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A SIMULATION MODEL FOR DESIGNING STRADDLE CARRIER-BASED CONTAINER TERMINALS

Pasquale Legato
Rina Mary Mazza

Department of Informatics, Modeling, Electronics and System Engineering (DIMES)
University of Calabria
Via P. Bucci 42C
Rende (CS), 87036, ITALY

ABSTRACT

Designing the storage yard in a container terminal is a major step towards efficient terminal operations. The problem may cover both long-term decisions, such as selecting the yard layout and the material handling equipment, and short-term decisions, such as assigning storage space and dispatching and routing the material handling equipment. We present a discrete-event simulation model to investigate the best yard layout in terms of block position, number and capacity in a straddle carrier-based transshipment hub bearing a perpendicular yard layout. The simulation model is highly detailed and it captures the blocking, locking and further waiting conditions occurring during real-time operations. Numerical experiments carried out for a real container terminal show how the model may easily support the operations manager in choosing the block design that minimizes the waiting times of straddle carriers and the makespan of the integrated container discharge/loading process.

1 INTRODUCTION

According to MarCom Working Group 135 (2014), 90% of all world trade is carried by water and a significant and growing part of this world trade is now carried by containers. In this scenario, container terminals are *de facto* the interface between worldwide container shipping networks and the markets they serve. The success of individual terminals depends upon their capacity to meet customer demand with high standard quality service, while keeping operations lean.

One of the main steps to efficient terminal operations lies in the design of the tightly interrelated container subsystems among which the storage yard. The role of a yard is to provide storage space for inbound containers (imported by vessel), outbound containers (exported by vessel) and transshipped containers (transferred from one vessel to another). A yard is usually divided into large areas or zones and, in turn, these areas, are divided into smaller units called blocks, as illustrated in Figure 1. A block features a given number of *i*) rows or lanes (one of which may be used by trucks), *ii*) stacks defined by different heights or tiers, and *iii*) bays that represent the length of a row.

With respect to the overall yard layout design problem, there are many decisions that can be made. The most important refer to:

- internal transfer equipment (self-lifting or non-lifting vehicles);
- stacking/retrieval equipment (cranes and vehicles);
- parallel or perpendicular (to the quay and/or truck area) layout;
- land availability and usage;
- block position, number and capacity in terms of number of rows, tiers and bays.

Some of the above decisions are independent, while others are closely related to one another. In general, decisions must account for the different types of resources that are already available on the premises of a facility. For instance, the land usage in a terminal is closely related to both the land availability and block capacity. In fact, in the attempt to improve land usage, one may either increase block capacity by stacking containers higher or use a larger area. In turn, increasing block capacity by means of the stacking height is limited by the technical restrictions of the available stacking equipment.

