

Strategies for improving a long-established terminal's performance: a simulation study of a Turkish container terminal

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Abstract Due to a long-lasting increase in global trade, only interrupted by the late-2000s economic crisis, container traffic has grown dramatically. As a result, new terminals have opened and existing terminals face much higher container handling than before. In order to meet these challenges, one of the biggest container terminals in Turkey has begun to reconsider its terminal operations and to achieve improvements of its overall logistics performance. Because the factors impacting the terminal's performance are highly interrelated, a simulation model was developed to analyze the terminal operations, to identify potential bottleneck resources and to highlight directions for the future development of the configuration and the operational control system. For a long-established terminal like the one considered in this study the options for improving the overall performance are limited by the geographical dimensions and by the existing terminal equipment. By use of the simulation model the terminal operations are evaluated under different workload scenarios and alternative configurations are tested in order to support strategic decisions on the terminal's development.

Keywords Simulation · Performance evaluation · Seaport container terminal · Maritime transport

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1 Introduction

Despite the breakdown due to the economic crisis in the late-2000s, container transportation has by far shown the highest growth rate among all freight transportation systems during the recent decades. The use of standardized containers to store and transport goods of all kinds has tremendously improved the efficiency of maritime transportation. The business environments and challenges of ports, railroads, and freight forwarders have dramatically changed as a result of this “container revolution”.

Containerized cargo shipment has significantly affected the operation mode of most transportation systems. The new challenge with containerization is how to develop more efficient concepts for the interaction of transportation modes, i.e. combining ship, rail, and road haulage for directing freight from the origin to the final destination of a transportation order. The need for combined freight transportation systems has brought about innovative transportation facilities, equipment, and management practices dedicated to inter-modal freight carriage.

Specifically, issues of logistics control in seaport container terminals have produced a wealth of publications in the scientific literature, cf. Stahlbock and Voß (2008) for a recent overview. Among the logistics control problems investigated, the overall performance analysis of container terminals, the evaluation of alternative configurations, berth allocation, stowage planning, scheduling of the handling equipment, storage and stacking policies, quayside and landside transportation planning have been areas of primary interest.

In practice, numerous studies have been undertaken on the design and re-design of facilities and equipment along with the development of logistics control software and information systems. While most of the academic studies analyze a hypothetical large-sized terminal under green-field assumptions, we consider the case of a long-established medium-sized terminal located in Turkey which operates as a hub and feeder base to serve the Mediterranean and the Black Sea region. Due to the globalization of trade and the enlargement of the European Union, Turkey’s ports located at the geographical interface between Eastern Europe and the Mediterranean region (see Fig. 1) faced a rapidly growing demand for handling containerized goods (cf. Türklüm 2010). During the period from 2003 to 2008 the number of containers handled by Turkey’s ports has more than doubled. Turkey with its coast line of 8,333 km is geographically located between Europe, Asia, and Middle East countries and faces four different seas and two straits connecting the Black Sea to the Aegean and to the Mediterranean Sea. The ports of Ambarlı and Haydarpaşa at the Marmara Sea, İzmir at the Aegean Sea and Mersin at the Mediterranean Sea have vital importance in foreign trade, since they host large industrial areas. At the same time, Turkish ports play an important role as feeder ports, rendering services for the delivery of containers in the region and linking local ports to the major international vessel routes.

The terminal at hand located in Istanbul has been selected as an object of investigation mainly for two reasons. First, the extension of Turkey’s maritime container handling capacity becomes a critical issue and imposes new challenges for existing seaport container terminals to improve their performance (cf. Celik et al.



Fig. 1 Turkish container ports

2009). Second, the container terminal was selected because it provides a typical example of a long-established terminal configuration which has to improve its total handling capacity under tight base area restrictions in order to cope with the increasing competition among private and public terminals in the region. Under these conditions, improving the configuration of the terminal appears to be far more difficult compared to new terminal projects developed under green-field conditions. The obtained case study based results are therefore also relevant for the further development of established terminal configurations particularly of small and medium size in other parts of the world.

In order to evaluate the performance of the container terminal under various workload conditions and to analyze the impact of changes in the terminal configuration and the logistics control system, an Arena-VBA based simulation model is proposed. The model allows analyzing some pre-defined performance criteria such as total container handling, average resource utilization and average waiting times, e.g. of quay cranes waiting for a carrier, to identify potential bottlenecks in the operational areas (quay cranes, storage yard or transportation system) of the terminal.

The remainder of this article is organized as follows. In the next section a brief review of the relevant literature with a focus on simulation modeling is given. In Sect. 3 the basic container terminal operations are explained and the investigated container terminal is introduced. Section 4 provides details of the simulation model including its main features and the generation of input data. Results of the numerical experimentation are presented in Sect. 5 including a statistical analysis of the results. Finally, conclusions are drawn and the results of the simulation study are summarized.

2 Literature review

Planning and control of seaport container terminal operations has become a popular topic of academic research worldwide. Hence, a huge amount of papers has been published focusing on different planning and control aspects or on specific types of terminal equipment. For comprehensive reviews of the container terminal literature we would like to refer to the surveys by Vis and de Koster (2003), Steenken et al. (2004) and Stahlbock and Voß (2008). Further analyses and reviews of terminal-related operations and issues of decision making in container terminals are provided by Murty et al. (2005a, b) and Günther and Kim (2006). Thus the following literature review is confined to papers being relevant for the specific issues addressed in our investigation and on selected simulation studies.

In logistics research, simulation is considered the standard approach for performance evaluation of seaport container terminals (cf. Steenken et al. 2004). The high popularity of simulation methodology, in particular discrete-event based simulation, is primarily due to the lack of analytical methods which are capable of dealing with the complexity of the logistics operations in a container terminal involving numerous transportation and handling resources and to adequately reflect the stochasticity of the application environment. Simulation models greatly differ in their objective and the level of detail at which the entities and the processes of the real system are modeled. Only a few models have been published which consider the terminal with its logistics processes as a whole, cf. Liu et al. (2002, 2004), Petering (2011), and Sun et al. (2011). To reduce the complexity of the simulation model, many simulation-based studies aggregate operational decisions and processes. For instance, simulation studies which focus on automated guided vehicle (AGV) dispatching for quayside transport like Briskorn et al. (2006) and Grunow et al. (2006) usually neglect landside transport and model stacking operations by use of distribution functions for yard crane handling times. These assumptions are rectified by the specific orientation of the simulation study. While the majority of the published simulation models are based on an abstract design of a container terminal, only a few papers deal with a real system. For instance, Shabayek and Yeung (2002) are concerned with the Kwai Chung terminal in Hong Kong and develop a simulation model to predict the actual container terminal operations. Nam et al. (2002) examine the optimal number of berths and quay cranes for a terminal in Busan. The model of Duinkerken et al. (2006) is applied to a future extension of the Maasvlakte area. Another topic of simulation-based evaluation is the intermodal container traffic between seaborne and onshore transportation, cf. Parola and Sciomachen (2005) who analyze the performance of the entire logistic chain related to the Northeastern Italian port system.

