EFFECTS OF LOADING CONDITIONS AND QUAY CRANE ASSIGNMENTS ON CONTAINER TERMINAL PERFORMANCE

João Vitor Marques de Oliveira Moita[1], Jean-David Caprace[2,*]

ABSTRACT

Good planning and management of container terminal operations reduces waiting time of the vessels and lead to the improvement of the terminal productivity. Moreover, being faster in ports allows a ship to transit at slower speeds (slow steaming) and to save fuel as well as to reduce emissions. Important key factor to reduce unproductive times are the optimization of berth allocation, quay crane allocation as well as scheduling. However, it can only be done if a good understanding on how the resources are interacting and affecting the berthing time of ships is obtained. This paper investigates the effect of quay cranes assignments and scheduling on the container terminal productivity through stochastic simulations. A container vessel berthing simulation model is created based on the data warehouse of an actual container terminal. The uncertainties and unpredictable events related to operations are implemented using stochastic variables. Calibration of the simulation model is based on five operations of the same container carrier in the terminal. Following the setting of the stochastic parameters included in the model, the simulation is repeated until sufficiently large sets of iterations are available for statistical analysis. Results of the simulation of 9 scenarios considering various loading conditions and crane allocation are compared. Then, the dispersion of the net average berthing time and net cranes productivity are discussed and confronted to measured data. We advocate that simulation provide a good decision assistance tool to perform operational productivity studies for both ship owners (bay plan optimization) and container terminals (layout optimization). Therefore, some patterns and recommendations are formulated to help to improve the productivity in container terminals.

1. INTRODUCTION

1.1 Context

Rising global container port demand and ever larger vessels are driving terminal operators to make significant investments regarding to efficiency and capacity. It is predicted an average global container port demand growth of 4.5% per year towards 2019, which equates to an additional 168 million TEU of port traffic, bringing the global total to nearly 850 million TEU (Research, 2015). As consequence of this massive growth, container terminals congestions are expected, such as the congestions at the key Asian ports, stated in September 2014, which occur until today and are the worst bottlenecks of the last 20 years (Brett, 2014).

Additionally, energy efficiency has become one of the main concerns for maritime operators. Today container freight rates is the lowest on records since 2009 (Bimco, 2015). Therefore, increasing bunker price, lube oil, manning and maintenance costs induced ship owners to find ways to reduce operational costs. As the single biggest cost factor in merchant shipping, solutions regarding fuel consumption have to be considered. The simplest way to reduce this cost is to reduce ship speed, which is called slow steaming (Wiesmann, 2010). By doing slow steaming, ship owners reduce bunker costs as well as gas emissions.

Considering the problems stated above, improving container terminals efficiency is a key aspect that should be carefully considered. It allows to increase the terminal capacity, to decrease the berthing time of ships and minimize the problems due to congestions hence reducing operational expenses and waiting queues. Also, ships might sail at slower speeds applying slow steaming.

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1.2 Gap

The transshipment of containers between a vessel and the quay is generally performed by specialized cranes, called portainers, which are mounted on rail tracks alongside the quay. The assignment of these quay cranes to vessels and the determination of work plans for the cranes are key decision to be taken by the scheduling department of the terminal. Even if container terminal operations can be highly automated, operational times still cannot be accurately planned due to many complexities such as human factor, weather conditions, equipment delays and defects, etc. This combination of complexities causes difficulties for planning the berth occupancy and operational time precisely.

The assignment and the scheduling of the cranes are problems difficult to be dissociated, (Bierwirth & Meisel, 2015). For each vessel included in the berth plan, the volume of containers to be loaded and unloaded is known as well as the maximum number of cranes allowed to serve it simultaneously. The cranes are supposed to be lined up alongside the quay. They can be moved to every vessel but they are not able to pass each other. The assignment problem is to dedicate cranes to vessels such that all required transshipments of containers can be fulfilled in a minimum time, (Steenken, Voß, & Stahlbock, 2005). The minimization of the makespan of the cranes schedule is generally pursued because it represents the handling time of the considered vessel. Scheduling of the activities of the cranes can be defined on the basis of group of bays, or single bays, or on the basis of container stacks, or eventually individual containers. The idea of dividing the workload of a vessel into a group of bays is to serve each bay area exclusively by one crane. If the bay areas are non overlapping, crane interference is completely avoided. However, a sufficient balance of the workload distribution among the cranes might not be possible.

The present study investigates the effect of quay cranes assignments and scheduling on the container terminal productivity through stochastic simulations.

1.3 State of the art

Physical limitations such as channel depth, storage yard space, berthing facilities, and landside productivity determine how much throughput a port can potentially handle in a given year. The proper planning and management of port operations in view of the ever growing demands in global trade represents a big challenge because of restrictions such as the length of the quay and depth of access channels which causes increased difficulties for berthing operations planning and the loading and unloading of ships, (Sheikholeslami, Ilati, & Yeganeh, 2013).

