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SYNCHRONIZED SCHEDULING MODEL FOR CONTAINER TERMINALS USING SIMULATED DOUBLE-CYCLING STRATEGY

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ABSTRACT: Global ocean-based trade has been increasing significantly. To keep pace with this growth, a new generation of large vessels has been introduced to maximize shipping productivity. The primary goal of container terminals is to accelerate vessel turnaround time through effective coordination of the main handling components. This study proposes an efficient strategy to handle containers by employing double-cycling to minimize the number of empty travel trips of yard trucks. To verify the efficiency of the proposed strategy, two simulation models were developed and implemented based on a real-life case study considering uncertainties in the work task duration. The integrated single-cycling model predicted productivity with an accuracy rate of over 97%, compared with the actual site productivity. When compared to the standard single-cycling model, the double-cycling model enhanced productivity and reduced vessel turnaround time by up to 62% and 38%, respectively, and achieved cost savings of up to 27%.

Keywords: Container Terminal Handling, Productivity, Integrated Operations, Double-Cycling, Simulation

1. INTRODUCTION

Container terminals are essential port facilities and key to international trade. Over 60% of the world’s cargo is transported through seas in standard containers with a capacity of 20-foot equivalent units (TEU) or 40-foot equivalent units (2TEU) (Statista Research Department 2020). The volume of cargo shipped by containers in vessels has risen from approximately 102 million metric tons in 1980 to 1.83 billion metric tons in 2017. Additionally, the global shipping container market was worth about US$4.6 billion in 2016, and is expected to reach US$11 billion by 2025 (Statista Research Department 2020). The expansion of global volumes of transported containers has proportionately increased the complexity of port logistics (Stahlbock and Voβ 2008). This has impelled shipping and port authorities to identify ways to keep pace with this development. Furthermore, an unexpected increase in global trade requires quick and efficient shipment cycles. One of the potential solutions was increasing the capacity of container vessels. The present generation of container vessels has a capacity of 18,000 TEUs, compared to 2,400 TEUs in the 1970s. In 2017, the capacity increased to more than 20,000 TEUs, and presently, the largest vessel in the world that was built in 2019 has a capacity of more than 23,000 TEUs.

Although increasing the capacity of vessels can minimize transportation unit costs, the vessel turnaround time continues to be an issue. The vessel turnaround time is the time taken for a vessel to be unloaded and loaded at its berth, that is, the difference between the vessel’s arrival and departure time. Accordingly, the larger capacity vessels will have a longer vessel turnaround time. This led researchers to investigate various container handling strategies to minimize turnaround time by improving the productivity of one or more container handling components, that is, quay cranes, yard trucks, and yard cranes. One of the major strategies proposed to enhance productivity was considering “double-cycling” quay cranes instead of the traditional “single-cycling.” Improving the productivity of modeling container handling operations alone is insufficient if they are impractical. Essentially, most of the previous studies ignored the effects of integrating container handling component cycles. Such integration is essential to compare the efficacy of one handling component over the other. Therefore, the main aim of this research is to present the development and formulation of a new container handling strategy to improve container handling operations and minimize unit cost by employing yard trucks' double-cycling. Based on this strategy, a simulation model was developed by integrating the cycles of various container handling components to enhance productivity practicably.

2. BACKGROUND

2.1 Container Terminal Handling Operation

Large vessels are generally used to transfer containers through large container terminals, to be transshipped by smaller vessels called feeders between medium or small terminals before being sent to their final destination. Occasionally, the containers may be transferred directly to their final destination without additional seaborne transfer. These processes of container transshipment usually require four major components for handling the shipped containers at the terminal, namely, Quay Crane (QC), Yard Truck (YT), Yard Crane (YC), and Storage Yard (SY). At the berth (or quay) side, a QC unloads a container with import consignment from a vessel and loads it onto a YT or unloads a container with export material from a YT and loads it onto a vessel. QCs move parallel to the length of the vessel on a railway and each QC can lift two 20-foot containers simultaneously or one 40-foot container. YTs are used to transport the containers from the quay side to the SY and the other way around. A YC loads and unloads containers from or onto trucks going to or from the SY. Meanwhile, SY is the storage space where containers with import and export materials are stored temporarily before being moved to their assigned destinations.

2.2 Previous Studies

Improving container terminal handling efficiency to minimize the turnaround time of vessels has attracted the attention of many researchers in the last two decades. Such improvements were employed at both the berth and the yard sides of the terminal. At the berth side, the operations include: (1) allocating berths to the vessels arriving (i.e., Berth Allocation Problem, BAP); (2) assigning QCs to the vessels (i.e., Quay Crane Assignment Problem, QCAP); and (3) scheduling the different work tasks handled by the QCs (i.e., Quay Crane Scheduling Problem, QCSP). Conversely, at the yard side, the operations include: (1) allocating containers to specific areas of the SY (i.e., Storage Yard Allocation Problem, SYAP); (2) scheduling the different work tasks handled by the YTs (i.e., Yard Truck Scheduling Problem, YTSP); (3) scheduling the different work tasks handled by the YCs (i.e., Yard Crane Scheduling Problem, YCSP); and (4) sequencing the loading of the container (i.e., Container Sequencing Problem, CSP), (Diabat and Theodorou 2014).

Different heuristics and algorithms were applied extensively to solve the three main assignment and allocation problems separately or by integrating two or three of them under a single platform as summarized in Table 1. Other efforts were exerted to solve the scheduling problems of the QCs, YTs, and YCs whether separately or through integration as summarized in Table 2. Furthermore, assignment and allocation problems were integrated with the scheduling problems as shown in the table. Most of these scheduling problems employed the traditional single-cycling approach of the QCs. A different approach was initiated by Goodchild and Daganzo (2006) to solve the QCSP through a double-cycling strategy for the QCs. This double-cycling strategy considers that the loading and unloading tasks of the containers onto and from the vessel by a QC occurs consecutively. The strategy was employed as an alternative to the traditional single-cycling strategy where the loading of the vessel occurs only after the completion of the unloading process. Thereby, the empty travel time of the QC to unload a new container from the vessel is minimized, which in turn increases its productivity and minimizes the vessel turnaround time. However, for vessels with deck hatches, applying QCs double-cycling may not be useful for the containers above a hatch, as all these containers must be unloaded before applying double-cycling. Accordingly, Zhang and Kim (2009) modified QCs' double-cycling strategy so that it would no longer be limited to the stacks under a hatch, but can also be employed for above-hatch stacks. The QCs' double-cycling was also adopted by other researchers to solve the QCSP while considering the CSP (Zheng et al. 2019c; Liu et al. 2015; Wang and Li 2015; Meisel and Wichmann 2010). Similar to the concept of incorporating double-cycling strategy for the QCs, introduced by Goodchild and Daganzo (2006), Nguyen and Kim (2010) introduced a double-cycling strategy, but this time for the YTs, which aimed to minimize the empty trip time of the YTs and cause minimum delay for vessel operations. Cao et al. (2018) also employed the YTs' double-cycling to minimize the vessel turnaround time by integrating the QCSP with the YTSP using the mixed integer programming method.

In light of the above, several limitations were found in the literature with respect to solving scheduling problems, which is the focus of our study. First, the QCs' double-cycling strategy introduced by Goodchild and Daganzo (2006) may not be effective for vessels with deck hatches, given that all the containers above the hatch must be unloaded before applying double-cycling. Although Zhang and Kim (2009) provided a solution for this hitch, double-cycling the QCs still requires more YTs than in single-cycling because of its longer cycle, which means that some YTs are not utilized during the application of single-cycling in each row. Specifically, a YT has to wait for the QC to be loaded before its departure, as the discharge time is considered idle time for the YT. Accordingly, minimizing YTs' idle time is a concern, and employing a double-cycling strategy for the YTs can help address this concern, as reported by Nguyen and Kim (2010). However, their study did not consider an integrated scheduling of the YTs with the QCs and YCs. This brings us to the second limitation where most of the previous studies considered improving the cycles of either the QCs, YTs, or YCs independently. Although improving the efficiency of one of these handling components could result in an increase in the overall handling productivity and minimize the vessel turnaround time, scheduling them separately is still considered impractical. Effectively, the handling components have mutual work tasks. If one of these mutual work tasks is disturbed, it will eventually affect the other tasks due to the interaction between them. For example, a study by Kizilay et al. (2018) showed that an infinite number of YTs were assumed to be available in which there will never be an idle time for the QCs and YCs to load and unload a YT. In reality, this assumption is unreasonable due to uncertain factors that could affect the performance of the YTs, and also owing to the different cycle times of the QCs, YTs, and YCs. Thus, integrating or coordinating the scheduling of the three main handling components is essential. The third limitation is that although integrated scheduling was considered in some studies, uncertainty of the durations of the different work tasks (apart from Jonker et al. 2019) and employing a double-cycling strategy were not considered.

To overcome these limitations, this study proposes a synchronized scheduling simulation-based model for the QCs, YTs, and YCs simultaneously. Furthermore, a double-cycling strategy for the YTs is employed, and uncertainty of the durations of the different work tasks conducted by each handling component is considered. To the knowledge of the authors, none of the previous studies considered these limitations simultaneously. Accordingly, the output of this research is expected to contribute in adding practicality to the process of container handling that closely mimics reality. This is achieved throughout considering the idle times of any of the handling components as a result of their scheduling integration as well as considering stochastic durations for any work task. Together with added practicality, the productivity is improved by employing the YTs' double-cycling strategy to minimize vessels turnaround times and eventually minimizing the handling costs.

Table 1: Assignment and Allocation Problems Literature Summary

Citation	Assignment/Allocation Problem Solved
Zheng et al. 2019a	Integrated BAP-QCAP
Jacomino et al. 2019	SYAP
Schepler et al. 2019	BAP
Correcher et al. 2019	BAP
Guerra-Olivares et al. 2018	SYAP
Wang et al. 2018	Integrated BAP-QCAP-SYAP
Al-Hammadi and Diabat 2017	Integrated BAP-SYAP
Lin and Chiang 2017	SYAP
Peng et al. 2015	Integrated BAP-SYAP
Iris et el. 2015	Integrated BAP-QCAP
Budipriyanto et al. 2015	BAP
Wang et al. 2014	SYAP
Lajjam et al. 2014	QCAP
Karam et al. 2014	QCAP
Xiao and Hu 2014	Integrated BAP-QCAP
Zampelli et al. 2013	Integrated BAP-QCAP
Chen and Lu 2012	SYAP
Raa et al. 2011	Integrated BAP-QCAP
Chang et al. 2010	Integrated BAP-QCAP
Safaei et al. 2010	Integrated BAP-SYAP
Golias et al. 2009	BAP
Bazzazi et al. 2009	SYAP
Monaco and Sammarra 2007	BAP
Zhang et al. 2003	SYAP
Imai et al. 2001	BAP