The majority of the published papers, however, use simulation as a pragmatic approach for experimenting with user-defined scenarios and to evaluate alternative equipment configurations and operation strategies. For instance, the performance of different transportation systems is compared under realistic conditions. Yang et al. (2004) as well as Vis and Harika (2004) apply a simulation-based performance analysis to compare AGVs and automated lifting vehicles (ALVs). They show that in an automated container terminal the number of ALVs can be reduced while

retaining the same service level as with AGVs. This means that ALVs are generally superior to AGVs because they do not need to wait at buffer zones for the handshake operations with yard or quay cranes. Apart from AGVs and ALVs, Duinkerken et al. (2006) also evaluate the performance of multi-trailers. Their numerical experiments confirm results from the previous papers. Handling operations at yard storage blocks are analyzed by Vis (2006). The results of the simulation study show that automated transport and handling equipment outperforms manual equipment in the investigated terminal configuration.

Resource allocation in container terminals is another very common topic in literature. Multiple approaches to storage allocation of containers in the yard have been proposed. Examples are given in Preston and Kozan (2001), Lee et al. (2006) and Han et al. (2008) who determine container locations to minimize turn around times of container vessels and traffic congestion of yard trucks, respectively. Another topic is vehicle allocation, which assigns a transportation vehicle to a berth or quay crane. In contrast, a pooled allocation concept allows every vehicle to serve every berth or quay crane. Bae and Kim (2000) evaluated both strategies and conclude that the pooled strategy is superior to the dedicated allocation concept. Vis and van Anholt (2010) presented a simulation-based performance analysis of different berth layouts and show the superiority of an indented berth type. Nevertheless, many results in literature must be handled with care for roll-out in real container terminals because academic studies are often based on green-field assumptions and do not sufficiently take the limitations and specific issues into account which have to be considered in established seaport container terminals.

Our main contribution is to show how strategic decisions on the future development of a container terminal in Turkey can be supported by means of a simulation study. The terminal configuration and the related logistics processes have been modeled such that the simulation reflects the real operations. In our simulation experiments we investigate the possibilities of increasing the terminal performance in terms of container handling by exchanging the transportation system and extending the terminal equipment as well as applying resource allocation strategies. The simulation framework and the general experimental procedure are mainly relevant for long-established container terminals facing limited opportunities to improve their overall performance.

3 Container terminal operations

Containers enter and leave the terminal by different means of transport, such as trucks, trains, and ships. Seaport container terminals provide an interface between maritime and on-land transportation systems and, thus, represent the critical link in the inter-modal transportation chain. Three basic handling directions can be distinguished. Export containers arrive at the terminal usually by train or truck and are stored in the terminal yard before they are loaded onto a container vessel for transport to the destination port. Import container pass through the same steps in converse direction. Transshipment containers arrive by vessels and are taken onshore just for a short period until they are charged onto another vessel or taken

over by a regional shipping service. More recently, offshore service concepts were developed which enable the exchange of containers directly between vessels (Kim and Morrison 2011).

The handling of containers inside a terminal involves a number of different equipment units which perform dedicated transport or storage operations (cf. Günther and Kim 2006). The interaction between the main equipment units of a seaport container terminal is illustrated in Fig. 2. Basically, three types of equipment are used in container terminals: quay cranes, yard cranes and shuttle trucks for ground transport between the different terminal areas.

Quay cranes are used to load and unload containers to and from a ship. For unloading, the quay crane picks up containers from the ship one-by-one and puts them on shuttle trucks that move the containers to the storage yard in the terminal. To load a ship the quay crane unloads a container from a shuttle truck and puts it onto the ship.

Operations in the storage yard are more flexible than quay crane operations. This is due to the numerous ways in which containers can be moved and stored within this area. Typically, the storage yard is organized into blocks at which yard cranes are employed to stack containers. For instance, containers can be stacked by use of automated or manual *yard cranes* that take over the containers arriving from the hinterland or deliver the containers to shuttle trucks for transport to the quay side. The assignment of storage locations within a yard block requires close attention in order to prevent frequent reshuffles or misplaced containers.

A further key element of terminal operations is the transport of containers between the quay side and the storage yard by use of *shuttle trucks*. In automated container terminals AGVs (automated guided vehicles) or ALVs (automated lifting vehicles) can be found. AGVs are similar to conventional trucks, but operate driverless on a pre-defined guide path. ALVs are vehicles which move over a container, lift it up and transport it to the designated storage location. Contrary to ALVs, AGVs need to interact with a crane. In non-automated terminals, straddle carriers or conventional yard trucks are used for moving containers inside the terminal. On the landside, many European container terminals have railway links which are not so common in most Asian countries. The productivity of a container ship's journey depends on the berthing time at the terminal which is primarily affected by the coordination of the transport and handling equipment.

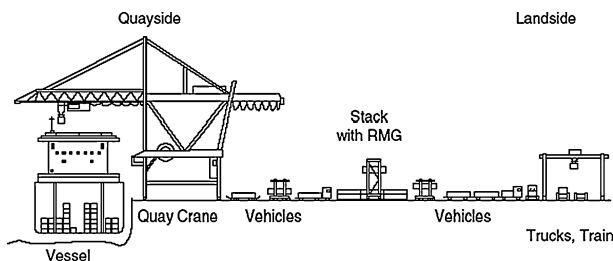


Fig. 2 Transportation and handling chain of a container (Vis and de Koster 2003)

In this paper we consider a terminal from the port of Istanbul as a case study. The layout of this terminal (see Fig. 3) is unique in that the berths are aligned perpendicularly at three legs of the storage yard. The container terminal with its three berths has a total quay length of 3,215 feet. Berths 1 and 2 are each equipped with two rail-mounted quay cranes (RMQC) while one rubber-tired quay crane (RTQC) is