Thus, due to the complexity and nature of the problems it is proposed to use the simulation approach. According to research by (Merkuryev, et al., 1998) and (Hartmann, 2005) it can be concluded that the simulation results provide valuable information to support the decisions made by programmers, operators and terminal managers. Efficient applications of simulation in support of complex management of container ports have been demonstrated by (Nam, Kwak, & Yu, 2002) and (Peng-fei, Zi-jian, & Xiang-qun, 2006). Simulation can guide terminal managers with evaluating all the terminal key resources (quays, cranes, RTGs, etc.) to understand their interactions with vessel delays and to assess and mitigate the risks arising from them. A list of challenges that a simulation model can help to tackle is included in (Carlo, A., & Roodbergen, 2014).

When the port is heavily congested with different types of vessels, effective berth allocation techniques could optimize the berth utilization and reduce the ship’s queuing time. (Bierwirth & Meisel, 2015) presented a thorough review of the previous attempts in solving the berth allocation and quay crane assignment problems. Particular focus in their article is put on integrated solution approaches which become increasingly important for the terminal management.

1.4 Outline

The outline of the paper is structured as follows. The methodology and modeling are explained in Section 2 while the case study and the discussion of the results are respectively presented in Section 3 and Section 4. Finally, recommendations and conclusions are provided in Section 5.

2 METHODOLOGY

A simulation model was implemented using a Discrete-Event Simulations algorithm (DES). The main advantage of DES is the consideration of random factors that affects operation of the system. It provides a stochastic modelling, where the uncertainties on the processes are considered by use of stochastic variables. For a container terminal, human, equipment and climate-related randomness can be introduced by using statistical data thus making it possible to create a system model able to give an idea of the outputs variability. It allows to apply different approaches or strategies regarding operation to see possible variations, thus providing the opportunity to assess the performance of new strategies and its outcomes.

Fig. 1 illustrates the flowchart of the major components of the simulation including the main input data and the calculation of the performance measures.

When a vessel arrive, the berth is allocated and considered always available. The number of lifts per ship call is generated based on the loading condition defined in the scenario, depending on the size of the vessels. Here, anchoring as well as the berthing and un-berthing time are neglected. The focus is placed on the study of the net berth time of the vessels between the launching of the first mooring line to the release of the last one ($(t_6 - t5)$ –Fig. 2). When the vessels is berthed, an appropriate number of quay cranes varying between 2 and 4 is assigned depending on the studied scenario. It is assumed that all cranes at a berth are dedicated to the service of the unique vessel, i.e. cranes are not shared with other operated vessels. Once the quay cranes are assigned, the loading and unloading operation start, and the working time is calculated. That is, for each scenario, total working time is estimated between the first and last movement. Upon completion of unloading and loading the vessel disappears from the model. Similar simulations were performed for each scenario. Fig. 3 give an insight of the graphical user interface (GUI) of the DES.

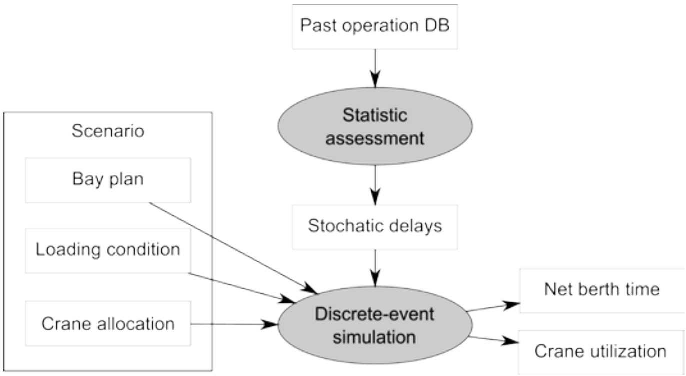


Fig. 1 Discrete-event simulation flowchart

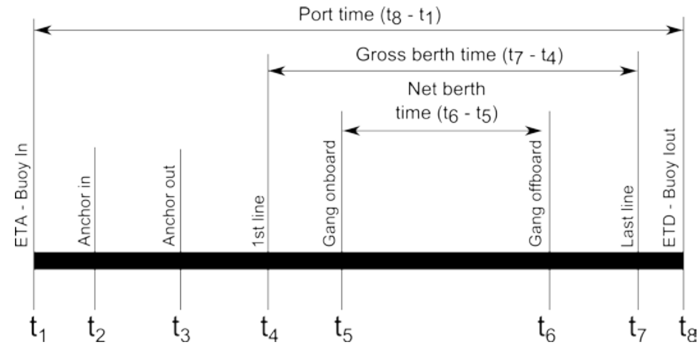


Fig. 2 Dwell time of a container ship in port measured between the estimated time of arrival ETA and the estimated time of departure ETD