Table 2: Scheduling Problems Literature Summary

Citation	Scheduling Problem Solved	Uncertainty Considered?	Double-Cycling?
Jonker et al. 2019	Integrated QCSP-YTSP-YCSP	Yes	No
Yue et al. 2019	Integrated QCSP-YTSP-YCSP	No	No
Zhen et al. 2019	Integrated QCSP-YTSP	No	No
Hu et al. 2019	QCSP	Yes	No
Zheng et al. 2019b	YCSP	Yes	No
Zheng et al. 2019c	QCSP with CSP	No	Yes
He et al. 2019	YCSP	Yes	No
Kasm et al. 2019	QCSP with integrated BAP-QCAP	Yes	No
Luo et al. 2018	YCSP	No	No
Msakni et al. 2018	QCSP	No	No
Zhang et al. 2018	QCSP	No	No
Kizilay et al. 2018	Integrated QCSP-YCSP	No	No
Wu and Wang 2018	Integrated QCSP-YCSP	Yes	No
Jiao et al. 2018	QCSP with BAP	No	No
Olteanu et al. 2018	QCSP with QCAP	Yes	No
Alsoufi et al. 2018	QCSP with QCAP	Yes	No
Agra and Oliveira 2018	QCSP with integrated BAP-QCAP	No	No
Grubisic and Maglic 2018	QCSP with integrated BAP-QCAP	Yes	No
Cao et al. 2018	Integrated QCSP-YTSP	No	Yes
Cao et al. 2017	Integrated YCSP-YTSP	No	No
Niu et al. 2017	YTSP	Yes	No
Yu et al. 2017	QCSP	No	No
Fan et al. 2017	YCSP with SYAP	No	No
Xiao et al. 2016	Integrated QCSP-YTSP-YCSP	No	No
Tan and He 2016	YCSP with SYAP	No	No
Idris and Zainuddin 2016	QCSP with BAP	Yes	No
He et al. 2015	Integrated QCSP-YTSP-YCSP	No	No
Kaveshgar and Huynh 2015	Integrated QCSP-YTSP	No	No
Al-Dhaheri and Diabat 2015	QCSP	No	No
Wang et al. 2015	YTSP with SYAP	No	No
Liu et al. 2015	QCSP with CSP	No	Yes
Wang and Li 2015	QCSP with CSP	No	Yes
Chen et al. 2014	Integrated YCSP-YTSP	No	No
Wu et al. 2014	QCSP with BAP	No	No
Diabat and Theodorou 2014	QCSP with QCAP	No	No
He et al. 2013	YCSP	Yes	No
Xue et al. 2013	YTSP with SYAP	No	No
Sharif and Huynh 2012	YCSP	Yes	No
Javanshir et al. 2012	YCSP	Yes	No
Nguyen and Kim 2010	YTSP	Yes	Yes
Cao et al. 2010a	Integrated YCSP-YTSP	Yes	No
Cao et al. 2010b	Integrated QCSP-YTSP	No	No
Lee and Wang 2010	QCSP with BAP	Yes	No
Meisel and Wichmann 2010	QCSP with CSP	No	Yes
Zhang and Kim 2009	QCSP	No	Yes
Lee et al. 2009	YTSP with SYAP	No	No
Lee 2007	YTSP	No	No
Sammarra et al. 2007	QCSP	No	No
Ng and Mak 2006	QCSP	Yes	No
Goodchild and Daganzo 2006	QCSP	Yes	Yes
Grunow et al. 2006	YTSP	Yes	No
Ng and Mak 2005	YCSP	Yes	No
Current Research	Integrated QCSP-YTSP-YCSP	Yes	Yes

3. PROBLEM DEFINITION AND FORMULATION

In this section, the scheduling framework and formulation of the different work tasks conducted by each container handling component will be discussed. The main assumption considered in this study is that the BAP, QCAP, SYAP, and CSP are predetermined. The notation for all the parameters used to formulate the cycles of the different components are shown in Table 3.

3.1 Quay Crane Cycle

The QC cycle can be segregated into unloading and loading cycles, and both are considered in this study to start from the YT lane as presented in Figure 1. The QC trolley makes different horizontal forward and backward moves as well as vertical upward or downward moves while loading or unloading a container. Figure 2a offers a better visualization of the possible QC trolley movements. Accordingly, the QC unloading (QC_U) and loading (QC_L) cycle time can be formulated in a similar manner as shown in Equations 1 and 2, respectively. Both equations are a sum of the duration (in minutes) of the different trolley movements carried in each cycle, in addition to the time of the actual lifting and loading of a container (i.e., t_{Q5} and t_{Q10}) as well as the waiting time for the YT to be available. The time taken for the trolley movement can be estimated based on the relationship between the distance (in ft) moved by the trolley and the speed (in ft/min) of such movements as shown in Equations (3 – 10). The distances are illustrated in Figure 2a. For example, let us consider the time for the QC to pass a horizontal-forward distance along the vessel width from the quay wall to the bay (i.e., t_{Q2}). As shown in Figure 2a, the distance to make such a move is denoted by "X", while the QC's trolley horizontal movement speed is denoted by "v_{Q1}" as shown in Table 3. Therefore, dividing the distance "X" by the speed "v_{Q1}" will result in "t_{Q2}" as shown in Equation

4. It should be noted that the unloading and loading cycle time varies in each cycle based on the position of the container to be lifted or loaded from or onto the vessel.

$$QC_U = \sum_{M=1}^{10} t_{QM} + It_{QU} \qquad (1)$$

$$QC_L = \sum_{M=1}^{10} t_{QM} + It_{QL} \qquad (2)$$

$$t_{Q1} = max\left(\frac{P}{v_{Q2}}, \frac{S}{v_{Q1}}\right) \qquad (3)$$

$$t_{Q2} = \frac{X}{v_{Q1}} \qquad (4)$$

$$t_{Q3} = max\left(\frac{H}{v_{Q2}}, \frac{R}{v_{Q1}}\right) \qquad (5)$$

$$t_{Q4} = \frac{h}{v_{Q2}} \qquad (6)$$

$$t_{Q6} = \frac{h}{v_{Q3}} \qquad (7)$$

$$t_{Q7} = max\left(\frac{H}{v_{Q3}}, \frac{R}{v_{Q1}}\right) \qquad (8)$$

$$t_{Q8} = t_{Q2} = \frac{X}{v_{Q1}} \qquad (9)$$

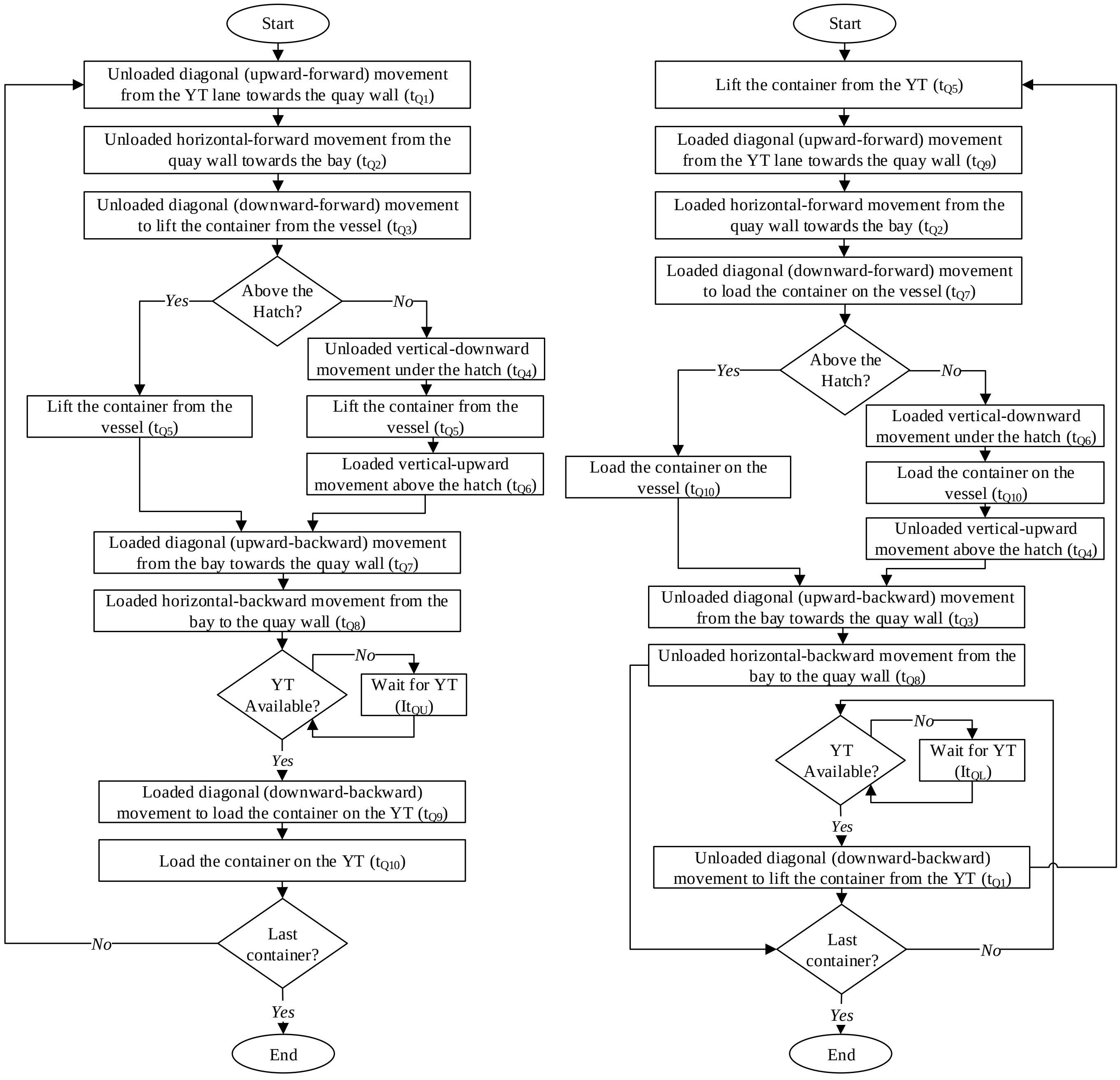
$$t_{Q9} = max\left(\frac{P}{v_{Q3}}, \frac{S}{v_{Q1}}\right) \qquad (10)$$

3.2 Yard Crane Cycle

Similar to the QC, the YC cycle can be categorized into unloading and loading cycles and both are considered to commence from the YT lane as illustrated in Figure 3. The same concept of the QC trolley movement is applied as shown in Figure 2b. Thus, the duration of YC unloading (YC_U) and loading (YC_L) cycles are formulated as shown in Equations 11 and 12, respectively. The time taken for YC trolley movements is formulated as shown in Equations (13 – 18).

