ORIGINAL RESEARCH (AR) DOI: 10.4274/jems.2024.59862

Journal of ETA Maritime Science 2024;12(3):319-331

Simulation Modeling Frameworks for Single-Cycling and Double-Cycling Strategies in Container Terminals

Gonca Tuncel[1], Özgür Yalçınkaya[2], Elvan Deniz[3], Soner Esmer[4]

[1]Dokuz Eylül University, Department of Industrial Engineering, İzmir, Türkiye
[2]Dokuz Eylül University, Graduate School of Natural and Applied Sciences, İzmir, Türkiye
[3]Çanakkale Onsekiz Mart University, Çan Higher Vocational School, Çanakkale, Türkiye
[4]Kocaeli University, Department of Maritime Business Administration, Kocaeli, Türkiye

Abstract

Container terminals are among the most critical parts of transportation systems. Reducing the ship turnaround time increases terminal efficiency and enhances global trade volumes. Such time reductions can be achieved by improving the operational efficiency of major resources at container terminals. Quay crane operating strategies are crucial for assessing the performance of container terminals. Simulation models are effective and reliable methods for interpreting and improving complex systems. This study proposes simulation models that include container loading and unloading tasks in marine container terminals implementing single-cycling and double-cycling strategies. Double-cycling is a quay crane operating strategy that attempts to improve container handling efficiency. The system was modeled using ARENA simulation software. The implementation results of the single-cycling and double-cycling strategies were compared in terms of the performance criteria, such as the utilization rates of the quay crane and yard trucks, ship turnaround time, and operating cost.

Keywords: Container terminal, Quay crane, Double-cycling, Simulation

1. Introduction

Container terminals are service businesses located over global distribution systems, and they are particularly concentrated on main trade routes serving global supply chains. Most container terminals have three types of handling equipment: quay cranes (QCs), yard cranes (YCs), and yard trucks (YTs). QCs, which are the basic equipment of the handling process and are located on the quay wall, significantly affect the operational efficiency of container terminals. Potential disruptions, such as the inefficient operation of QCs in any logistic process at the port, can affect the speed of handling operations and increase the turnaround time of the ships. Ships waiting at the quay prevent cargo owners from receiving their cargo at the scheduled time and also increase container terminal costs. Single-cycling and double-cycling strategies can be applied in the operation of QCs. Container terminals require a flexible decision-support tool that includes logistical processes related to handling, port transportation, and storage, can measure the performance of terminal equipment, provide timely information regarding bottlenecks, and evaluate different alternatives. Changing parameters in real-life systems, such as container terminals, carries some risks. Instead, it is much more advantageous to model the system and conduct experiments on the system model. Simulation can be used as an analysis method in planning and developing processes by conducting experiments on models [1]. This study consists of two parts that align to develop flexible simulation models applicable to all terminals by measuring the performance of container terminal handling operations using simulation models. The terminal operating system includes a QC and a Rubber Tyred Gantry (RTG) YC working with YTs. The first simulation model was implemented with the single-cycling strategy, and the second simulation model was implemented with the double-cycling strategy. Although a growing number of researchers have addressed the problems

Address for Correspondence: Gonca Tuncel, Dokuz Eylül University, Department of Industrial Engineering, İzmir, Türkiye
E-mail: gonca.tuncel@deu.edu.tr
ORCID iD: orcid.org/0000-0002-4237-1358

Received: 10.01.2024
Last Revision Received: 30.07.2024
Accepted: 03.08.2024

To cite this article: G. Tuncel, Ö. Yalçınkaya, E. Deniz, and S. Esmer, "Simulation Modeling Frameworks for Single-Cycling and Double-Cycling Strategies in Container Terminals." *Journal of ETA Maritime Science*, vol. 12(3), pp. 319-331, 2024.

of port design and operation, quite little attention has been given to investigating different QC operating strategies to improve the productivity of container handling components such as QCs, RTG cranes, and YTs.

In this paper, after an overview of the literature, single-cycling and double-cycling strategies are described. The simulation models developed for single-cycling and double-cycling cases are then presented. In addition, system performance concerning the considered measures was examined. Finally, the conclusions of this study and possible research directions are discussed.

2. Literature Review

"The QC double-cycling problem" (QCDCP) is well-known as the "QC scheduling problem" (QCSP), whose main issue is to find an entire QC working schedule that typically aims to reduce the operation time of the ship. The first scientific research on sequencing problems in double-cycling (or dual-cycling) operations was initiated by Goodchild and Daganzo [2]. The authors introduce a model expressed as a two-machine flow-shop SP to determine the permutation of stacks for a double-cycling operation flow. In their next study, the authors [3] presented the double-cycling effect on port operations, including crane, ship, and berth efficiency. The proximal stack strategy was described for double-cycling, and its effectiveness was assessed. The impact of the double-cycling strategy on the landside transportation operations was then evaluated. The authors report that double-cycling can decrease processing time by 10% by improving ship, crane, and berth efficiency. Zhang and Kim's study [4] expanded the problem to include multiple hatches. The objective of this study was to minimize the processing cycles of QC during loading/unloading operations in a ship bay. This is, of course, possible by maximizing the number of double-cycling operations. The authors developed a mixed IP (MIP) model for this purpose. A hybrid heuristic method was used to resolve this problem. Implementing a double-cycling strategy in terminals requires only functional changes without the need to purchase additional equipment. In addition, the YT operation method must be altered from the assigned system to the pooling system. The following year, some other authors studied the same problem involving YCs and YTs. Nguyen and Kim [5] used a modified MIP model and a heuristic algorithm to minimize the empty move seconds of YTs by the QC double-cycling method. A simulation technique was employed to evaluate the effect of unloading and loading schedules and storage plans for unloaded containers on the system efficiency, including the percentage of double-cycling operation of YTs. The authors note that the process type of QCs has a significant impact on the performance of YT processes. They considered the unloading of vehicles (YTs). Nevertheless, the unified scheduling of vehicle routes, YC processes, and QC processes can be considered in future studies. Additionally, the storage spaces of loaded containers should be considered in the context of YTs. By considering the features of double-cycling operations, Meisel and Wichmann [6] studied the problem of container sequencing for reshuffles in a shipping bay. An integer programming (IP) model and a heuristic solution method were used to arrange crane operations in internal reshuffles. The results provided insights into the performance enhancement of internal reshuffles associated with a single application of double crane cycling. The QCSP and other SPs in seaside planning and operation have been intensively reviewed by Bierwirth and Meisel [7,8]. Another study, which considered a more complex scenario considering hatch covers, was conducted by Lee et al. [9]. Liu et al. [10] investigated models and algorithms for general QCDCP with internal reshuffles. The integrated DCP of QCs and YCs was considered by Zhang et al. [11]. The aim was to minimize the processing time of QC and YC. They formulated a MIP model for the two-stage double-cycling process of container terminals. Numerical exercises showed that the specified model and algorithm were more efficient in terms of lower bounds presented in previous studies. In the same year, Zeng et al. [12] developed a scheduling model and designed algorithms for QCDCP. A MIP model was formulated to develop a stacking plan for outbound containers and the process order of QCs to increase the performance progress of the QCDC. Double-cycling QCSP was also investigated by Wang and Li [13]. The problem is presented as a two-machine non-permutation flow-shop scheduling model, and a composite heuristic for the problem is described. Zhang et al. [14] proposed "a mixed storage strategy" for horizontal transportation associated with the QCDCP to enhance the performance of yard processes. The authors discussed the impact of the mixed storage strategy on QC double-cycling operations. In light of the numerical results, the authors report that using a hybrid storage strategy and double-cycling can decrease the number of YTs per QC, the operation time of the YC, and the length of the YT travel. Although double-cycling increases the port capacity, some ports are reluctant to implement this strategy. In the same year, Ku and Arthanari [15] considered the multi-QCDCP. The problem was formulated as a MIP model and a two-stage hybrid heuristic approach was presented for double-cycling QCSP in numerous hatches. The process involves two stages: intra-phase and inter-phase sequencing. A mathematical model was presented by Chu et al. [16] for the "multiple-QC sequencing problem" with the strategy of double-cycling. An algorithm was designed based on Lagrange relaxation to solve the model. In addition, Kamble et al. [17] investigated the implementation barriers of a double-cycling strategy in