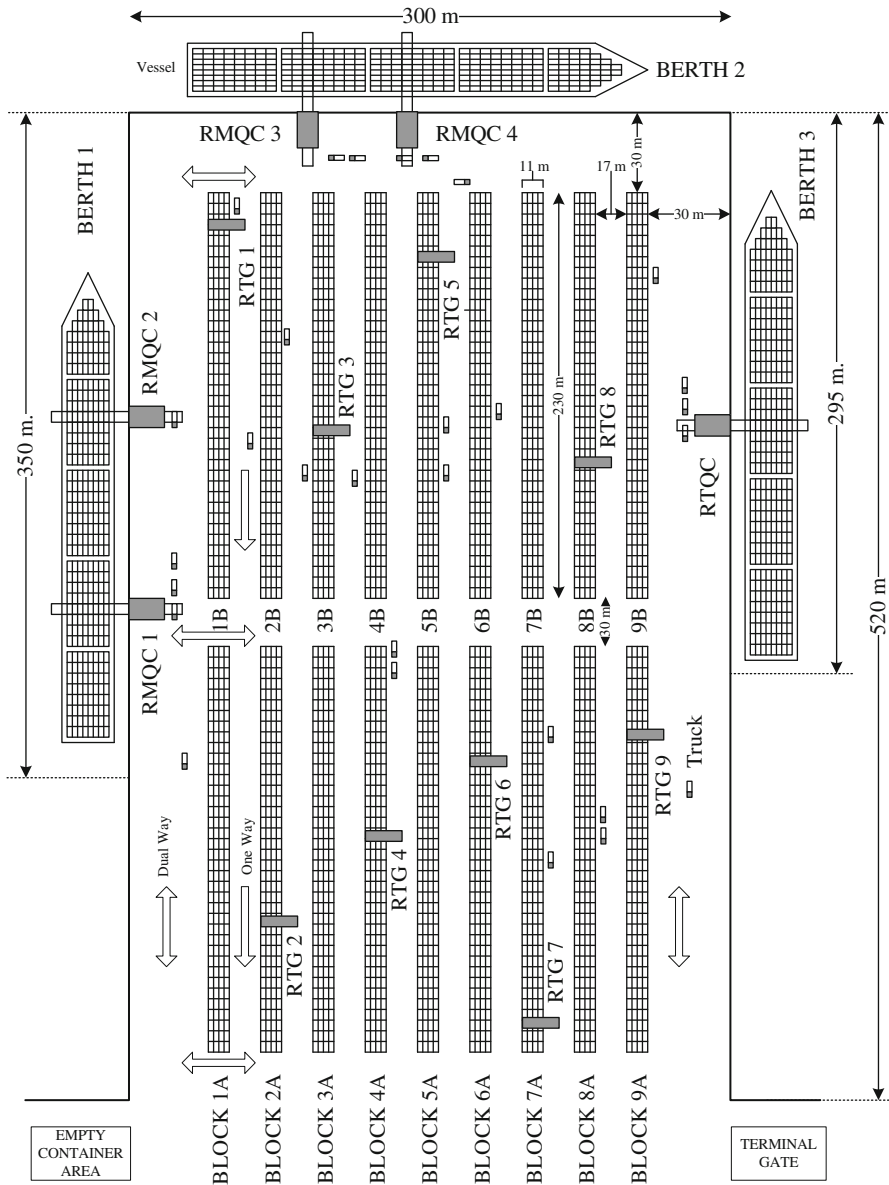


Fig. 3 Terminal layout

(RTQC) operates at berth 3. The storage area is divided into nine zones each consisting of two blocks in-line. One rubber-tired yard crane (YC) is assigned to each of the nine zones. Inside the terminal, transport operations are carried out by 30 manually driven trucks. With these specifications, the container terminal can be classified as a modern port facility, but automation of the handling and transport operations is still lacking. The container terminal is capable of servicing 1,700 container vessels per year which, considering the typical size of vessels calling at the port, corresponds to a total theoretical handling capacity of 750,000 TEU (twenty-foot equivalent units). The actual annual handling, however, is in the order of only around 400,000 TEU. As the terminal is located inside the urban area, its ground space is narrow and possibilities for expansion are very limited. Hence, it is very unlikely that the storage yard measuring 38.5 acres can be expanded. By stacking containers four-high a theoretical storage capacity per block of 608 TEU is possible, giving almost 10,944 TEU for the entire terminal. Often, terminal operators use dedicated stacking areas for export/import containers. In the terminal at hand, blocks 3, 6 and 7 are used for export containers whereas the other blocks are dedicated to import containers. However, these assignments are handled with flexibility depending on the specific demand for export/import containers. Also, storage space for empty containers is available outside the stacking area. The terminal is operated every day with three 8-h shifts.

4 Simulation model of the container terminal

To develop strategies for improving the terminal's performance, a simulation study was conducted. Simulation offers the possibility to mimic the terminal operations and to evaluate the system performance under different operating conditions and scenarios. Section 4.1 explains the directions of our simulation study followed by the presentation of the main features of the simulation model (Sect. 4.2) and the generation of the input and output data (Sect. 4.3).

4.1 Directions of the simulation study

The volume of containers handled by Turkey's ports has sextupled since 1998 with a throughput of over 4.7 million TEU in 2007. At the same time the rank of Turkey's ports in the world market has consequently improved. However, due to its land limitations the market share of the investigated container terminal has only slightly increased. Comparative empirical studies using Data Envelopment Analysis (DEA) classified the considered terminal as one of the most inefficient seaport container terminals within the benchmark group, cf. Cullinane and Wang (2006). Therefore, the general direction of our simulation study is to identify the bottlenecks which cause this observed inefficiency and, in a second step, to evaluate changes in the terminal configuration and in the resource allocation strategies in order to resolve the bottlenecks.

In view of the terminal's inefficiency compared to other container terminals in Europe, terminal management is seeking opportunities to increase the handling

capacity of the terminal in the long-run in order to improve its position on the maritime container market. Since expanding the base area is merely impossible, adding additional resources and a more sophisticated resource allocation appear to be the primary perspectives to improve the terminal's productivity. Another perspective is to review resource scheduling and dispatching strategies and to redesign the terminal's scheduling and dispatching processes. However, this is outside the scope of this paper.

Another, yet very costly strategy would be to replace the current equipment by using more powerful automated handling and storage technologies. Apart from increased handling performance automated rail-mounted gantry cranes, for instance, would also offer the possibility of stacking containers five-high and extending the width of the yard blocks, thus increasing the total storage capacity by more than 25%. However, such an increased storage capacity can only be utilized if at the same time capacities of quay cranes and of the internal transportation system are accordingly increased. Because of the considerable investments, this alternative is currently not pursued.

Simulation modeling is capable of experimenting with complex scenarios taking the interaction between the different equipment types into account and predicting the resulting increase in productivity. In particular, discrete event based simulation can be applied to model the terminal operations in a highly stochastic environment.

4.2 Main features of the simulation model

The simulation model was developed using Arena Enterprise Edition 10.0 in conjunction with Visual Basic Application (VBA). Arena combines event and process modeling approaches. It comprises both the Siman simulation language and animation systems, thus allowing an easy integration of animation elements with simulation constructs. Each Siman construct represents an activity of the real process. Arena's animation features are very convenient for validating the model and communicating with external clients. VBA was used to generate the entire Arena experimental frame and animation displays of the model. This technique allows simulation users to maintain and modify the required model data without knowing the details of the Arena simulation software. In addition, VBA was employed to provide the input data for the simulation. All model variables, attributes, expressions, resources, queues, and stations are specified by using VBA. Therefore, it is relatively easy to change or update the conditions for experimenting with the simulation model.

Major resources in the simulation model are the different equipment units such as quay cranes, yard cranes, and internal trucks, which are modeled with their specific operational characteristics. Specifically, the model simulates the time consuming processes of all equipment units considering the processes associated with the arrival of vessels, the handling and transportation of containers, as well as the interaction between the different types of equipment. Figure 4 illustrates the basic logic of the logistics processes covered by the simulation model. All activities occurring between the arrival and the departure of a vessel are displayed. In particular, the interaction between the loading and unloading activities by quay

