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Efficiency Evaluation of a Small Container Terminal with Perpendicular Yard Layout Using Shuttle Carriers

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Abstract: Productivity is an extremely important factor in the competitiveness of a container terminal. Productivity itself is largely influenced by the handling mechanisation, the main task of which is to serve the quay cranes on one side and the yard cranes on the other. One of the most effective types of mechanisation in this segment is shuttle carriers, which are used primarily in the larger terminals. The objective of this study was to determine if they can also be used effectively in smaller container terminals with different yard layouts. Therefore, this study shows the impact of the selected layout and handling mechanisation on terminal productivity. The focus is on the berth productivity, as it has the greatest impact on the handling of the vessel in the port. To this end, a discrete-event simulation modelling approach was used in a container terminal of small capacity. The performed simulations included all operations between berth and yard, focusing on the correct allocation of shuttle carriers to ensure optimal results on the sea side of the terminal. The result showed that the use of shuttle carriers brings a substantial performance effect to the container terminal and also has a different effect considering different terminal layouts in terminals with an annual throughput not exceeding 1 million TEU.

Keywords: container terminal operations; berth productivity; yard utilisation; shuttle carriers; perpendicular layout

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1. Introduction

A container terminal is a complex system, the main function of which is to serve container ships, temporarily store containers and transfer them between sea and land. It consists of three subsystems: berth, yard and gate [1,2]. Currently, several container terminals are being expanded, remodelled, or newly built to increase their handling capacity and competitiveness in the market. All of this is due to the decision of shipowners to build larger and larger ships, which require highly efficient terminals so that ships can leave the port as quickly as possible to reduce costs. This is usually measured in terms of operational productivity, such as ship turnaround time or yard utilisation. Unfortunately, this is no longer the case only in large ports, but also in smaller ports, which are forced to accommodate increasingly larger ships due to the cascade effect (which provides that when a new larger ship is built, the previously largest ships are deployed on direct lines between smaller ports), even though they were originally built for smaller Panamax and feeder ships [3]. The handling of ships depends not only on the operation of the quay cranes (QCs), but mainly on the operation of the transfer mechanisation, whose main purpose is to serve the QCs on the one hand and yard cranes (YCs) on the other, and secondarily on yard operations [4]. To achieve the terminal efficiency that satisfies the line operators by enabling fast operations on both the sea and land sides of the terminal, it is important that all three terminal subsystems are closely connected and well coordinated. This is achieved through the choice of the terminal operating system (TOS), but the layout of the yard itself also has an important impact on performance. There are two possible layouts: parallel to and perpendicular to the quay. The first is the most common choice for medium and smaller terminals and is still very common for large terminals, while the second is mainly found in larger terminals with a more powerful operating system that includes effective cargo-handling mechanisation. Among the more efficient transfer mechanisations are the shuttle carriers (ShCs), which belong to the so-called active equipment that can lift a container without the help of other cranes. This eliminates empty vehicle trips and reduces QC waiting time. The higher crane productivity, in turn, speeds up the clearance of a vessel. Compared to the use of a passive transfer mechanisation that cannot lift a container (mainly used in smaller terminals), the use of ShCs involves higher purchase, maintenance and operating costs. Nevertheless, due to their good performance and faster transfer between subsystems, we believe they also represent a possible option/solution for smaller container terminals that wish to maintain a high stacking density of yard cranes (YCs) and increase their operational capacity [5].

Since larger and modern terminals with a vertical yard layout and modern mechanisation achieve extremely good results, we wanted to see if smaller ports could also achieve better throughput performance in this way, thus offering terminal operators results based on validated simulations with real data. This will facilitate the extremely difficult and costly decision to optimise existing container terminal capacity and support the construction of new terminals with lower capacities. The objective of this study is to determine whether the use of ShCs for transfer purposes can provide good productivity results even in smaller container terminals with an annual throughput of no more than 1 million TEU. To this end, a discrete-event simulation modelling approach was used for a hypothetical container terminal created in FlexSim CT software. In addition, we provide new insights on (i) simulations at a container terminal with a yard parallel to the quay, as identified by Stojaković and Twrdy [6]; (ii) how the use of ShCs in a yard positioned perpendicular to the quay can affect the productivity of the berth; (iii) and the utilisation of the yard in the perpendicular layout. Simulations were performed for seven scenarios with different berth characteristics. During the simulations, the berth length, number and size of QCs were changed, as well as the number and size of vessel services that incrementally increased annual throughput. The number of ShCs deployed per QC was also changed during the scenarios. The results of the simulations conducted with a yard arranged perpendicular to the quay were discussed and compared with the previous results, which include simulations with a parallel yard arrangement. In this way, it was possible to determine the impact of the use of ShCs on the performance and productivity of QCs when the aim is to create optimal conditions for the fast and efficient handling of several post-Panamax vessels (PP) simultaneously at the terminal of small capacity with the perpendicular yard layout. The results highlight the importance of the selected handling mechanisation and terminal layout for the productivity achieved in the container terminal. Therefore, the work is also useful for port and terminal operators to make better planning decisions when developing a port strategy.

