 rows, 40 bays, and 5 tiers. The total number of container storage locations is fixed at 48000, which corresponds to the capacity of the stacking lanes to serve a deep-sea vessel at the ECT terminal at Rotterdam. The travel velocity of the AGV and the SC are assumed to be 6 m/s and 3m/s respectively. The area of the AGV path is 540m $\times$ 90m. There are 5 buffer lanes per stack block.

We validate the analytical model for the container terminal with AGVs using detailed simulations. The average percentage absolute errors in the expected queue lengths and the expected throughput times are less than 7%. To determine the optimal terminal layout configuration we varied the design parameters in the following manner: number of stack blocks is varied between 20 and 120 with an increment size of 20, number of rows/stack is varied between 4 and 10 with an increment of 2, number of tiers/stack is varied between 3 and 5 with an increment of 2.

The expected throughput times are determined for all possible layout combinations. Table 1 includes five poor layout choices whereas Table 2 includes five good layout choices. The results suggest that a small number of stack blocks and a large number of bays/block are a better design choice than a large number of stack blocks and a small number of bays/block.

Table 1: Poor terminal layout design choices

N_s	N_r	N_b	N_t	$\mathbb{U}_v$	$\mathbb{E}[T_u]$ (sec)
120	4	34	3	88.9%	1141.5
120	6	23	3	88.1%	1117.5
120	4	20	5	87.9%	1111.3
120	8	17	3	87.7%	1105.3
120	6	14	5	87.5%	1099.5

Table 2: Good terminal layout design choices

N_s	N_r	N_b	N_t	$\mathbb{U}_v$	$\mathbb{E}[T_u]$ (sec)
20	8	100	3	55.2%	632.0
20	6	80	5	53.8%	615.3
20	10	80	3	53.8%	615.3
20	8	60	5	52.3%	598.6
20	10	48	5	51.4%	588.5

5 Conclusions

In this research, we develop an integrated analytical model for the unloading operations in the container terminal using Automated Guided Vehicles. Numerical experiments suggest that stack configuration with small number of stacks and large number of bays (20 stacks, 80 bays) yields better throughput performance than large number of stacks and small number of bays (80 stacks, 20 bays). We believe that the stochastic models of the container handling operations can be used for rapid analysis of multiple design configurations for container port terminals and improve container handling efficiencies.

Acknowledgements

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