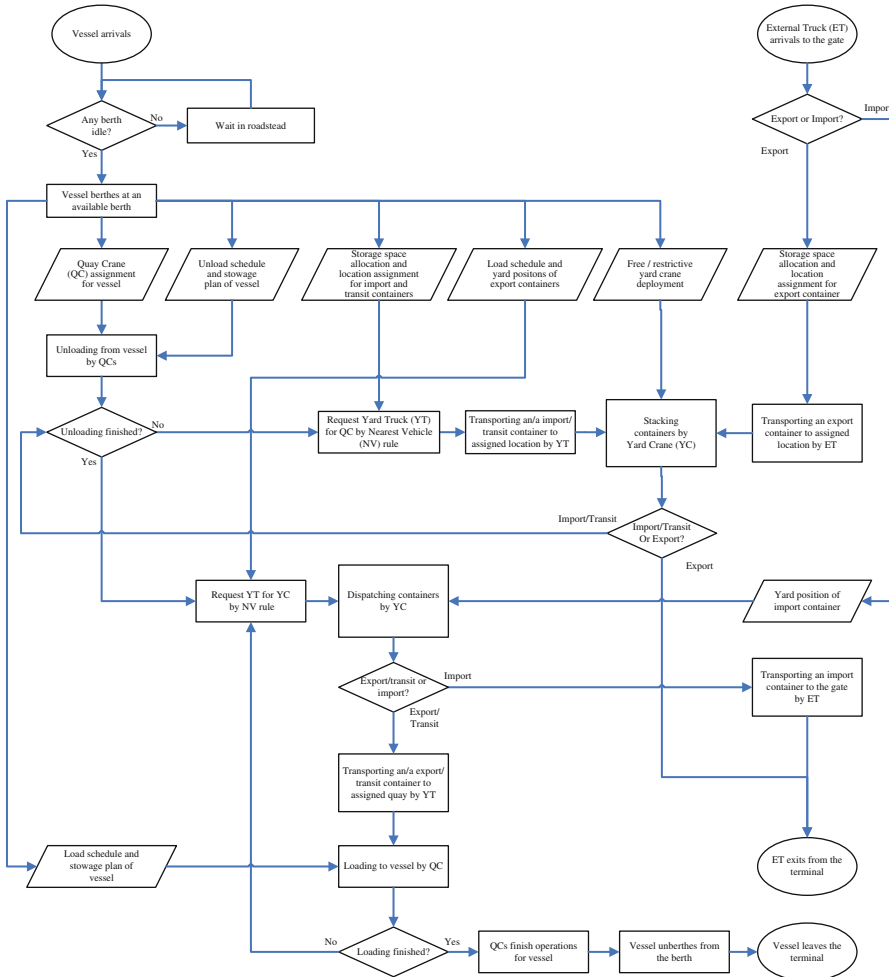


Fig. 4 Basic logic of the logistics processes covered by the simulation model

cranes and the yard operations by yard trucks and yard cranes are shown. In addition, the vertical branch on the right represents the interface to the terminal’s gate where external trucks take over and deliver the containers.

The arrival of vessels at the terminal is generated at the beginning of each simulation run according to the underlying arrival distribution. Next, the type of vessel, small, medium or large, is drawn from the assumed statistical distribution along with the number of containers to be charged and discharged at the terminal. If a berth is available, the vessel immediately starts berthing. Otherwise the vessel waits in the road stead and is assigned to the end of the queue of vessels waiting for berthing.

As in real terminals, quay crane operations are sequenced in advance based on the stowage plan of the vessel. Hence, in the simulation model each quay crane

performs the assigned loading and unloading operations following the predefined job sequence. Containers may only be passed from one resource to another if the resource satisfies a “handshake” criterion. This way, the transfer of individual containers between cranes and trucks is realistically modeled. During vessel loading and unloading the subsequent container handling operation can only be activated once the preceding quay crane operation is finished and the required yard truck arrives at the quay crane.

Each of the 30 man-driven yard trucks available in the terminal is allowed to haul only one container at a time. Travel times between locations in the terminal are derived from the real geometric distances considering realistic travel speed values. The simulation model also considers bypass lanes for trucks traveling along the horizontal roadways between storage blocks. These lanes help to avoid traffic jams. The nearest vehicle (NV), the random and the cyclic rule for the assignment of yard trucks to transportation jobs were tested by means of the simulation model to compare their effect on the performance of the container terminal. Details of the assignment rules can be found in Egbelu and Tanchoco (1984). As part of a preliminary study, experiments on the assignment rules were conducted and the results demonstrated the effectiveness of the NV rule. Hence, this rule was applied in the further studies. According to the NV rule a free yard truck located nearest to the respective quay or yard crane is assigned to the transportation job. First, the yard truck travels to the crane and waits for the container. Then the crane loads the container onto the truck. It might also occur that the crane has to wait for a yard truck to arrive. After receiving the container, the yard truck starts transporting the container to the stack. For unloading operations, this procedure is reversed. In case of simultaneous yard truck requests, priority is given first to quay side unloading, second to quay side loading, third to yard side unloading, and lastly to yard side loading operations.

Another important feature of the simulation model is the deployment of yard cranes among storage blocks. As shown in Fig. 3 each two blocks in a line form one zone to which a yard crane is assigned. Consequently, the yard crane has to move between the blocks in the same zone. This basic deployment strategy is called “free yard crane deployment” and is applied throughout the simulation study except for the experiments which consider an increased number of yard cranes. Only in these experiments, one yard crane is assigned to each block and the transfer of yard cranes between different storage blocks is not allowed. This policy is called “restrictive yard crane deployment”.

Since our investigation is concerned with the performance evaluation of a real container terminal, the simulation model has to mimic the real operational conditions and the logistics processes as closely as possible. Nevertheless, assumptions have to be made in order to exclude elements of minor relevance and to focus on those aspects which are of paramount interest. Major assumptions of our simulation model are the following:

- Although the terminal operates yard trucks which slightly differ in their technical specifications, we assume that all trucks are of the same type.
- We assume that operating conditions of the terminal are not affected by weather conditions and do not differ between the working shifts. Moreover, the model

does not handle rare events due to inexperienced operators and resulting from odd surface conditions of the yard ground.

- We also assume that vessel arrivals at berths are unscheduled and thus considered as random events.
- One of the major operational problems in the terminal is the condition of the ground in the stacking area because rubber tired yard cranes often damage the surface of the transportation paths and the storage area. Thus, these cranes sometimes do not work properly. We modeled this problem as equipment failure. Because the terminal does not keep statistics on these failures, distributions of failure ratios were estimated based on interviews with terminal managers.
- All scenarios are run with the same basic input data. Different workload scenarios are generated by shortening the time interval between vessel arrivals. In these scenarios, demand is based on total hinterland market demand from which the terminal at hand services as much as it can handle within the installed capacity.

4.3 Generation of input and output data

We developed the simulation model to analyze operations of an existing container terminal. Therefore, our aim in generating the input data for the simulation was to use as much input data from real terminal operations as possible. Major input data define the capacity of the container terminal including the number of berths, the number of quay cranes, yard cranes, and yard trucks with their operating times, equipment failure times, and the number of stacks in the yard. Further input data refer, for instance, to the arrival of vessels and external trucks, the type of vessels, and the distances in the container yard. The variety of both the inter-arrival time of container vessels and the service times of the resources were modeled using statistical distributions which reflect the real process times.

As far as possible data used in the simulation model were acquired from daily documental records of the existing terminal from 2000 to 2007 and the camera records of the year 2008. These data were analyzed using Arena Input Analyzer 10.0 and SPSS 15 following the concept of trace-driven simulation. Distributions with their parameters were determined with respect to minimum squared errors based on the Chi Square Test of the Arena Input Analyzer. Since there was no statistical past record for equipment failures related availability ratios were estimated based on interviews with the terminal operator. Likewise detailed past records on the arrival of external trucks were missing. Hence, corresponding arrival times were determined based on the average storage times of the import/export containers in the yard blocks. Major distributions and parameters used in the simulation model are shown in Table 1.