Indian ports. The authors concluded that the ability to use information technologies in ports and to integrate with other ports and partners is the primary barrier to implementation. On the other hand, Zhang et al. [18] focused on the complete handling efficiency and system strength of container terminals. The performance of double-cycling operations based on different equipment variations is analyzed using Tianjin port data. Tang et al. [19] developed "an agent-based simulation model" to define QCs, YCs, and YT operation processes. They concluded that peak shaving is a promising strategy for QC double-cycling. Ahmed et al. [20], presented a container handling strategy to improve terminal operations and minimize unit cost by applying double-cycling of YTs. The authors developed simulation models based on a real-life case study considering the uncertainties in the work task duration. Zhang et al. [21], proposed an automated guided vehicle (AGV) SP with multi-QC by employing the double-cycling strategy. The main objective was to minimize the total waiting time of AGVs and propose an AGV scheduling model with a high loading rate. A container planning sequence based on the Hybrid Particle Swarm Optimization algorithm with a penalty function was obtained for a time interval to the arrival of AGVs at the quayside. Minimizing the empty AGV trips could improve the container terminal transporting efficiency in terms of time. Zhu et al. [22], applied a mixed storage strategy for port-handling operations to accommodate double-cycle scheduling plans in container terminals. Fontes and Homayouni [23] investigated the joint SP of QCs and speed-adjustable AGVs under the double-cycling strategy. The authors address the energy consumption of seaports. In the same year, Wei et al. [24], investigated the energy efficiency optimization problem of automated QC operation sequences with time window constraints. A corresponding MIP model was established by decomposing the automated QC operations. The proposed double-cycle model was not combined with internal truck scheduling. Yue et al. [25] addressed the block allocation problem for inbound and transshipment containers based on a multi-ship block-sharing strategy, which can enhance the double-cycling of AGVs and YCs. The authors presented a two-stage MIP model that minimizes the handling cost. Cai et al. [26], presented a MIP model for the integrated SP of QCs, YCs, and intelligent guided vehicles under the double-cycling mode in a U-shaped container terminal. Li et al. [27] investigated the multiple-equipment integrated SP (MISP) in automated container terminals. The authors focus on optimizing the equipment scheduling and container job sequence in MISP by employing the double-cycling strategy. Tan et al. [28] considered the storage space allocation problem in a container yard under the double-cycle operation mode for internal YTs. Wang et al. [29] studied an integrated SP for automated stacking cranes and AGVs considering direct, buffer, and hybrid modes for transferring containers. The authors developed a genetic algorithm to solve this problem. Based on the double-cycle operations for AGVs, Zhang et al. [30] applied a branch and bound algorithm to assign container tasks to YCs, where two crossover YCs move on different rails.

Although the single-cycling strategy is more commonly employed in practice, a growing body of literature exists on the incorporation of the double-cycling mode in recent years. However, most previous studies only analyzed the YT transportation or the efficiency of equipment, such as QCs and YCs, independently. Scheduling the handling components separately is considered impractical because they involve mutual work tasks [20]. On the other hand, few studies analyzed both QC and YT operations or, in an integrated way, QCs, YCs, and AGVs in automated container terminals. Due to the very different conditions in container terminals, there is still a gap between the requirements of real configuration problems and the status of research. This study aims to develop flexible simulation models that can be applied to all container terminals by modifying only the system parameters for analyzing the handling performance. The first of the simulation models was applied to a single-cycling strategy, and the second was applied to a double-cycling strategy. This study differs from the literature in terms of measuring the loaded and unloaded travel time ratios of the YTs for both strategies.

3. Modeling QC Operating Strategies

3.1. Single-Cycling Strategy

Single-cycling strategy is an operating technique in which containers are loaded in the ship bay after the QCs complete unloading tasks. With the single-cycling strategy applied using a single QC and a single bay, the handling operation starts with the arrival of the ship. The QC starts the container handling process from the related pre-planned bay. It loads the related container onto the YT, which takes it to the stockyard. The RTG stacks the containers in the stockyard, and the YT is released. The QC performs either loading or unloading activities in each cycle, covering the crane's round trip between the ship and the shore. After the unloading tasks are completed, the containers to be transported to the same ship are loaded onto the YTs by the RTG in the relevant stockyard. The YT is released once a container is delivered to the QC. The QC then loads the container onto the ship and completes the handling operation in a single cycle.

3.2. Double-Cycling Strategy

Double-cycling strategy is an operating technique in which QCs simultaneously perform their loading and unloading tasks in the same ship bay. In the double-cycling strategy implemented using a single QC and a single bay, the QC starts the container handling process from the relevant bay and loads the related containers onto the YTs, which transport them to the stockyard. The RTG then unloads the YTs and stacks the containers in the yard blocks. Unlike single-cycling, the released YTs do not return empty. Instead, they are directed to the nearest stockyard where the containers are loaded. The containers to be transported by the ship are loaded onto the YTs by the RTG in the yard. Once the QC picks up the container, the YT is released. The container is then loaded onto the ship by the QC, and the handling process is completed in the same crane cycle. The double cycle continues until the handling of the ship bay is completed. Single-cycling and double-cycling strategies are compared in Figure 1.

4. Simulation Modeling Frameworks

We developed two simulation models for a case study based on a real container terminal. Single-cycling and double-cycling strategies are employed in each model. The main resources defined in these models are QC and RTG cranes. In addition, the use of one or more YTs is allowed in the process. The process flows of the single-cycling and double-cycling strategies are presented in Figures 2 and 3, respectively.

The parameter values were set based on the work-study conducted during terminal visits and interviews with operation managers. After data collection and evaluation, simulation models are created depending on the determined processes and identified routes. The operation of the considered simulation model is based on the following assumptions:

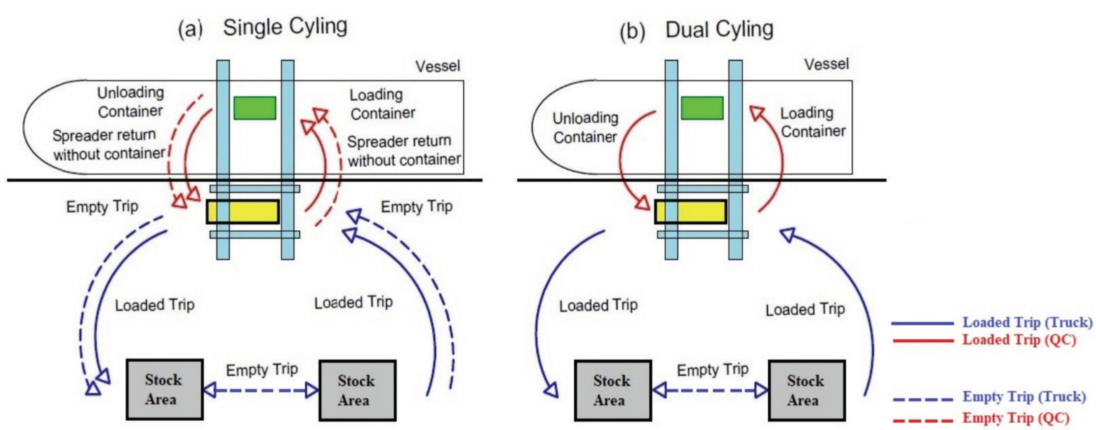

Figure 1. *Comparison of single-cycling and double-cycling strategies [31]*

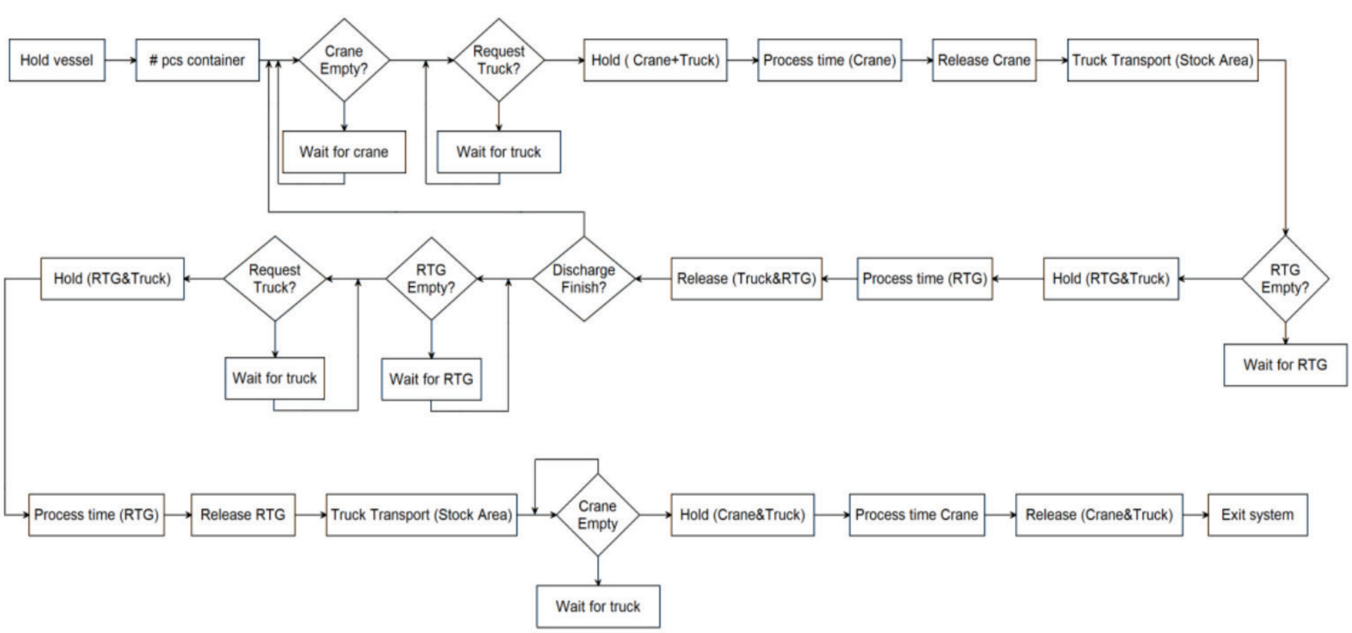

Figure 2. *Flow chart of the single-cycling strategy*

• One QC, one RTG crane, and one or more YTs are in the system.

• Containers to be loaded or unloaded during ship operation are 40 feet.

• The handling time of work tasks by the QC is generated from a uniform distribution with a range, [2 min.+uniform (0;0.5)], and the processing time for unloading/loading by the RTG is also generated from a uniform distribution with a range, [5 min.+uniform (0;1)].

• The YT velocity was assumed to be 20 km per hour.

We used ARENA 14.0 simulation software to build the simulation models for the container terminal. The developed models are generic and can be easily adapted to changing operating conditions. The elements of the simulation models are given in Figures 4 and 5 for the single-cycling and double-cycling models, respectively.

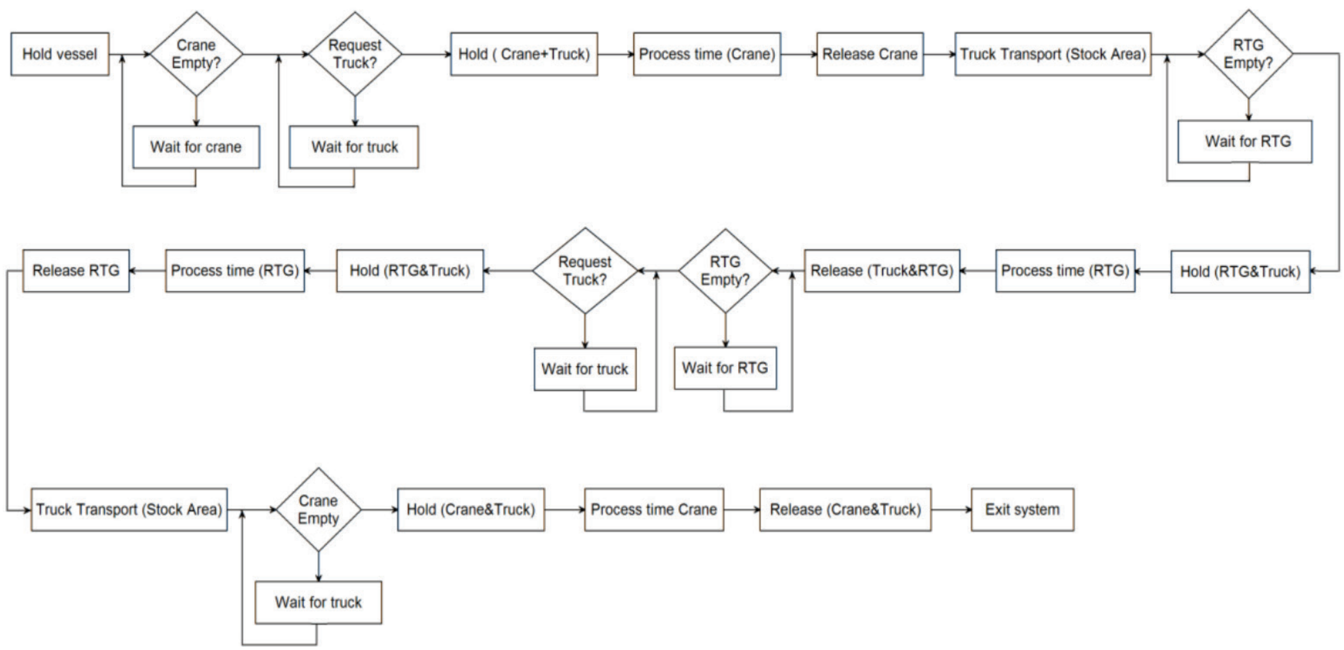

Figure 3. Flow chart of the double-cycling strategy

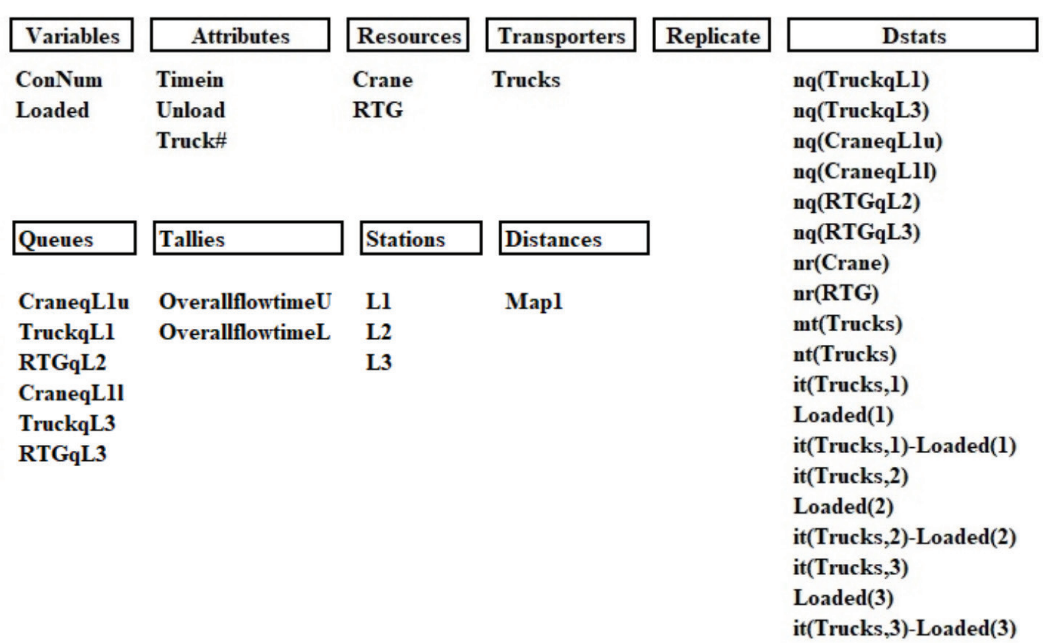

Figure 4. Elements of the single-cycling model

4.1. Elements

Attributes; Timein is the record of the loading and unloading service times of the containers, and Unload is the record of the YTs' loading and unloading service times.