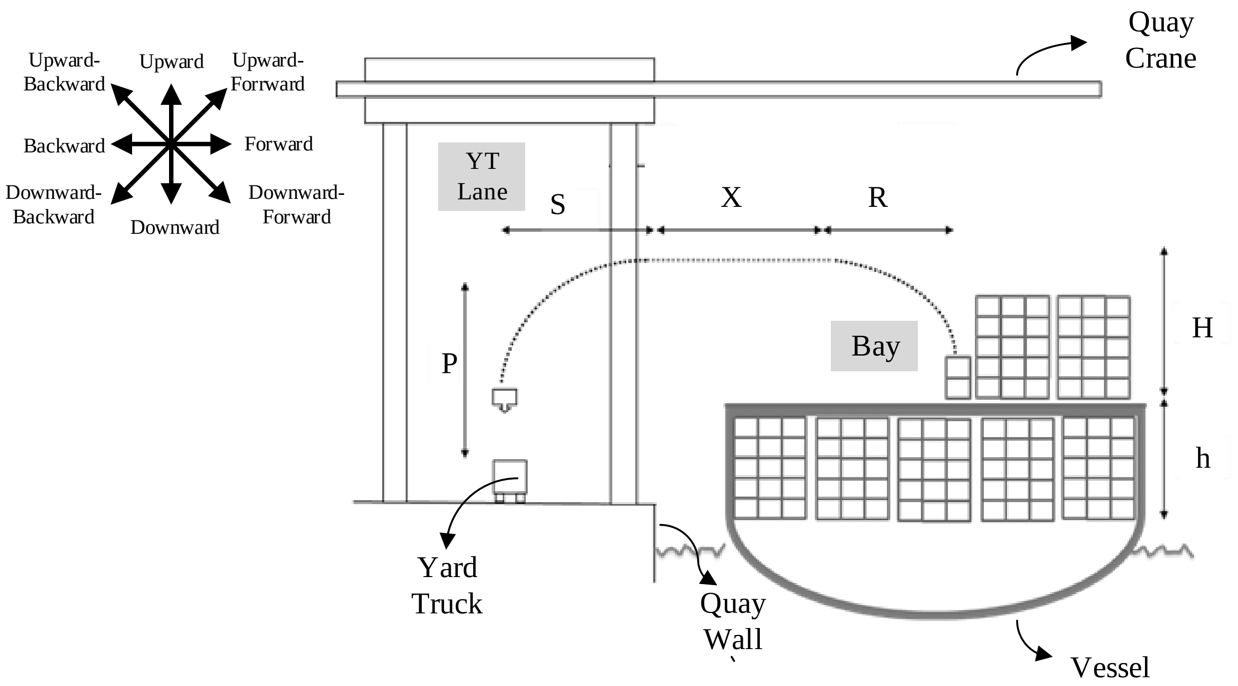
Table 3: Notations used in Scheduling Formulation

Handling Component	Notation	Description
Quay Crane	QC_U	QC unloading cycle time
	QC_L	QC loading cycle time
	t_{Q1}	Time for QC (unloaded) to make a diagonal (upward-forward) movement from the YT lane towards the quay wall, or Time for QC (unloaded) to make a diagonal (downward-backward) movement from the quay wall towards the YT lane
	t_{Q2}	Time for QC to pass a horizontal-forward distance along the vessel width from the quay wall to the bay
	t_{Q3}	Time for QC (unloaded) to make a diagonal (downward-forward) movement to lift the container from the vessel, or Time for QC (unloaded) to make a diagonal (upward-backward) movement from the bay towards the quay wall
	t_{Q4}	Time for QC (unloaded) to make a vertical-downward (or upward) movement under the hatch (or to pass the hatch)
	t_{Q5}	Time for QC to lift the container from the vessel or the YT
	t_{Q6}	Time for QC (loaded) to make a vertical-downward (or upward) movement under the hatch (or to pass the hatch)
	t_{Q7}	Time for QC (loaded) to make a diagonal (upward-backward) movement from the bay towards the quay wall, or Time for QC (loaded) to make a diagonal (downward-forward) movement to load the container on the vessel
	t_{Q8}	Time for QC to pass a horizontal-backward distance along the vessel width from the bay to the quay wall
	t_{Q9}	Time for QC (loaded) to make a diagonal (downward-backward) movement to load the container on the YT, or Time for QC (loaded) to make a diagonal (upward-forward) movement from the YT lane towards the quay wall
	t_{Q10}	Time for QC to load the container on the YT or the vessel
	It_{QU}	QC idle time while waiting for the unloaded YT to be available
	It_{QL}	QC idle time while waiting for the loaded YT to be available
	v_{Q1}	QC's trolley horizontal movement speed
	v_{Q2}	QC's trolley unloaded vertical movement speed
	v_{Q3}	QC's trolley loaded vertical movement speed
	M	Number of QC's trolley movements
Yard Crane	YC_U	YC unloading cycle time
	YC_L	YC loading cycle time
	t_{Y1}	Time for YC to lift the container from the SY or the YT
	t_{Y2}	Time for YC (loaded) to make a diagonal (upward-forward) movement from the YT lane towards the SY area, or Time for YC (loaded) to make a diagonal (downward-backward) movement to load the container on the YT
	t_{Y3}	Time for YC to pass a horizontal-forward distance along the SY width
	t_{Y4}	Time for YC (loaded) to make a diagonal (downward-forward) movement to load the container in the SY area, or Time for YC (loaded) to make a diagonal (upward-backward) movement from the SY area towards the YT lane
	t_{Y5}	Time for YC to load the container on the YT or in the SY
	t_{Y6}	Time for YC (unloaded) to make a diagonal (upward-backward) movement from the SY area towards the YT lane, or Time for YC (unloaded) to make a diagonal (downward-forward) movement to lift the container from the SY area
	t_{Y7}	Time for YC to pass a horizontal-backward distance along the SY width
	t_{Y8}	Time for YC (unloaded) to make a diagonal (downward-backward) movement to lift the container from the YT, or Time for YC (unloaded) to make a diagonal (upward-forward) movement from the YT lane towards the SY area
	It_{YU}	YC idle time while waiting for the unloaded YT to be available
	It_{YL}	YC idle time while waiting for the loaded YT to be available
	v_{Y1}	YC's trolley horizontal movement speed
	v_{Y2}	YC's trolley unloaded vertical movement speed
	v_{Y3}	YC's trolley loaded vertical movement speed
	N	Number of YC's trolley movements
Yard Truck	YTS_U	YT unloading single-cycle time
	YTS_L	YT loading single-cycle time
	YTD	YT double-cycle time
	t_{S1}	Time for YT (unloaded) to travel from SY side to berth side
	t_{S2}	Time for YT (loaded) to travel from berth side to SY side
	t_{S3}	Time for YT (loaded) to travel from SY side to berth side
	t_{S4}	Time for YT (unloaded) to travel from berth side to SY side
	t_{S5}	Time for YT (unloaded) to travel from QC1 to QC2
	t_{S6}	Time for YT (unloaded) to travel from YC2 to YC1
	x_1	Distance of path taken by the YT from SY side to berth side
	x_2	Distance of path taken by the YT from berth side to SY side
	x_3	Distance between QC1 and QC2
	x_4	Distance between YC1 and YC2
	It_{TQU}	YT (unloaded) idle time while waiting for the QC to be available
	It_{TYL}	YT (loaded) idle time while waiting for the YC to be available
	It_{TQL}	YT (loaded) idle time while waiting for the QC to be available
	It_{TYU}	YT (unloaded) idle time while waiting for the YC to be available
	v_{T1}	YT unloaded speed
	v_{T2}	YT loaded speed