The stochastic variables attributed to delays has been derived on the basis of the analysis of 197 berthing operation performed between 1 January 2014 and 6 August 2014. It correspond to 500 crane operations and 78180 containers movements. From that amount, 53% was related to FEUs and 43% TEUs. The data collected within the terminal gave the sum of each specific delay occurred during each single operation. These delays corresponding to idle times of the cranes has been grouped in three different categories:

- Failure – This delay is due to the possible failure of the crane or the spreader during the transhipment. Based on the statistical analysis, the best fit probability density function of failure is given by equation (1) where $\lambda = 0.7488$ and $\gamma = 0$, see Fig. 4.
- Waiting – This waiting time occur when an empty trucks (chassis) arrives late during an unloading operation or similarly when a chassis with a container arrives late during a loading operation. The probability of such delays depends on the number of cranes used in the operation, crane workload, traffic congestion, and several managing problems. Based on the statistical analysis, the best fit probability density function of waiting is given by equation (2) where $\alpha = 1.059$, $\beta = 1.538$ and $\gamma = 0$, see Fig. 5.
- Other – These delays are related to others factors including the passage of a vessel in the vicinity of the operated ship, the movement of OOG (out of gauge) containers, the safety inspections, bad weather conditions and or accidents. Based on the statistical analysis, the best fit probability density function of these delays is given by equation (3) where $\sigma = 0.4762$, $\mu = 0.6462$ and $\gamma = 0$, see Fig. 6.

These delays has been applied in the DES just before and just after the engagement and disengagement of the spreader on every single container movement.

$$f(x) = \lambda \exp\left(-\lambda(x-\gamma)\right) \tag{1}$$

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right) \tag{2}$$

$$f(x) = \frac{\exp\left(-\frac{1}{2}\left(\frac{\ln(x-\gamma)-\mu}{\sigma}\right)^2\right)}{(x-\gamma)\sigma\sqrt{2\pi}} \tag{3}$$

For each scenario, the simulation is repeated until sufficiently large sets of iterations are available for statistical analysis. Then, the dispersion of results regarding the net berth time are discussed and compared to measured data.

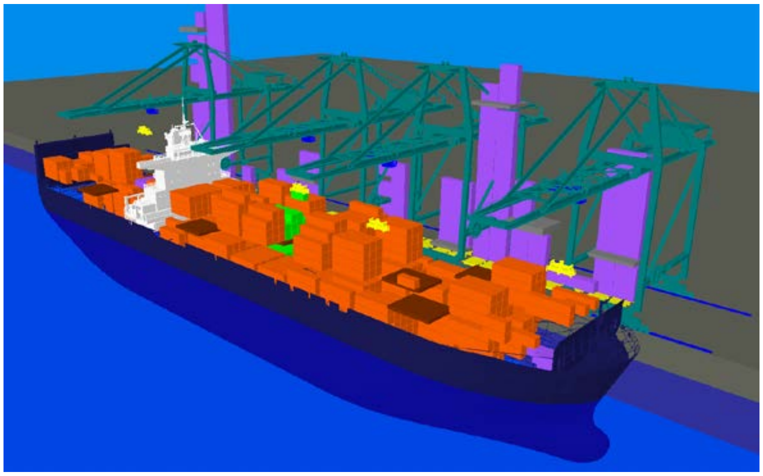


Fig. 3 Graphical user interface of the discrete-event simulation where orange means that container is not going to be moved, green means that the container is going to be unloaded and purple means that the container is going to be loaded.