The paper is organised as follows: Section 2 provides a literature review; Section 3 explains the model formulation and the simulation optimisation approach and methodology. The simulation results can be found in Section 4, while discussion and conclusions are presented in Section 5.

2. Literature Review

As container terminals have become an important part of any port, many researchers have focused their work on container terminal operation and optimisation. As a result, an increasing number of publications have appeared in this area. The basis for further research was provided by Steenken, Voß and Stahlbock [7] and Stahlbock and Voß [8], whose work focused on the handling operation and handling mechanisation of container terminals, while Vis and De Koster [9] and Kim and Günther [10] addressed the problem of decision making in the terminal design and operation phase. In this regard, Böse [11] also provides an explanation of various possible TOS in the Handbook of Terminal Planning. The problem of the increase in the size of container ships and its impact on the performance requirements of container terminals, which have increased significantly, and the highlighting of necessary changes in their layout, infrastructure and equipment have been discussed in detail by

Musso and Sciomachen [12], Merk et al. [3], Park and Suh [13], Martin, Martin and Pettit [14], Meng, Weng and L [15] and others. Sys, Blauwens, Omey, Van De Voorde and Witlox [16] pointed out that the berth subsystem is most dependent on vessel size, as it is the first subsystem that the vessel encounters in the terminal and actually determines the maximum size of the vessel that can enter the terminal. Therefore, it is primarily important that the physical capacity of the berth is adequate, but handling efficiency is also necessary to meet the main requirement of shipowners: the rapid clearance of the ship at the port. According to Seyedalizadeh Ganji, Babazadeh and Arabshahi [17], ship turnaround time is considered the most important measure of a container terminal's effectiveness, along with the time the ship waits for the berth to become available, so reducing this time increases the terminal's productivity. Vessel turnaround time depends mainly on QC productivity. This is measured by the number of moves per hour. Bartošek and Marek [18] and Zhao and Goodchild [19] have studied QCs in detail. However, there are other factors that affect QC productivity, and thus the length of time a ship stays in port. These include berth allocation, the number of QCs assigned to the vessel, the type and number of horizontal handling equipment used for manipulation, the handling strategy employed and yard factors. In this context, the berth allocation problem (BAP) and the quay crane scheduling problem (QCSP) have been analysed by Bierwirth and Meisel [20], Bierwirth and Meisel [21], Liang, Hwang and Gen [22] and Giallombardo, Moccia, Salani and Vacca [23], mostly using generic algorithms. Carlo, Vis and Roodbergen [24] discussed the main trends and developments for storage yard operations. They noted that most of the work focuses on storage space assignment, scheduling and routing of handling equipment and reshuffling decisions. Part of their research relates to the most commonly used handling equipment in the terminal. An overview of the main types of container handling systems has also been provided by Brinkmann [5]. In her study, she summarises the main advantages and disadvantages of each type of handling system and emphasises the importance of making the right choice when selecting the so-called transfer mechanisation for the transfer between quay and yard and vice versa. The transfer mechanisation can be assigned to a specific QC or to several QCs at the same time. For this reason, a good degree of synchronisation between QCs and YTs and YTs and YCs is essential to avoid congestion. Zhao and Goodchild [19] analysed the impact of transfer mechanisation on terminal transshipment effects. Kress, Meiswinkel and Pesch [25] and Chen, Langevin and Lu [26] also studied the efficiency and operation of various yard facilities. Even though the yard subsystem is of secondary importance in ship reception, it is extremely important for the operational productivity of the terminal itself, as bottlenecks often occur in this area in particular. Bierwirth and Meisel [20] found that system design and yard layout are important strategic decisions that affect all other terminal decisions. The impact of layout and system design on terminal performance has been studied by a number of researchers. Martin Alcalde, Kim and Marchán [27], Zhen [28] and Zhen, Xu, Wang and Ding [29], studied the yard arranged parallel to the quay, while Wiese, Suhl and Kliewer [30] and Gharehgozli, Zaerpour and de Koster [31] addressed typical strategic and tactical layout problems. K. H. Kim, Park and Jin (2008) proposed a method for determining the layout of container yard, while Lee and Kim [32] proposed a method for determining an optimal layout of container yard considering the storage space requirements and throughput capacities of yard cranes and transporters. For this purpose, a sensitivity analysis was conducted to investigate the effects of various design parameters on the optimal layout of the yard. Lee, Lee and Chew [33] discussed a design process to maximise the throughput capacity as well as minimise the resource configuration when designing the yard layout. For this purpose, various experiments were conducted and analysed to show the effects on layout structure and resource configuration for the two types of yard layouts. Taner, Kulak and Koyuncuoğlu [34] used a built-in simulation software (ARENA) to develop a simulation model for container terminals and study the effects of transport dispatching rules and resource allocation strategies in terms of total annual throughput. They found that terminal performance is significantly affected by yard layout and transporter dispatching rules and allocation strategies. Due to the complexity of the TOS, analyses of at least two CT subsystems using various integrated simulation tools such as ARENA, AnyLogic, MicroPort and FlexSim are very common. An overall review of the available literature research on CTs using simulation models until 2015 was presented by Dragović, Tzannatos and Park [35]. For example, Sislioglu, Celik and Ozkaynak [36] used data envelopment analysis (DEA) along with ARENA software to improve the productivity of CT. They focused on minimising the average ship turnaround time at the port while maximising container throughput, while Kotachi, Rabadi and Obeid [37] analysed how different inputs affect outputs such as throughput, resource utilisation and waiting time by modelling generic port operations. Stojaković and Twrdy [38], in turn, used FlexSim CT to build a CT model and improve its berth and yard productivity by allocating the right number of YTs to QCs, and analysed the performance of the same CT model by switching the transfer mechanisation to ShCs. [6]. It was found that ShCs gave better results compared to YTs for both analysed subsystems. In this study, the same simulation methodology has been adopted. By running simulations with the same container terminal model using ShCs in a perpendicular yard layout, it is now possible to determine whether ShCs can provide better productivity results in a small container terminal than in a large terminal in both subsystems, thus providing a good alternative to the usual TOS decisions. However, the results obtained were not compared with other studies dealing with terminal design, as they differed mainly in the size of the terminal, the simulation strategy applied and the TOS used, focusing on automated stacking cranes (ASCs) in combination with automated guided vehicles (AGVs) or straddle carriers (SCs), which makes comparison difficult.