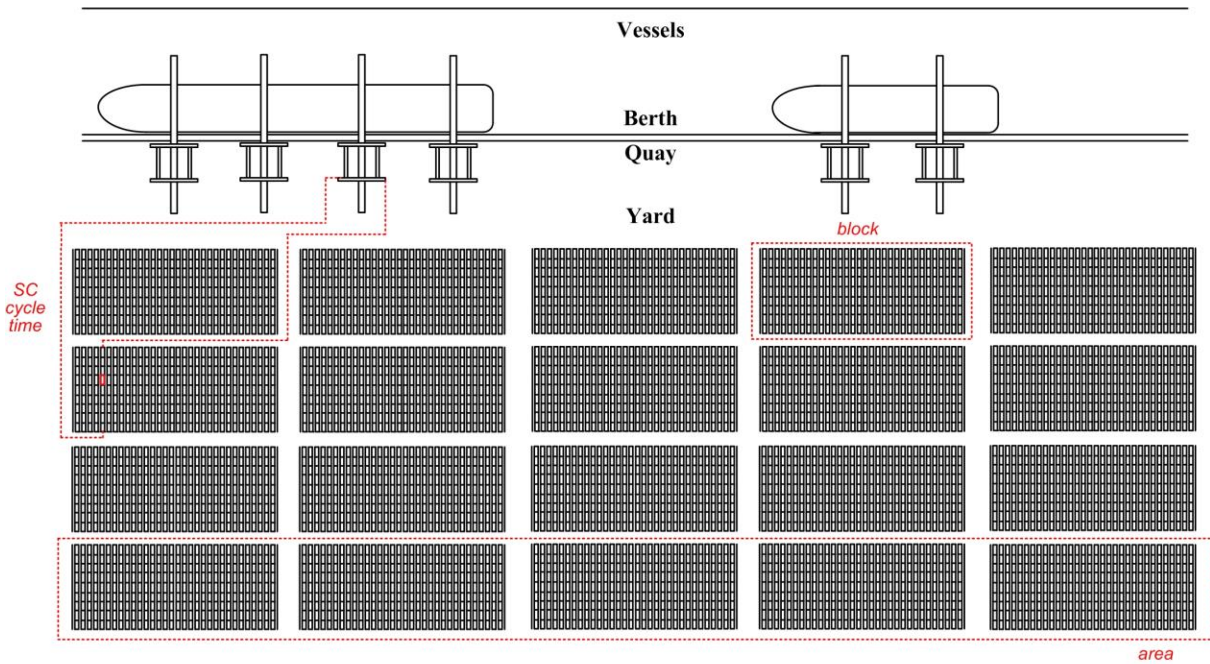

Figure 1: Example of the yard layout in a container terminal.

In our study, we consider yard layout design issues for a container terminal devoted to pure transshipment in which container transportation between the quay and yard, as well as stacking/retrieval operations on the yard are performed by human-operated straddle carriers (SCs). This is the case occurring in the Eurogate container terminals in Europe and, in particular, in the mega-hub we refer to which is located in Gioia Tauro, Calabria, Italy. Since different types of SCs are already available in this terminal and the layout of the yard area is already perpendicular to the quay, we propose a simulation model to investigate the best layout in terms of block position, number and capacity. The object of the study is to minimize the waiting times caused by standard waiting conditions, as well as blocking and locking conditions connected to layout configuration and service organization within the overall container discharge/loading (D/L) process in a dynamic and stochastic environment.

The rest of the paper is organized as follows. An overview of the literature on the yard layout design problem is given in Section 2. The simulation model for designing the yard layout in an SC-based container terminal is described in Section 3. Numerical experiments for scenario analysis via a what-if approach are reported in Section 4. Finally, conclusions are drawn in Section 5.

2 LITERATURE REVIEW

Considerable research has been devoted to studying the yard in container terminals. Some studies focus on long-term decision problems such as yard design, the selection of material handling equipment and the storage yard layout. Others focus on short-term decision problems such as assigning storage space to containers, dispatching and routing the material handling equipment and optimizing the reshuffling of containers (Carlo, Vis, and Roodbergen 2014b). In this study we focus on the design of the storage yard of a container terminal. Thus, we summarize below the related literature with respect to either mathematical programming and simulation techniques or a combination of the two for problem solving.

Starting with mathematical programming approaches, Kim, Park, and Jin (2008) propose ways to decide which layout type and what sized blocks should be used for a given size of a rectangular shaped yard. They consider parallel and perpendicular layout types for container yards equipped with transfer cranes. Procedures are suggested for optimizing the yard layout with respect to the travel cost of trucks and the relocation cost of transfer cranes. Wiese (2009) focuses on a facility featuring a parallel yard layout and rubber tired gantry cranes for container stacking/retrieval on the yard. The author derives formulas to estimate the different impacts of block widths on the yard performances and costs which can be used to identify adequate block widths. Lee and Kim (2010) focus on the design of a single block. Their goal consists in determining the number of bays in a block, the number of rows in a bay, and the number of tiers for a given (parallel or perpendicular) block layout within a yard bearing cranes and internal trucks. The authors define two problems: the first maximizes the throughput capacity, subject to the minimum block storage capacity of a block; the second, maximizes the storage capacity, subject to the maximum truck waiting time at the block. In Wiese, Suhl, and Kliewer (2010), the decision problem is to find the optimal positions to install driving lanes in the yard. The authors consider rubber tired gantry cranes for stacking operations and trucks for horizontal transports. For a given (parallel or perpendicular) orientation of the blocks, an integer linear program formulation is proposed. The problem is reformulated as a special type of a resource constrained shortest path problem and solved using linear program relaxation for rectangular-shaped yards, against a variable neighborhood descent heuristic for other types of shapes. Lee and Kim (2013) determine the optimal layout of an entire container yard, which is specified by the dimensions of a block and the number of aisles. They provide formulations and enumerative procedures for optimizing parallel and perpendicular types of yard layout. The aim is to minimize the construction cost of the storage space and the fixed overhead and operating costs of yard cranes and transporters under constraints on the storage space requirement and the expected service times for transporters and road trucks. In Wiese, Suhl, and Kliewer (2013), the yard design problem consists in determining the optimal number of driving lanes in the yard layout with the aim of minimizing the cycle times of SCs. An analytical yard layout planning model for an SC-based container terminal is proposed for a parallel and perpendicular layout and different driving and storage space compensation strategies.