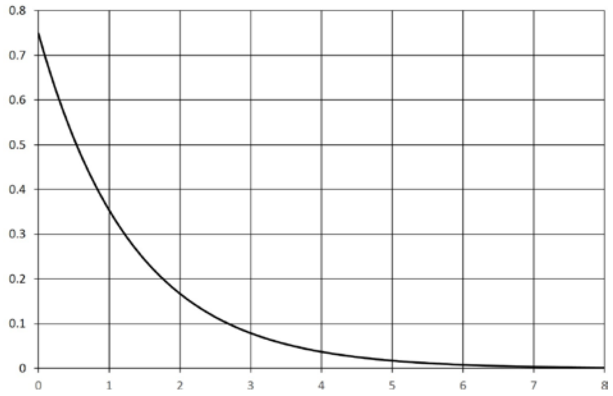


Fig. 4 Exponential probability density function

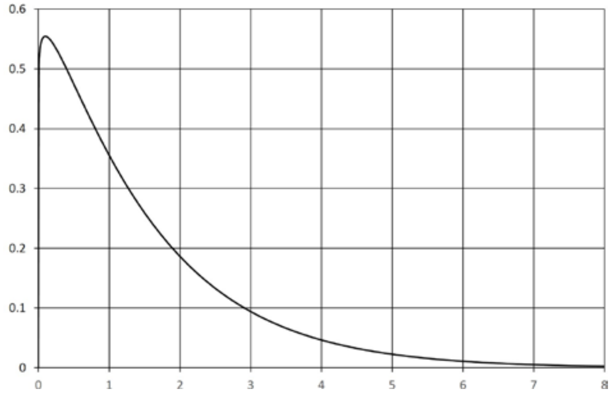


Fig. 5 Weibull probability density function

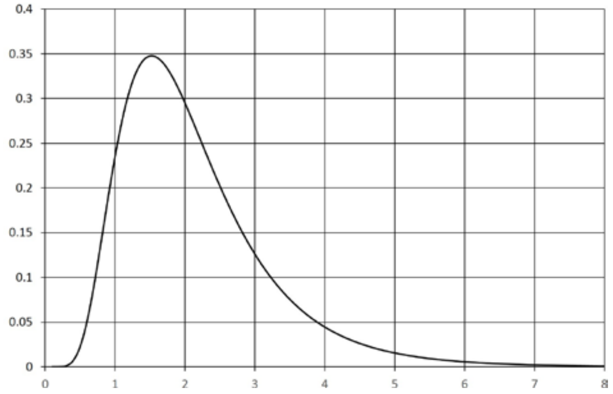


Fig. 6 Log-normal probability density function

3 CASE STUDY

The case study focus on the analysis of the comparison of various operations of a container carrier of 5527 TEUs having 66280 GT, a deadweight of 68228 tons and a displacement of 91187 tons. The overall length of this ship is 275.8 m and the extreme breadth 40.1 m. The average annual throughput of the terminal during the studied period is about 340000 TEUs. From an operational point of view a container ship can be interpreted as a three dimensional grid of potential container slots. The grid consists of several bays (longitudinal axis), rows (transversal axis) and tiers (vertical axis). Each slot in the grid corresponds to one TEU (Twenty-foot Equivalent Unit). In longitudinal direction of each bay two neighboring slots could be occupied by one FEU (Forty-foot Equivalent Unit). The ship considered in this study has 32 bays numbered from 1 to 63, 16 rows and 15 tiers where 9 are below hatch cover.

Five scenarios of real loading conditions has been selected, see Fig. 7 – Fig. 11. Each loading condition correspond to a certain number of box movement varying between 167 for scenario 1 to 496 for scenario 4. The number of TEUs and FEUs to be loaded and unloaded respectively above and below the hatch covers are indicated in the grid of the above mentioned figures. The total of container movement is indicated just below the bulbous bow of the figures. The number below the keel line of the figure correspond to the total of box movement gathered by twin bays.

Hatch cover opening and closing operations are performed by the quay cranes for this size of ships. They are handled basically as a container by the mean of the spreader and then located on the shore until the operation within the hatches is finished. To be moved hatch cover required to be free of containers. Here the number of hatch cover movements has been mentioned in the black horizontal line of Fig. 7 – Fig. 11.

Various schedules of cranes has been considered for each scenario and are reported below the figures with the black and light gray lines. The number in the horizontal bar indicates the number of container movements while the length of the bar corresponds to the number of the bays deserved by this crane. For clarity, all the possible configurations has been numbered with two digits number where the first digit represent the number of the scenario and the second digit represent the number of quay crane allocated for the operation. In other terms, alternative 43 correspond to scenario 4 where 3 quay cranes are operated.

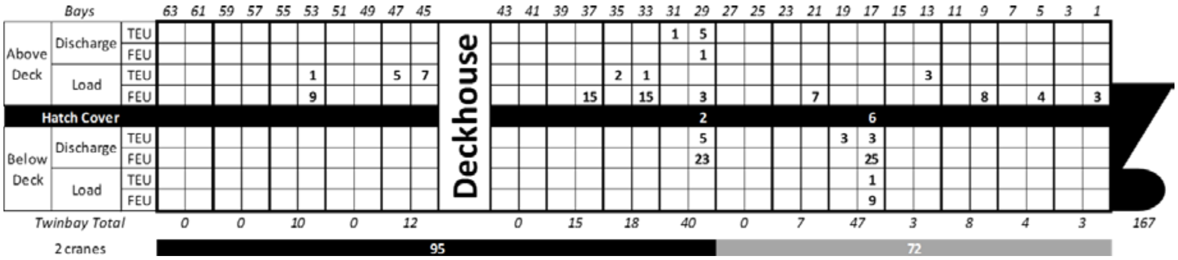
Several assumptions were made to simplify the model:

- All cranes are equal in terms of speed, accelerations and delays.
- The spreader and the crane hoist are not moving simultaneously above the ship.
- There is no possible overlap between the cranes.
- The weather conditions (wind, waves, tide) are not taken into account.
- There is no difference of spreader vertical speed above and below the hatch covers.
- Neither the container weight nor the container size affect the speed of the crane.
- The vessel is considered stable during the entire operation, hence the draft and the trim of the vessel are constant.
- The reallocation of containers from one bay to another bays are only possible passing by the stacking yard.
- The height of the trailers has been considered constant and equal to 1.055 meters.