Resources; The following two resources were defined in the simulation model:

- Crane
- RTG

Queues; The following nine queues were defined in the simulation model:

- Craneq
- RTGq
- Truckq
- CraneqL1u
- RTGqL2
- TruckqL1
- CraneqL1l
- TruckqL3
- RTGqL3

Variables; ConNum is implemented as a counter to determine the number of containers unloaded from the ship.

Loaded is a variable used to determine the container-loaded YT rate.

Dstats; Statistics on the utilization rate of each resource, and the average number of containers waiting in each queue are recorded.

Tallies; Tallies are defined as the record of the overall flow time of containers and the time spent on containers (loading and unloading).

Replicate; The replication number was set to 10.

Transport; The transporter element describes the operating characteristics of the transporters used in the model. A transporter type (YT) is identified in the simulation model.

Distances; The distance between all stations is shown on the transporter's system map.

Stations; The three stations L1, L2, and L3 were defined in the simulation model.

4.2. Blocks

The effectiveness of the QC operating strategies was tested using the simulation models. The first simulation model was developed by applying the single-cycling strategy, where the loading tasks of the containers onto the ship started after the unloading of the ship was completed. In the second simulation model, handling operations are carried out simultaneously by unloading the inbound containers from the ship and loading the corresponding outbound containers onto the ship in a double cycle. The entities in the proposed models represent 40' containers.

Figure 6 shows the blocks of the single-cycling model. Container/Entity arrivals are defined in the "Create" block for containers. Each created entity is transferred to the "Assign" block with m attributes and is unloaded. Then, they join the L1 station, and their handling operations (loading or unloading) are checked in the "Branch" block. Containers join the QC queue for unloading operations, are seized by

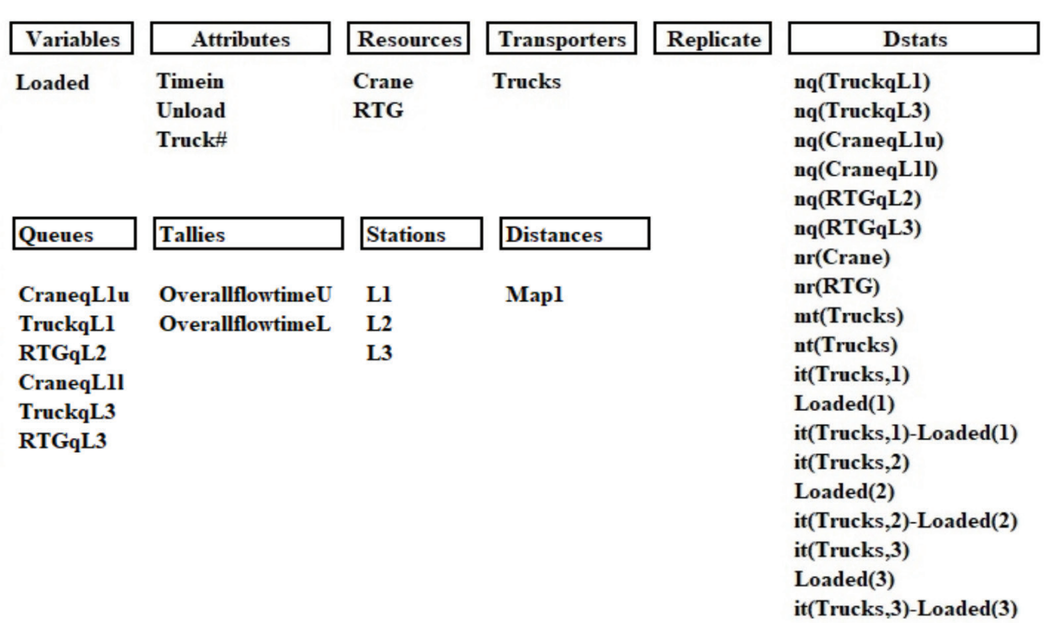

Figure 5. *Elements of the double-cycling model*

the QC, and spend operation time in the "Delay" block. The QC then releases the containers. YTs are requested for containers from the L1 station to the L2 station by the "Request" block. After the loaded variables are assigned in the "Assign" block, the YTs transport the containers in the "Transport" block. The containers join the RTG queue after seizing the RTG and spend the operation time in the "Delay" block. Later, the container releases the RTG and YT. The loaded and ConNum variables are assigned in the "Assign" block. In the "Branch" block, containers are unloaded from the ship. After joining the "Tally" block, which records the handling operation times, the container exits the system via the "Dispose" block. If the container's ConNum is equal to the number of containers in the "Branch" block, the container joins the "Duplicate" block. Containers are created in the "Duplicate" block to start the loading process. Unload, Timein, and m (enter systems) are assigned in another "Assign" block. Then, the RTG is seized and the operation time is spent in the "Delay" block. Afterward, the RTG is released. YTs are requested to be transported from the L3 station to the L1 station by the "Request" block. The loaded variables are assigned in the "Assign" block after the YTs are transported from the L3 station to the L1 station in the "Transport" blocks. Containers join the QC queue for loading, seize the QC, and spend operation time in the "Delay" block. Then, the QC is released by the "Release" block and the YT is set free. After the "Tally" block records the handling operation times, the container exits the system via the "Dispose" block.

Figure 7 shows blocks of the double-cycling model. The entities created in the first "Create" block leave the system by the "Dispose" block after the signal codes are generated and defined in the "Signal" block. In the second "Create" block, entities representing containers are created and entered into the system. Each created entity is transferred to the "Assign" block with *m* attributes and unloaded, as in the single-cycling model. Then, the related container is redirected to the L1 station, which is assigned to the "Station" block. The container arriving at the "Branch" block is put into the QC queue by activating the "Queue" block according to the probability of unloading=1 if it is unloaded from the ship and the probability of unloading=0 if it is loaded onto the