Turning the attention to simulation approaches, Liu et al. (2004) develop and use simulation models to demonstrate the impact of automation and terminal layout on terminal performance. A multi-attribute decision making method is used to assess terminal performance and determine the optimal number of automated guided vehicles to be deployed for parallel and perpendicular types of yard layouts and three common operational scenarios (loading, unloading, and combined loading and unloading operations). Choi et al. (2006) propose a simulation study to evaluate centralized, alternating and distributed layouts of reefer containers in terminals equipped with automated guided vehicles and automated transfer cranes. The aim of the study is to determine which layout minimizes the makespan of loading and unloading operations in a realistic and stochastic environment. The simulation model proposed by Petering (2009) focuses on the design of multiple-berth seaport container terminals devoted to pure transshipment. Assuming a parallel layout of the yard and both human-operated yard trucks and rubber tired gantry cranes, the author investigates how the width of the storage blocks in a terminal’s container yard affects the overall, long-run performance of the container terminal as measured in terms of gross crane rate, i.e. the average number of lifts achieved at a terminal per quay crane working hour. Petering and Murty (2009) use a simulation model to reproduce the multi-objective, stochastic, real-time environment at a multiple-berth facility in which the yard trucks and yard cranes are the equipment involved in container transfer and handling on the yard. Their study investigates how the system that deploys yard cranes among blocks in the same zone and the length of the storage blocks in a terminal's container yard affect the overall, long-run performance of a container terminal in terms of gross crane rate. Kemme (2012) uses simulation to study the strategic layout planning of storage yards at seaport container terminals that are operated by gantry cranes. The goal of the study is to evaluate which combination of yard block layout and yard crane system is best for the performance of the storage yard and the whole terminal.

Concluding this review with a combination of the two approaches, to design the yard in a mega-container terminal Zhou et al. (2016) propose a framework that embeds two-stage stochastic programming and system simulation. The former evaluates the capital costs and benefits of various yard layouts, while the latter estimates internal truck traffic and equipment moving at the terminal. Their study is based on a parallel layout of the yard equipped with manually operated cranes and transfer lanes.

Our simulation model has some come grounds with the analytical model proposed by Wiese, Suhl, and Kliewer (2013). Both focus on planning issues pertaining to an SC-based yard bearing a perpendicular layout. However, Wiese, Suhl, and Kliewer (2013) do not consider some major effects that occur during real-time operations. For example, traffic jams in the yard and SCs blocked in front of yard rows due to stacking/retrieval operations already occurring in the identical or adjacent rows are not considered. Moreover, organizational aspects that influence decisions on layout are not considered or discussed in their paper. This stated, our model is noteworthy in that *i*) it allows to compare alternate block designs in a dynamic and stochastic environment under different types of container assignment policies; *ii*) it considers the interactions among the major entity types across all three subsystems of the container terminal; *iii*) all quay cranes (QCs) and SCs have stochastic handling and traveling times; *iv*) delays are propagated realistically within the overall container D/L process; *v*) the handling and transfer of every individual container is explicitly modeled, while accounting for system infrastructure, traffic, security issues and human behavior of the man-operated SCs.

3 DESIGNING SC-BASED YARD BLOCKS

As required in real-life planning, alternative layouts for an SC-based storage yard must be evaluated in conjunction with the entire operational scenario, including the available fleet of SCs, the terminal practices and the compliance with security rules and regulations. Simulation is commonly used to study existing operational policies. With discrete-event simulations one can determine the best yard layout, the number of vehicles required and their (average) utilization and waiting times for different realistic scenarios by embedding the routing, the dispatching and the security policies in the simulation model (Carlo, Vis, and Roodbergen 2014a), also under multiple metrics (Lee et al. 2010; Li et al. 2015).

In this section, we first describe the conceptual model behind the simulation study in which SCs are used as both transfer and yard vehicles. We then provide some technical details with respect to the implementation of the simulation model.

3.1 Conceptual Model

The object of the following model is to investigate the best yard layout in terms of block position, number and capacity in a transshipment hub with an SC-based perpendicular storage yard. Bearing this in mind, we need to account for the physical and organizational features that, within the integrated container D/L process, may affect waiting conditions connected to yard block configuration. For the sake of brevity, in the following we refer to the discharge process alone, as one may comprehend that loading occurs in the reverse order. The container discharge process depicted in Figure 2 has been conceived according to an SC-centric point of view: SCs are entities cycling through the terminal subsystems (see SC cycle in Figure 1) that carry-out operations and seize/release resources while doing so.