4 RESULTS

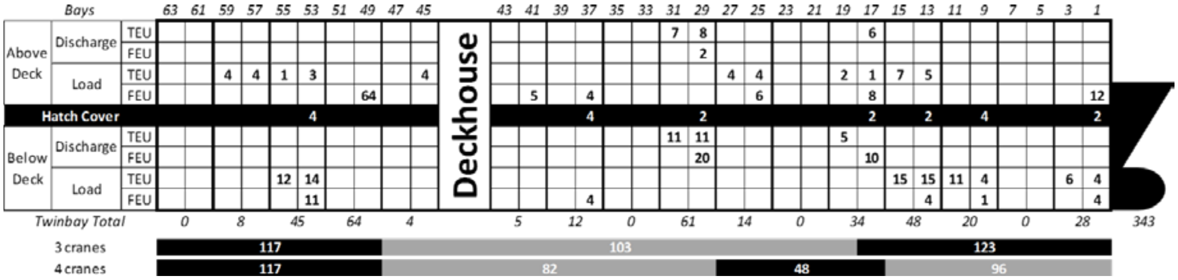
The effects of quay cranes allocation and loading condition on the key performance of the terminal are presented in this section. A simulation model has been generated for each scenario above mentioned and ran along 400 iterations until the convergence of the results is observed, see Fig. 12. Computational time depends on number of cranes in the model.

Fig. 13 displays the results of the all simulated scenarios. The key measure is the total average berth time (tot) as well as the operating time of each quay crane plotted in hours. The operational time of each quay crane has been measured between the first and last container movement performed by the device while the total berth time is measure between the earliest and latest movements of all allocated cranes.



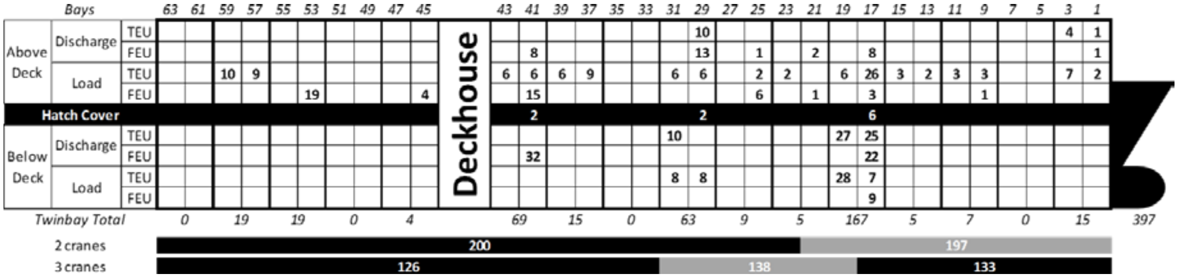
	Bays		63	61	59	57	55	53	51	49	47	45		43	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1	
Above Deck	Discharge	TEU											Deckhouse							1	5															
		FEU																			1															
	Load	TEU						1			5	7						2	1										3							
		FEU						9									15		15		3				7						8		4		3	
Hatch Cover																					2						6									
Below Deck	Discharge	TEU																			5					3	3									
		FEU																			23						25									
	Load	TEU																									1									
		FEU																									9									
Twinbay Total			0		0		10		0		12			0		15		18		40		0		7		47		3		8		4		3		167
2 cranes			95																			72														