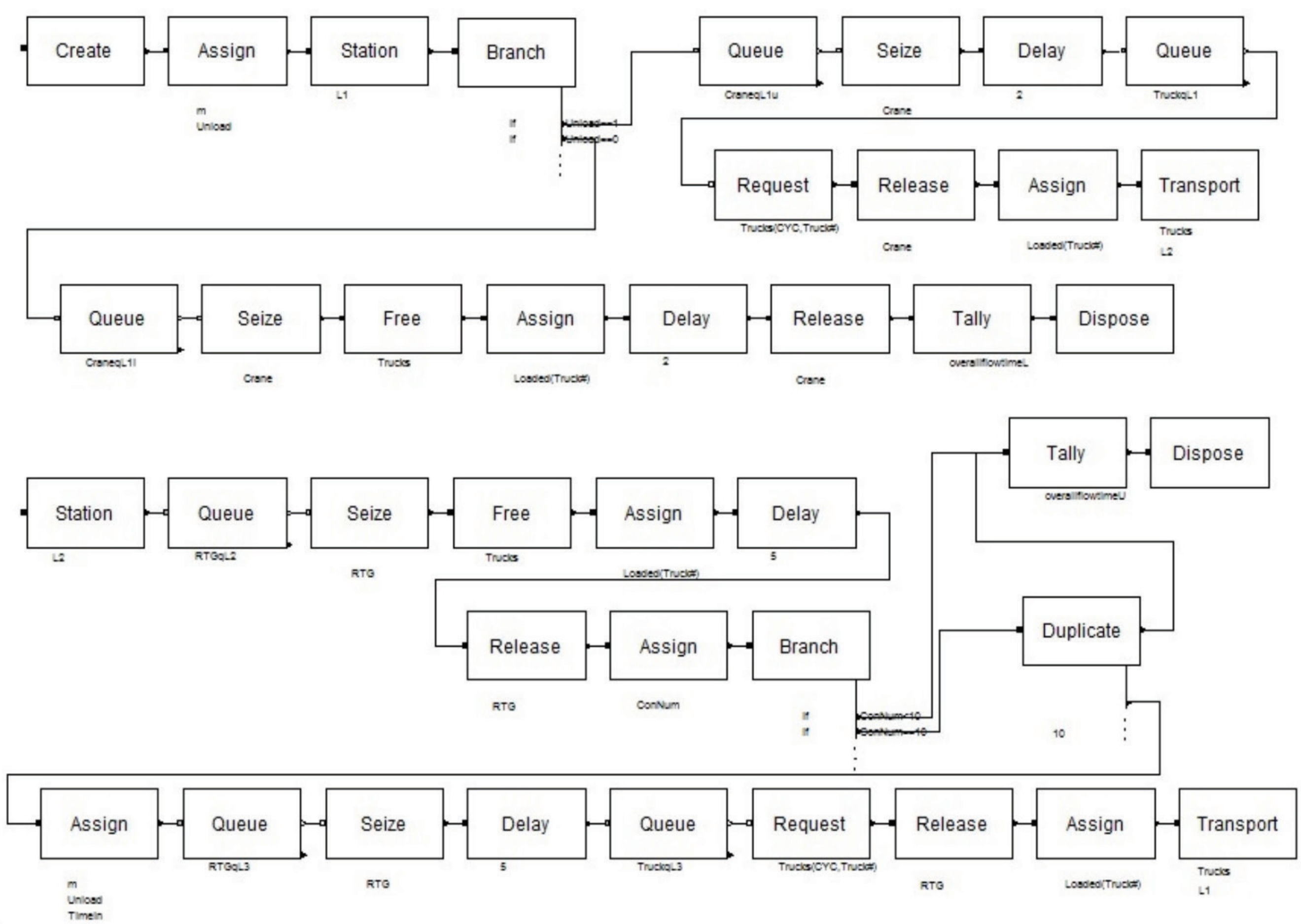

__Figure 6.__ Blocks of the single-cycling model

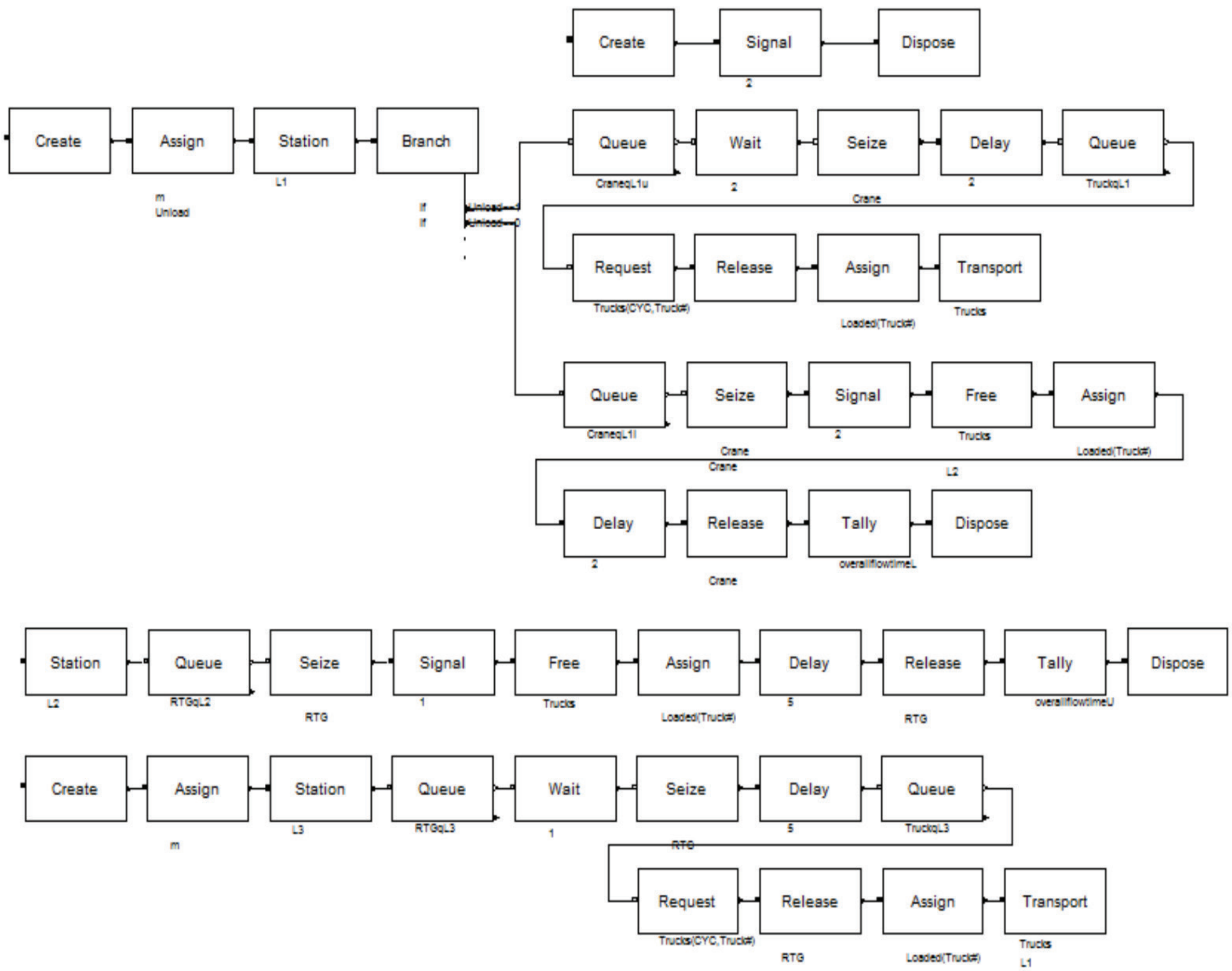

__Figure 7.__ Blocks of the double-cycling model

ship. Then, the "Wait" block keeps the movements of the container on hold until the signal code arrives from the "Signal" block. In the meantime, the container seizes the QC by the "Seize" block to initiate the unloading process and releases the source (QC) it holds by the "Release" block at the end of the operation time in the "Delay" block. The YT is requested through the "Request" block, and the arriving YT joins the queue. After the loading task is executed, the value of the loaded variable is incremented in the "Assign" block. The YT transports the container by the "Transport" block to the relevant station. The loaded YT arriving at the L2 station waits in the RTG queue. The container released with the signal code in the "Signal" block, seizes the RTG by the "Seize" block. The YT is released in the "Free" block by reducing the value of the loaded variable, which acts as a counter, after activating the "Assign" block. At the end of the operation time in the "Delay" block, the container releases the source (RTG) it holds by the "Release" block. After the "Tally" block records handling operation times, the container exits the system via the "Dispose" block.