Once an SC has been assigned to a QC, it waits in front of the crane until a container requiring transfer to the yard has been discharged. The SC then picks up the container and delivers it to the assigned stacking position on the yard. Since SCs need clearance on both sides of containers in order to handle them, the loaded SC must wait until any other operation already taking place in the row of the target location or in the adjacent rows has been completed. After stacking the container, the unloaded SC returns to the QC. This cycle is repeated until there are no more containers left to be discharged.

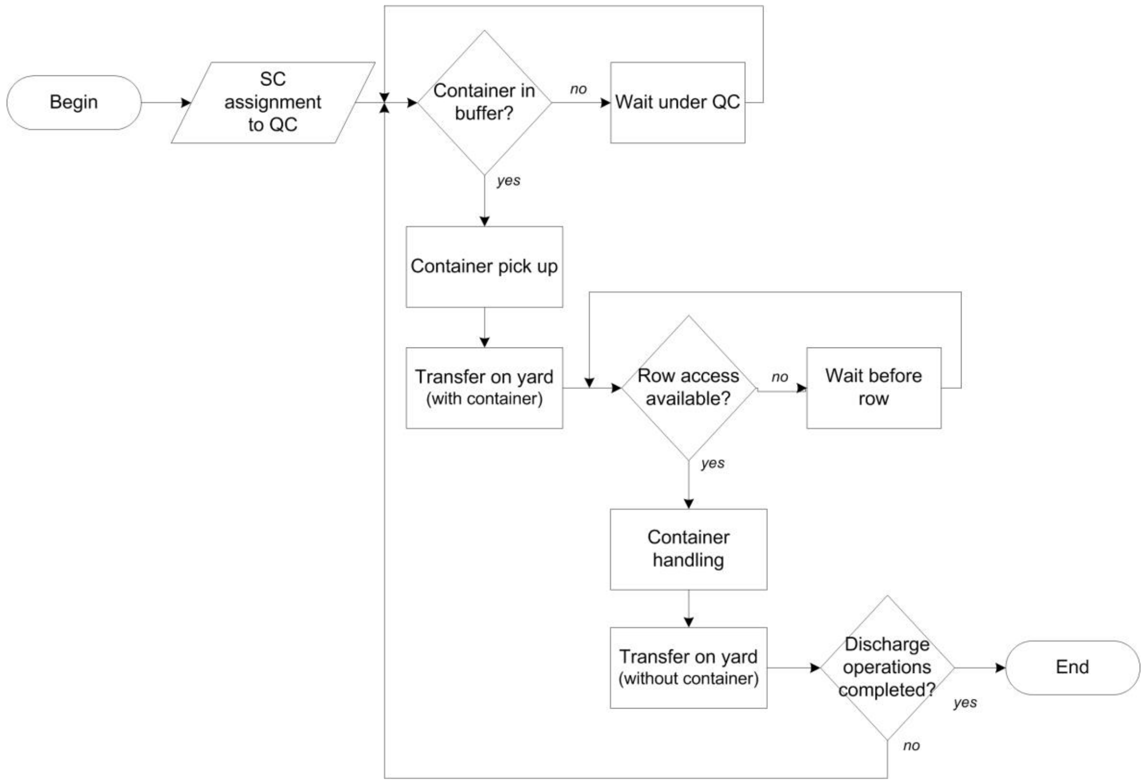

Figure 2: The logic of an SC-centric container discharge process.

The following assumptions are introduced for modeling the yard layout problem:

- We assume that the terminal is rectangular and has a single straight quay wall, while each block in the yard has the same number of bays and the same number of rows.
- All the human and mechanical resources required to perform container transfer due to D/L operations occurring between the yard and quay areas are not shared with other container transfer and handling activities such as housekeeping operations (Cordeau et al. 2015).
- QCs can set down a container discharged from a vessel in their own buffer area only if there is at least one buffer space free; otherwise, crane blocking occurs.
- SCs deliver containers according to a dedicated, rather than pooling modality between D/L points on the quay and storage locations on the yard. According to the former modality a set of SCs is allocated to a given QC and every time an SC moves a container it also has to perform an unfruitful (empty) travel of the same length, but in the opposite direction (Garro et al. 2015).
- An SC can move up to 20km/h when unloaded and 15km/h when loaded. The actual speed of each SC and, thus, the travel time of an SC is computed according to Greenshields' model (1935) $v=v_f-(v_f/k_j)*k$ where v is the mean speed at density k, v_f is the free speed and k_j is the jam density. The travel time of an SC does not include the time needed by an SC to enter or leave a container row. This time is considered in the container stacking/retrieval time.
- The storage yard is divided into four different areas: A, B, C and D. 20-foot (a.k.a. 1 TEU - twenty equivalent units) containers are stored in A, 40-foot (a.k.a. 2 TEUs) containers are stored in B, refrigerated containers (a.k.a. refers) are stored in C and empty containers are stored in D.
- Four different container stacking strategies on the yard are used and referred to as the so-called "width" or horizontal factor. This factor stands for the distance (in blocks) between the