Fig. 7 Containers movements per bay for scenario 1



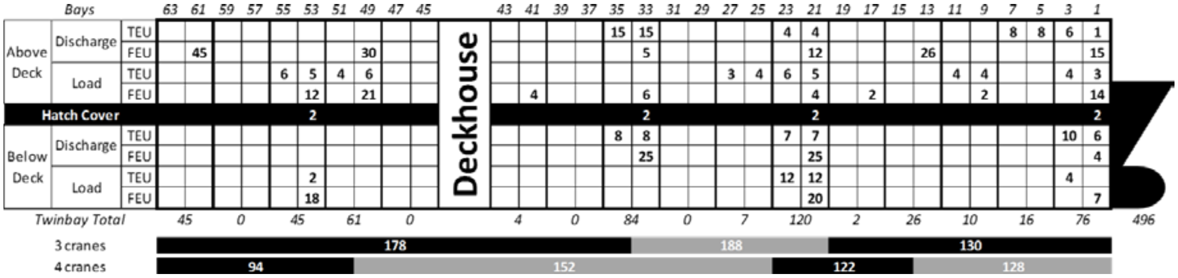
	Bays		63	61	59	57	55	53	51	49	47	45		43	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1	
Above Deck	Discharge	TEU											Deckhouse							7	8						6									
		FEU																			2															
	Load	TEU			4	4	1	3				4										4	4			2	1	7	5							
		FEU								64					5		4						6				8								12	
Hatch Cover								4									4				2						2		2		4				2	
Below Deck	Discharge	TEU																		11	11					5										
		FEU																			20						10									
	Load	TEU					12	14																				15	15	11	4			6	4	
		FEU						11									4												4		1				4	
Twinbay Total			0		8		45		64		4			5		12		0		61		14		0		34		48		20		0		28		343
3 cranes			117								103																123									
4 cranes			117								82											48						96								

Fig. 8 Containers movements per bay for scenario 2



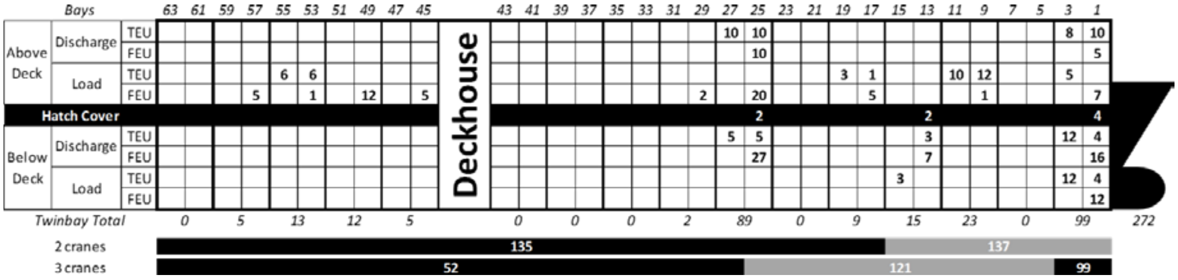
	Bays		63	61	59	57	55	53	51	49	47	45		43	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1	
Above Deck	Discharge	TEU											Deckhouse								10													4	1	
		FEU													8						13		1		2		8								1	
	Load	TEU			10	9								6	6	6	9			6	6		2	2		6	26	3	2	3	3			7	2	
		FEU						19				4			15								6		1		3				1					
Hatch Cover															2						2						6									
Below Deck	Discharge	TEU																		10						27	25									
		FEU													32												22									
	Load	TEU																		8	8					28	7									
		FEU																									9									
Twinbay Total			0		19		19		0		4			69		15		0		63		9		5		167		5		7		0		15		397
2 cranes			200																						197											
3 cranes			126																	138							133									

Fig. 9 Containers movements per bay for scenario 3



	Bays		63	61	59	57	55	53	51	49	47	45		43	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1	
Above Deck	Discharge	TEU											Deckhouse					15	15					4	4							8	8	6	1	
		FEU		45						30									5						12				26						15	
	Load	TEU					6	5	4	6												3	4	6	5					4	4			4	3	
		FEU						12		21					4				6						4		2				2				14	
Hatch Cover								2											2						2										2	
Below Deck	Discharge	TEU																8	8					7	7									10	6	
		FEU																	25						25										4	
	Load	TEU						2																12	12									4		
		FEU						18																	20										7	
Twinbay Total			45		0		45		61		0			4		0		84		0		7		120		2		26		10		16		76		496
3 cranes			178																188							130										
4 cranes			94							152														122					128							

Fig. 10 Containers movements per bay for scenario 4



	Bays		63	61	59	57	55	53	51	49	47	45		43	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1	
Above Deck	Discharge	TEU											Deckhouse									10	10											8	10	
		FEU																					10												5	
	Load	TEU					6	6																		3	1			10	12			5		
		FEU				5		1		12		5									2		20				5				1				7	
Hatch Cover																							2						2						4	
Below Deck	Discharge	TEU																				5	5						3					12	4	
		FEU																					27						7						16	
	Load	TEU																										3						12	4	
		FEU																																	12	
Twinbay Total			0		5		13		12		5			0		0		0		2		89		0		9		15		23		0		99		272
2 cranes			135																									137								
3 cranes			52																				121											99		