Activity records obtained from the real system are provided to the simulation model in chronological order. Thus it becomes possible to validate the simulation outcomes against the corresponding real response measures by performing appropriate statistical tests (cf. Legato and Mazza 2001). In this paper, validation

Table 1 Major distributions/parameters used in the simulation model

Process	Distribution	Units
Inter arrivals times of vessels	Exponential (0.0685)	Hours
Inter arrivals times of external trucks	Exponential (0.7692)	Minutes
Load to be charged onto a vessel	Normal (118, 3)	TEU
Load to be discharged from a vessel	259 + beta (1.31, 1.43)	TEU
Handling time of quay cranes	Triangular (1, 2.6, 4)	Minutes
Handling time of yard cranes	Triangular (2.1, 4.8, 7.6)	Minutes
Empty travel time of yard trucks	Normal (12, 3)	Km/hours
Laden travel time of yard trucks	Normal (8, 3)	Km/hours
Average storage time in yard blocks (import and export)	3 and 4, respectively	Days
Import/export ratio	2.33	–
Time-between-failure for quay crane	Triangular (10, 30,45)	Days
Down time for quay crane failure	Triangular (1, 36,72)	Hours
Time-between-failure for yard crane	Triangular (7, 15, 60)	Days
Down time for yard crane failure	Triangular (1, 48, 96)	Hours
Time-between-failure for yard truck	Triangular (7, 30, 60)	Days
Down time for yard truck failure	Triangular (1, 36, 96)	Hours

tests of the simulation model are based on total container handling because this measure includes all parameters affecting the overall performance of the terminal. The average values of the simulated data and the real data over a period of 1 year are analyzed by using the Student t test resulting in significance probabilities of more than 0.05. As a result, the simulation model is deemed to be accurate in estimating the system output of the container terminal.

The primary output parameter of the simulation model is the total number of import, export, and transshipment containers handled by the quay cranes per year. Secondary performance measures include the average utilization of quay cranes, yard cranes, yard trucks, and the average waiting times of these resources. These performance criteria are used to identify potential bottlenecks of the operational system and the resources in the container terminal. Prior to the main simulation runs, a number of preliminary tests have been carried out to investigate the effect of different simulation parameters such as warm-up period, number of replications etc. For example, the number of replications was set as five according to the results of Analysis of Variance (ANOVA) tests which indicated that the null hypothesis (equal mean performance of the simulated scenarios resulting from 5, 10 and 15 replications, respectively) could be accepted. In other words, the observed total number of containers handled per year did not show significant differences for the respective simulation setups. In addition, the comparison of factors such as average time between failures and the occupancy rate of the terminal system supported the choice of the simulation parameters. Therefore, throughout the numerical investigation, experiments are repeated five times with different randomly generated data. Each simulation run covers 1 year of terminal operation with one additional month considered as warm-up period.

5 Numerical experimentation

The starting point for the numerical experimentation was the obvious inefficiency of the terminal resulting from benchmarking studies, e.g. Cullinane and Wang (2006). In order to develop strategies for the improvement of the terminal's performance a first experiment was conducted with the aim to analyze the current configuration and to identify bottlenecks which limit the entire container turnover of the terminal (Sect. 5.1). Next, two investment strategies were considered, namely the exchange of the current yard trucks by straddle carriers (Sect. 5.2.1) and doubling the number of the installed yard cranes (Sect. 5.2.2). Finally, resource allocation strategies were evaluated which reserve parts of the storage space and the yard truck fleet for dedicated purposes (Sects. 5.3.1 and 5.3.2, respectively.) As the terminal operator's priority is not to introduce a new type of equipment like straddle carriers, an increased number of yard cranes was finally considered in combination with resource allocation strategies. These options were thus analyzed by means of an ANOVA study (Sect. 5.4).

5.1 Analysis of the current terminal configuration

In a first set of experiments, the simulation model is used to evaluate the performance of the current terminal configuration under different workload scenarios. In the simulation experiments the handling demand per year was varied between 100,000 and 1,000,000 TEU (twenty-foot-equivalent unit). These workloads are generated by shortening the vessel arrival time interval. This way the critical workload can be determined at which the capacity of the terminal is reached.

From our experiments, the results shown in Fig. 5 were obtained. Once different workloads are generated by shortening the arrival interval of vessels, the critical workload of the terminal is reached at about 400,000 TEU. The corresponding Fig. 5a shows that beyond this point no further increase of the total container handling can be achieved. It can be seen in Fig. 5b that the utilization rates of resources are thus limiting the total container handling of the terminal. For quay cranes a maximum utilization rate of about 60% is achieved. It should be noted that, due to berthing and un-berthing times of the vessels at the quay side and the necessary repositioning of quay cranes, these resources usually cannot reach a higher utilization rate. Similarly the utilization of yard cranes is affected by the

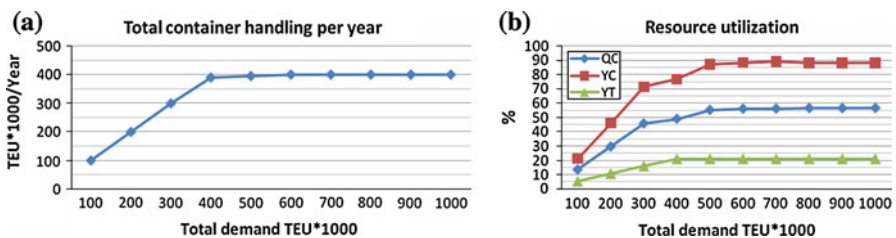


Fig. 5 a Average total container handling; b average resource utilization (QC quay cranes; YC yard cranes; YT yard trucks)

berthing conditions though at a much lesser extent. For yard cranes, Fig. 5b shows maximum utilization rates of about 90% which complies with experience from real terminal operations. In contrast, even though yard trucks are dealing with transportation orders most of the time, the productive utilization rate for them is at most around 20%. This is due to the long non-productive waiting time of trucks at the yard until they get served by a yard crane. Obviously, the highly utilized yard cranes constitute a major bottleneck and impair the efficient use of the trucks. Hence, the question arises whether the current number and types of equipment employed should be reconsidered.

5.2 Investment strategies

As the initial performance analysis of the terminal has identified yard cranes as the major bottleneck in the system, two investment strategies were developed which focus on the replacement of conventional yard trucks with straddle carriers in order to enable independent operation of yard handling and transportation activities (Sect. 5.2.1) and on a considerably increased yard crane capacity (Sect. 5.2.2).

5.2.1 *Impact of vehicle types*

In container terminals different types of vehicles can be employed for transporting containers between berths and the yard and from the yard to the landside interface. Basically, transportation vehicles can be classified into two different types. Vehicles of the first type are passive vehicles in a sense that they are not able to lift containers by themselves. Loading and unloading operations of these vehicles are realized by using either quay or yard cranes. Conventional trucks and multi-trailers as well as AGVs belong to this class. In order to ensure high utilization of cranes, trucks are usually dispatched ahead of the effective transportation date so that waiting times occur. To prevent these waiting times, many container terminals employ vehicles of a second type which are capable of lifting containers by themselves. Straddle carriers, forklifts, reach stackers and ALVs belong to this class (cf. Steenken et al. 2004). The major advantage of these types of vehicles is that other resources, like quay or yard cranes, are not blocked when the assigned vehicle has not arrived on time. As a result, the productivity of the entire terminal can be improved.