discharge/loading point on the quay and the storage/retrieval point of the yard. We assume that containers can travel across the quay to the nearest block (option 0), to the blocks immediately to the right and left (option 1) of the nearest block, to the two blocks to the right and to the left (option 2) or to all the blocks (option 3).

- Given the width of the (horizontal and vertical) yard corridors and the clearance of the SCs, two SCs, one in each direction, can travel along the two-lane corridor where no overtaking occurs (i.e. no lane changing is implemented).
- SCs enter a row only if they have to perform a stacking (retrieval) operation and, in doing so, they always enter from the bottom of a row and exit from the top of a row on the yard.
- The human behavior of SC drivers follows an *en route* rationale, meaning that they are provided with travel-related information after they start their trip (Chowdhury and Sadek 2003). When traveling towards a target yard location bearing coordinates (*area*, *row*), drivers choose the vehicle route that minimizes the total travel time according to both distance and traffic.
- While traveling on the yard, if an intersection is not free, SC drivers queue before the intersection until it becomes available for vehicle crossing (i.e. no gap acceptance).

Other operational settings can be decided at run time, such as the number of QCs, the length of the berth in bollards (i.e. the 24-meter spaced posts along the berth around which vessel ropes are fastened) or the (average) workload to be carried out per QC.

3.2 Simulation Model

During the design and the development of the simulation model, we certainly had to refer to a specific world view (Banks et al. 2000). Alike many researchers, we agree that world views are hard to compare since they describe system behavior at different levels. Although it is difficult to assess whether or not there is an execution rate advantage to our choice, we decided to adopt the event-scheduling world view. This approach best matches the detailed way we need to look at specific events within the overall complex logistic process at hand in order to collect the data required to define event-based performance measures.

All the events of our simulation model are listed in Table 1, along with their effect on system state in terms of actions and resources seized and/or released. Each event marks the beginning or the end of a given model activity and must be counted only once.

Table 1: Discrete events of the simulation model.

Event	**Actions**	**Resources**	
		Seize	**Release**
containerdischarge	schedules *containerinbuffer* or queues request	QC	
containerinbuffer	schedules *containerhandling* or queues request	buffer space	QC
containerhandling	schedules *SCcrossquay* or queues request	SC	
SCcrossquay	schedules *SCroadtravel* or queues request or schedules *containerhandling* or queues request		buffer space SC
SCatintersection	schedules *SCroadtravel* or queues request	intersection	road
SCroadtravel	schedules *SCatintersection* or *SCarrivalatrow* or *SCcrossquay*	road	intersection
SCarrivalatrow	schedules *SCdeparturefromrow* or queues request	row	road
SCdeparturefromrow	schedules *SCroadtravel*	road	row

The performance measures estimated in this analysis are:

- container transfer time given as *SCarrivalatrow.time – Sccrossquay.time*;
- probability of SCs waiting at intersections which is accounted for in *SCatintersection*;
- SC waiting time at intersections which is accounted for in *SCatintersection*;
- probability of SCs waiting in front of yard rows which is accounted for in *SCarrivalatrow*;
- SC waiting time in front of (busy/locked) yard rows which is accounted for in *SCarrivalatrow*;
- probability of SCs waiting under quay cranes which is accounted for in *SCarrivalatrow*;
- SC waiting time under QCs given as *containerhandling.time - containerinbuffer.time*;
- probability of QC blocking which is accounted for in *containerinbuffer*;
- QC blocking time given as *containerdischarge.time - containerinbuffer.time*.

In consideration of the fact that writing space is limited, while the set of steps used to conduct a thorough and sound simulation study is rather large (Banks et al. 2000), here we just highlight a couple of issues pertaining to output analysis and, specifically, how our simulation model returns confidence intervals for the above performance measures.

When estimating probabilities through (binomial) sample proportions, we avoid using the classical Wald interval (Agresti and Coull 1998) whose chaotic behavior in coverage, even under large sample sizes, has been well assessed (Brown, Cai, and DasGupta 2001). Following the further recommendation by Zhou, Li, and Yang (2008) on adopting the score interval whenever no *a priori* information is available on the true value of the probability to be estimated, we resort to the last proposal on the score method, called generalized score method (Guan 2012). This also because, under a suitable setting of the "generalization parameter", the user may reproduce a popular adjustment to the Wald interval (Agresti and Coull 1998), whose aim is to reduce the fall in the actual coverage when the values of the true probabilities come close to 0 or 1 (e.g. 84% instead of 95% when $p \leq 0.002$ or $p \geq 0.998$).