Fig. 11 Containers movements per bay for scenario 5

The results has been validated by comparing simulation outputs to the actual case. Tab. 1 shows the comparison of the simulation results and the actual performance of the operation for the 5 scenarios. The average simulated net berth time is 5.76 hours. This is 2.8% higher than the actual case. The results shows that the average simulated berthing time is a little higher than that from the actual data with a maximum error of -9.3% for scenario 44. These discrepancies can be explained by the small differences existing between the simulation model and the real case. First, shifting of containers directly from one bay to another bay was not allowed in the simulation models. It means that in the real case these operation accounted for one container movement while it is counted for two movements in the simulation, i.e. one unloading and one loading. Another possible explanation of the observed gap between simulation and real case is that the allocation of the cranes in simulation has been performed by bays while in real case the allocation has been performed by group of containers or even by container stack. Therefore, there is small differences between the number of box movements per allocated quay cranes. Finally, the spreader and the quay crane hoist are not moving simultaneously above the ship in the simulation while in reality, depending of the loading condition, crane operators are sometimes using the combination of the vertical and horizontal movements to improve the productivity.

The impact of the different scenarios is determined by comparing the key performance measures between the scenarios. It is observed on Fig. 13 that an average reduction of 26.8% and 30.6% of the average net berthing time can be obtained respectively using 3 quay cranes instead of 2 (scenarios 32, 33, 52, 53) or 4 quay crane instead of 3 (scenarios 23, 24, 43, 44). The total average quay crane efficiency (utilization ratio) for all scenario is 88.8% with a minimum of 79.7% and a maximum of 92.9%. These values present a good accordance with the recommendations of (Nam, Kwak, & Yu, 2002). The average crane productivity of different scenarios expressed in net lifts per hour are presented in Fig. 14. The total average productivity per crane of a specific scenario has been calculated dividing the total number of movements by the number of cranes and the average net berth time of the operation. The average value of this key indicator for all the scenarios is 18.0 movements per hour not far from the value of 19.78 proposed by (Nam, Kwak, & Yu, 2002) for a Korean container terminal having a throughput of 1200000 TEUs per year.

Fig. 15 support the argument that there is a negative correlation between the average quay crane productivity and the variance of the workload of the quay cranes of each scenario. In other words, it shows that the allocation strategy of the quay crane should minimize this variance to improve the global productivity of the operations. It is especially notable for scenario 52 and 32.

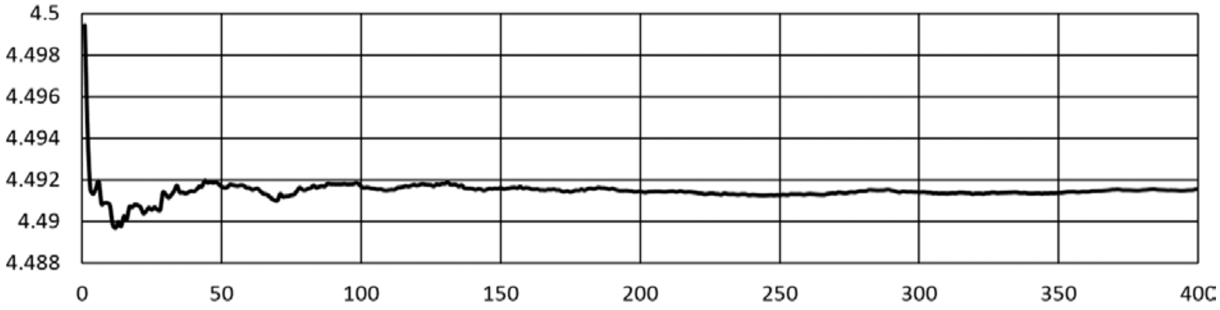


Fig. 12 Convergence of the average net berth time observed for scenario 12 after 400 iterations

Scenario	Realized	Simulated	Error
12	4.41	4.49	-1.8%
24	4.80	4.76	0.8%
33	7.50	7.42	1.1%
44	6.30	6.88	-9.3%
53	5.00	5.25	-5.0%
Avg	5.60	5.76	-2.8%

Tab. 1 Comparison of the net berth time simulated and realized

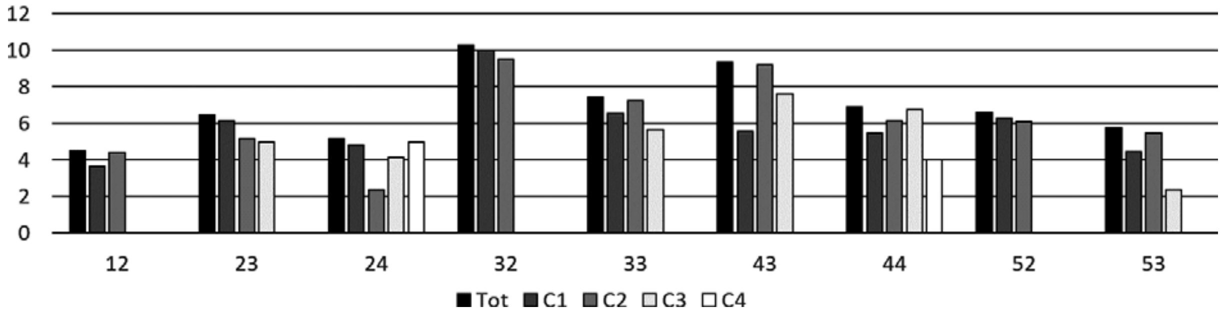


Fig. 13 Simulated average net berth time of the different scenarios expressed in hours (400 iterations)