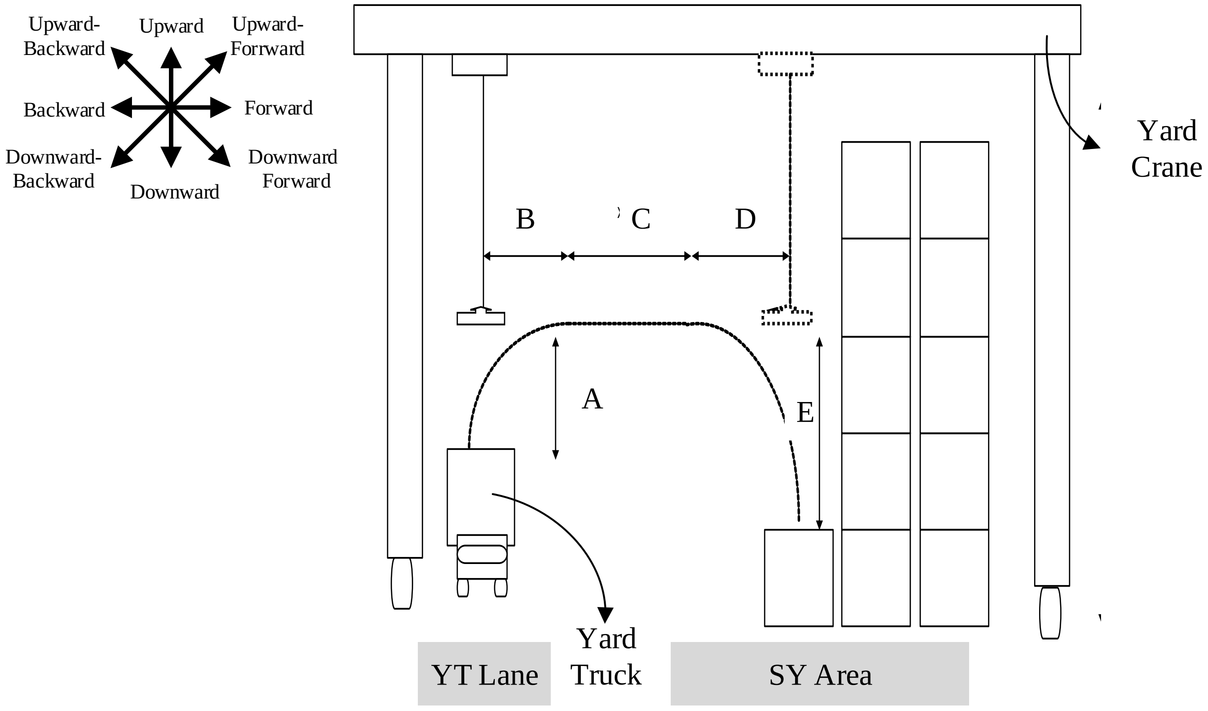


(a) QC Unloading Cycle **(b) QC Loading Cycle**

Figure 1: Quay Crane Cycles

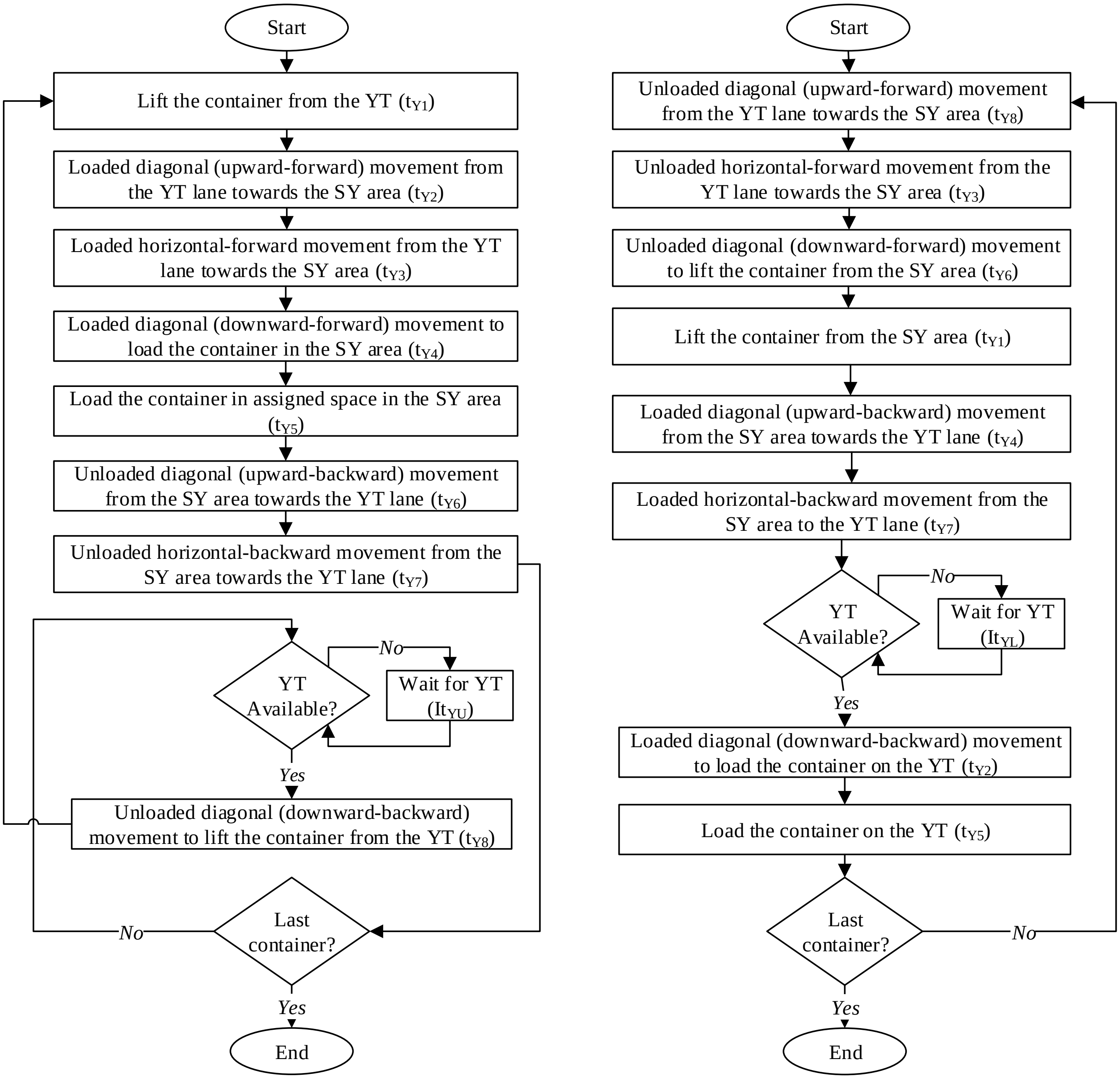


(a) QC's Trolley Movements



(b) YC's Trolley Movements

Figure 2: Possible Trolley Movements of the QC and YC



(a) YC Unloading Cycle **(b) YC Loading Cycle**

Figure 3: Yard Crane Cycles

$$YC_U = \sum_{N=1}^{8} t_{YN} + It_{YU} \quad \text{(11)}$$

$$YC_L = \sum_{N=1}^{8} t_{YN} + It_{YL} \quad \text{(12)}$$

$$t_{Y2} = max\left(\frac{A}{v_{Y3}}, \frac{B}{v_{Y1}}\right) \qquad (13)$$

$$t_{Y3} = \frac{C}{v_{Y1}} \qquad (14)$$

$$t_{Y4} = max\left(\frac{E}{v_{Y3}}, \frac{D}{v_{Y1}}\right) \qquad (15)$$

$$t_{Y6} = max\left(\frac{E}{v_{Y2}}, \frac{D}{v_{Y1}}\right) \qquad (16)$$

$$t_{Y7} = t_{Y3} = \frac{C}{v_{Y1}} \qquad (17)$$

$$t_{Y8} = max\left(\frac{A}{v_{Y2}}, \frac{B}{v_{Y1}}\right) \qquad (18)$$

3.3 Yard Truck Single-Cycle

Furthermore, the YT single-cycling will be divided into an unloading and loading cycle as shown in Figure 4. Accordingly, the unloading (YTS_U) and loading (YTS_L) single-cycle time will be the sum of the YT's travel and return time in addition to the loading and unloading of the YT as well as any idle time, as shown in Equations 19 and 20, respectively. The loaded and unloaded travel and return time formulations are shown in Equations (21 – 24).

$$YTS_U = t_{S1} + t_{Q10} + t_{S2} + t_{Y1} + It_{TQU} + It_{TYL} \qquad (19)$$

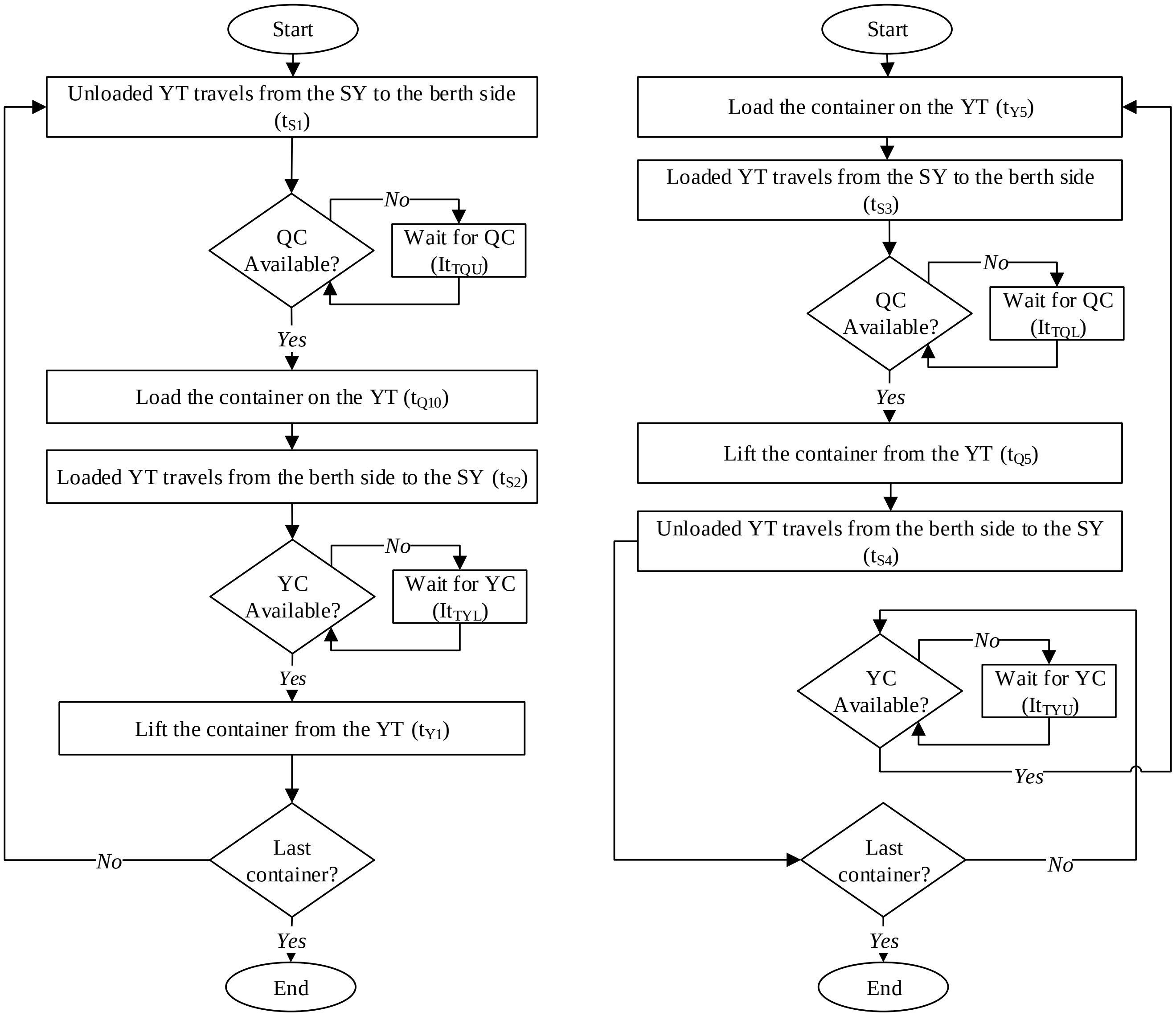
$$YTS_L = t_{Y5} + t_{S3} + t_{Q5} + t_{S4} + It_{TQL} + It_{TYU} \qquad (20)$$

$$t_{S1} = \frac{x_1}{v_{T1}} \qquad (21)$$

$$t_{S2} = \frac{x_2}{v_{T2}} \qquad (22)$$

$$t_{S3} = \frac{x_1}{v_{T2}} \qquad (23)$$

$$t_{S4} = \frac{x_2}{v_{T1}} \qquad (24)$$



(a) YT Unloading Single-Cycle **(b) YT Loading Single-Cycle**

Figure 4: Yard Truck Single-Cycling

3.4 Yard Truck Double-Cycle

The main concept of the YT double-cycling strategy is to combine two QCs to work as a single unit with one crane discharging the vessel and the other loading it (Ahmed 2015). Specifically, both QCs will serve the same YT where one will be unloading a container from the YT to be loaded onto the vessel and the other unloading a container from the vessel to be loaded onto the YT. Each YT will transport containers from the SY to the vessel and from the vessel to the SY in the same cycle. Just as with the QCs, two YCs will load and discharge the trucks at the SY.

Accordingly, as shown in Figure 5, the first YC (i.e., YC1) initiates the cycle by loading the YT at the export lane. The loaded YT then moves to the berth side to be discharged by the first QC (i.e., QC1). After discharging, the empty YT moves to the second QC (i.e., QC2) to be loaded. Subsequently, it returns to the SY to unload the container at the import lane. Thus, the second YC (i.e., YC2) will discharge the YT which will then depart empty to the export lane to be loaded by the first YC (i.e., YC1), thus commencing a new cycle. Based on such complete cycle, the YT double-cycle time (YTD) will appear as formulated in Equation 25. As shown in the equation, two new variables are introduced that represent the travel time by the YT between QC1 and QC2 (t_{S5}) and between YC1 and YC2 (t_{S6}). The formulation of these new travel times is available in Equations 26 and 27.

$$YTD = t_{Y5} + t_{S3} + It_{TQL} + t_{Q5} + t_{S5} + It_{TQU} + t_{Q10} + t_{S2} + It_{TYL} + t_{Y1} + t_{S6} + It_{TYU} \ldots\ldots (25)$$

$$t_{S5} = \frac{x_3}{v_{T1}} \ldots\ldots (26)$$

$$t_{S6} = \frac{x_4}{v_{T1}} \ldots\ldots (27)$$

4. SOLUTION APPROACH

In the previous section, the scheduling process and formulation of each container handling component cycle were introduced independently. Thus, in order to consider the interaction between the mutual work tasks conducted by these components, their different cycles are to be integrated. Such integration helps in synchronizing the real-life movement of the different resources used in the overall handling process, and eventually measures the impact of the delay or non-availability of one resource over the other. To model the integrated cycles, the EZStrobe® (Martinez 2001) discrete-event simulation system is utilized. EzStrobe is a simulation tool that was initially developed to model construction operations; however, it can still be used for other types of operations in various disciplines. This simulation tool is based on activity cycle diagrams to represent the essentials of a model. It generally consists of built-in circles and rectangles that represent idle resources, activities, and their precedence. The rectangles represent activities (resources collaborating to achieve a task), the circles represent queues (idle resources), and the links between them represent the flow of resources. The EzStrobe also employs clock advance and event generation mechanisms based on activity scanning (Martinez 2001). Simulation in general is an effective medium to mimic real-life operations by monitoring the workflow of the resources used, whether in their active or idle states. Moreover, it helps in solving the problem of real-life uncertainty by considering probabilistic durations for the different work tasks involved in the operation under study. To test the effectiveness of the YT double-cycling strategy, two simulation models were developed. The first and second model considers the traditional YT single-cycling and the YT double-cycling strategies, respectively, integrated with the cycles of the QC and YC.