As for estimating expected performance measures for both transient and steady-state simulations, the decision of adopting a batching technique within a single-replicate method for generating confidence interval estimations has been well supported by the guidelines and consolidated procedures discussed by Nakayama (2006).

Finally, we pursue bootstrapping (Bekki, Nelson, and Fowler 2010) in the construction of confidence interval estimates when estimating rare blocking, locking and waiting events.

4 NUMERICAL EXPERIMENTS

For illustrative purposes, let us consider a typical case that may call for a different block organization on the yard. As often happens in practice, shipping companies ask the terminal management to dedicate one or more specific blocks of the yard and the nearby quay to their vessel services (Cordeau et al. 2007).

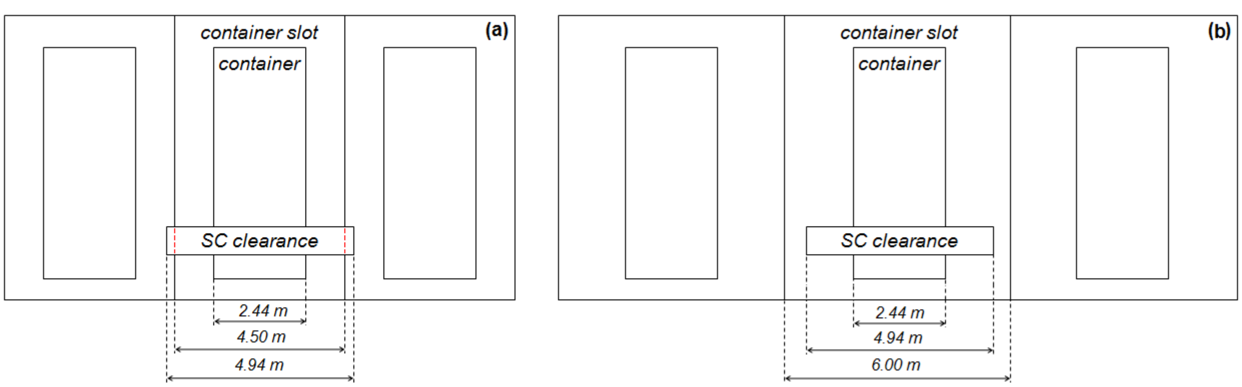

Figure 3: SC-based block layouts with ground slots wide 4.5m (a) and 6m (b).

In the terminal of reference, blocks are currently organized in 32 rows, 16 bays and 3 tiers and, thus, the overall capacity of each block is equal to 1536 TEUs. Within the block, containers, which are approximately 2.44 meters wide, are stacked one on top of the other, starting from a ground slot that is 4.50 meters wide. Since the clearance of an SC is 4.94 meters, as shown in Figure 3a, it is obvious why the SC cannot access the yard row if other container stacking/retrieval operations are already occurring either in that row (the target row is referred to as "busy") or in the adjacent ones (the target row is referred to as "locked").

An alternative block design featuring wider ground slots, on one hand, could eliminate the above "locking" condition; on the other, it could inflate the "busy" condition because of a smaller number of rows and, most likely, carry a greater service time within the row if the number of tiers grows as well. Some possible alternative block designs are listed in Table 2. All the alternatives listed herein allow retaining the current perpendicular layout, the transfer paths and the yard equipment. Moreover, the locking condition is removed if blocks are organized in a number of rows ranging from 24 to 28. Figure 3b illustrates why this occurs, for instance, for a block design featuring 24 rows, 16 bays and 4 tiers (1536 TEUs of block capacity) and ground slots that are 6 meters wide.

Table 2: Alternative yard block scenarios.

N° of rows	**Width of ground slot (m)**	**N° of bays & tiers**	**Block capacity (TEUs)**
24	6	16, 4	1536
25	5.75	16, 4	1600
26	5.54	16, 4	1664
27	5.33	16, 4	1728
28	5.14	16, 4	1792
29	4.96	16, 3	1392
30	4.80	16, 3	1440
31	4.64	16, 3	1488
32	4.50	16, 3	1536

Let us consider the most promising alternative design, i.e. 28 rows, 16 bays and 4 tiers. This option removes the locking condition and has the best overall block capacity. We compare the terminal's current block design to this option and refer to them as scenario A and scenario B, respectively. The main features are summarized in Table 3, including the two types of SCs that are available and suitable for performing container stacking/retrieval operations when the blocks bear a different number of tiers.