3. Model Formulation and Methodology

For the purpose of the research, which is to understand the behaviour of—and test different strategies in—the container terminal system, a hypothetical container terminal of small size was created. Most of its characteristics were taken from the North Adriatic port of Koper. The terminal consists of a continuous quay divided into two berths. The first berth is 250 m long, equipped with four Panamax (P) QCs and intended for Panamax and feeder vessels, while the second is 350 m long, equipped with four post-Panamax (PP) QCs and intended exclusively for larger post-Panamax vessels. All QCs operate in a single cycle. For the simulation, the yard was oriented perpendicular to the quay with block access at the sides. It consists of three stacking zones: import, export and the zone for empty containers. The blocks are served by RTGs, while the horizontal transport of containers between the quay and the storage yard is performed by ShCs. All resources of the same type have the same specification (Figure 1).

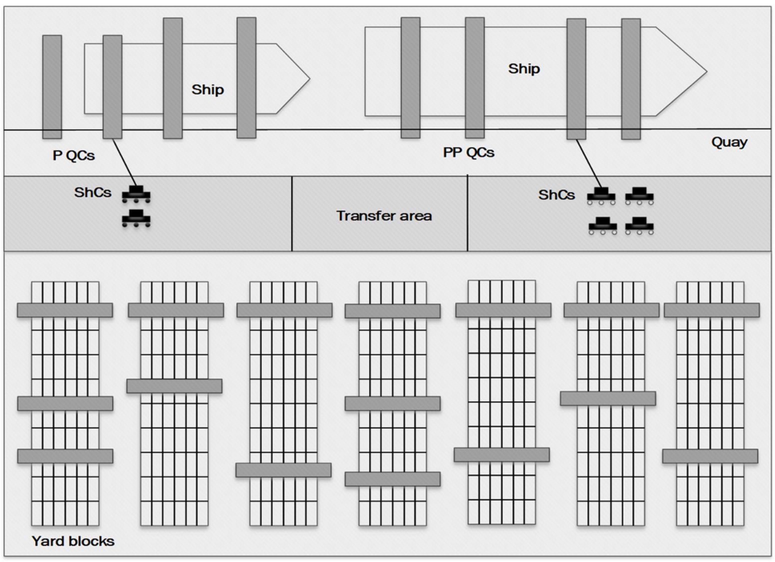

Figure 1. Perpendicular terminal layout.

The terminal's traffic is based on a fixed ship arrival schedule, in which thirteen services with different capacities call at the terminal each week. Post-Panamax vessels account for the largest share of traffic, approximately 65%, and also bring the most containers, although they represent a small percentage of vessels (31%).

The simulations include all the operations in the quay–yard–quay zone, i.e., the unloading of the ships, the transfer of the containers from shore to yard and vice versa, and the stacking operations at yard, while the operations at the gate were abstracted by the software according to the input data. The simulations were run for one week or until the completion of the work on the last ship in the plan. The concept is based on the key factors of a container terminal that define a functioning system and are divided into two subsystems, which include berth length, QCs, yard space, YCs and handling mechanisation. The input data included berth length, number and size of QCs, ships, number and size of import and export containers, number of ShCs, yard area and YCs.

The simulations were performed in two sets. The results of the first set of simulations, in which the yard area was laid out parallel to the quay, have already been published in the work of Stojaković and Twrdy [6]. However, since we wanted to see how a small terminal behaves when the storage area is arranged perpendicular to the quay, we performed a second set of simulations. This is not a common arrangement for smaller terminals, as existing terminals of this size are arranged horizontally, but could be of interest when building new terminals or reorganising the existing ones. Our goal was to show how the arrangement of the yard area affects the performance and productivity of the berth subsystem on the one hand, and the storage area on the other. Since the performance of both subsystems is strongly influenced by the transfer mechanisation, in this study a highly efficient mechanisation—ShCs—has been used. To maximise throughput capacity, their number was correctly allocated.