4.1 Single-Cycling-Based Integrated Model

Since unloading precedes the loading process, the empty YT will move from the SY towards the berth side. Simultaneously, the empty QC moves towards the targeted container to be unloaded from the vessel. Once the YT arrives at the berth, the QC loads the container onto the YT. Subsequently, the loaded YT moves to the incoming SY to be discharged by the YC and then returns empty to the berth side for another cycle. Meanwhile, the YC moves the container into the lane at the SY. The other YTs repeat this process until the last imported container is unloaded from the vessel. Consequently, the loading process starts by loading containers on the YTs at the export SY by the YC, to be transported to the berth, where the QC loads the containers onto the vessel. Similarly, the QCs, YCs, and YTs will move back and forth repeating the loading cycle until the last exported container is loaded onto the vessel. The flow chart of the full integrated single-cycle process is shown in Figure 6.

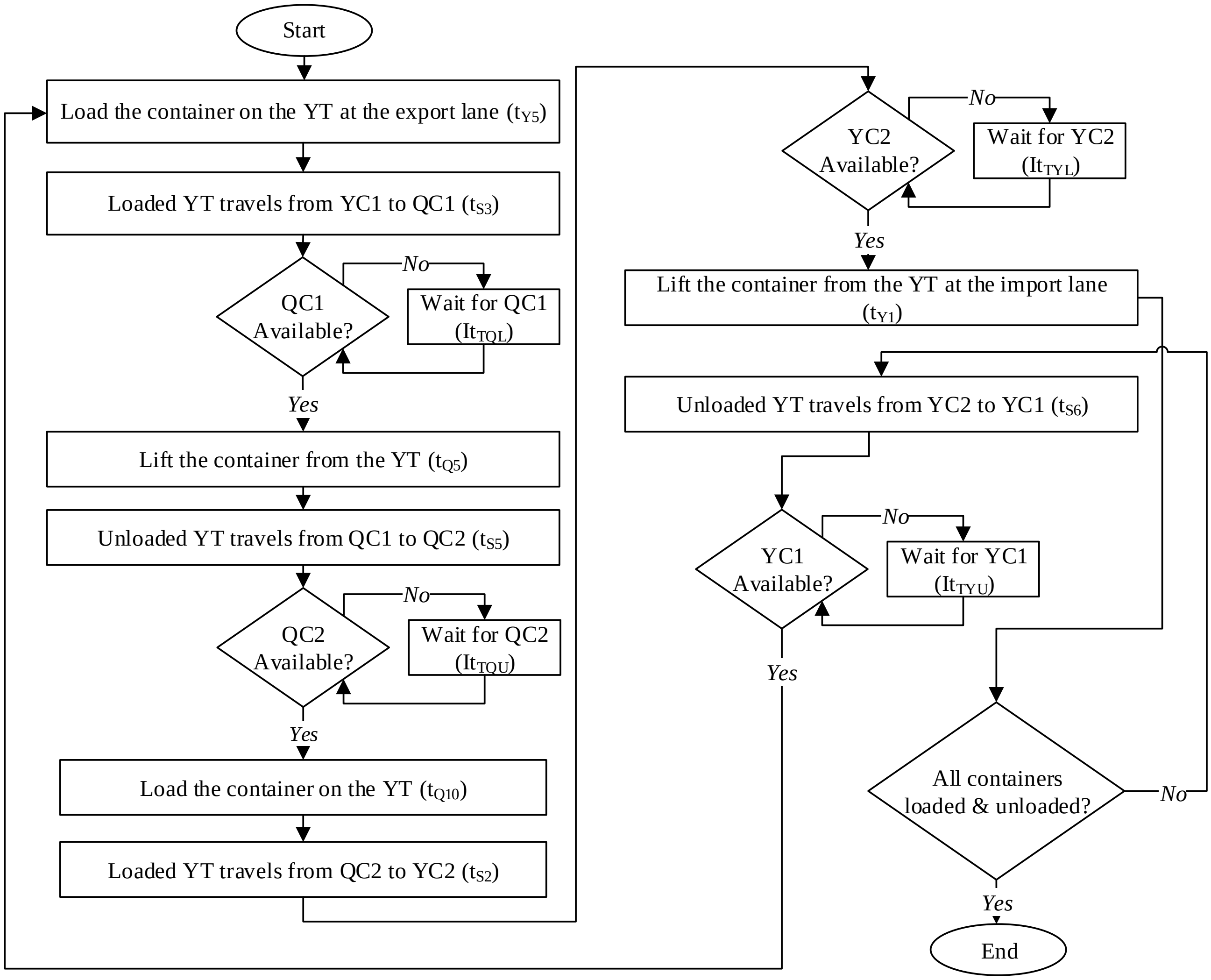
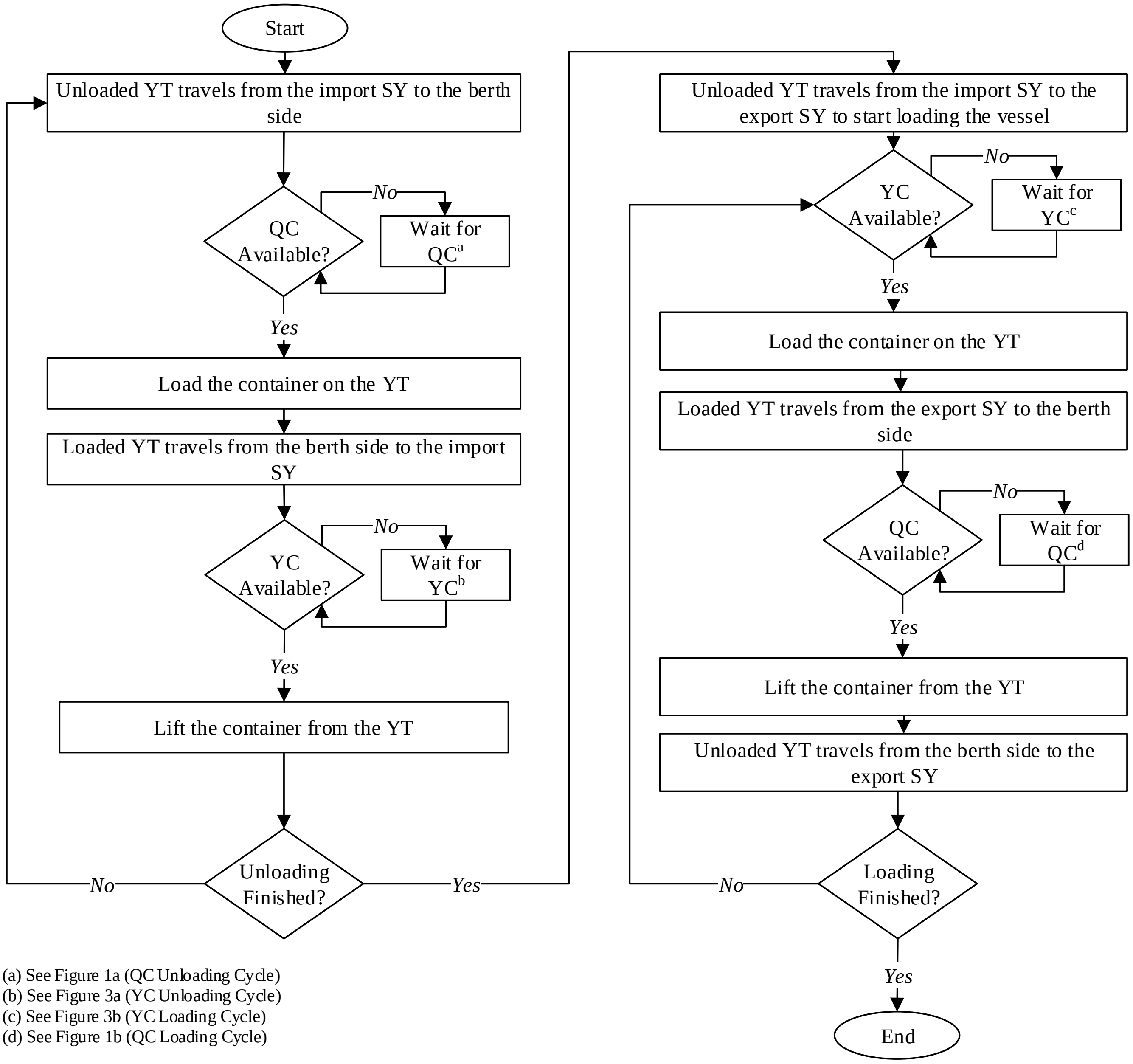


Figure 5: Yard Truck Double-Cycling

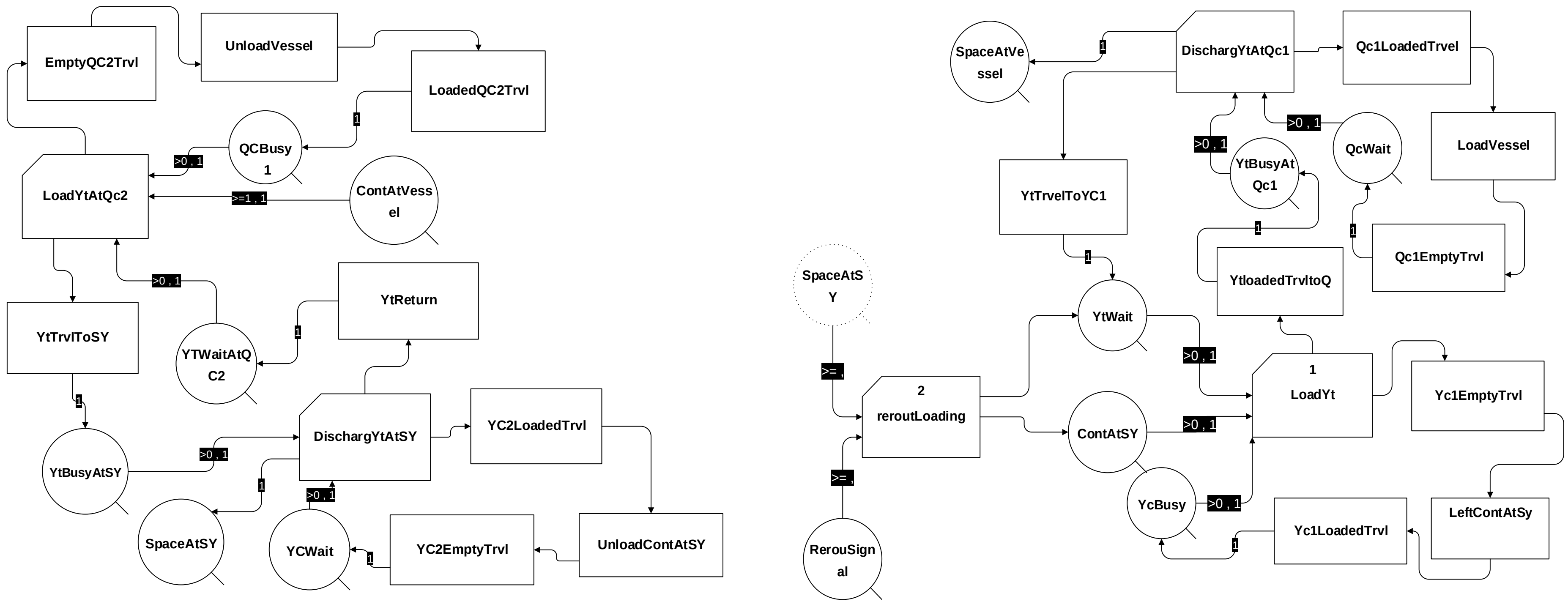


(a) See Figure 1a (QC Unloading Cycle)
(b) See Figure 3a (YC Unloading Cycle)
(c) See Figure 3b (YC Loading Cycle)
(d) See Figure 1b (QC Loading Cycle)

Figure 6: Single-Cycling Integrated Model Flowchart

To convert the process shown in Figure 6 into a simulation model using EZStrobe®, various resources required to accomplish the job and the work tasks involved were identified. Consequently, the work tasks were linked logically to identify the workflow of the different resources involved as shown in Figure 7. In EZStrobe®, the main types of elements to model an operation are the “Queue,” “Combi,” and “Normal” elements. The “Queue” element, represented by the Q-shaped node, is to model any type of resource in its idle state (e.g. a QC waiting for the YT to be available). It is not only the handling components (i.e., QCs, YTs, and YCs) that are considered as resources, but the spaces at the SY or the vessel as well, and are accordingly modeled as the “Queue” element. Also, the container units themselves are considered as resources. Finally, the “Queue” element can act as a signal resource for diverting a certain sequence of work. For instance, after the entire unloading process is completed, a rerouting signal resource is released by the “Queue” element to start the loading process.