Table 3: Alternative yard block scenarios.

Feature	**Scenario A**	**Scenario B**
n° of rows	32	28
n° of tiers	3	4
n° of bays	16	16
block capacity	1536	1792
width of ground slot (m)	4.5	5.14
SC equipment	1-over-3	1-over-4
security issues	row locking	-

Let us also suppose that the designs are to be compared with respect to thousands of containers to be discharged by 8 QCs according to a 16-order Erlang distribution for service duration per container (mean=2 minutes). 4 SCs are assigned to each QC for transferring the containers to a specific block (i.e.

option 0 of the "width" factor), for instance, block n°3 in area C, as requested by a major shipping company. The best design should contribute to minimizing SC waiting time and, thus, the makespan of the integrated D/L process (i.e. the completion time of the QC that is the last to finish).

As expected, different designs affect the performance measures of interest in different ways. The interval estimates reported in Table 4 show that the container transfer times benefit of the smaller number of rows per block featured by scenario B, whereas the operation time of an SC in a row is likely to grow. To understand why, although this illustrative example considers stacking operations alone, we also report the SC operation time in a row when performing retrieval operations as well. Unlike the stacking case, container retrieval requires performing unproductive movements, also known as container reshuffling, when the target containers are not located on top of the stack. So, the greater stacking height in scenario B is likely to carry greater operation times in the row due to container reshuffling.

Table 4: Comparison of SC quay-yard times (sec).

Performance	Scenario A	Scenario B
container transfer time	[123.9-125.6]	[119.1-120.3]
container return transfer time	[129.6-130.9]	[121.3-122.3]
SC waiting time in front of a row	[88.43-99.56]	[126.1-145.8]
SC operation time in row	[82.72-85.16]	[89.91-92.89]

Another surprising result for scenario B is related to row locking: although this condition is not present, the waiting phenomenon in front of a row still grows larger because of a greater busy condition (see Table 5).

Table 5: Detection of the queuing phenomena in front of a row.

Performance	Scenario A	Scenario B
P(SC waits in front of a row)	[48.3%-51.1%]	[57.5%-60.3%]
P(busy row|SC waits)	[33.8%-37.1%]	[57.5%-60.3%]
P(locked row|SC waits)	[62.9%-66.2%]	-

As a matter of fact, the probability of finding SCs already engaged in container stacking (retrieval) within a row grows as the number of rows becomes smaller (see Table 6).

Table 6: Expected number of SCs queuing in front of yard rows.

Performance	Scenario A	Scenario B
P(finding n=0 SCs already waiting)	[68.1%-81.9%]	[62.2%-75.2%]
P(finding n=1 SC already waiting)	[14.0%-26.7%]	[19.5%-31.7%]
P(finding n=2 SCs already waiting)	[2.30%-9.50%]	[3.20%-10.0%]
P(finding n=3 SCs already waiting)	-	-

On average, the longer queues in front of the yard rows in scenario B relieve congestion along the pathways, as well as at the road intersections (numbered 1 to 25) crossed by the SCs during container transfer. However, the traffic at the intersections surrounding block 3 in area C (i.e. intersections 13, 14, 18 and 19) is, more or less, the same in the two scenarios (see Table 7).

It is also worth observing that some intersections are crossed more frequently than others (e.g. intersection 18) due to the closer distance from some of the D/L points. Moreover, even if all them are not listed in Table 7, additional intersections (i.e. intersections 6, 7 and 8) are crossed when adopting the block design of scenario B.

Table 7: Comparison of SC waiting probabilities (WP) and waiting times (WT) at road intersections.

Intersection n°	**Scenario A**		**Scenario B**	
	WP	**WT (secs)**	**WP**	**WT (sec)**
11	[16.9%-19.4%]	[2.52-2.79]	[14.7%-17.1%]	[2.41-2.67]
12	[12.5%-14.7%]	[2.09-2.36]	[10.8%-12.9%]	[2.02-2.30]
13	[12.9%-15.1%]	[2.21-2.47]	[14.9%-17.1%]	[2.27-2.53]
14	[8.20%-10.9%]	[2.17-2.58]	[10.8%-13.5%]	[2.31-2.66]
16	[20.0%-22.5%]	[2.82-3.10]	[20.2%-22.6%]	[2.69-2.92]
17	[17.4%-19.7%]	[2.43-2.66]	[16.1%-18.3%]	[2.07-2.28]
18	[21.2%-23.4%]	[7.47-8.93]	[19.1%-21.4%]	[5.47-6.81]
19	[14.7%-17.3%]	[2.23-2.52]	[10.6%-13.1%]	[2.07-2.36]