The simulation process began by creating a basic container terminal model based on real data (Scenario 1). The annual throughput of the base version of the terminal is 630,000 TEU per year. After the simulation runs, the obtained outputs were reviewed and evaluated, and later the final results were obtained. Since the goal was to accommodate larger vessels in a smaller terminal and thus increase annual throughput, the capacity and traffic of the base model were increased (Scenario 2). The simulations were run again and new results emerged. Thus, the model's traffic was increased with larger PP services and the terminal's capacity was increased until an annual throughput of 1 million TEUs was reached. The simulation process is shown in Figure 2.

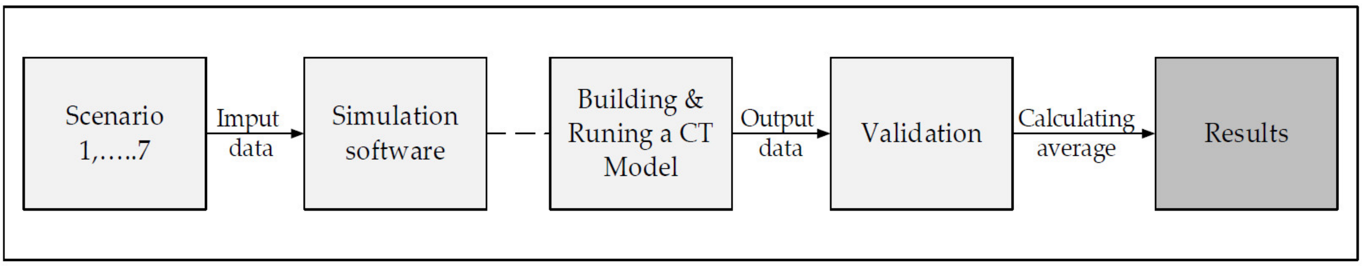

Figure 2. CT simulation methodology.

Between simulation scenarios, several terminal characteristics were changed (berth length, number and type of services, type of QCs and storage capacity). Under the specific scenario, the amount of horizontal equipment was also adjusted. Small QCs were equipped with 2 ShCs, and the large ones with 3 to 4. The scenarios are shown in Table 1.

Since this study focuses on the capacity and productivity of the terminal to accommodate larger ships and increase annual throughput, several performance metrics were analysed to show us the problems and efficiency of the two terminal subsystems under consideration. These metrics (Table 2) serve as our benchmark.

Table 1. Scenario description.

Scenario	1	2	3	4	5	6	7
Annual Throughput (TEU)	630,000	630,000	689,000	768,000	844,000	899,000	990,000
Quay (m)	600	700	700	700	700	700	700
QCs	4 P + 4 PP	2 P + 6 PP	2 P + 6 PP	2 P + 6 PP	1 P + 7 PP	1 P + 7 PP	0 P + 8 PP
No. of Feeder and Panamax services	9	9	7	6	5	5	4
No. of post-Panamax Services	4	4	5	6	7	7	7

Table 2. Performance metrics to evaluate operations of CT with perpendicular layout.

Performance Metrics	Definition of Metrics	Measured Dimensions
QC		
Working time	QCs working time on ships during simulation run	%
Productivity	Number of containers handled by QCs	Moves per hour
Berth Occupancy	Berth utilisation by ships in a simulation run	%
Yard Utilisation	Yard utilisation in a simulation run	%
YCs waiting time	Time spent by YCs waiting for ShCs	min

4. Results

The results were obtained through the simulation and result validation process. The simulation showed very good performance results for both subsystems considered. The results of all seven scenarios are presented in Table 3 and in more detail in Figures 3–7.