By contrast, both the “Combi” and “Normal” elements are meant to model any type of resource in its active state, that is, they represent a work task that consumes time. The “Combi” element, represented by a rectangular node with a diagonal corner cut, is a work task that can only start whenever the resources that are available in the Queues that precede it are sufficient to support the task. For example, the “loading of a YT by a QC” work task will require both resources (i.e., YT and QC) to be available to begin the task. The unavailability of at least one of these two resources will hamper the task. The “Normal” element, represented by a rectangular node, is a work task that can only start whenever an instance of any preceding work task ends. For example, the “loaded travel of the YT to the SY” work task can only start after the previous work task, which is “loading of a YT by a QC,” ends. In this manner, all the different work tasks, whether in their idle or active states, were modeled and logically linked, as shown in Figure 7.



(1) Unloading Cycle Phase **(2) Loading Cycle Phase**

Figure 7: Single-Cycling Simulation Model

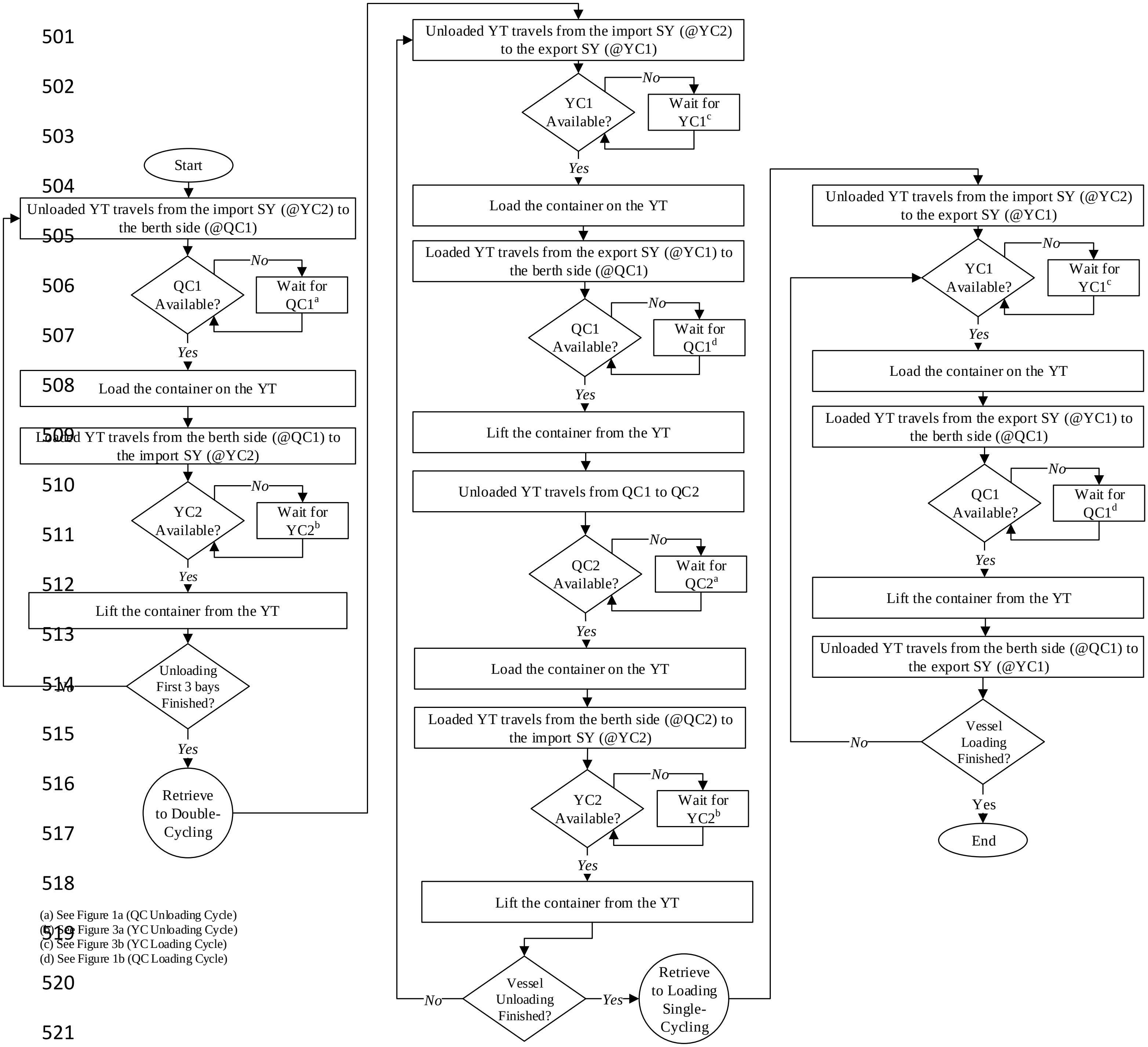
To run the simulation model, the inputs and outputs are identified. The inputs involve identifying the work task duration, the number of resources, the "Queue" elements at which a resource will be initialized, and the costs. Conversely, the outputs are identified based on defined parameters and formulas. For example, the simulation model will usually run over several cycles until the full process of unloading and loading the vessel concludes based on the number of containers identified. Considering the duration of the work tasks and the idle time, the model records the full simulation time. Since the work duration is calculated in minutes, an equation is identified to determine the vessel turnaround time as an output in hours by dividing the recorded simulation time by 60 minutes. Similarly, the other outputs, namely, productivity rate, unit cost, and total cost, were formulated.

4.2 Double-Cycling-Based Integrated Model

Depending on the vessel size, in double-cycling, at least a pair of QCs and YCs each are utilized and each pair acts as a single unit. Practically, the double-cycling cannot start as soon as a vessel arrives at the terminal. Since the arriving vessel will be usually loaded with containers for import, the containers meant for export will require some space before being loaded onto the vessel. Thus, the double-cycling integrated model will begin as the normal unloading single-cycling for a certain period of time, after which the double-cycling will commence, before concluding with a normal loading single-cycling. It is worth mentioning that based on expert opinion, QCs should not cross each other and the clearance between two adjacent QCs should be at least 40 ft (i.e., two bays). In order to add more safety margins, the minimum clearance between two adjacent QCs will be assumed to be three bays for this study. Moreover, to explain the integrated double-cycling process in this context, let us assume that a single pair of QCs and YCs are utilized. Accordingly, as shown in Figure 8, the process starts with a single-cycle unloading mode until the first three bays of the imported containers are unloaded by QC1 from the vessel and loaded at the import SY by YC2. By having three bay spaces available in the vessel, the double-cycling can start in which QC1 will change from unloading the containers for import to loading the containers for export on the vessel, starting from the first bay to the last bay. Simultaneously, QC2 will start unloading the containers set aside for import from the fourth bay to the last bay. On the SY side, the YC2 will continue unloading the imported containers while YC1 will start loading the containers for export. Having more than one YT, each YT will make the double-cycling route elucidated earlier (i.e., from YC1 to QC1 to QC2 to YC2 then back to YC1 to start a new double-cycle). The QCs, YTs, and YCs will continue to repeat their respective cycles until the last container for import is unloaded and transported to the import SY. At this stage, the fleet size will be reduced to one QC (i.e., QC1) and YC (i.e., YC1) each to complete loading the remaining containers for export on the vessel as a normal single-cycle loading mode. Similar to the single-cycling simulation model, the double-cycling process shown in Figure 8 is converted to a simulation model as shown in Figure 9.

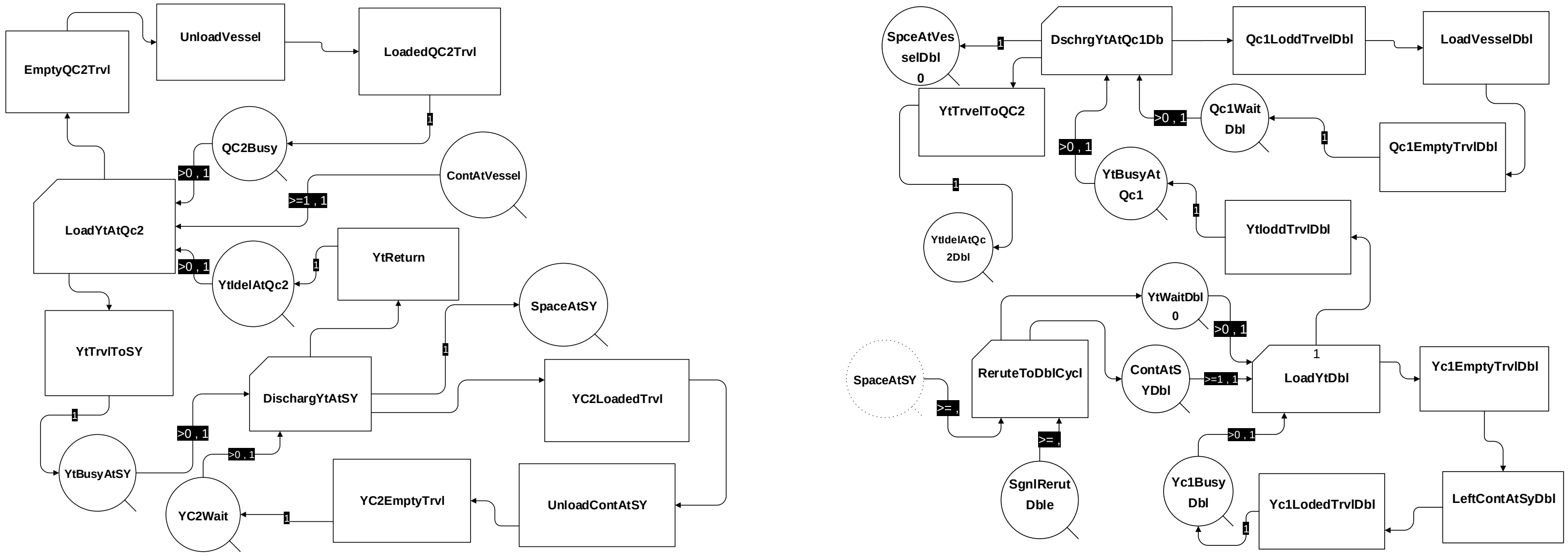
5. DATA COLLECTION

In order to implement the developed models, different types of data were collected from a container terminal that is located in Tangier, Morocco, and operated by APM Terminals, which is a worldwide container terminal company based in the Netherlands. The main types of data collected were the actual time of the different work tasks by each container handling component as well as their costs to be considered as an input for the developed models. Moreover, the productivity rates of the components were recorded.