In the third "Create" block, entities are also defined as containers. They enter the system and are directed to the "Assign" block. After joining the L3 station (Stock Yard Area) and the RTG queue, the containers wait for the signal in the "Wait" block and then seize the RTG. It spends the operation time in the "Delay" block and then releases the RTG. Next, the YT is requested to travel from the L3 station to the L1 station by the "Request" block. Loaded variables are assigned in the "Assign" block, and the "Transport" block transports the containers by YTs. The containers join the QC queue, send the signal in the "Signal" block, seize the QC, and spend the operation time in the "Delay" block. Then, it releases the QC and sets the YT free. After the "Tally" block records handling operation times, the container exits the system via the "Dispose" block.

5. Implementation Results

The system performance was measured in the following ways:

• Time periods are defined and constituted using the tally element,

• Resource, transporter, and queue statistics are determined using the Dstats element,

Two tally variables were defined: Overall Flow Time (Overall_Flow_TimeU and Overall_Flow_TimeL) and replication ended time. Statistics regarding the utilization rate of each YT and source in the Dstats element and the average number of containers waiting in the queue were also recorded and displayed as simulation results based on the changes in the Tally variables and the discrete change variables. The implementation results of the single-cycling and double-cycling models are summarized in Figures 8-15.

Figure 8 shows the total operation time of the single-cycling model. The total operation time decreased from 242.53 to 119.02 minutes.

As can be seen in Figure 9, the total operation time decreased from 263.12 minutes to 119.02 minutes in the double-cycling model. Note that the total operation time achieved with ten YTs in the single-cycling model is achieved with four YTs in the double-cycling model.

The average utilization of the QC for the single-cycling model decreased from 53.65% to 33.61% when the number of YTs increased from 1 to 10 (see Figure 10).

Figure 11 shows the average utilization rate of the QC for the double-cycling strategy. The average utilization rate increased from 15.20% to 33.61% as the number of YTs increased.

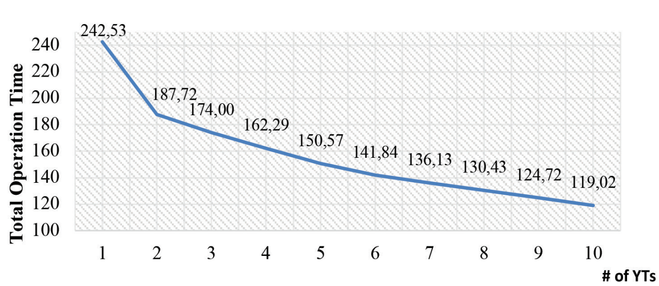

***Figure 8.** Total operation time of the single-cycling model*

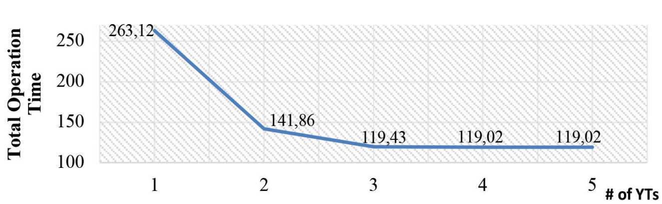

***Figure 9.** Total operation time of the double-cycling model*

In Figure 12, another discrete-change variable called the average utilization of YTs is given. It can be seen that the average utilization of the YTs for a single-cycling model is 94.23% for one YT and that the minimum average utilization of the YTs is 21.69% for ten YTs.

As shown in Figure 13, when the number of YTs increases from 1 to 5, the average YT utilization rate decreases from 46.79% to 42.75%.

Loaded and unloaded travel times were measured in the single-cycling model simulated from one YT to 10 YTs.

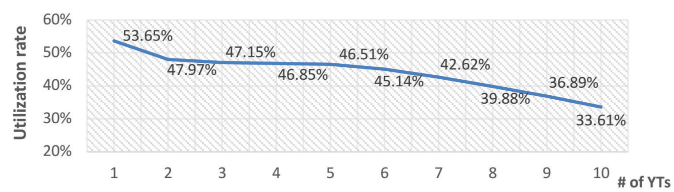

***Figure 10.** Average utilization rate of the QC in the single-cycling model*

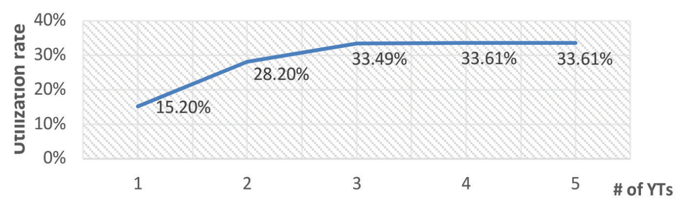

***Figure 11**. Average utilization rate of the QC in the double-cycling model*

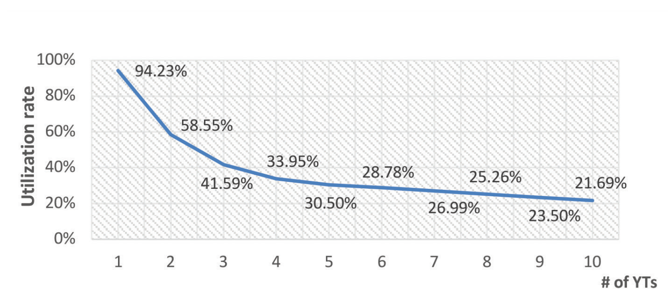

***Figure 12**. Average utilization rate of the YTs in the single-cycling model*

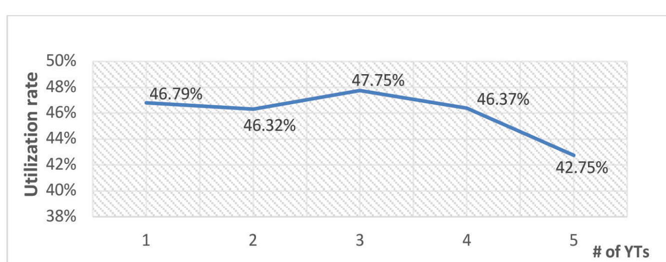

***Figure 13**. Average utilization rate of the YTs in the double-cycling model*

Table 1. *Average travel time ratios of loaded and unloaded YTs in the single-cycling model*

Number of YTs in the system	Average travel time ratios of loaded YTs in the single-cycling model	Average travel time ratios of unloaded YTs in the single-cycling model
1	0.4953	0.4470
2	0.3280	0.2576
3	0.2531	0.1628
4	0.2266	0.1129
5	0.2233	0.0818
6	0.2292	0.0586
7	0.2299	0.0400
8	0.2272	0.0253
9	0.2219	0.0131
10	0.2144	0.0025

Table 2. *Average travel time ratios of loaded and unloaded YTs in the double-cycling model*

Number of YTs in the system	Average travel time ratios of loaded YTs in the double-cycling model	Average travel time ratios of unloaded YTs in the double-cycling model
1	0.4565	0.0114
2	0.4526	0.0106
3	0.4691	0.0084
4	0.4574	0.0063
5	0.4224	0.0051

Table 1 shows the average travel time ratios of loaded and unloaded YTs in the single-cycling model for each number of YTs operating in the system. When the table is examined, it can be seen that as the number of YTs increases, the general averages of the loaded and unloaded travel time ratios tend to decrease. However, the difference between the average loaded travel time rates after the number of YTs exceeded four is insignificant. On the other hand, the reduction in the overall average unloaded travel time ratio was much more noticeable.

According to Figure 14, as the number of YTs used in the system increases, a significant reduction in the average unloaded travel time ratio is observed for each number of YTs.

Furthermore, loaded and unloaded travel time ratios were measured in the double-cycling model simulated from one to ten YTs. Table 2 gives the average loaded and unloaded travel time ratios for each number of YTs operating in the system. As the table shows, the average loaded travel time ratios of the YTs have an irregular tendency with minor differences in the double-cycling model. Besides, it is seen that as the number of YTs increases, the average unloaded travel time ratio of the YTs decreases significantly.

As shown in Figure 15, the average unloaded driving time ratio for each number of YTs was negligible compared to the single-cycling model. The implementation results showed that the unloaded driving time ratio for each number of YTs was higher in the single-cycling model than in the double-cycling model. The double-cycling model has been shown to reduce travel rates for empty YTs. Moreover, in terms of the total operation time, four YTs for completing the handling operation employing the double-cycling strategy would be a preferred choice, whereas ten YTs would be the preferred choice for the single-cycling strategy.

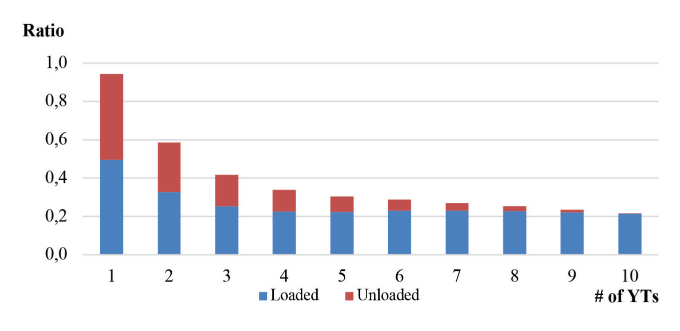

Figure 14*. Average loaded and unloaded travel time ratios for each number of YTs in the single-cycling model*

Table 3 summarizes the performance analysis results of the single-cycling strategy for one to ten YTs and the double-

Table 3. Performance analysis results of implementation scenarios

Number of YTs	Single-cycling			Double-cycling			Productivity improvement		Time saved		Cost saved	
	Productivity rate (TEUs/hr)	Average turnaround time (hrs)	Operating cost (US$)	Productivity rate (TEUs/hr)	Average turnaround time (hrs)	Operating cost (US$)	TEUs/hr	%	hrs	%	US$	%
1	2.47	242.53	195.77	2.28	263.12	117.64	-0.19	-7.83	-20.59	-8.49	78.12	39.91
2	3.2	187.71	156.59	4.23	141.86	94.17	1.03	32.32	45.85	24.43	62.42	39.86
3	3.45	174.00	147.51	5.02	119.43	96.21	1.58	45.7	54.58	31.37	51.30	34.78
4	3.70	162.29	141.02	5.04	119.02	104.38	1.34	36.36	43.27	26.66	36.64	25.98
5	3.98	150.57	135.55	5.04	119.02	110.08	1.06	26.52	31.56	20.96	25.47	18.79
6	4.23	141.84	131.68									
7	4.41	136.13	127.95									
8	4.60	130.43	123.21									
9	4.81	124.72	117.46									
10	5.04	119.02	110.72									

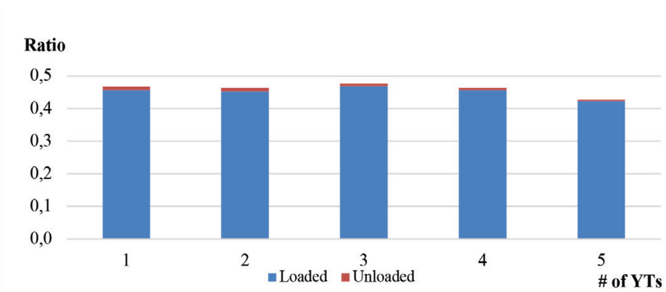

***Figure 15**. Average loaded and unloaded travel time ratios for each number of YTs in the double-cycling model*

cycling strategy for one to five YTs. When the number of YTs exceeds these values, there is no significant increase in efficiency. The operating cost includes the cost of the QC, RTG, and YTs based on their utilization rates, the operator cost, the hourly fuel cost, and the maintenance and repair cost. We draw the following conclusions from the implementation results;

• We note that for the double-cycling strategy to work effectively in this system, at least two YTs must complete the container handling process.

• Compared with the single-cycling strategy, we observe a 45.70% increase in productivity, a 31.37% decrease in the average turnaround time of ships, and a 34.78% decrease in the cost when using three YTs in the double-cycling strategy.

• On the other hand, the highest productivity rate and the shortest ship turnaround time were achieved in the double-cycling strategy when 4 and 5 YTs were used and in the single-cycling strategy when 10 trucks were used. This is consistent with the general expectation; a higher number of YTs will result in quicker responses to the QC unloading and loading cycles and, thus, better performance. However, when we consider the cost of additional YTs as well as the operating cost and the traffic problems that may occur due to the movement of many YTs in the system, the double-cycling strategy is more advantageous.

• Considering productivity and operating costs, the double-cycling strategy employing three YTs is the preferred option for this case study. We can see that increasing the number of YTs does not always increase productivity or reduce costs because inadequate QCs and RTGs increase the idle time of YTs and other handling equipment. Beyond additional YTs, further improvements can be achieved by increasing the number of QCs and RTG cranes, especially when dealing with large ships [20]. It should also be noted that although a double-cycling strategy does not require significant capital investments, increasing the number of cranes requires additional financial resources.

Minimizing empty YT trips and reducing the ship turnaround time can improve terminal productivity in terms of reasonable time and cost. The results of the application study demonstrate the cost and performance differences between handling operations using single-cycling and double-cycling strategies. When the two operational strategies are compared, double-cycling can be seen to provide a remarkable improvement in terms of performance criteria as a cost-effective option.

6. Conclusion

Operational efficiency at container terminals has become one of the most discussed topics in recent years. Global container operators are constantly increasing their ship capacities due to economies of scale. Today, mega ships with a capacity of 24 thousand TEU serve on world maritime routes. Such an increase in ship capacities has also increased the port efficiency expectations. For this reason, ports have had to develop many strategies. At this point, the modernization of equipment is not enough. Operational strategies also need to be reviewed and improved. This paper is a technical study based on these efficiency concerns in ports. QC operation efficiency is one of the vital criteria used to evaluate the performance of terminal operating systems. We developed simulation models for single-cycling and double-cycling strategies to plan QC operations. The simulation results were analyzed in terms of the average driving time for each loaded and unloaded YT, total operation time, and productivity rate. When the two models are compared in terms of the total operation time, the lowest total operation time is achieved when four YTs are used in the double-cycling model and ten YTs are used in the single-cycling model. We note that four YTs with the double-cycling strategy handle the same number of containers in the container terminal. From the viewpoint of firms, the handling operation is carried out by using six YTs less with the double-cycling strategy, which is significantly advantageous in terms of investment and cost. As a result of the implementation study, we observed that the productivity rate in the double-cycling model is higher than that in the single-cycling model. Furthermore, the double-cycling strategy reduced the total cost by decreasing the number of YTs and increasing the efficiency of the cranes and YTs. Therefore, double-cycling operations can be implemented to achieve cost savings and efficient operation in container terminals. One limitation of this study is that it is based on the operating strategies of a single QC in a container terminal layout. It would be insightful to consider multiple QCs operating in different container terminal layouts, such as parallel and U-shaped layouts. The other possible development following this research is to incorporate the breakdown and repair process of the equipment used in the handling process so that realistic factors can be better addressed. Furthermore, Port 4.0, an extension of the Industry 4.0 paradigm to the port and maritime industry, is a growing trend that has the potential to significantly improve efficiency and competitiveness compared to traditional terminals. Automation and integration of container terminals reduce operator workload and minimize human error and delays at ports. In addition, occupational health and safety measures will be provided using intelligent technologies, such as artificial intelligence, and an environmentally friendly structure will be created. As a further research area, similar studies can be conducted by integrating these smart technologies with optimization methods.