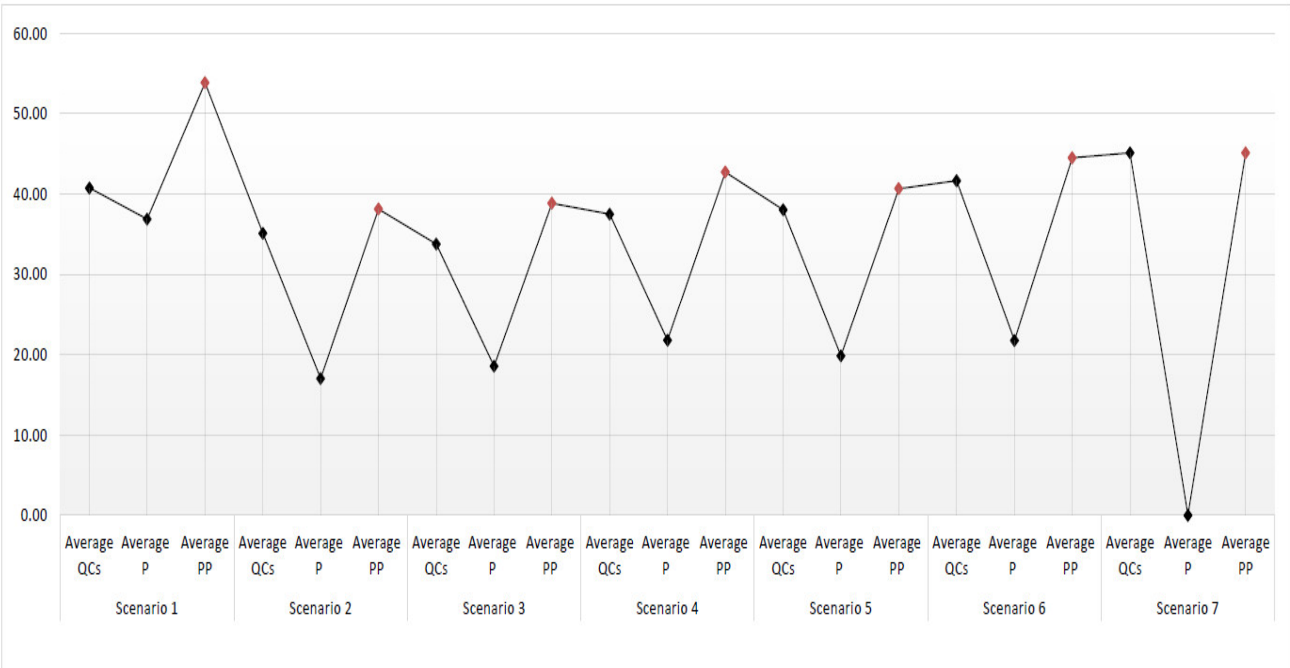

Figure 3. QC working time (%). The average working time for P and for PP QCs separately, and the average working time for all eight QCs together in all 7 simulated scenarios.

Table 3. Simulation results.

Scenarios	QC Working Time (%)		QC Moves per Hour		Berth Occupancy Ratio (%)	Average Yard Utilisation (%)	YC Average Waiting Time (min)
	P	PP	P	PP	/	/	/
Scenario 1	36.87	53.84	20.48	28.47	57.84	45.00	5.13
Scenario 2	17.04	38.11	16.57	28.82	35.96	44.88	5.31
Scenario 3	18.56	38.83	19.66	29.10	39.85	47.03	4.82
Scenario 4	21.80	42.71	17.90	30.38	43.55	48.33	4.84
Scenario 5	19.85	40.64	19.82	30.92	45.38	48.76	5.08
Scenario 6	21.76	44.49	19.19	30.47	45.83	50.70	4.73
Scenario 7	0.00	45.10	0.00	30.31	49.33	50.29	6.47

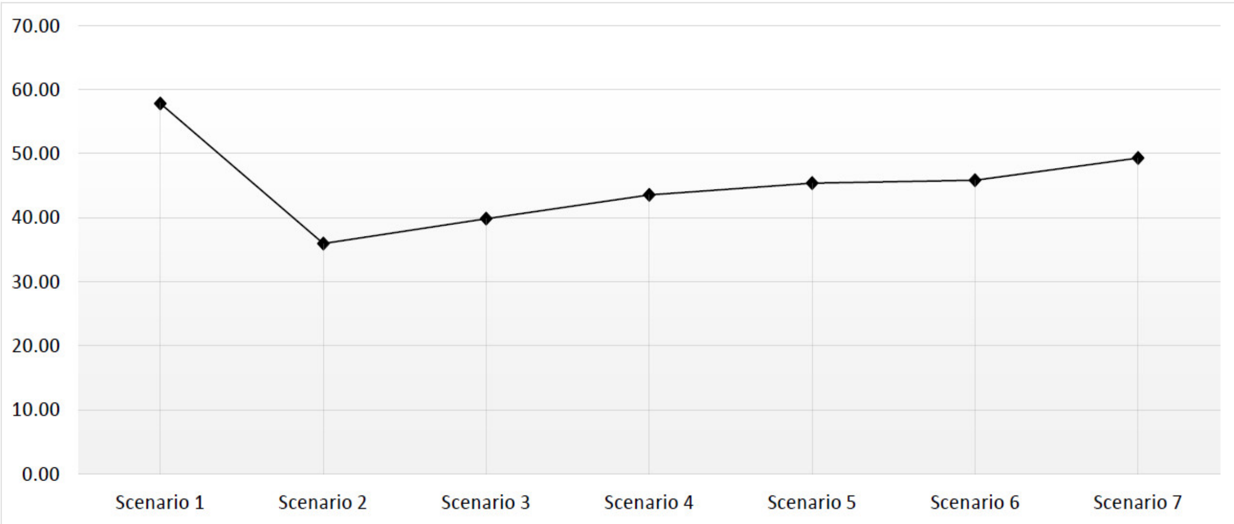

Figure 4. Berth occupation ratio (%). The berth occupancy ratio in seven simulated scenarios.