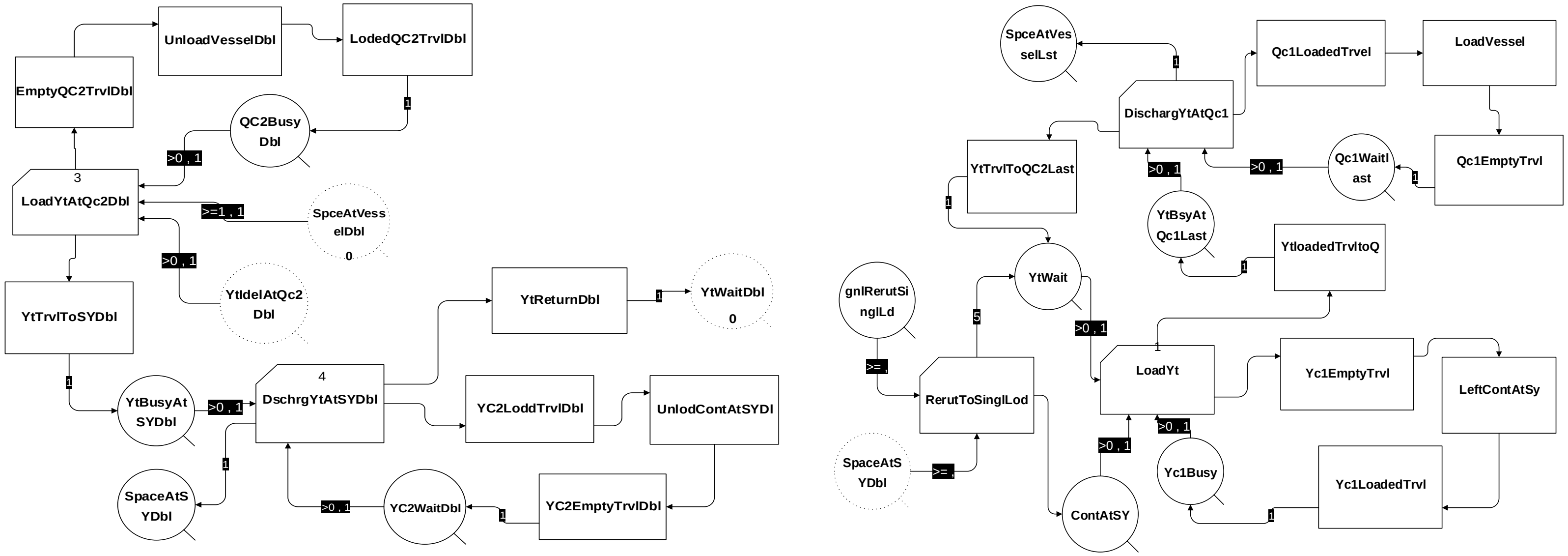
(a) See Figure 1a (QC Unloading Cycle)
(b) See Figure 3a (YC Unloading Cycle)
(c) See Figure 3b (YC Loading Cycle)
(d) See Figure 1b (QC Loading Cycle)

Figure 8: Double-Cycling Integrated Model Flowchart



(1) Unloading Single-Cycling Phase

(2) Loading Double-Cycling Phase



(3) Unloading Double-Cycling Phase

(4) Loading Single-Cycling Phase

Figure 9: Double-Cycling Simulation Model

Starting with the time, a breakdown of the work tasks that make a complete cycle of each component individually was conducted. For instance, the QC unloading cycle was divided into: (1) unloaded forward move towards the vessel; (2) container lifting from the vessel; (3) loaded backward move towards the yard; and (4) container loading on the YT. These four work tasks are equivalent to the QCs' work task movements formulated earlier in Equations (3 – 10). For example, the "unloaded forward move" is equivalent to "$t_{Q1} + t_{Q2} + t_{Q3} + t_{Q4},$" while the "loaded backward move" is equivalent to "$t_{Q6} + t_{Q7} + t_{Q8} + t_{Q9}.$" The reason for combining these work tasks under a single work task is to simplify the time recording process. The same concept was applied for the QC loading cycle as well as the other two components' cycles (i.e., YC and YT). Accordingly, over several visits to the terminal, the duration of the different work tasks were recorded using a stopwatch for a vessel with a capacity of 16,000 TEUs. The time of each work task is usually unpredictable and changes from one cycle to another. Such changes occur due to many reasons, such as the container location on the vessel or in the SY varies in each cycle (different row, above hatch, under hatch etc.). Human factor is another reason in which the equipment operators' proficiency and consistency is considered. In order to take into account such variations, the time recording was carried out more than once for each work task (i.e., over several repeated cycles). Having a set of different durations for the same work task, the EasyFit® (Schittkowski 2002) distribution fitting software was used to fit the data. The distribution type, mean, and standard deviation for each work task time is summarized in Table 4 for the different components and their respective cycles. The time taken for the YT loading and unloading work tasks carried out by either the QC or the YC are not presented in the table for the YT cycles, since these work tasks are common and are already presented in the QC and YC cycles. Moreover, it is worth mentioning that the visited terminal applies the traditional YT single-cycling strategy. As such, two additional work tasks were considered for the YT double-cycling strategy, the YT travel from QC1 to QC2 and from YC2 to YC1, that is, t_{S5} and t_{S6}, respectively. The time taken for these two additional work tasks were estimated based on the distance traveled and the YT's speed and were considered deterministic, as shown in Table 4. With the distances traveled or moved on-site by the handling components as well as their relative speed, all the recorded time shown in Table 4 were compared and verified by applying the formulations presented earlier. Finally, some work tasks were not considered such as the movements of the QCs or the YCs from a bay to another due to their minor values when compared to the total cycle time.

Table 4: Work Tasks' Times Collected Data

Handling Component	Cycle Type	Work Task	Distribution	Mean Time (min)	Standard Deviation (min)
Quay Crane	Unloading	Unloaded forward move	Normal	0.84	0.22
		Container lifting from the vessel	Normal	0.36	0.30
		Loaded backward move	Normal	0.87	0.33
		Container loading on the YT	Normal	0.30	0.36
	Loading	Container lifting from the YT	Normal	0.20	0.11
		Loaded forward move	Normal	0.64	0.25
		Container loading on the vessel	Normal	0.21	0.16
		Unloaded backward move	Normal	0.66	0.11
Yard Crane	Unloading	Container lifting from the YT	Normal	0.34	0.13
		Loaded forward move	Normal	0.77	0.25
		Container loading in the SY	Normal	0.28	0.21
		Unloaded backward move	Normal	0.62	0.28
	Loading	Unloaded forward move	Normal	0.67	0.16
		Container lifting from the SY	Normal	0.18	0.07
		Loaded backward move	Normal	1.12	0.33
		Container loading on the YT	Normal	0.23	0.11
Yard Truck	Unloading (Single-Cycle)	Unloaded travel from SY to QC	Normal	2.77	1.04
		Loaded travel from QC to SY	Normal	2.74	0.53
	Loading (Single-Cycle)	Loaded travel from SY to QC	Normal	3.26	1.06
		Unloaded travel from QC to SY	Normal	2.48	0.54
	Double-Cycle	Unloaded travel from QC1 to QC2	Deterministic	0.16	-
		Unloaded travel from YC2 to YC1	Deterministic	0.75	-

Several cost items contribute to the total cost of the container handling process at the terminal such as tug services, wharfage charges, berth hire as well as the equipment used in handling. Since this study focuses only on the handling process, the costs of the main resources used to load or unload a vessel are considered (i.e., the QCs, YCs, YTs, and the operators). For confidentiality purposes, the financial department at the terminal provided the authors only with approximate hourly ownership and operating costs for the handling components without the operators. These hourly costs were US$105, US$87, and US$60 for a single QC, YC, and YT, respectively. An additional 25% to these costs will be considered in this study to account for operator costs. It is worth noting that the developed models are flexible to input different costs based on the terminal planner estimate considering different geographical locations, time factors, and any other unaccounted costs that contribute to the handling cost.

In addition to the time and cost data collected, the productivity rate in TEUs per hour for each handling component was recorded. As shown in Table 5, the productivity rates were recorded separately for vessel unloading and loading. For example, the unloading productivity rate of a single QC was determined based on the number of containers lifted from the vessel during a one-hour timespan. This process was repeated over several hours to consider the variation in the number of containers unloaded each hour. Similarly, the productivity rate was determined for the loading cycle. Since the vessel unloading and loading productivities were determined independently for each handling component; their average was calculated in order to observe the actual productivity rate of the overall handling process (i.e., both vessel unloading and loading). As a reminder, the productivity rates presented in Table 5 are based on the traditional single-cycling strategy.

Table 5: Productivity Rates Collected Data

Handling Component	Statistical Parameter	Unloading Productivity Rate (TEUs/hr)	Loading Productivity Rate (TEUs/hr)	Overall Productivity Rate (TEUs/hr)
Quay Crane	Mean	55.33	68.03	61.68
	Standard Deviation	15.53	9.58	12.56
Yard Crane	Mean	61.86	53.59	57.73
	Standard Deviation	13.93	13.24	13.59
Yard Truck	Mean	12.85	13.81	13.33
	Standard Deviation	3.43	3.91	3.67

6. MODEL IMPLEMENTATION AND TESTING

To test the developed models, they were implemented on a case study using the EZStrobe® simulation software by identifying the required inputs and outputs. The case study considered is the 16,000 TEUs vessel from which the required data were collected as elucidated in the previous section. For both models, the inputs constitute the resources used, the considered costs, and the work task duration. The defined resources are the number of QCs, YCs, and YTs used in the process as well as the number of containers to be loaded and unloaded. Usually a vessel carries a combination of 20’ and 40’ containers. In each cycle of the handling process, either one 40’ container or two 20’ containers are transferred from or to the vessel as well as from or to the SY. Specifically, in each cycle, 2TEUs are transferred. Thus, in the developed models, the input regarding the number of containers was replaced by the number of loads, where each load is equivalent to 2TEUs. Accordingly, for the 16,000 TEU vessels, the number of loads will be 8,000, assuming that the number of imported and exported loads are equal. The costs input considered the hourly costs of each QC, YC, and YT used in addition to the those of the operators by adding 25% as explained in the previous section. Finally, the stochastic durations for all the considered work tasks shown in Table 4 were used as the third input to consider uncertainty in the developed models. Meanwhile, the output of both models include the productivity rate (TEUs/hr), vessel turnaround time (hrs), handling unit cost (US$/TEU), and handling total cost (US$).

For the single-cycling model, one QC and YC each, and five YTs were assumed to complete the job. Conversely, two QCs and YCs each, and five YTs were assumed for the double-cycling model. The results of both implementations are shown in Table 6 for handling 32,000 TEUs (i.e., 16,000 TEUs imported and 16,000 TEUs exported). Using the traditional single-cycling model, the productivity rate was 56.39 TEUs/hr. This value represents the overall productivity for both loading and unloading. The system overall productivity is evaluated based on the minimum productivity of the three components used. The actual system overall productivity rate can be estimated based on Table 5 where the QC, YC, and five YTs overall productivities were 61.68, 57.73, and 66.65 TEUs/hr, respectively. Thus, comparing the productivity rate obtained by the model with the actual system overall productivity rate in Table 5 which was 57.73 TEUs/hr, verifies the practicality of the developed single-cycling model in representing the real-life situation with less than 3% difference. To compare the effect of applying the YT double-cycling strategy with the traditional single-cycling, Table 6 shows a significant improvement with respect to the productivity rate and eventually to the vessel turnaround time. The productivity rate was improved by 34.74 TEUs/hr (i.e., 61.6% improvement) and the vessel turnaround time was reduced by 216.4 hrs (i.e., 38.1% time saving). Furthermore, the total handling cost was cut by US$48,767.6 (i.e., 14% cost saving) when applying the double-cycling. These results demonstrate the efficiency and effectiveness of employing the YT double-cycling strategy in containerized terminals.