In the investigated terminal, the current ground conditions are not adequate for the use of automated vehicles like AGVs or ALVs. Moreover, introducing automated transportation technology requires major investments into the guide path and the traffic control system and thus appears to be impractical for most existing terminal configurations. Also forklifts and reach stackers are not effective for long-distance transportation inside the terminal due to their limited lifting capability. On the other hand, straddle carriers (SCs) are adequate transportation vehicles to be used as shuttles between the blocks in the yard and the berths. Therefore, we consider them in our simulation experiments as an alternative to the existing truck transportation system mainly to analyze the effect of a self-loading type of vehicle on the productivity of the terminal. In our experiments, we still consider yard cranes operating at the storage blocks while straddle carriers merely serve as shuttles

operating between the yard and the berths. We assume that yard cranes exchange the containers with the straddle carriers via a small-sized buffer area so that the crane and the vehicle operations are decoupled. Similarly, buffers are introduced at the quay cranes so that the cranes do not need to wait for a vehicle to discharge or to charge the containers. In accordance with terminal operators, for our experiments we assumed a buffer size of five containers per block and ten containers per quay crane.

In a series of experiments we compared two alternative transportation systems, namely conventional yard trucks and straddle carriers. As an experimental parameter, the fleet size was varied between 21 and 33 vehicles and the demand was set to 800,000 TEU per year. Comparative performance results are shown in Fig. 6.

The first observation is that, depending on the truck fleet size, the total container handling of the terminal could be improved by around 30–50,000 TEU per year if self-loading vehicles, e.g. straddle carriers, are introduced as shown in Fig. 6a. However, this comparison is based on the assumptions that straddle carriers and conventional yard trucks otherwise offer the same technical performance, e.g. travel speed in laden and un-laden condition. Hence, the simulation results demonstrate the effect of using a self-loading type of vehicle.

The second observation is that reducing the fleet size of the vehicles impairs the performance of the entire terminal. Obviously, quay cranes and yard cranes represent the bottleneck resources and get less utilized when the availability of transportation vehicles is decreased and thus longer waiting times occur as in Fig. 6b and c. However, this effect is considerably smaller for the straddle carrier option due to the self-loading capability of these vehicles.

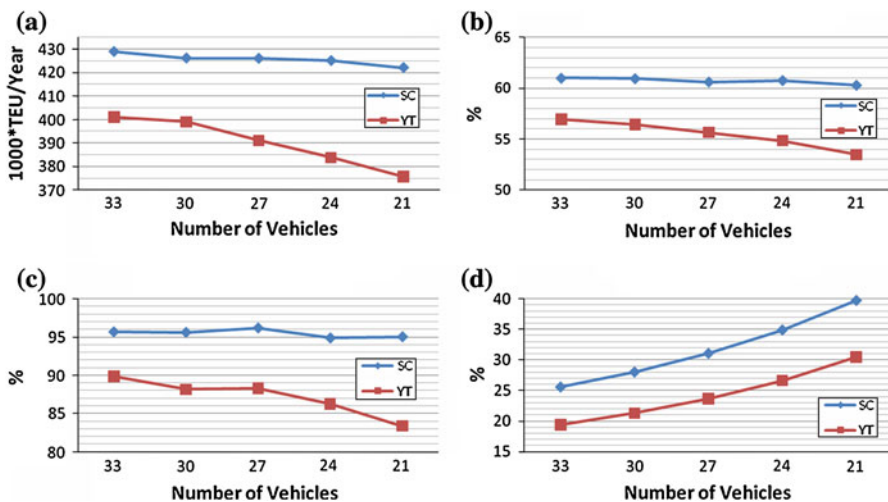


Fig. 6 Comparison of different types of vehicles (SC straddle carriers; YT yard trucks); **a** total container handling per year; **b** quay crane utilization; **c** yard crane utilization; **d** vehicle utilization

As for the fleet size, Fig. 6a shows that a fleet of 21 straddle carriers significantly outperforms a fleet of 33 yard trucks in terms of container handling. Moreover, it can be seen from Fig. 6d that the vehicle utilization of yard trucks is always smaller as for straddle carriers. This is due to higher waiting times of yard trucks in buffer zones, whereas straddle carriers allow the otherwise wasted waiting time to be utilized as additional travel time.

5.2.2 Impact of the number of yard cranes

It is of utmost importance that activities of yard cranes are properly coordinated so that they serve quay cranes effectively. There are some reasons why yard cranes often constitute bottleneck resources in the terminal. Firstly, cycle times of yard cranes are much higher compared to quay cranes. Secondly, yard cranes, unlike quay cranes, operate in multi-task mode, i.e. they store import containers unloaded from one vessel at the berth and retrieve export containers from the storage block designated for transfer to another vessel at the berth. Thirdly, as one yard crane in the investigated terminal is assigned to two blocks in the same zone, yard cranes have to cover large distances for moving between the blocks while quay cranes are virtually immobile.

For the simulation of the current terminal configuration, the number of yard cranes was nine and the “free yard crane deployment” policy was assumed. Since the total yard crane capacity is supposed to be the bottleneck within the entire terminal configuration, the number of yard cranes is doubled in the next series of experiments. In this enhanced configuration a yard crane is not serving two blocks in the same area as before, but is assigned to one single block. This way, the transfer of yard cranes between blocks in the same area can be avoided.

Simulation results for a demand of 800,000 TEU per year are presented in Fig. 7. Comparing the results for the enhanced and the current terminal configuration, it can be seen that total container handling is increased by approximately 50%, reaching more than 600,000 TEU in total per year. These comparative simulation results are further analyzed by use of ANOVA tests (see Sect. 5.4).

The simulation results indicate that utilization rates of yard cranes and yard trucks significantly decreased and increased, respectively. Obviously, this is due to the fact that waiting times can be eliminated to a large extent. Furthermore, as the utilization rate of quay cranes is around 90%, quay cranes turn out to be the system bottleneck instead of yard cranes and it appears to be difficult to handle more than 650,000 TEU per year unless their number is increased or the individual cycle time of quay cranes is reduced. Indeed, after doubling the yard crane capacity the bottleneck shifted from the yard stacking area to the quay side. Thus extending the yard crane capacity could be recommended to the terminal operator as a very effective means for improving the overall performance of the terminal. Redesigning the terminal configuration this way is particularly indicated as in the investigated terminal the space for extension is limited by geography and, therefore, increasing the berthing and quay crane capacity is not considered.