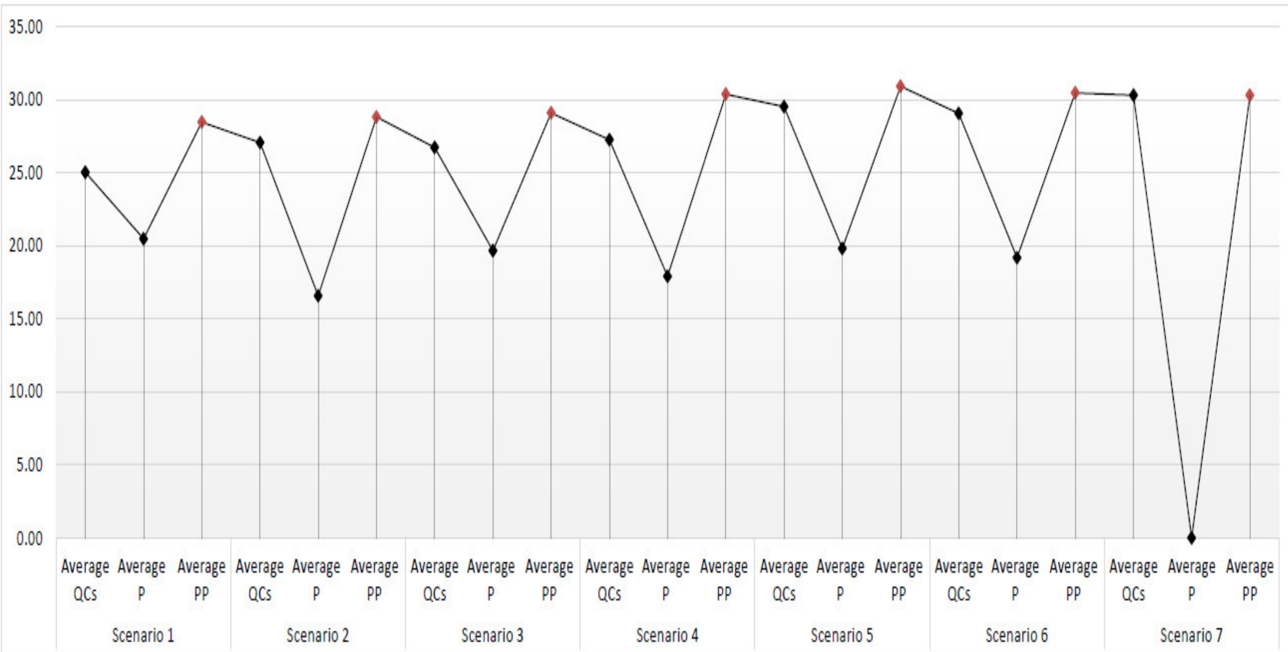

Figure 5. QC moves per hour. The average number of moves per hour performed by the P QCs and the PP QCs. It also shows the average total number of moves per hour by all eight QCs in seven simulated scenarios.

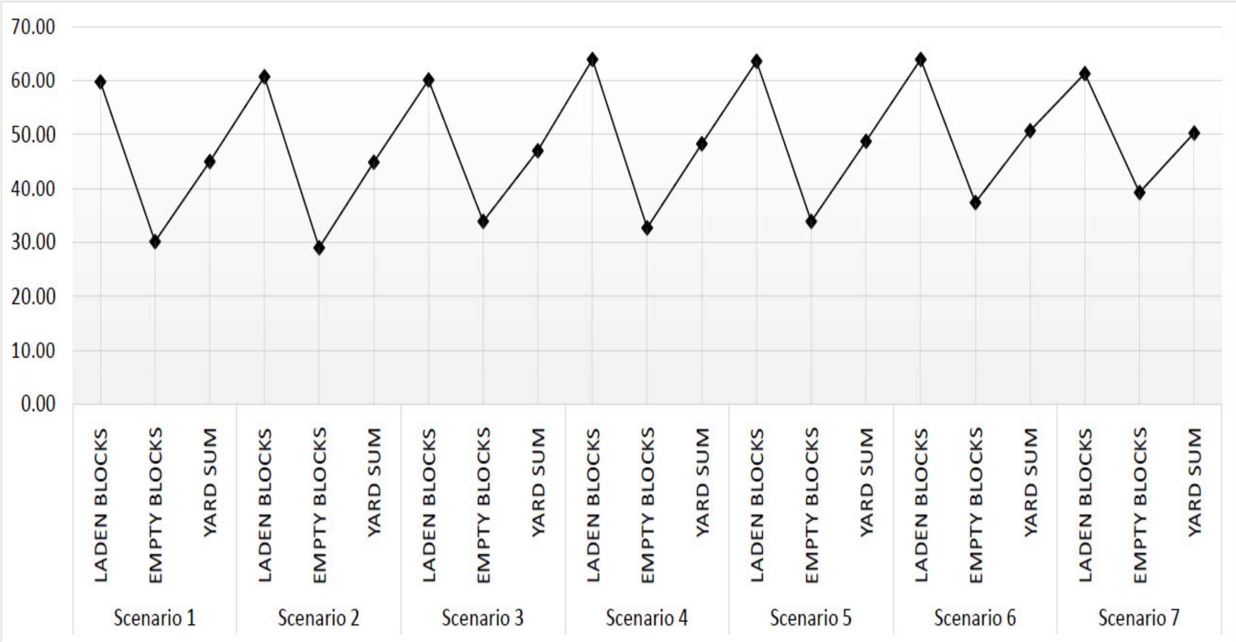

Figure 6. Yard utilisation (%). The average occupancy of the whole yard area as well as separately, i.e., the average occupancy of a zone with blocks for full containers as well as a zone with blocks for empty containers for all seven simulated scenarios.

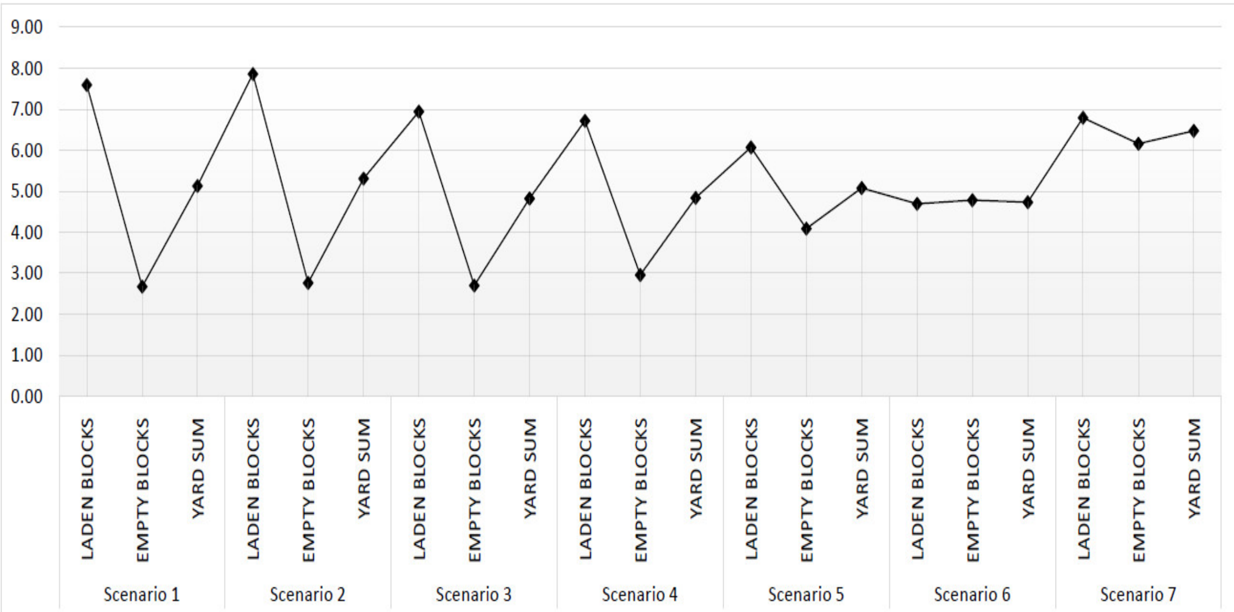

Figure 7. YC waiting time (min). It represents the average waiting time of all YCs, as well as separately the average waiting times of YCs positioned in the full container zone and the average waiting time of YCs in the empty container zone.

To make the analysis more transparent, the results for each subsystem are presented separately. This makes it easier to see how each scenario affects the subsystems.

4.1. Berth

In the berth subsystem, QC utilisation ranged from 34% to 45%. The smaller cranes recorded a slightly higher percentage (36.87%) only in scenario 1, when many feeder and Panamax services arrived at the terminal, while from scenario 2 onwards, when the number of services decreased, their utilisation was also lower (up to 22%). This was also influenced by the fact that two larger, faster and more efficient PP QCs were installed at berth 1. The performance of the PP QCs was particularly important to our study because their optimal performance is key to handling larger services. Like the smaller cranes, they achieved the highest operating percentage (53.84%) in scenario 1. Later, as the quay length increased, their operating share decreased significantly at first, but increased again from scenario 4. Nevertheless, it never exceeded 46%.

This means that the performance of the QCs did not exceed the maximum utilisation rate, which had an extremely positive effect on the length of time ships stayed at the terminal and consequently on the berth occupancy rate. This must be kept as low as possible if the terminal is to increase its traffic and accommodate new services. It ranged from 36% to 58% in all scenarios. The highest value was recorded in scenario 1, which is understandable given the short quay length and traffic volume. The results were particularly good in the last scenarios, when the terminal had the highest number of PP ships and a traffic volume close to 1 million TEU. In this case, the berth occupancy rate did not exceed 50%, which means that there is still room to increase traffic at the terminal without causing overcrowding and lowering the operating level, which would be a concern if the occupancy rate exceeded 65%.

The productivity of the QCs was also very good, averaging 25 to 30 movements per hour. The P QCs performed between 17 and 21 movements per hour in all scenarios, which is fully in line with realistic data for comparable ports, while the PP QCs achieved between 29 and 31 movements per hour, which is an extremely good result for smaller ports that want to handle large vessels quickly and efficiently.