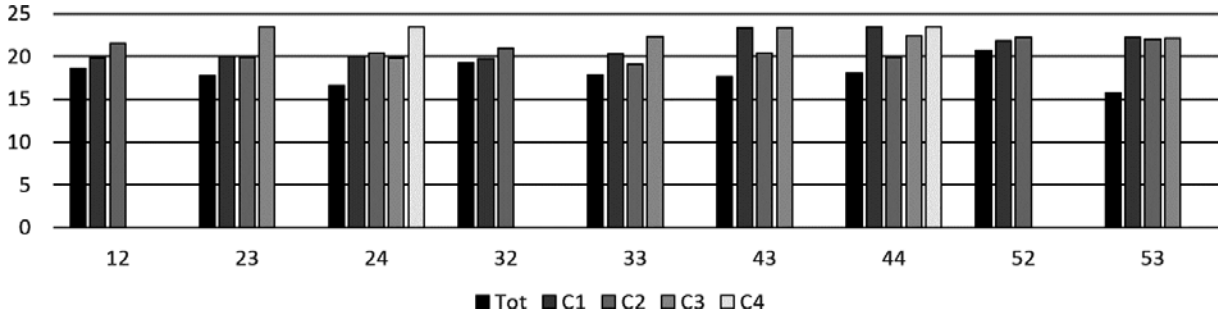


Fig. 14 Simulated average crane productivity of different scenarios expressed in net lifts per hour (400 iterations)

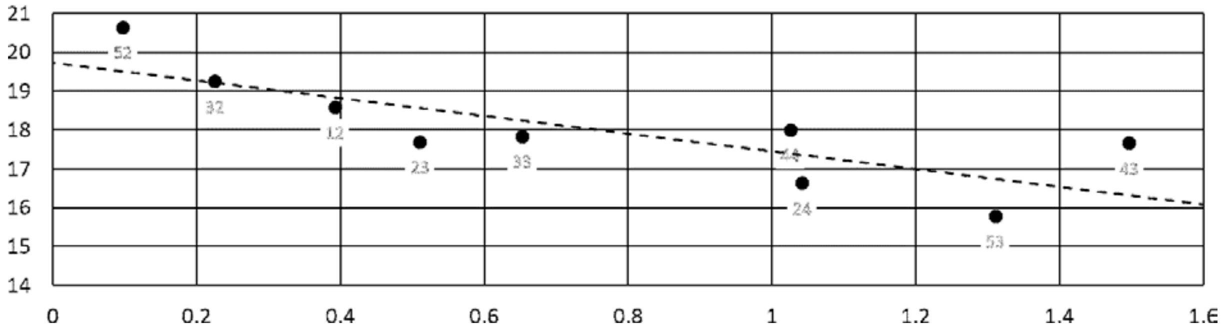


Fig. 15 Relation between average crane productivity in movements per hour and the variance of the workload of the quay cranes for each scenario

5 CONCLUSIONS

Container terminals are high capital assets mainly consisting of various cargo handling equipment, labor, and infrastructure. Therefore, the terminal resources have to be utilized as efficiently as possible to improve the productivity of the terminal. A critical issue in this respect is the way in which the use of terminal resources can be adequately modeled to analyze the current simulation of a terminal operation and to evaluate possible future situations. This study, in this respect, has revealed that simulation modeling is a very effective method to examine the feasibility and impacts of loading conditions and quay crane allocation on the productivity of a container terminal.

The results presented here support the argument that the productivity of the terminal might be increased increasing the number of quay cranes allocated per operation. However a careful crane assignment and scheduling is recommended in order to minimize the variability of the workload between the cranes used in the same operation. Therefore, further studies need to be carried out to optimize the quay crane allocation and scheduling in order to maximize the productivity of the container terminals.

Though the approach we adopted seemed to be appropriate and seemed to provide meaningful results, a number of points for future consideration remain. Unlike most simulation studies on container terminal including detailed economic analysis with respect to various planning alternatives, this study could only provide results on net berth times and quay crane productivity. Generally, as cost is a key measure in the selection of alternatives, further effort needs to be made to incorporate a cost analysis. Future research could also consider total dwell time in port instead of only net berthing time by determining probability density function of unproductive related activities such anchorage time and vessel transit time in port.

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