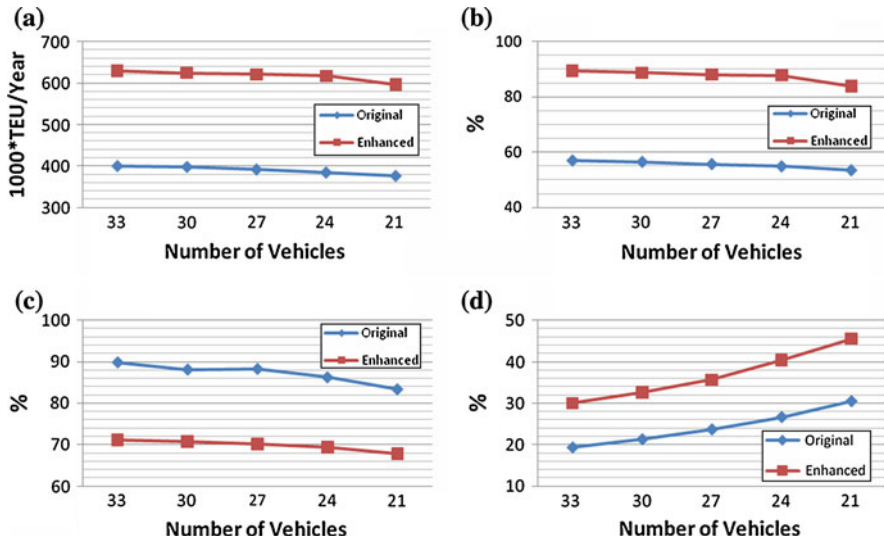


Fig. 7 Effect of doubling the number of yard cranes; **a** total container handling per year; **b** quay crane utilization; **c** yard crane utilization; **d** vehicle utilization

5.3 Resource allocation strategies

In the previous experiments considerable investments in terminal equipment were assumed, whereas the next series of experiments investigates the possible effects of improved resource allocation strategies. As an alternative to the current allocation strategy, we consider specific strategies, like the dedicated assignment of resources to berths. Because of the unique layout of the terminal with three separate berths (see Fig. 3) and only one and two quay cranes, respectively, per berth no specific allocation strategies for berths and quay cranes are considered. The terminal configurations for the following simulation experiments are based on the setting of the previous section, i.e. there is one yard crane per block, the demand is 800,000 TEU per year and containers are transported by yard trucks within the terminal. The fleet size of yard trucks is varied as 21, 24, 27, 30 and 33.

5.3.1 Yard allocation

In order to increase the utilization of resources and to reduce transportation times, certain parts of the container yard can be allocated to specific berths. Actually, it is common practice in many container terminals to store export containers close to the berth where the designated vessel is scheduled to moor. To evaluate the effect of this policy we introduced a strict allocation of storage blocks (see Fig. 3). In the corresponding experiments the three leftmost vertical blocks are assigned to berth 1, the three middle blocks to berth 2 and the final three blocks to berth 3. Blocks 3(A + B), 6(A + B) and 7(A + B) are used for export containers, whereas the other blocks are designated for import containers. As approximately 70% of the

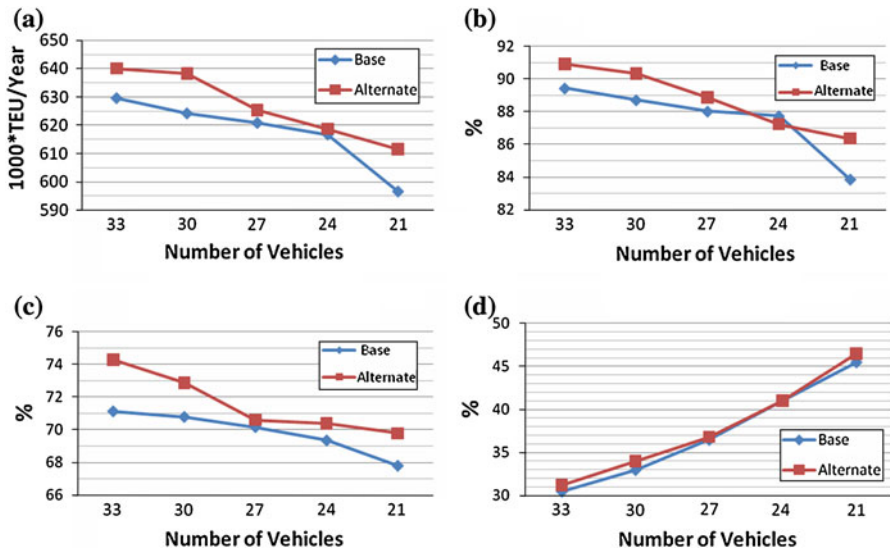


Fig. 8 Impact of an alternative yard allocation strategy; **a** total container handling per year; **b** quay crane utilization; **c** yard crane utilization; **d** vehicle utilization

handled containers are import containers, twice as large areas are allocated for import than for export containers. Because the focus of the experiments is on yard allocation, we assume conventional yard trucks for horizontal transportation as in the current terminal configuration.

The results of the simulation model with the yard allocation strategy defined above (Alternative) are shown in Fig. 8 and compared to the results of the model with an increased number of yard cranes (Base). It can be seen that a significant improvement in total container handling is achieved by applying the yard allocation strategy. The reason is that the overall travel time of trucks highly decreased whereas the waiting time of trucks at the yard cranes just slightly increased. This means that it is possible to achieve a higher utilization rate for trucks and to increase the container handling per year with the proposed yard allocation strategy. The results indicate that quay cranes are still the bottleneck resource in the new system. The simulation results are further analyzed by ANOVA tests in Sect. 5.4.

5.3.2 Truck allocation

Currently, terminal management does not apply any specific rule for the assignment of the available 30 yard trucks within the terminal, i.e. there is a total flexibility in the assignment of trucks to quay cranes. However, in the terminal considered here the three berths are located at different sides of the container yard. Hence, travel distances of trucks interchanging between the berths can get quite long and unbalanced. Therefore, in the final series of experiments, we compare the basic single-pool strategy to a dedicated deployment strategy which assigns one third of

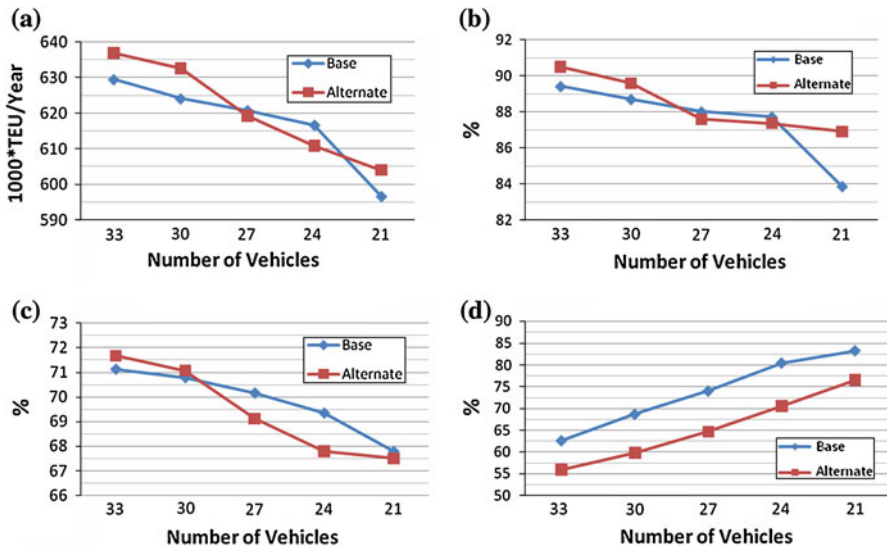


Fig. 9 Impact of an alternative truck allocation strategy; **a** total container handling per year; **b** quay crane utilization; **c** yard crane utilization; **d** yard truck utilization

the truck fleet to each of the berths thus creating dedicated truck pools. At each berth, trucks may serve any of the available quay cranes. For the experiments, the fleet size of trucks was varied as 21, 24, 27, 30 and 33.

In the application of the dedicated truck allocation strategy, a priority rule is used to re-allocate trucks when the berth they are assigned to is idle. With the aid of this rule, vehicles are assigned in advance with high priority to their original berths and with low priority to other berths. Owing to this priority setting, if a vessel is moored at the berth to which the truck is assigned to, the truck will primarily serve this berth. If there is no vessel at the berth where the truck is assigned to, the truck will be directed to one of the other berths.

The results of the simulation experiments for using yard truck allocation (Alternate) are shown in Fig. 9 and compared to the simulation results with the increased number of yard cranes (Base). The simulation experiments were carried out for a demand of 800,000 TEU per year. Generally, total container handling can be increased with the proposed yard truck allocation for the established fleet size of 30 vehicles and the increased fleet size of 33 while with 27 vehicles both strategies perform equally well. However, in the simulation experiments with 24 vehicles total handling decreases below the base case due to the limited flexibility of the alternative allocation strategy. The case of 21 vehicles represents an extreme scenario causing unnecessary waiting times of quay cranes under the basic allocation strategy as can be seen from Fig. 9b. Possible reason for this unbalanced effect could be the increased difficulty of controlling man-driven yard trucks and yard cranes in the case of a considerably reduced fleet size and the resulting high variance between the replications.

5.4 Statistical analysis of results using ANOVA tests

In this study, we started off with a simulation scenario in which the current system configuration is modeled. In the further simulation experiments, we explored possibilities to improve the performance of the container terminal by considering an increased number of yard cranes, the replacement of yard trucks through straddle carriers, and by applying an alternative resource allocation strategy for yard blocks and yard trucks. As an additional parameter, the number of vehicles, either yard trucks or straddle carriers, was varied between certain limits. In the simulation experiments total container handling is seen as the key performance parameter. Additional performance indicators are the average utilization of the terminal equipment.

The main outcome of the simulation study is that yard cranes represent the bottleneck resources in the current terminal configuration, in particular, as yard cranes have to traverse between two adjacent storage blocks. In a series of experiments we found out that doubling the number of yard cranes promises some 50% improvement of the entire terminal performance in terms of total container handling per year. Therefore, in the second stage of the simulation study we assumed an accordingly increased number of yard cranes. In addition, the impact of the different yard and truck allocation strategies on the performance criteria is discussed. Results indicate that both yard and yard truck allocation strategies only slightly improve the terminal performance.

As it turned out in the first stage of the experiments that doubling the number of yard cranes was highly effective, we defined three scenarios based on the doubled yard crane capacity, e.g. assuming one yard crane per storage block. As for the horizontal transportation system, we adopted the current configuration consisting of 30 yard trucks. Accordingly, the following three scenarios are analyzed:

- Base scenario: current system configuration with 30 yard trucks and doubled number of yard cranes
- Model with yard allocation: base scenario with dedicated storage yards (see Sect. 5.3.1)
- Model with yard truck allocation: base scenario with dedicated yard trucks (see Sect. 5.3.2)

Statistical results for all scenarios mentioned above are presented in Table 2. ANOVA tests are performed in order to underline the statistical significance of the comparative results. ANOVA is a standard statistical procedure used in experimental studies to partition the variability of the experimental results into orthogonal components from identifiable sources (cf. Montgomery 1997). The ANOVA test results indicate that the null hypothesis (equal mean performance of the simulated scenarios) must be rejected. In other words, the observed total container handling per year significantly differs between the scenarios with significance probability of less than 0.05. When the performance results of the alternative configurations are compared with the results for the current configuration, it can be seen that results represent significant differences in the improvement of terminal operations. However, the Levene test points out that all scenario results have homogeneous variance. Therefore, Tukey HSD tests are carried out as to determine groups which

Table 2 ANOVA test results (total container handling per year)

Scenario results					
Replication	Base scenario	Model with yard allocation		Model with truck allocation	
1	624,630	637,800		627,870	
2	605,230	642,940		633,090	
3	618,890	640,960		639,814	
4	617,920	632,440		643,940	
5	631,890	632,910		611,150	
Average	619,712	637,410		631,172	
SD	9,824	4,698		12,778	
ANOVA					
	SS	DF	MS	<i>F</i>	Sig.
Between groups	8.1 E+008	2	4.0 E+008	4.288	0.039
Within groups	1.1 E+009	12	9.3 E+006		
Total	1.9 E+009	14			
Test of homogeneity of variances					
Levene statistic		DF1		DF2	Sig.
1.195		2		12	0.336
Homogenous subsets					
Scenarios	N	Subsets for alpha = 0.05			
		1		2	
Base scenario	5	619,712			
Model with truck allocation	5	631,172		631,172	
Model with yard allocation	5			637,410	

SS sum of squares, *DF* degrees of freedom, *MS* mean square, *F* F-ratio, *N* total number of replications, *Sig.* significance probability of *F*

have different average results. This way, two different groups were determined. The results of the model with yard allocation are superior to the results of the base scenario. Only the average results of the model with truck allocation are positioned in both groups. In other words, the model with truck allocation provides insignificant improvement in comparison to the model with yard allocation.

6 Conclusion

This paper presents a simulation study of a long-established seaport container terminal which allows evaluating the performance of scenarios with various configurations using pre-defined performance criteria. In this study, a present and an alternative scenario analysis for a container terminal in Istanbul has been carried out

using a simulation approach. Within the scope of the present situation, the analysis of various workload scenarios has been accomplished in order to identify bottlenecks in the terminal system.

In a first series of simulations, we considered strategies which require substantial financial investments. It was shown that by replacing yard trucks with self-loading vehicles, namely straddle carriers the container handling per year could be increased by almost 30,000 TEU for the current terminal configuration. Furthermore, it was shown that increased container handling was possible even with a lower number of straddle carriers. This confirms the results from Yang et al. (2004) and Vis and Harika (2004) who made similar observations for a comparison of AGVs and ALVs. In addition, experiments have been carried out with a doubled number of yard cranes, which are seen as major bottleneck in our simulation of the current terminal configuration. It was shown that the container handling can be increased by at least 50% for different fleet sizes of yard trucks. Moreover, quay cranes become the new bottleneck in the terminal system.

In a second series of simulations, the configuration with a doubled number of yard cranes was enhanced by two resource allocation strategies, namely yard and yard truck allocation. It was shown that yard allocation can further increase the container handling. This is a result which backs up the findings from analytical investigations performed by Preston and Kozan (2001), Lee et al. (2006) and Han et al. (2008). Principally, the performance of the yard allocation strategy could be affected by the ratio of import/export containers. The impact of this relationship, however, was not analyzed since for the considered terminal no major changes in the import/export ratio are expected in the near future.

Ambivalent results were gained for using the yard truck allocation strategy. Promising results for a pooled allocation strategy as proposed in Bae and Kim (2000) and Murty et al. (2005a) cannot be reproduced for the investigated terminal. Possible reason for this effect could be the unique terminal layout and its specific equipment as well as the possible inefficiency of dispatching strategies for man-driven yard trucks and yard cranes.

The use of simulation has shown to be extremely appropriate and highly reliable results were achieved. Special care was taken to develop the simulation model such that it reflects the real terminal operations with sufficient accuracy and to make sure that the used input data comply with the real terminal operation. As a result, more effective terminal configurations have been identified with the aid of the simulation model. Therefore, it is believed that the informational value of the simulation results is considerable for the future development of the terminal and also for other established terminals in different parts of the world.

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