4.2. Yard

The utilisation rate of the yard area gradually increased with the increase in terminal traffic. It reached its highest percentage in scenarios 6 and 7, when it averaged 50%. The highest percentage, which was already close to the critical limit of the recommended level (65%), was observed in the full container blocks from scenario 4, when the traffic volume increased to 844,000 TEUs and more. At that time, the percentage was between 61% and 64%, which could lead to congestion problems and lower productivity in the yard and consequently at the berth if the traffic volume continued to increase and the storage area was not optimised. No problems were identified with the empty container blocks, as utilisation did not exceed 40% even in scenario 7, when terminal throughput was nearly 1 million TEUs.

In the zone with full containers, the YCs waited the longest in scenario 1, and then the wait time decreased until scenario 6, where it reached a low of 4.7 min. In the empty container blocks, the situation was somewhat different. In the first three scenarios, the waiting time did not exceed 3 min, but from scenario 4 it increased slightly due to the increased traffic in the terminal. As expected, the longest waiting times in both zones occurred in scenario 7, when the traffic volume reached almost 1 million TEU annual throughput. YCs waited longest for transfer mechanisation in the more distant import blocks and less in the export blocks closer to the quay.

5. Discussion and Conclusions

The paper presents the results of simulations performed on a hypothetical container terminal of small size (63,000 TEU). The main objective of the paper was to determine whether a yard positioned perpendicular to the quay with the use of ShCs for transfer purposes could achieve good productivity effects both at the berth and in the yard area of a small container terminal. From the literature reviewed, it appears that such a layout is very efficient for large, sophisticated terminals, but not common for smaller terminals. To this end, we ran simulations in seven scenarios, slightly changing the terminal's characteristics in each scenario and gradually increasing the volume of the incoming ship services, and consequently the annual throughput, up to 1 million TEUs.

Simultaneous reception and efficient handling of multiple PP vessels is crucial for smaller ports today, as the size of new buildings is constantly increasing, and with it the pressure from shipowners to handle them quickly. This is only possible if the physical capacity of the terminal is adequate and the productivity of the berth is high in the first phase, but the productivity of the yard must also be at the same level, otherwise congestion and bottlenecks will occur, which in turn will reduce the productivity of the berth. The simulation results showed that perpendicularly positioned blocks with ShCs make sense from an operational point of view and are very efficient, even for terminals with smaller capacities. The results obtained at the berth were very good, as the PP cranes were utilised on average less than 50% when the traffic volume increased and reached up to 31 movements per hour, allowing for high productivity of the berth itself and fast ship turnaround in the port. The yard also performed well, with an average utilisation rate of 50% or less, while the full container blocks achieved a slightly higher utilisation rate, the capacity of which is also expected to increase with additional services.

Comparing the obtained results with those published in previous research where simulations were performed using the same methodology on a hypothetical terminal with a parallel arrangement of blocks to the quay, it can be seen that they are very similar. The PP QCs achieved a similar percentage until scenario 4; from then on, better results were obtained with a perpendicular block arrangement. The productivity of the QCs is also similar, but the increase in traffic to 844,000 TEU results in slightly better productivity with perpendicular blocks. Berth occupancy is very similar, with negligible differences between the two layouts, especially up to scenario 6. In the last two scenarios, the quay empties faster in the perpendicular layout. On the other hand, the largest difference in storage areas is observed from scenario 5 onwards, when the perpendicular layout is slightly better and the waiting time for YCs on ShCs is also shorter. It can be seen that as the traffic volume increases, the choice of perpendicular block arrangement is more favourable, which is understandable since this arrangement is more common for larger terminals with high traffic volume than for smaller terminals. Nevertheless, the results of the two studies are comparable and relevant.

We therefore conclude that even for smaller terminals, it would make sense to arrange the yard perpendicularly, as this would produce the best results. However, this would require a high coordination effort between the handling equipment, and last but not least, major optimisation measures through changes in the storage areas and the operating system, which would be a major financial burden for the already existing smaller ports. The perpendicular block arrangement therefore offers itself as a good alternative to the conventional block arrangement, especially when building new terminals. There, such an arrangement would lead to excellent productivity results.

Since the previously published simulation results of CT with parallel block arrangement differ only slightly or negligibly from ours in many cases, this means that they are still excellent. A smaller terminal with a parallel storage layout that currently uses passive transfer mechanisation could therefore achieve extremely good throughput performance simply by switching to ShCs, which is of course less expensive. This would involve much less terminal restructuring intervention, which consequently means much less cost to the ports. However, the choice of port usually focuses on temporary productivity improvements with the existing operating system, such as acquiring an additional amount of mechanisation already in use at the terminal or changing the storage method. In summary, the results show how important the selected handling mechanisation and terminal layout are for the performance of the selected terminal. This is especially true when we aim for maximum productivity in a limited space. The paper is certainly an added value for port and terminal operators, as it allows them to make better planning decisions and prepare a port strategy.

As the size of ships has increased during the simulation period, our further research will focus on optimisation measures to berths and yard subsystems in smaller ports to accommodate ships with a capacity of 15,000 TEU.

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