It is also important to see how the different block designs affect the SC cycling time on the quay side. As shown in Table 8, in scenario B SCs are likely to queue less in front of the crane they are assigned to. While this may appear as an advantage, its disadvantage lies in the fact it takes more time to empty the buffer at the feet of the QC. Thus, in scenario B the QC will likely be blocked more frequently than in scenario A (see Table 9). Summed together with the other queuing phenomena on the yard, this explains the greater makespan value (in hours) of scenario B [21.85-22.04] vs [20.07-20.20] of scenario A.

Table 8: Comparison of SCs queuing in front of QCs.

Performance	**Scenario A**	**Scenario B**
P(finding n=0 SCs already waiting)	[77.3%-83.3%]	[78.4%-84.3%]
P(finding n=1 SC already waiting)	[15.7%-21.6%]	[14.6%-20.3%]
P(finding n=2 SCs already waiting)	[0.30%-1.70%]	[0.50%-2.10%]
P(finding n=3 SCs already waiting)	-	-

Table 9: Comparison of QC blocking probabilities (BP) and blocking times (BT).

(Crane, Bollard)	**Scenario A**		**Scenario B**	
	BP	**BT (sec)**	**BP**	**BT (sec)**
(1,8)	[9.40%-14.8%]	[46.0-53.2]	[26.0%-33.6%]	[63.9-70.2]
(2, 10)	[6.90%-11.1%]	[42.2-50.0]	[18.7%-24.8%]	[63.6-69.9]
(3, 16)	-	-	[6.20%-10.4%]	[56.8-69.2]
(4, 21)	-	-	[7.80%-12.7%]	[56.4-63.8]
(5, 27)	[9.10%-13.8%]	[49.7-56.5]	[8.90%-13.7%]	[59.8-68.2]
(6, 28)	[13.1%-18.9%]	[47.5-53.5]	[18.2%-24.8%]	[57.8-64.8]
(7, 30)	[11.0%-16.5%]	[47.9-55.0]	[21.2%-28.1%]	[63.6-70.4]
(8, 34)	[21.0%-28.3%]	[54.6-60.0]	[17.9%-24.9%]	[60.3-67.4]

5 CONCLUSIONS

Event-based simulation in a stochastic modeling environment has been successfully pursued in this paper, under the goal of providing an effective tool for supporting the performance-oriented design of the yard storage blocks in a maritime container terminal. The micro-reproduction of container handling and transfer between the quay and yard blocks performed by man-operated straddle carriers has allowed to overcome the difficulties arising in resource coordination during real-time operations. The proper number of rows and tiers in a yard block has been determined through numerical experiments. A block design featuring 32 rows and 3 tiers has outperformed one with 28 rows and 4 tiers. Despite the presence of a locking condition, the former design has allowed to reduce: *i*) the queuing probability and time of straddle carriers in front of the yard rows; *ii*) the blocking probability and time of quay cranes due to full output buffers; *iii*) the completion time of the quay cranes in the discharge/loading process integrated with the storage process. The occurrence of rare events and small samples in simulation output analysis may call for the further refinement of interval estimates for both expected waiting times and probability measures related to resource allocation in container handling operations. This is left as future work.

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AUTHOR BIOGRAPHIES

PASQUALE LEGATO is an Associate Professor of Operations Research in the Department of Informatics, Modeling, Electronics and System Engineering (DIMES) at the University of Calabria, Rende (CS, Italy). He has been a member of the Executive Board of the University of Calabria as well as university delegate for the supervision of associations and spin-offs from the University of Calabria. He has been involved in several EEC funded research projects aimed at the technological transfer of SO procedures and frameworks in logistics. He is a member of the INFORMS Simulation Society. His research focuses on queuing networks, stochastic simulation and optimization. His e-mail address is: legato@dimes.unical.it and his web-page can be found at http://wwwinfo.dimes.unical.it/legato.

RINA MARY MAZZA is the Research Manager of the Department of Informatics, Modeling, Electronics and System Engineering (DIMES) at the University of Calabria, Rende (CS, Italy). She graduated in Management Engineering and received a PhD in Operations Research from the above university. She has been a consultant for operations modeling and simulation in container terminals. Her current research interests include discrete-event simulation and optimum-seeking by simulation in complex systems. Her e-mail address is: rmazza@dimes.unical.it.