Authorship Contributions

Concept design: G. Tuncel, Ö. Yalçınkaya, and S. Esmer, Data Collection or Processing: G. Tuncel, Ö. Yalçınkaya, E. Deniz, and S. Esmer, Analysis or Interpretation: G. Tuncel, Ö. Yalçınkaya, E. Deniz, and S. Esmer, Literature Review: G. Tuncel, and E. Deniz, Writing, Reviewing and Editing: G. Tuncel, and E. Deniz.

Funding: The authors declare that no funds, grants, or other support was received during the preparation of this manuscript.

References

[1] A. Wisniewska, M. Deja, M, Dobrzynski, and M. Siemiatkowski. “Simulation studies into quayside transport and storage yard operations in container terminals”. *Polish Maritime Research,* vol. 24, pp. 46-52, May 2017.

[2] A. V. Goodchild, and C. F. Daganzo, “Double-cycling strategies for container ships and their effect on ship loading and unloading operations”. *Transportation Science,* vol. 40, pp. 473-483, Nov 2006.

[3] A. V. Goodchild, and C. F. Daganzo, “Crane double cycling in container ports: Planning methods and evaluation”. *Transportation Research Part B: Methodological,* vol. 41, pp. 875-891, Oct 2007.

[4] H. Zhang, and K. H. Kim, “Maximizing the number of dual-cycle operations of quay cranes in container terminals”. *Computers & Industrial Engineering,* vol. 56, pp. 979-992, Apr 2009.

[5] V. D. Nguyen, and K. H. Kim, “Minimizing empty trips of yard trucks in container terminals by dual cycle operations”. *Industrial Engineering and Management Systems,* vol. 9, pp. 28-40, Mar 2010.

[6] F. Meisel, and M. Wichmann, “Container sequencing for quay cranes with internal reshuffles”. *OR Spectrum*, vol. 32, pp. 569-591, Dec 2010.

[7] C. Bierwirth, and F. Meisel, “A survey of berth allocation and quay crane scheduling problems in container terminals”. *European Journal of Operational Research,* vol. 202, pp. 615-627, May 2010.

[8] C. Bierwirth, and F. Meisel, “A follow-up survey of berth allocation and quay crane scheduling problems in container terminals”. *European Journal of Operational Research,* vol. 244, pp. 675-689, Aug 2015.

[9] C. Y. Lee, M. Liu, and C. Chu, “Optimal algorithm for the general quay crane dual-cycling problem”. *Transportation Science,* vol. 49, pp. 957-967, Nov 2014.

[10] M. Liu, S. Wang, C. Chu, and F. Zheng, “A branch-and-price framework for the general double-cycling problem with internal-reshuffles”, in *IEEE 12th International Conference on Networking. Sensing and Control (ICNSC),* 09-11 April 2015, Taipei, Taiwan [Online] Available: IEEE Xplore, https://ieeexplore.ieee.org [04 June 2015].

[11] R. Zhang, Z. Jin, Y. Ma, and W. Luan, “Optimization for two-stage double-cycle operations in container terminals”. *Computers & Industrial Engineering,* vol. 83, pp. 316-326, May 2015.

[12] Q. Zeng, A. Diabat, and Q. Zhang, “A simulation optimization approach for solving the dual-cycling problem in container terminals”. *Maritime Policy & Management,* vol. 42, pp. 806-826, May 2015.

[13] D. Wang, and X. Li, "Quay crane scheduling with dual cycling". *Engineering Optimization,* vol. 47, pp. 1343-1360, 2015.

[14] X. Zhang, Q. Zeng, and Z. Yang, "Modeling the mixed storage strategy for quay crane double cycling in container terminals". *Transportation Research Part E: Logistics and transportation Review*, vol. 94, pp. 171-187, Oct 2016.

[15] D. Ku, and T. S. Arthanari, "On double cycling for container port productivity improvement". *Annals of Operations Research*, vol. 243, pp. 55-70, Aug 2016.

[16] Y. Chu, X. Zhang, and Z. Yang, "Multiple quay cranes scheduling for double cycling in container terminals". *PLoS One,* vol. 12, pp. e0180370, Jul 2017.

[17] S. S. Kamble, A. Gunasekaran, and R. D. Raut, "Analysing the implementation barriers of dual cycling in port container terminal using interpretive structural modeling-Indian context". *International Journal of Logistics Research and Applications*, vol. 22, pp. 119-137, 2019.

[18] X. Zhang, Q. Zeng, and J. B. Sheu, "Modeling the productivity and stability of a terminal operation system with quay crane double cycling". *Transportation Research Part E: Logistics and Transportation Review,* vol. 122, pp. 181-197, Feb 2019.

[19] G. Tang, M. Qin, Z. Zhao, J. Yu, and C. Shen, "Performance of peak shaving policies for quay cranes at container terminals with double cycling". *Simulation Modelling Practice and Theory*, vol. 104, pp. 102129, Nov 2020.

[20] E. Ahmed, M. S. El-Abbasy, T. Zayed, G. Alfalah, and S. Alkass, "Synchronized scheduling model for container terminals using simulated double-cycling strategy". *Computers & Industrial Engineering,* vol. 154, pp. 107118, Apr 2021.

[21] H. Zhang, L. Qi, W. Luan, and H. Ma, "Double-cycling AGV scheduling considering uncertain crane operational time at container terminals". *Applied Sciences,* vol. 12, pp. 4820, May 2022.

[22] Zhu, Z. Tan, Z. Yang, and L. Cai, "Quay crane and yard truck dual-cycle scheduling with mixed storage strategy". *Advanced Engineering Informatics,* vol. 54, pp. 101722, Oct 2022.

[23] D.B.M.M. Fontes and S.M. Homayouni, "A bi-objective multi-population biased random key genetic algorithm for joint scheduling quay cranes and speed adjustable vehicles in container terminals". *Flexible Services and Manufacturing Journal,* vol. 35, pp. 241-268, Mar 2023.

[24] M. Wei, J. He, C. Tan, J. Yue, and H. Yu, "Quay crane scheduling with time windows constraints for automated container port". *Ocean & Coastal Management,* vol. 231, pp. 106401, Jan 2023.

[25] L.-J. Yue, H.-M. Fan, and H. Fan, "Blocks allocation and handling equipment scheduling in automatic container terminals". *Transportation Research Part C - Emerging Technol,* vol. 153, 104228, Aug 2023.

[26] L. Cai, W. Li, B. Zhou, H. Li, and Z. Yang, "Robust multi-equipment scheduling for U-shaped container terminals concerning double-cycling mode and uncertain operation time with cascade effects". *Transportation Research Part C,* vol. 158, 104447, Jan 2024.

[27] Y. Li, Z. Sun, and S. Hong, "An exact algorithm for multiple-equipment integrated scheduling in an automated container terminal using a double-cycling strategy". *Transportation Research Part E: Logistics and Transportation Review,* vol. 186, 103565, Jun 2024.

[28] C. Tan, T. Qin, J. He, Y. Wang, and H. Yu, "Yard space allocation of container port based on dual cycle strategy". *Ocean & Coastal Management,* vol. 247, 106915, May 2024.

[29] Y.-Z. Wang, Z.-H. Hu, and X.-D. Tian, "Scheduling ASC and AGV considering direct, buffer, and hybrid modes for transferring containers". *Computers & Operations Research,* vol. 161, 106419, Jan 2024.

[30] X. Zhang, H. Li, and J.-B. Sheu, "Integrated scheduling optimization of AGV and double yard cranes in automated container terminals". *Transportation Research Part B: Methodological,* vol. 179, 102871, Jan 2024.

[31] E. Deniz, G. Tuncel, O. Yalcinkaya, and S. Esmer, "Simulation of multi-crane single and dual cycling strategies in a container terminal". *International Journal of Simulation Modelling,* vol. 20, pp. 465-476, 2021.