On a separate note, it is impractical to just assume that a single crane (on the berth side and the SY side) can handle a 16,000 TEUs vessel in the single-cycling model. However, such an assumption was intended in order to have a fair comparison when matching the results of both the single-cycling and double-cycling models. Although in the double-cycling model, two QCs and YCs each were used, these pair of cranes still act as a single unit as explained earlier. Moreover, the double-cycling introduced in this study is applied only for the YT. Hence, the effect of changing the number of YTs on the productivity rate and the unit cost is intended to be emphasized when comparing both models as will be discussed in the next section.

Table 6: Model Implementation Results

Model	Productivity Rate (TEUs/hr)	Vessel Turnaround Time (hrs)	Unit Cost (US$/TEU)	Total Cost (US$)
Single-Cycling	56.39	567.5	10.91	348,998
Double-Cycling	91.13	351.1	9.38	300,230

7. SENSITIVITY ANALYSIS

To investigate the effect of changing the number of YTs on the models' main outputs, a sensitivity analysis was conducted, implementing both developed models several times by varying the number of YTs while keeping all other inputs constant. The analysis results are shown in Table 7 and plotted for better visualization in Figure 10. For the single-cycling model, the productivity rate was 49.66 TEUs/hr when using only three YTs as shown in Table 7. The rate increases in proportion to the number of YTs up to a certain limit, after which enhanced productivity becomes insignificant, and eventually, the reduction in the vessel turnaround time is minimized. Therefore, considering only the productivity rate as a decision criterion, five YTs would be an optimal choice for completing the handling process using the single-cycling strategy. This can be better observed in Figures 10a and b where, after five YTs, both curves almost stabilize, with minimal fluctuations, irrespective of how many YTs are added. The same pattern is observed when using the double-cycling strategy, where, again, using five YTs would be a preferred choice after which the improvement is insignificant. Considering only the total cost as a decision criterion, the decision maker would opt to select three YTs and four YTs for the single-cycling and the double-cycling strategies, respectively, as shown in Figure 10c. Although increasing the number of YTs was expected to enhance productivity and cut costs, this did not happen in this case study, as the number of QCs and YCs considered were insufficient. Particularly, increasing the YTs with insufficient cranes increases the idle time of the YTs. Therefore, increasing the number of cranes with the YTs, especially when dealing with large vessels, is essential to ensure that YTs are utilized efficiently.

Comparing both strategies, it is obvious that the double-cycling strategy results in a significant improvement with respect to the productivity rate and vessel turnaround time, regardless of the number of YTs used, as shown in Figures 10a and b. As shown in Table 7, above 54% and above 35% improvement was achieved with respect to the productivity rate and vessel turnaround time, respectively, when using the double-cycling strategy. Regarding the cost, Table 7 and Figure 10c show that the double-cycling strategy was always a more economical option due to its significant higher productivity. This is despite the fact that the hourly cost using the double-cycling strategy is higher than the single-cycling strategy as two QCs and two YCs are used.

Table 7: Sensitivity Analysis Results

Number of YTs	Single-Cycling				Double-Cycling				Productivity Improvement		Time Saved		Cost Saved	
	Productivity Rate (TEUs/hr)	Vessel Turn-around Time (hrs)	Unit Cost (US$/TEU)	Total Cost (US$)	Productivity Rate (TEUs/hr)	Vessel Turn-around Time (hrs)	Unit Cost (US$/TEU)	Total Cost (US$)	TEUs/hr	%	hrs	%	US$	%
3	49.66	644.4	9.36	299,638	76.57	417.9	9.21	294,632	26.91	54.2%	226.5	35.1%	5,005	1.7%
4	55.23	579.4	9.78	312,873	87.51	365.7	8.91	285,225	32.28	58.4%	213.7	36.9%	27,649	8.8%
5	56.39	567.5	10.91	348,998	91.13	351.1	9.38	300,230	34.74	61.6%	216.3	38.1%	48,768	14.0%
6	56.81	563.3	12.15	388,664	91.84	348.4	10.13	324,042	35.03	61.7%	214.8	38.1%	64,622	16.6%
7	56.99	561.5	13.42	429,549	92.15	347.3	10.91	348,996	35.16	61.7%	214.2	38.2%	80,553	18.8%
8	57.01	561.3	14.73	471,496	92.21	347.0	11.71	374,797	35.2	61.7%	214.3	38.2%	96,700	20.5%
9	57.06	560.8	16.04	513,144	92.41	346.3	12.50	399,957	35.35	62.0%	214.5	38.3%	113,187	22.1%
10	57.18	559.6	17.31	554,040	92.62	345.5	13.28	424,962	35.44	62.0%	214.1	38.3%	129,078	23.3%
11	57.21	559.3	18.62	595,700	92.29	346.7	14.14	452,487	35.08	61.3%	212.6	38.0%	143,213	24.0%
12	57.22	559.2	19.92	637,539	92.46	346.1	14.93	477,612	35.24	61.6%	213.1	38.1%	159,927	25.1%
13	57.11	560.3	21.27	680,791	92.5	345.9	15.73	503,351	35.39	62.0%	214.4	38.3%	177,440	26.1%
14	57.41	557.4	22.47	719,038	92.59	345.6	16.52	528,783	35.18	61.3%	211.8	38.0%	190,256	26.5%

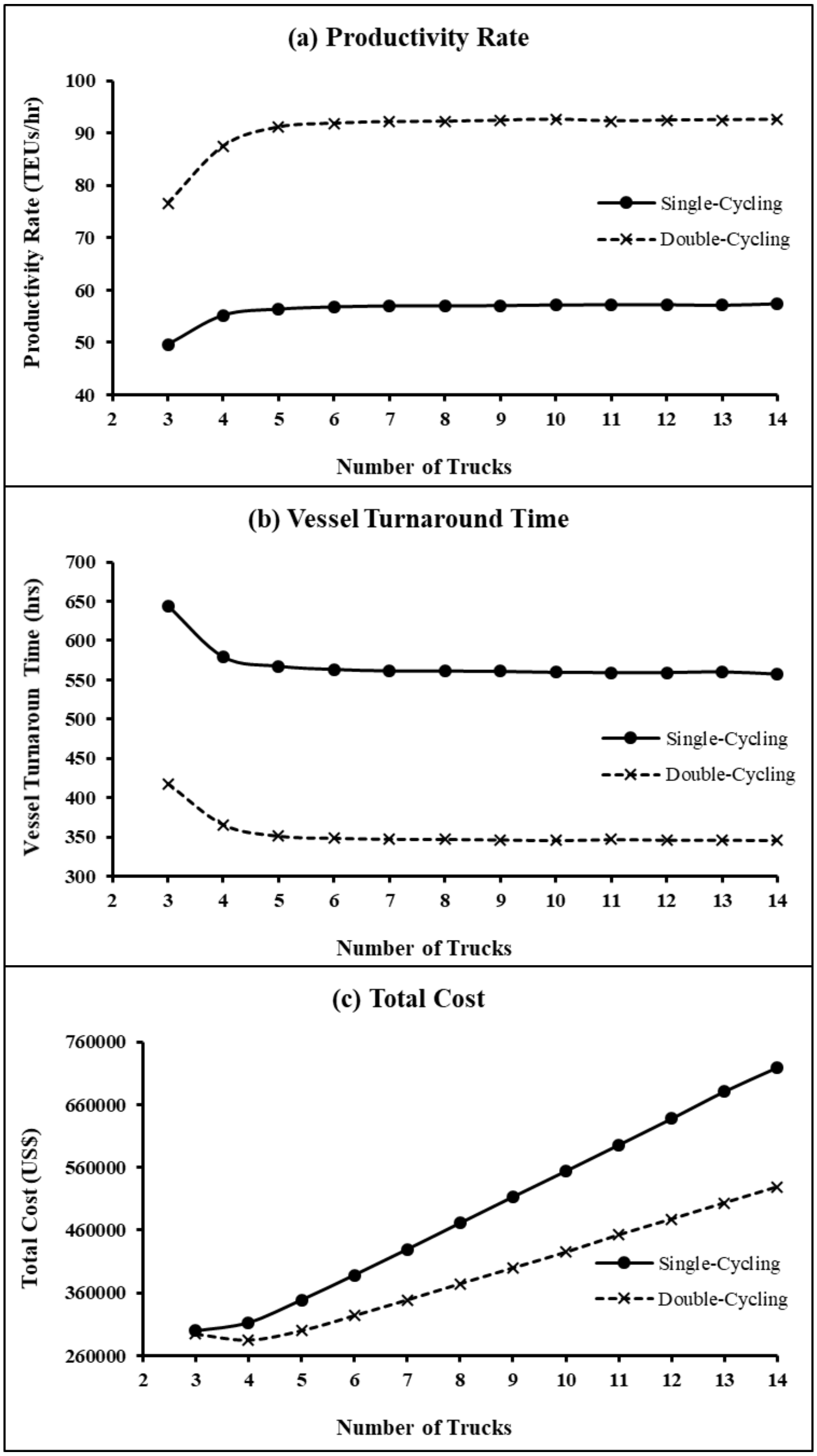


Figure 10: Sensitivity Analysis Plots

8. CONCLUSIONS

This study presented the formulation and development of two integrated scheduling models for container terminal handling operations by synchronizing the work tasks of the QCs, YTs, and YCs simultaneously. The first model was developed by employing the traditional single-cycling strategy while the second employed a double-cycling strategy for the YTs to improve productivity, minimize vessel turnaround time, and cut costs. Simulation was used for developing the models considering stochastic durations for the different work tasks to mimic real-life situations and taking into consideration uncertainty.

Both models were implemented based on a real-life case study of a 16,000 TEUs vessel capacity. The single-cycling model resulted in a predicted productivity rate, with a less than 3% difference, when compared with the actual overall productivity rate. This suggests the robustness of the model in predicting close to practical real-life productivity as it considered both uncertainties and interactions between the different resources used. To compare both strategies, a sensitivity analysis was conducted for both models by varying the number of utilized YTs. It was found that employing the double-cycling strategy for YTs resulted in up to a 62% productivity improvement and up to a 38% reduction in the vessel turnaround time. Even with respect to costs, the double-cycling strategy achieved up to almost 27% cost savings, when compared with the traditional single-cycling. Simultaneously, it was found that double-cycling requires not only increasing the number of YTs to achieve enhanced productivity and cost reduction, but it also requires more cranes to maintain all equipment utilized efficiently.

Despite the promising results achieved by both models, there is still room for further improvement. For example, to add practicality and take into account uncertainty, additional work tasks should be added that consider the breakdown, repair, and/or periodical minor maintenance for the equipment used in the handling process. In addition, it is imperative to take into account the BAP, QCAP, and SYAP together with the presented scheduling problems, given that all of these operations are interrelated and their relative impact should be considered. Finally, as a future work, an optimum balance between the number of resources used in the handling process (i.e., QCs, YTs, and YCs) should be investigated.

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LIST OF TABLES:

LIST OF FIGURES: