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Research Article

Performance Comparison of Real-Time Yard Crane Dispatching Strategies at Nontransshipment Container Terminals

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Yard crane operations are often a bottleneck at a container terminal. This paper aims to investigate the effects of various real-time yard crane dispatching strategies on operational cost and gross crane rate (GCR) for nontransshipment container terminals. A general cost estimation model is introduced to incorporate the detailed costs incurred during container handling process within terminal area. The formulas of container handling related parameters are mathematically derived to validate the simulation model. Results reveal that the common nearest truck first served strategy yields the lowest operational cost but the lowest GCR. On the other hand, earliest YT strategy achieves the highest GCR at the expense of higher operational cost with more vessel calls, while nearest YT strategy produces the highest GCR and is the second economical with fewer vessel calls. Under any of the proposed yard crane dispatching strategies, the strategy that separately stacks import and export containers into different blocks outperforms the scattered stacking strategy in terms of GCR, although no distinct cost advantage is obtained. The results provide fundamental insights into the connection between real-time yard crane dispatching strategies and operational performance at manually controlled nontransshipment container terminals.

1. Introduction

Container terminals (CTs) are crucial nodes in multimodal transportation networks. The past decade has witnessed the ever-increasing worldwide container throughput which contributes to the prosperity of CTs all over the world while at the same time creating operational challenges for terminal operators in providing efficient services. The service efficiency of CTs is usually measured by gross crane rate (GCR) which is equal to the average number of lifts achieved at a terminal per quay crane (QC) working hour and has a significant influence on the time vessels spend at port [1]. Normally, the objective of operating a successful CT is to decrease the operational cost whilst providing a desirable GCR to ensure the service quality [2]. However, when situations such as inclement weather and massive vessel arrival happen, the terminal operator has to pursue a higher GCR to accelerate the vessel handling speed at a higher operational cost. The competing trade-off between reducing operational cost and improving GCR is affected by too many factors from strategic planning to operational management. As previous studies on yard crane (YC) dispatching/scheduling have pointed out that YC operations are of great importance and likely to be a potential bottleneck to the overall CT performance [3, 4], this paper specifically focuses on evaluating the effects of real-time YC dispatching strategies on the operational cost and GCR of nontransshipment container terminals (NTCTs).

At the NTCTs, external trucks (ETs) arrive at the yard randomly to deliver or pick up containers, so the arrival time and task location are hard to be well predicted or effectively controlled in practice. In addition, the arrival time of a yard truck (YT) at the yard may also derive from the expected time due to real-time traffic situation and personal skill. Consequently, schedules for detailed yard operations that are based on integer programming (IP) models become outdated almost immediately after their construction [1]. Constructing real-time schedules with the latest information is often impractical because runtimes of IP heuristics are usually too long to be feasible. Thus, the YC operators are often given the freedom to select a YT or ET from the queues of trucks to

serve based on their experience or prescriptive real-time YC dispatching strategy such as first come first served (FCFS) or nearest truck first served (NTFS). However, very few studies have analyzed the effects of real-time YC dispatching strategies on operational performance of container terminals especially NTCTs so far. To the best of our knowledge, most CTs and related researches simply employ the NTFS strategy without giving more details about its effectiveness [5], but it is unclear whether the current practice is optimal and how real-time YC dispatching strategies could be ameliorated [6]. Therefore, the motivation of this study is stimulated by a lack of knowledge about the effectiveness of various real-time YC dispatching strategies at NTCTs. This study makes two major contributions. First, it introduces a general cost estimation model for NTCT operations and derives mathematical formulas for container handling related variables in the model to validate the proposed simulation model. Second, both the operational costs and GCRs of different YC dispatching strategies at NTCTs are evaluated and compared via a simulation study which realistically reproduces the real-life operational environment.

The remainder of this paper is organized as follows. Section 2 summarizes the related works in the literature, followed by the studied problem of this work in Section 3. Section 4 describes a detailed cost estimation model for NTCT operations and derives the mathematical formulas for key parameters in the cost estimation model. Section 5 briefly introduces the proposed simulation model and then describes the experiments, reports the results, and discusses their insights. Section 6 concludes this paper and proposes further researches.

2. Literature Review

In the recent review works, CT operations are divided into three main categories: seaside operations [7], storage yard operations [8], and transport operations [9]. Earlier comprehensive surveys were conducted by Vis and De Koster [10], Vis and De Koster [10], and Stahlbock and Voß [11]. The literature highly relevant to this study includes those works that investigated the YC dispatching and CT simulation models.

The YC dispatching is the problem of dispatching YCs to serve a given set of truck jobs with different ready times (truck arrival time) in the container yard. A series of mathematical models have been developed for the YC dispatching problem. As it is NP-complete [12], some researches only focus on the dispatching of a single YC. For example, K. H. Kim and K. Y. Kim [13] minimized the sum of setup time and travel time of a YC for loading operations of export containers with a mixed integer program (MIP) and employed heuristic algorithms. Ng and Mak [14] proposed integer programming (IP) to minimize the total truck waiting times and developed a heuristic. Vis and Roodbergen [15] reformulated the YC dispatching problem as a traveling salesman problem and solved it with dynamic programming, and a simulation study showed that their optimal approach outperforms the FCFS strategy. Guo et al. [16] aimed at minimizing the average truck waiting time with predicted vehicle arrival information and results showed the advantage of their proposed algorithms over the real-time YC dispatching strategies such as FCFS and NTFS. Gharehgozli et al. [17] minimized the total YC travel time by an IP and proposed a two-phase solution method to optimally solve it. However, multiple YCs usually work in the same zone or block at the same time in real-world environments and thus should be simultaneously considered during dispatching decision process. In this respect, Cheung et al. [18] developed a MIP to minimize the total unfinished workload at the end of each time period and proposed a Lagrangian decomposition method and a successive piecewise-linear approximation method. Ng [19] minimized the total job completion time by an IP and developed a dynamic programming-based heuristic. Lee et al. [20] and Cao et al. [21] minimized the loading time of export containers by an IP and developed various heuristics. Li et al. [3] proposed a MIP to minimize a linear combination of the retrieval earliness and storage and retrieval delays and developed heuristics and rolling-horizon algorithm. He et al. [4] aimed at minimizing the total delayed workloads and the total times of YC movement, developed a hybrid algorithm, and used a simulation model to evaluate the proposed approach. Chang et al. [22] established an IP to minimize the total task delays and applied a heuristic along with a simulation study. Mathematical approaches for YC dispatching can achieve objectives such as minimizing the total YC travel time or the average truck waiting time for a short planning period but cannot ensure the lowest operational cost or the highest GCR obtained. On the other hand, the achievement of optimal or local optimal solutions for YC dispatching problem is based on the assumption that the arrival times and locations of trucks are predetermined or well predicted, which, however, can only be known once the trucks arrive at the yard in real-life terminals.

The research most relevant to our study includes that of Kim et al. [23], Petering et al. [1], and Huynh and Vidal [6]. Kim et al. [23] compared average truck waiting times, average YC gantry travel distances, and total delay costs of trucks of different dispatching rules for a single YC with a simulation study where only delivery and receiving operations were considered. Petering et al. [1] initially presented a detailed simulation study to evaluate the effects of twelve real-time rule-based YC dispatching strategies on the GCR of pure-transshipment CTs (PTCTs). Huynh and Vidal [6] developed an agent-based simulation model to analyze average truck waiting times under distance-based YC dispatching strategy and time-based YC dispatching strategy and how they can be used together to accomplish the CT's operational objectives, but they only considered YC dispatching for delivery operations among four yard blocks. Specifically, none of the three articles compared the operational costs of different YC dispatching strategies.

Considering the complexity and stochasticity of the NTCT system, a vast pool of CT simulation models have been developed for various decision-making purposes [24]. The most common modeling approach for CTs is discrete event simulation, which is usually built in a process-oriented mode [5, 25] or an object-oriented mode [26, 27]. In order to directly model the interactions between individual equipment operators, another emerging modeling approach, called multiagent simulation, has been introduced in several studies

with a decentralized logic [28, 29]. However, since most CTs are centrally controlled in nature, Sun et al. [30] proposed a hybrid modeling system which combined both the multiagent system and the central controlling procedure to realistically represent a CT system.

In summary, a large body of outstanding articles dedicated to studying the YC dispatching problem was found in the literature. Nevertheless, no works have been carried out to investigate how various real-time YC dispatching strategies affect both terminal operational cost and GCR in the long term instead of a short planning period. As a result, there is a necessity to conduct such a study.

3. Problem Description

This study is performed over a typical manually controlled NTCT system in China as shown in Figure 1, which is composed of seaside operation, horizontal transportation, storage yard operation, and landside operation. The major components in this system include vessels; containers; facilities, such as berths, apron, storage yard, parking lot, inspection area, and gate; and equipment, such as QCs, YCs, YTs, and ETs. For the detailed operations in CTs, refer to the dissertation of Petering [27].

As illustrated in Figure 1, YCs are major handling equipment in storage yards, which must successively perform multiple tasks such as the storage of import/export containers from YTs/ETs and the retrieval of import/export containers onto ETs/YTs. The stochasticity of YT/ET arrivals and the difference between individual YC operator's skills greatly aggravate the complexity of the YC dispatching problem. Given a limited number of YCs available, the strategy followed by YCs in serving YTs/ETs has a great influence on the gantry travel time of YCs and the waiting time of YTs and ETs in the yard as well as terminal's operational cost. On the other hand, the handling time and waiting time of QCs together determine the GCR. If a QC is starved of YTs during operation process, it has to wait until an available YT arrives. To guarantee the YCs and YTs serve the QCs effectively, the activities in the container yard should be properly coordinated. To sum up, YC operations are closely linked to terminal operational cost and GCR, and thus a rational YC dispatching strategy essentially holds great promise in facilitating the achievement of terminal operators' objective.

All the containers need to be allocated a storage space in the yard after they arrive at the terminal. The storage space allocation decision depends on the tactical-level stacking strategy together with the operational-level storage space assignment strategy. The tactical-level stacking strategy determines which blocks should be dedicated to stacking a certain type of containers, and the operational-level storage space assignment strategy figures out into which stack an individual container should be placed [31]. The tactical-level stacking strategy is of significance in that it drastically affects the performance of yard operations and YC dispatching.

Therefore, this paper aims to evaluate the total operational cost and the GCR for various YC dispatching strategies under two common tactical-level stacking strategies.

3.1. YC Dispatching Strategies. Currently, most terminals around the world do not have an automated system for controlling or dispatching YCs [1]. Instead, the YC operators have the freedom to decide which truck in the feasible region to serve according to prescriptive real-time YC dispatching strategy [6]. The YC's feasible region is a continuous area that extends left and right from a YC's current position to include all the slots in the same zone that are located at a safety distance from the YC's neighboring cranes. The decisions made by YC dispatching strategies are represented by the four question marks near YC 8 in Figure 1. If YC 8 becomes free, which of the four trucks in block 5 should it serve next?

Four different rule-based real-time YC dispatching strategies are investigated in this study, which are (1) nearest truck, (2) earliest truck, (3) nearest YT, otherwise nearest ET, and (4) earliest YT, otherwise earliest ET. In these four strategies, the tasks in the YC's current slot have priority over all other tasks. If there are no tasks in the YC's current slot, the next task handled by the YC is selected as follows. In strategy (1), the YC serves the nearest truck (either YT or ET) that arrived or is expected to arrive in its feasible region. In strategy (2), the YC serves the first truck that arrived or is expected to arrive in its feasible region. In strategy (3), the YC serves the nearest YT first, otherwise the nearest arrived ET first if there are no YTs that arrived in its feasible region. In strategy (4), the YC handles the earliest arrived YT first, otherwise the earliest arrived ET first if there are no YTs that arrived in the feasible region.

3.2. Yard Stacking Strategies. Two common stacking strategies in the tactical level are compared in this paper [32]. The first one is the *separate stacking strategy* that stores import and export containers separately at different blocks, which usually stacks export containers close to seaside blocks and import containers close to landside blocks; the second is the *scattered stacking strategy*, which refers to evenly stacking import and export containers into any block. The advantage of the separate stacking strategy is that only two types of handling operations (e.g., storing and retrieving import containers in import blocks) simultaneously exist in one block, and thus it minimizes the interference between different operations and enables easier management of storage yard. However, the separate stacking strategy may lead to high workload and utilization imbalances among blocks. Consequently, in certain land scarce terminals, the scattered stacking strategy is widely accepted although it complicates the yard operations.

4. Cost Estimation Model of Container Terminal Operations

To evaluate the operational costs of different YC dispatching strategies, a cost estimation model (Section 4.1) for the NTCT operations is formulated based on Lee and Kim [33]. Since some variables in the cost estimation model cannot be estimated mathematically due to the high stochasticity of NTCT operations, a simulation model (Section 4.2) is proposed to generate the values of all variables. To validate the accuracy of the proposed simulation model, Section 4.3 derives mathematical formulas for some critical variables

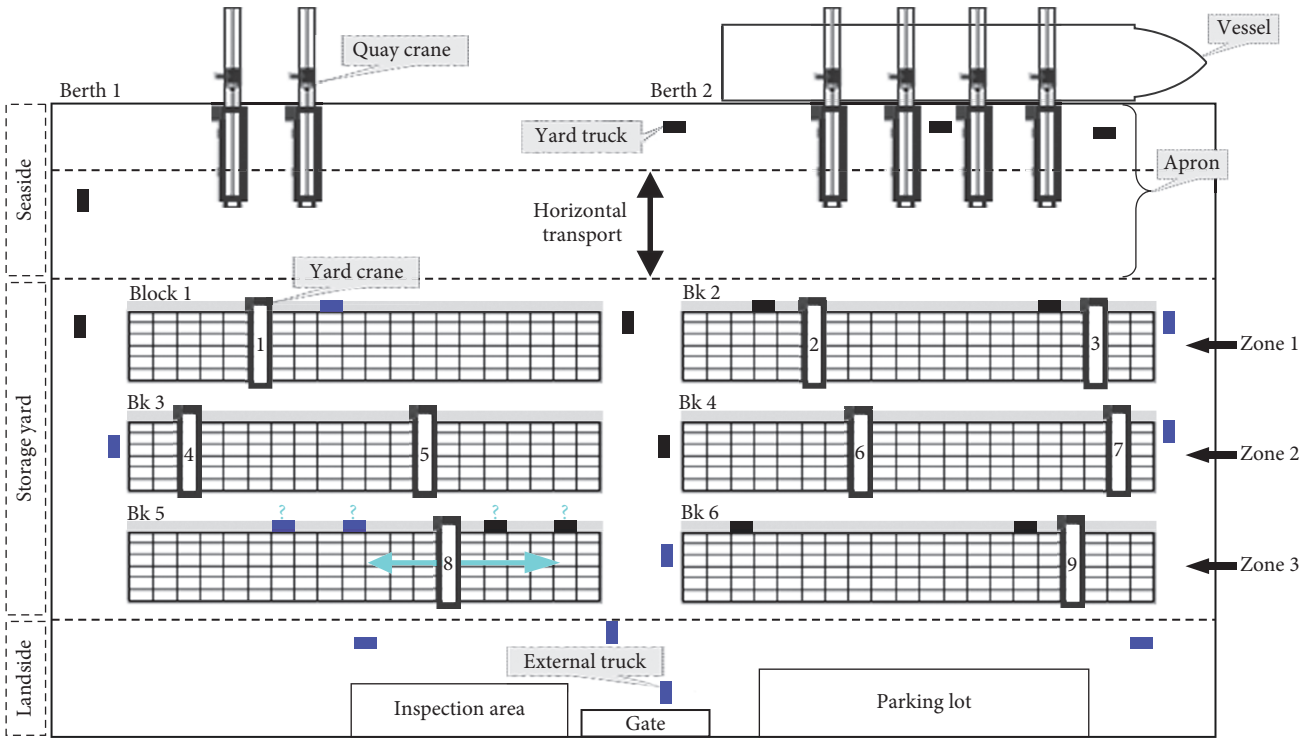

Figure 1: Bird's eye view of a typical nontransshipment container terminal.

in which the expected waiting time of trucks is estimated via queueing theory. As is known, the derivations based on queueing theory usually adopt FCFS rule [34, 35] which corresponds to the earliest truck strategy in this paper. Thus, the mathematical formulas derived in this section are suitable to validate the simulation results under the earliest truck strategy.

4.1. Operational Cost Estimation Model. The proposed operational cost estimation model is formulated based on the model for evaluating a new built CT layout in Lee and Kim [33] which included the construction cost of facilities and fixed overhead cost of equipment but excluded the cost related to QC operations. However, for the established terminals, the construction cost and fixed overhead cost are not affected by operational decisions. Therefore, the proposed cost estimation model in this study only covers the operational costs that are incurred during the container handling processes within the terminal area, including the handling cost of QCs and YCs; the traveling cost of YCs, YTs (yard trucks), and ETs; and the waiting cost of QCs, YTs, and ETs as shown in expression (1).

The notations to formulate the cost function are presented as follows:

n_B : number of berths,

N : number of columns of blocks,

R : number of rows of blocks (i.e., number of zones),

H : maximum number of tiers of a stack,

l_b : length of a block (m),

w_b : width of a block (m),

w_v : width of a vertical lane (m),

w_h : width of a horizontal lane (m),

w_a : width of the apron area (m),

w_g : distance from the gate to the first landside block (m),

n_u : expected number of containers unloaded from one vessel (import containers),

n_l : expected number of containers loaded onto one vessel (export containers),

h : total working time per week (min),

n_s : number of vessels calls per week,

n_{YC} : average number of YCs deployed for each zone,

n_{QC} : average number of QCs allocated to a vessel,

γ : the TEU factor, which is equal to the sum of 1.0 and the ratio of $40'$ containers among all the containers handled in the terminal,

u_{QC} : average utilization of a QC ($0 \le u_{\mathrm{QC}} < 1$),

t^h_{QC} : average time taken by a QC to handle a single container (min),

t^h_{YC} : average time taken by a YC to handle a single container (min),

θ : peak ratio of QC operations to consider the peak workload requirement in the total productivity of QCs ($0 < \theta < 1$),

δ : peak ratio of arriving ETs for receiving and delivery containers ($0 \le \delta < 1$). ETs arrive randomly, and thus there are fluctuations in the arrival rate of ETs,

ω : average throughput rate at the quay per minute, estimated by $n_B n_{\mathrm{QC}} u_{\mathrm{QC}} / t^h_{\mathrm{QC}}$,

a_{ET} : arrival rate of ETs for receiving and delivery containers, which is estimated by $(1+\delta)(n_u + n_l)n_s/h$,

$A^{\mathrm{YC}}_{\mathrm{ET}}$: arrival rate of ETs for receiving and delivery containers per YC, which is estimated by $a_{\mathrm{ET}}/(n_{\mathrm{YC}}R)$,

$A^{\mathrm{YC}}_{\mathrm{YT}}$: arrival rate of YTs for discharging and loading containers per YC. Because the workload is relatively intensive in certain blocks during discharging or loading operations, more YCs will be dispatched to those busier zones, and thus the arrival rate of YTs per YC is evaluated by $\omega(1+\theta)/(n_{\mathrm{YC}}R)$,

v_e : travel speed of an empty truck within the terminal area (m/s),

v_l : travel speed of a laden truck within the terminal area (m/s),

v^g_{YV} : gantry travel speed of a YC (m/s),

c^h_{QC} : operational cost of a QC per minute during loading and discharging operations (¥/min),

c^w_{QC} : waiting cost of a QC per minute (¥/min),

c^h_{YC} : operational cost of a YC per minute during handling operations (¥/min),

c^g_{YC} : gantry travel cost of a YC per meter (¥/m),

c^m_T : travel cost of a truck per minute (¥/min),

c^w_T : waiting cost of a truck per minute (¥/min),

t^w_{QC} : waiting time of a QC per container (min). During the loading process, if a QC is starved of YTs, it has to wait in idling state until a laden YT arrives underneath it. The total waiting time of QCs is spread out over every container handled,

d^g_{YC} : gantry travel distance of a YC per container within a zone (m),

t^{gi}_{YC} : fixed YC interzone movement time (min). Note that YC interzone movement is only allowed under the separate stacking strategy,

s^{gi}_{YC} : total YC interzone movement times,

d^m_{YT} : round-trip travel distance of a YT (m),

t^m_{YT} : round-trip travel time of a YT (min),

$t^{w\mathrm{YC}}_{\mathrm{YT}}$: waiting time of a YT per container in the yard (min),

$t^{w\mathrm{QC}}_{\mathrm{YT}}$: waiting time of a YT per container under QC (min),

d^r_{ET} : round-trip travel distance of an ET (m),

t^m_{ET} : round-trip travel time of an ET (min),

t^w_{ET} : waiting time of an ET per container in the yard (min).

The operational cost for handling a single container within terminal area is expressed as follows:

$$\begin{aligned} c_o = {} & c^h_{\mathrm{QC}} E\left(t^h_{\mathrm{QC}}\right) + c^w_{\mathrm{QC}} E\left(t^w_{\mathrm{QC}}\right) + c^h_{\mathrm{YC}}\left[2E\left(t^h_{\mathrm{YC}}\right)\right] \\ & + c^g_{\mathrm{YC}}\left\{2E\left(d^g_{\mathrm{YC}}\right) + \frac{t^{gi}_{\mathrm{YC}} s^{gi}_{\mathrm{YC}}}{\left[n_s\left(n_u + n_l\right)\right]}\right\} + c^m_T E\left(t^m_{\mathrm{YT}}\right) \\ & + c^w_T E\left(t^{w\mathrm{QC}}_{\mathrm{YT}}\right) + c^w_T E\left(t^{w\mathrm{YC}}_{\mathrm{YT}}\right) + c^m_T E\left(t^m_{\mathrm{ET}}\right) \\ & + c^w_T E\left(t^w_{\mathrm{ET}}\right). \end{aligned} \tag{1}$$

In expression (1), the operational cost per container comprises the operational cost of a QC for handling a single container, the waiting cost of a QC per container, the operational cost of a YC for handling a container (any import/export container needs to be handled twice by YCs), the gantry movement cost of a YC per container (including gantry travel within the zone and interzone movement), the traveling cost of a YT and an ET for transporting a container, and the waiting cost of a YT and an ET per container.

4.2. Simulation Model. The simulation model is developed using AnyLogic (Lee and Kim [33]) in conjunction with Java [36]. The modeling framework primarily comprises *statics*, *events*, *dynamics*, and *decision-making functions*. The *statics* describes the simulated layout scenarios (i.e., the number of berths, the dimension of apron, the layout of storage yard, the location of gate, and the amount of equipment) and encapsulates the entities (i.e., berths, QCs, YCs, YTs, ETs, vessels, and containers). The *events* drive the advance of the simulation progress in a chronological order, which is the control logic behind the discrete-event simulation. Events occur at discrete time points and trigger the state transitions of various entities. Figure 2 displays the main events that relate to container flows within the terminal area. The dynamics track the real-time statuses of the entities during the simulation run. Figure 3 describes the possible status of a YC. For example, when an empty YT that is serving a loading QC is traveling to the yard and is assigned to an "idle" YC, the YC first makes "linear gantrying" if it is not over the bay of the assigned task. On arrival at the destination bay, the YC starts "handling retrieval task." After retrieval completion, the YC keeps "waiting for empty truck" if the YT is still on the way; otherwise, it transfers the container onto the YT and becomes "idle." The *decision-making functions* implement the management strategies/rules with prescriptive algorithms, such as berth allocation algorithm, QC/YC dispatching algorithm, storage space assignment algorithm, and loading sequence decision algorithm. Figure 4 presents a 3D animation of running the proposed simulation model, which is used to observe the operation processes to ensure all the important entities and their individual behaviors were included in the simulation model in the right sequence and output the values of all variables finally.

4.3. Mathematical Formulas for Critical Variables

4.3.1. Expected Handling Time and Its Variance. The handling time of a QC or a YC is the time taken by the equipment to

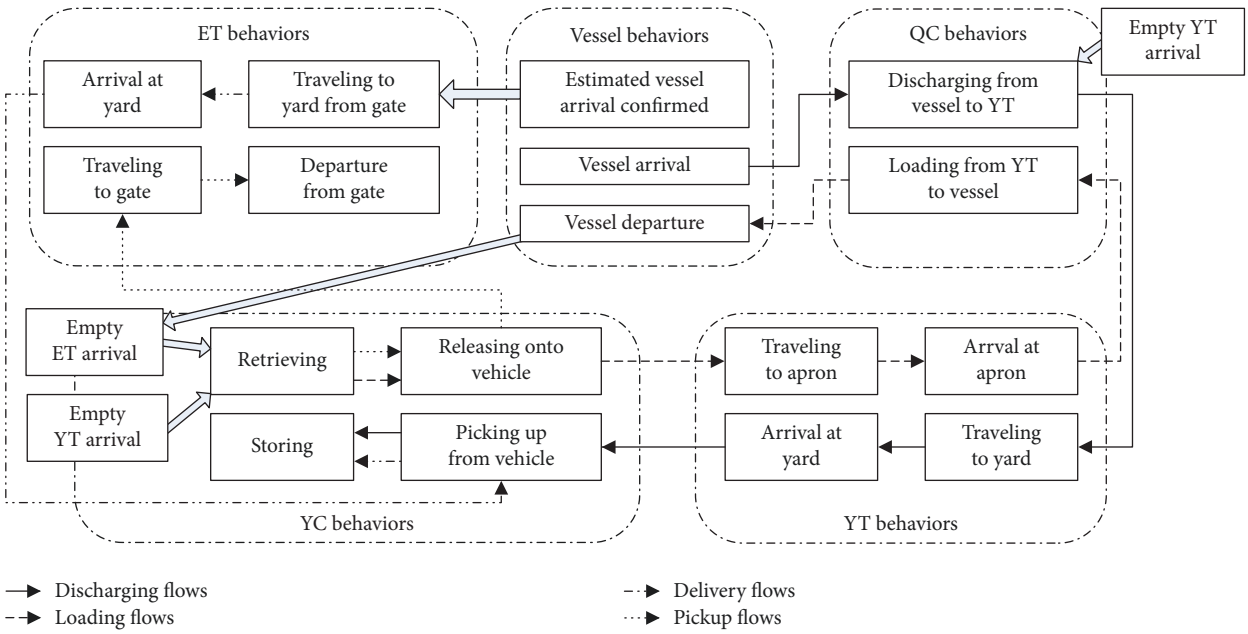

Figure 2: Container flows related main events within terminal area.

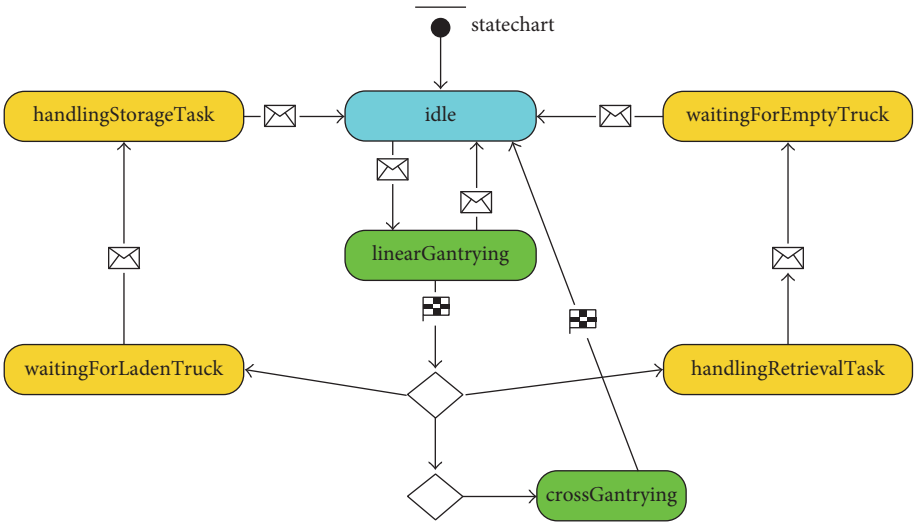

Figure 3: The seven possible states of a YC.

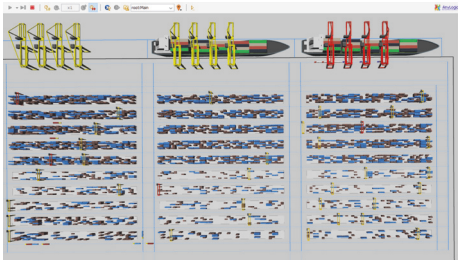

Figure 4: A screenshot of 3D animation.

handle a single container, which consists of vertical movement time of the spreader and trolley movement time [37]. According to Petering et al. [1], the handling time is assumed to follow a triangular distribution with lower limit a, upper limit b, and mode c. Thus, the expected handling time and its variance are calculated as follows:

$$\begin{aligned} E(x) &= \int_a^b x f(x)\,dx \\ &= \int_a^c x \frac{2(x-a)}{(b-a)(c-a)} dx \\ &\quad + \int_c^b x \frac{2(b-x)}{(b-a)(b-c)} dx = \frac{a+b+c}{3}, \\ \operatorname{Var}(x) &= E\left(x^2\right) - E^2(x) \\ &= \frac{a^2+b^2+c^2-ab-ac-bc}{18}. \end{aligned} \tag{2}$$

4.3.2. Expected YC Gantry Travel Distance. YCs need to make a gantry travel between two consecutive tasks if the storage slots of the tasks are not located in the same bay. In practice, the gantry travel of YCs occurs fairly frequently. For simplicity, we consider the expected YC gantry travel distance as the weighted average distance of gantry travels that a YC makes for receiving, loading, discharging, and delivery operations and derive its value as follows.

Since the length of the working area in the horizontal direction is $Nl_b + (N-1)w_v$, the length of each YC's service area is equal to $[Nl_b + (N-1)w_v]/n_{\mathrm{YC}}$. For the receiving or delivery operations, the expected gantry travel distance of a YC serving an ET is estimated by

$$E\left(d_{\mathrm{YC}}^{g\mathrm{ET}}\right) = \frac{Nl_b + (N-1)w_v}{3n_{\mathrm{YC}}}, \tag{3}$$

where $d_{\mathrm{YC}}^{g\mathrm{ET}}$ is the YC gantry travel distance for serving ETs [34].

For the discharging operation, import containers with the same characteristics are consecutively stored in the same stack until the stack is full. For the loading operation, since a QC tends to load export containers of the same group consecutively, export containers of the same group are usually stored in the same stack (i.e., a homogenous stacking strategy [1]) and will be retrieved successively. Thus, import containers allocated to the same stack or export containers retrieved from the same stack might be consecutively handled by the same YC if there is no interference of ETs. Theoretically, the discharging or loading operation is performed consecutively H times at the same bay, where H is the maximum number of tiers of a stack. However, because the random arrival of ETs interferes with the consecutive YC operations at the same bay under the FCFS rule, the consecutive operation times at the same bay are reduced and the reduction factor is $(A_{\mathrm{YT}}^{\mathrm{YC}} - A_{\mathrm{ET}}^{\mathrm{YC}})/(A_{\mathrm{YT}}^{\mathrm{YC}} + A_{\mathrm{ET}}^{\mathrm{YC}})$. Finally, the expected gantry travel distance of a YC for discharging or loading operations is estimated by

$$\begin{aligned} E\left(d_{\mathrm{YC}}^{g\mathrm{YT}}\right) &= \frac{\left(Nl_b + (N-1)w_v\right)/3n_{\mathrm{YC}}}{\left(H\left(A_{\mathrm{YT}}^{\mathrm{YC}} - A_{\mathrm{ET}}^{\mathrm{YC}}\right)/\left(A_{\mathrm{YT}}^{\mathrm{YC}} + A_{\mathrm{ET}}^{\mathrm{YC}}\right)\right)} \\ &= \frac{\left[Nl_b + (N-1)w_v\right]\left(A_{\mathrm{YT}}^{\mathrm{YC}} + A_{\mathrm{ET}}^{\mathrm{YC}}\right)}{3n_{\mathrm{YC}} H\left(A_{\mathrm{YT}}^{\mathrm{YC}} - A_{\mathrm{ET}}^{\mathrm{YC}}\right)}, \end{aligned} \tag{4}$$

where $d_{\mathrm{YC}}^{g\mathrm{YT}}$ is the YC gantry travel distance for serving YTs. Note that $H(A_{\mathrm{YT}}^{\mathrm{YC}} - A_{\mathrm{ET}}^{\mathrm{YC}})/(A_{\mathrm{YT}}^{\mathrm{YC}} + A_{\mathrm{ET}}^{\mathrm{YC}}) \le 1$ means there are no consecutive operations at the same bay, and $E(d_{\mathrm{YC}}^{g\mathrm{YT}}) = E(d_{\mathrm{YC}}^{g\mathrm{ET}})$.

Export (import) containers are received from the ETs (YTs) and later retrieved to the YTs (ETs) by a YC. Thus, the probability that a YC makes a gantry travel for a YT or ET is 1/2, and the expected gantry travel distance of a YC between two moves is obtained by

$$\begin{aligned} E\left(d_{\mathrm{YC}}^{g}\right) &= \frac{1}{2}\left[E\left(d_{\mathrm{YC}}^{g\mathrm{ET}}\right) + E\left(d_{\mathrm{YC}}^{g\mathrm{YT}}\right)\right] \\ &= \frac{Nl_b + (N-1)w_v}{6n_{\mathrm{YC}}}\left[1 + \frac{A_{\mathrm{YT}}^{\mathrm{YC}} + A_{\mathrm{ET}}^{\mathrm{YC}}}{H\left(A_{\mathrm{YT}}^{\mathrm{YC}} - A_{\mathrm{ET}}^{\mathrm{YC}}\right)}\right]. \end{aligned} \tag{5}$$

4.3.3. Expected Truck Travel Distance. This section only deduces the expected round-trip travel distance of YTs and ETs under the *separate stacking strategy*, and that under the *scattered stacking strategy* is obtained similarly and is omitted here. The following assumptions are introduced: (a) YTs move counterclockwise, whereas ETs move clockwise; (b) the numbers of rows and columns of blocks are even, and the numbers of import and export blocks are the same; (c) the expected numbers of import and export containers are the same; (d) the gate is located in the middle of the landside boundary.

Based on the above assumptions, the truck flows under the separate stacking strategy are presented in Figure 5. The expected YT/ET travel distance is equal to the sum of the probability of each case multiplied by the travel distance in each case [38].

(1) Expected YT Travel Distance. During the vessel discharging and loading process, YTs need to move back and forth along the vertical and horizontal lanes between the yard and the berth to continuously serve the working QCs. Thus, we decompose the round-trip travel distance of YTs (d_{YT}^{r}) into horizontal travel distance (d_{YT}^{rh}) and vertical travel distance (d_{YT}^{rv}) and deduce their values separately.

To reduce YT travel distance, containers are usually stored in the blocks near a vessel's home berth, where the home berth is the preferred berthing place of a vessel upon its arrival. In this paper, we assume that the containers of a vessel are uniformly distributed in the two nearest columns of blocks behind the vessel's home berth (suppose that $N \ge 2$, where N is the number of columns of blocks). For example, the containers belonging to the vessels whose home berth is berth 1 or berth 2 (labeled in Figure 4) will be evenly stored in column 1 and column 2 of blocks upon their arrival at the yard. Thus, the probability that containers are stored in each column of blocks is 1/2. When the column of blocks is located

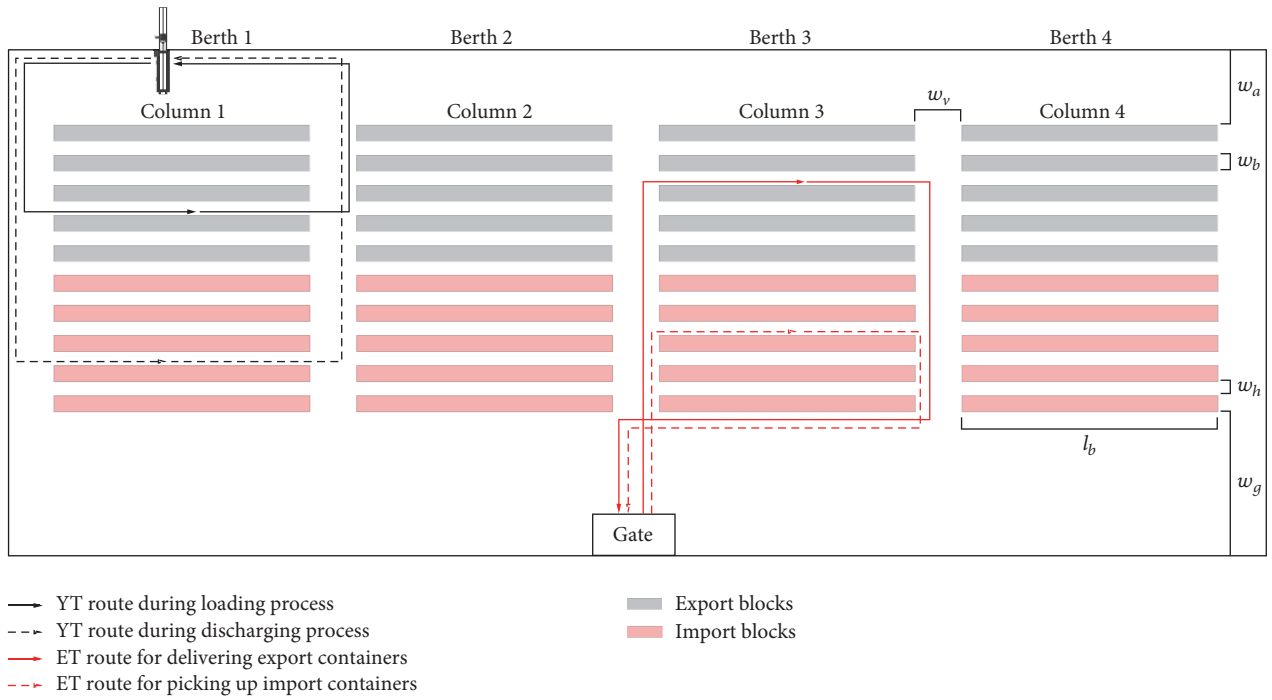

Figure 5: Truck flows under the separate stacking strategy.

directly behind the home berth, the horizontal travel distance of YTs is $2l_b + 2(1 + 1/2)w_v = 2l_b + 3w_v$. On the other hand, when the column of blocks is located near the home berth, the horizontal travel distance of YTs is $4l_b + 2(2 + 1/2)w_v = 4l_b + 5w_v$. Finally, the expected horizontal travel distance of YTs is obtained:

$$E\left(d_{\mathrm{YT}}^{rh}\right) = \frac{1}{2}\left(2l_b + 3w_v\right) + \frac{1}{2}\left(4l_b + 5w_v\right) = 3l_b + 4w_v. \quad (6)$$

The storage locations of containers are uniformly distributed in the vertical direction as the expected number of import containers and export containers is assumed to be the same. When the transfer location is in the kth row of blocks from the seaside ($k = 1, 2, \ldots, R$), the vertical travel distance becomes $2[w_a + (k-1)(w_b + w_h)]$, and the probability is $1/R$. Then, the expected travel distance of YTs in the vertical direction is represented by

$$\begin{aligned} E\left(d_{\mathrm{YT}}^{rv}\right) &= \sum_{k=1}^{R} \frac{1}{R} 2\left[w_a + (k-1)\left(w_b + w_h\right)\right] \\ &= \frac{2}{R}\left[Rw_a + \frac{R(R-1)}{2}\left(w_b + w_h\right)\right] \\ &= 2w_a + (R-1)\left(w_b + w_h\right). \end{aligned} \quad (7)$$

Finally, the expected round-trip travel distance of YTs is estimated by

$$\begin{aligned} E\left(d_{\mathrm{YT}}^{r}\right) &= E\left(d_{\mathrm{YT}}^{rh}\right) + E\left(d_{\mathrm{YT}}^{rv}\right) \\ &= 3l_b + 4w_v + 2w_a + (R-1)\left(w_b + w_h\right). \end{aligned} \quad (8)$$

(2) Expected ET Travel Distance. The round-trip travel distance of ETs refers to the travel distance of ETs between the gate and the yard, which can be derived in a similar way to that of YTs.

The storage locations of containers are randomly distributed in the yard, and thus the probability that ETs arrive at each column of blocks is $1/N$. Since the gate is located in the middle of the landside boundary, when the transfer location is in the nth columns of blocks ($n = 1, 2, \ldots, N/2$) from the gate, the horizontal travel distance is $2n(l_b + w_v) - w_v/2$ and the probability is $2/N$. Thus, the expected horizontal travel distance of ETs can be estimated by

$$\begin{aligned} E\left(d_{\mathrm{ET}}^{rh}\right) &= \sum_{n=1}^{N/2} \frac{2}{N}\left[2n\left(l_b + w_v\right) - \frac{w_v}{2}\right] \\ &= \frac{2}{N}\left[2\frac{N}{4}\left(1 + \frac{N}{2}\right)\left(l_b + w_v\right) - \frac{N}{2}\frac{w_v}{2}\right] \\ &= \frac{N+2}{2}\left(l_b + w_v\right) - \frac{w_v}{2}. \end{aligned} \quad (9)$$

When the transfer location is in the kth row of blocks ($k = 1, 2, \ldots, R$) from the landside, the vertical travel distance of ETs becomes $2[w_g + k(w_b + w_h)]$, and the corresponding

probability is $1/R$. Then, the expected vertical travel distance of ETs is represented by

$$\begin{aligned} E\left(d_{\mathrm{ET}}^{rv}\right) &= \sum_{k=1}^{R} \frac{1}{R} 2\left[w_g + k\left(w_b + w_h\right)\right] \\ &= \frac{2}{R}\left[R w_g + \frac{R(R+1)}{2}\left(w_b + w_h\right)\right] \\ &= 2w_g + (R+1)\left(w_b + w_h\right). \end{aligned} \tag{10}$$

Finally, the expected round-trip travel distance of ETs is obtained:

$$\begin{aligned} E\left(d_{\mathrm{ET}}^{r}\right) &= E\left(d_{\mathrm{ET}}^{rh}\right) + E\left(d_{\mathrm{ET}}^{rv}\right) \\ &= \frac{N+2}{2}\left(l_b + w_v\right) - \frac{w_v}{2} + 2w_g \\ &\quad + (R+1)\left(w_b + w_h\right). \end{aligned} \tag{11}$$

4.3.4. Expected Truck Waiting Time. Expected truck waiting time is another important performance measure for CTs which not only reflects the operational efficiency but also affects the total operational cost to some extent. Expected truck waiting time is highly related to the cycle time of handling equipment which is equal to the sum of the handling time and gantry travel time [37]. In this paper, we derive the average truck waiting time with the well-known Pollaczek-Khintchine (P-K) formula for an M/G/1 queuing system [35]:

$$W_q = \frac{\rho E(T)}{2(1-\rho)}\left(1 + \frac{\mathrm{Var}(T)}{E^2(T)}\right), \tag{12}$$

where W_q is the expected truck waiting time, ρ is the traffic intensity (the sum of different truck arrival rate multiplied by the corresponding expected cycle time of handling equipment), $E(T)$ is the expected cycle time of handling equipment, and $\mathrm{Var}(T)$ is its variance.

For a QC, since it is virtually immobile during the operational process, its cycle time is equal to the handling time. For a YC, we assume that the expected gantry travel time of a YC obtained from (5) is a constant. Thus, the cycle time of a YC still follows a triangular distribution as the handling time, and the expected cycle time and its variance are derived from (2). Finally, (12) is used to estimate the average waiting time that a YT spends waiting for QCs at the apron and that a YT/ET spends waiting for YCs in the yard.

5. Experiments, Results, and Discussion

5.1. Experimental Setup. As shown in Figure 6, the case study used in the simulation experiments is a typical layout of NTCTs in China. The terminal has 4 50000-DWT (dead weight tonnage) berths; each berth is deployed with 4 QCs, and each QC is deployed with 9 YTs. The yard is composed of 10 zones; each zone contains 4 blocks, and each block has the capacity to store 42 bays, 6 rows, and 5 tiers of 20′ containers (i.e., 1260 TEU and only 20′ and 40′ standard containers are considered). The yard handling equipment is Rubber Tyred Gantry Cranes (RTGs), and 5 RTGs are equipped in each zone.

For the *separate stacking strategy*, the 5 zones close to the seaside are used to store export containers, and the 5 landside zones store import containers, which often leads to high workload imbalance among zones when multiple vessels are being loaded (or discharged) at the same time. Thus, inter-zone YC dispatching is required and only allowed under the separate stacking strategy. The dispatching of YCs is conducted under the principles of retaining a safe distance between any two YCs and no gantry across each other. In addition, to reduce the interference among YCs, one YC or two YCs are allowed in one block.

5.2. Settings of Simulation and Calculation Parameters. In all the simulation runs, the arrival of vessels follows a regular weekly schedule, which means the vessels from the same liner service are scheduled to visit the terminal at the same time from week to week. The weekly schedule consists of the home berth assignment and the expected arrival time of each liner service. The home berths are assigned to vessels such that the berths are evenly utilized, and the export containers are assigned a proper space in the yard. Despite being predetermined, the actual arrival time usually deviates from the scheduled time due to the uncertainties of en route weather conditions and the service level of the last terminal that it visits. The perturbation range of the arrival time is uniformly distributed between −2 hours and 12 hours. The durations of the auxiliary operation activities of a vessel, such as berthing, handling preparation, unberthing preparation, and unberthing, are also considered in this model, which are usually ignored in the other CT simulation models. Two vessel schedule scenarios are considered. The scenario with "more vessels" has 36 vessel calls per week, while the scenario with "fewer vessels" has 24 vessel calls per week.

The handling time of a QC and a YC follows a triangular distribution with the parameters (1.0, 1.5, 2.0) min and (1.2, 2.0, 3.4) min, respectively [1]. Without consideration of gantry movement time, the maximum handling capacity of a QC is approximately 40 lifts per hour and that of a YC is around 30 lifts per hour. The average speed of an empty and laden truck is, respectively, 40 km/h and 25 km/h.

The main parameters used in the experiments are listed in Table 1.

We assume that export containers are allowed to be delivered to the terminal 4 days before the scheduled vessel arrival time. To ensure the reliability of the results, the simulation period is set as 18 days. As the storage yard is empty in the beginning of each simulation run, in the first 4 days, only ETs are delivering export containers to the terminal. Thereafter, the weekly schedule of vessels is performed. After the warming-up period (from the 1st to the 11th day), data collection begins at the beginning of the 12th day and terminates at the very end of the 18th day. An entire week's data are collected.

The operational cost is calculated with the average values of parameters obtained from simulation experiments. It was assumed that $t_{\mathrm{YC}}^{gi} = 15$ min, $c_{\mathrm{QC}}^{h} = 6$ ¥/min, $c_{\mathrm{QC}}^{w} = 3.5$ ¥/min, $c_{\mathrm{YC}}^{h} = 3.6$ ¥/min, $c_{\mathrm{YC}}^{g} = 30$ ¥/min, $c_{T}^{m} = 3$ ¥/min, and $c_{T}^{w} = 2.6$ ¥/min.

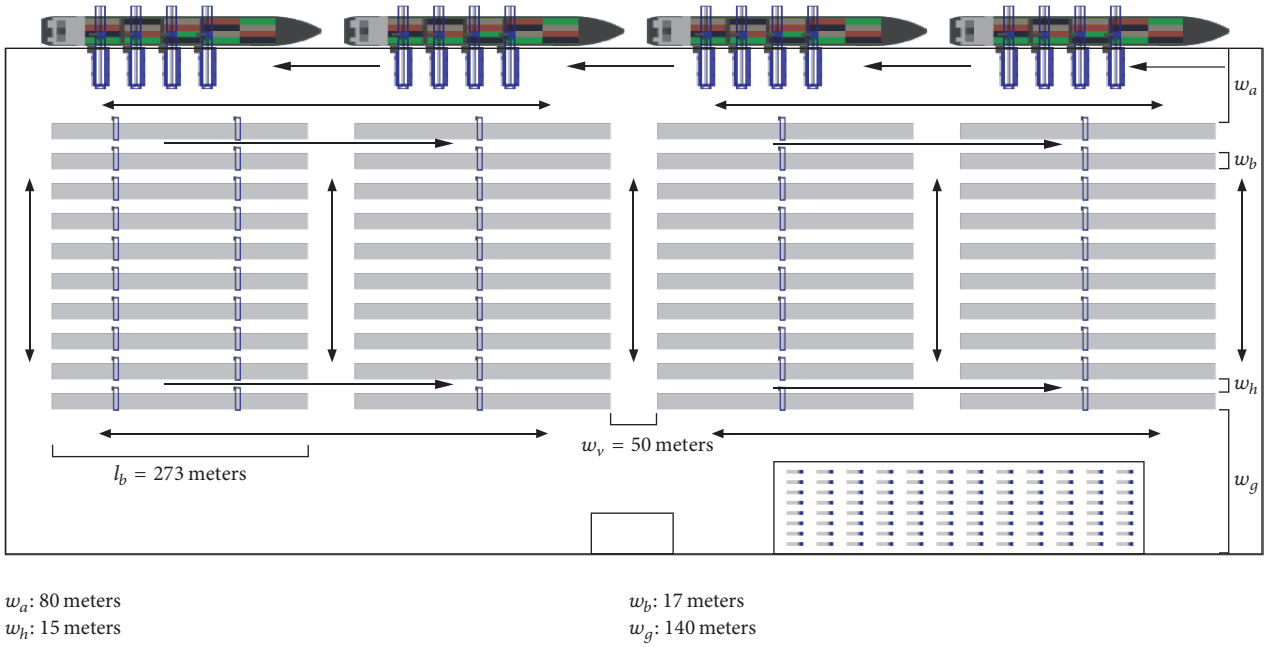

Figure 6: The layout of a nontransshipment container terminal.

Table 1: Settings in the simulation experiments.

Parameters	Value
Vessel calls per week	36/24
Unloaded conts. per vessel	600
Loaded conts. per vessel	600
Ground slots in the yard	10080
Number of berths	4
Number of QCs per berth	4
Number of YTs per QC	9
Number of YCs per zone	5
Empty truck speed (km/h)	40
Laden truck speed (km/h)	25
YC gantry speed (m/min)	100
Ratio of 20′ to 40′ conts.	2 : 1
Ratio of heavy to empty conts.	4 : 1
Duration of import heavy conts. (d)	Tri (1, 5, 7)
Duration of import empty conts. (d)	Tri (3, 5, 7)
Duration of export conts. (d)	Tri (1, 2.6, 4)
QC handling time (min)	Tri (1.0, 1.5, 2.0)
YC handling time (min)	Tri (1.2, 2.0, 3.4)
Berthing time (h)	Tri (0.5, 1.0, 2.0)
Handling preparation (h)	Tri (0.2, 0.6, 1.0)
Unberthing preparation (h)	Tri (0.2, 0.6, 1.0)
Unberthing time (h)	Tri (0.5, 0.75, 1.0)

5.3. Validation and Verification of the Simulation Model. The accuracy of the simulation model with the earliest truck strategy and more vessels scenario under two stacking strategies was validated with the formulas in Section 4.3, as shown in Table 2. The value of θ and δ in the mathematical model is set to be 0.85 and 0.15, respectively, which is obtained from the historical data of Dalian Port.

The differences in expected YT round-trip times, expected ET round-trip times, expected YC gantry travel times, and expected YC handling times are less than 3%. However, the difference in expected truck waiting times in yard is as high as 8.25%. In addition, the difference in expected QC handling times is as high as 7.33%, because the mathematical model cannot estimate the waiting time of QCs when a QC holds an import container in its spreader waiting for YTs. Furthermore, the uncertainties of yard operations and QC operations together result in as high as 7.89% difference between expected YT waiting times under QC. In general, despite various uncertainties, the gaps between simulation experiments and analytical results still lie in the acceptable range. Thus, the proposed simulation model well represents the CT system and is used to evaluate the operational costs and GCR of these four real-time YC dispatching strategies.

5.4. Results and Discussion. Our experiments considered four YC dispatching strategies under two stacking strategies with two vessel schedule scenarios. Each setup was replicated 6 times. Thus, the results were obtained from a total of 96 simulation runs. The detailed simulation results are reported in Table 3, and the GCR values and operational cost values are plotted in Figure 7. The experiments were executed in the Windows 10 environment using a workstation with Intel Xeon E3-1505M CPU @2.8 GHz and 64 GB of RAM. The CPU runtime for every individual experiment was less than 50 minutes. The highest GCR values and the lowest operational cost values under each stacking strategy are highlighted in bold as shown in Table 3.

Table 2: Comparing the results between the mathematical model and the simulation model.

Data contents	Value by mathematical model (A)	Average by simulation		Gap between A and B (%)	Gap between A and C (%)
		Separate stacking (B)	Scattered stacking (C)		
Expected YT round-trip time	2.86	2.83	2.82	−1.07	−1.42
Expected ET round-trip time	3.35	3.38	3.38	1.01	1.01
Expected YC gantry time	0.77	0.76	0.75	−0.61	−2.17
Expected YC handling time	2.20	2.20	2.21	0.18	0.65
Expected truck waiting time in yard	4.81	4.43	5.20	−7.76	8.25
Expected QC handling time	1.50	1.53	1.61	2.00	7.33
Expected YT waiting time under QC	5.43	5.86	5.24	7.89	−3.54

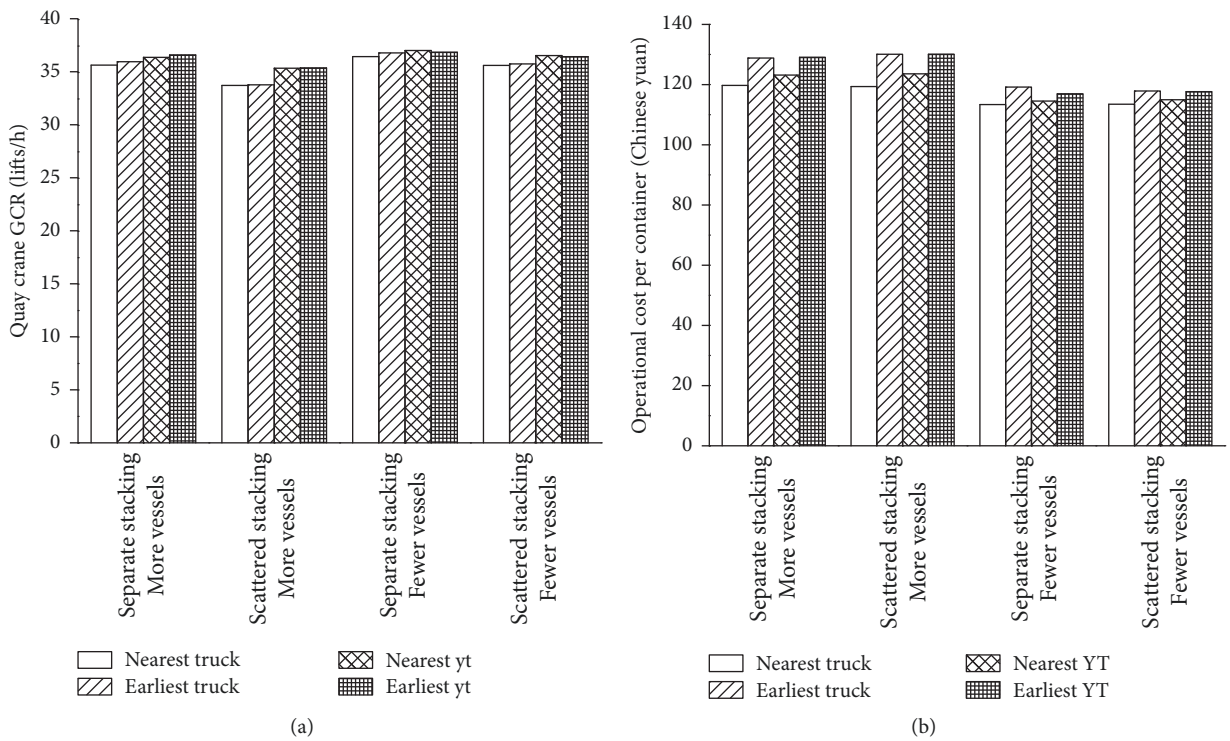

Figure 7: GCR and operational cost per container under different YC dispatching strategies for two stacking strategies with two vessel schedule scenarios.

5.4.1. GCR under Various YC Dispatching Strategies. GCR is the performance embodiment of a terminal's equipment deployment and operational strategies in the long term, and thus with the same equipment configuration a higher GCR usually means the related operational strategies are more efficient. From Figure 7, it is found that the earliest YT strategy outperforms the other three YC dispatching strategies in terms of GCR with more vessels, and the nearest YT strategy outperforms the other three YC dispatching strategies in terms of GCR with fewer vessels. As GCR is highly affected by average QC waiting time during vessel loading and discharging operations ($t^h_{\mathrm{QC}} + t^w_{\mathrm{QC}} - 1.5$, where 1.5 is the theoretical expected QC handling time), giving YTs the highest priority helps decrease the waiting time of QCs, but which strategy is more efficient also depends on the number of vessel calls per week. On the other hand, though it is easy to implement in practice, the nearest truck strategy yields the lowest GCR.

For the *separate stacking strategy* with more/fewer vessels and for the *scattered stacking strategy* with fewer vessels, the differences between the four YC dispatching strategies are relative (less than 1.0 lifts/h). However, for the *scattered stacking strategy* with more vessels, the nearest YT strategy and the earliest YT strategy are basically neck to neck, but a significant GCR difference (more than 1.5 lifts/h) is found between the earliest truck strategy (or the nearest truck strategy) and the earliest YT strategy. When more vessels arrive at the terminal, since YC interzone dispatching is not allowed for the scattered stacking strategy, QCs have to wait longer to be served by YTs due to inadequate YC deployment in certain blocks under the earliest truck strategy

Table 3: Experimental results of four YC dispatching strategies under two stacking strategies with two vessel schedules.

Vessel calls	Stacking strategy	YC dispatching strategy	c_o (¥)	GCR (lifts/h)	t^h_{QC} (min)	t^w_{QC} (min)	t^h_{YC} (min)	t^g_{YC} (min)	s^{gi}_{YC} (times)	t^m_{YT} (min)	t^{wYC}_{YT} (min)	t^{wQC}_{YT} (min)	t^m_{ET} (min)	t^{wYC}_{ET} (min)	$t^{wYC}_{YT} + t^{wQC}_{YT} + t^{wYC}_{ET}$ (min)
More (36)	Separate stacking	Nearest truck	**119.75**	35.70	1.52	0.04	2.20	**0.65**	385	2.83	5.02	6.02	3.38	2.87	**13.91**
		Earliest truck	128.83	36.02	1.53	0.02	2.20	0.76	370	2.83	5.15	5.86	3.38	3.69	14.70
		Nearest YT	123.19	36.44	1.51	0.02	2.20	0.66	390	2.83	4.38	6.45	3.38	4.08	14.91
		Earliest YT	129.07	**36.66**	1.51	0.02	2.20	0.74	380	2.83	4.40	6.39	3.38	4.53	15.32
	Scattered stacking	Nearest truck	**119.35**	33.78	1.57	0.06	2.21	**0.62**	-	2.83	6.34	5.24	3.38	3.09	**14.67**
		Earliest truck	130.10	33.84	1.61	0.02	2.21	0.75	-	2.82	6.46	5.24	3.38	3.95	15.65
		Nearest YT	123.61	35.41	1.53	0.04	2.21	0.64	-	2.83	5.32	5.78	3.38	4.81	15.91
		Earliest YT	130.09	**35.43**	1.54	0.02	2.21	0.73	-	2.82	5.21	5.90	3.38	5.15	16.26
Less (24)	Separate stacking	Nearest truck	**113.37**	36.50	1.51	0.03	2.21	**0.61**	190	2.83	3.92	6.86	3.38	1.60	**12.38**
		Earliest truck	119.20	36.86	1.51	0.02	2.21	0.69	185	2.83	3.98	6.78	3.38	2.10	12.85
		Nearest YT	114.57	**37.09**	1.50	0.01	2.21	0.63	165	2.83	3.40	7.24	3.38	1.90	12.54
		Earliest YT	116.92	36.92	1.50	0.02	2.21	0.66	160	2.84	3.56	7.11	3.38	2.08	12.75
	Scattered stacking	Nearest truck	**113.50**	35.67	1.52	0.03	2.22	**0.60**	-	2.82	4.89	6.17	3.38	1.82	**12.88**
		Earliest truck	117.90	35.82	1.53	0.01	2.22	0.67	-	2.83	4.75	6.26	3.38	1.97	12.97
		Nearest YT	114.99	**36.61**	1.51	0.02	2.22	0.62	-	2.83	4.26	6.55	3.38	2.31	13.11
		Earliest YT	117.66	36.50	1.52	0.01	2.22	0.66	-	2.82	4.18	6.64	3.38	2.35	13.17

GCR: gross crane rate (the total number of QC lifts made/the total number of QC hours beside a busy berth).

and the nearest truck strategy. Furthermore, without any exceptions, the *separate stacking strategy* is visibly superior to the *scattered stacking strategy* under any of the four proposed YC dispatching strategies in the aspect of GCR. Under the nearest truck strategy with more vessels, the separate stacking strategy increases the GCR by 5.68% compared with the scattered stacking strategy.

Finally, the results with more vessels at NTCTs are compared with those from Petering et al. [1] which focused on real-time YC dispatching strategies at PTCTs. Since ETs are not considered in Petering et al. [1], the nearest YT and the earliest YT strategy correspond to the nearest truck and the earliest truck strategy under the scattered stacking strategy in this study. The values are selected from the small terminal with more equipment scenario which has the same terminal layout and equipment configuration ratio as our experiments. The GCR values are 36.15 lifts/h at PTCTs and 33.78 lifts/h at NTCTs under the nearest truck strategy and 35.57 lifts/h at PTCTs and 33.84 lifts/h at NTCTs under the earliest truck strategy. The comparison indicates that the better strategy at PTCTs does not show better performance at NTCTs, and the disturbance from the random arrival of ETs decreased the GCR at NTCTs, which distinctly illustrates the effect of ETs on the performance of YC dispatching strategies and verifies the necessity of this study.

5.4.2. Operational Cost under Various YC Dispatching Strategies. In regard to the operational cost, the minimum value is achieved under the nearest truck strategy for each stacking strategy and vessel schedule scenario as shown in Figure 7. Table 3 provides some explanations for these observations. It can be seen that while intuitive and straightforward, the nearest truck strategy indeed significantly reduces the total truck waiting time ($t_{\mathrm{YT}}^{w\mathrm{YC}} + t_{\mathrm{YT}}^{w\mathrm{QC}} + t_{\mathrm{ET}}^{w\mathrm{YC}}$) and the YC gantry travel time per container, compared to the other YC dispatching strategies. This finding is spontaneous given that when the nearest truck strategy is adopted, the YC always selects the nearest truck in its feasible region to serve such that the YC could arrive at the task position as soon as possible and the truck waiting time can be reduced. On the contrary, with the other three YC dispatching strategies, a YC might end up making long gantry travels from one position of the yard to another while ignoring nearby waiting trucks. With more vessels, the nearest truck strategy saves approximately 2.79% and 3.45% of operational cost under the separate stacking strategy and the scattered stacking strategy, compared to the second most economical strategy—the nearest YT strategy. In addition, the earliest truck and earliest YT strategies are uneconomical compared to the nearest truck strategy.

Another interesting finding in Table 3 is that, with any combination of the proposed YC dispatching strategy and vessel schedule, the operational cost for the *separate stacking strategy* is basically less than that for the *scattered stacking strategy*, but the differences between the two stacking strategies are very small. For established CTs, the parameters that highly affect the operational cost include the total truck waiting time, YC gantry travel time, and YC interzone movement time. As can be seen from Table 3, the total truck waiting time per container for the separate stacking strategy is obviously lower than that for the scattered stacking strategy, whereas the YC gantry travel time per container is the opposite. The total truck waiting time is decreased for the separate stacking strategy because YC interzone dispatching is allowed and more YCs will be dispatched to intensively serve the high workload blocks. However, the expected YC gantry travel time for the separate stacking strategy is increased since the YCs in the low workload blocks must relatively frequently perform long gantry travels. In addition, YCs must conduct interzone movement for the separate stacking strategy. As a result, no apparent advantage is gained using the separate stacking strategy in terms of operational cost.

5.4.3. Discussion. Overall, the nearest truck strategy is the most economical but achieves the lowest GCR under any combination of the proposed stacking strategy and vessel schedule scenario, which demonstrates its effectiveness for the terminal operators seeking to decrease the operational cost. On the contrary, the earliest YT strategy yields the highest GCR but is the least economical with more vessels, while the nearest YT strategy produces the highest GCR and is the second economical with fewer vessels. Therefore, one cannot be sure which strategy is more efficient as GCR also depends on the number of vessel calls per week. As is known, GCR has a direct influence on the waiting time and berthing time in port which significantly affect the revenue of liner services. Normally, the nearest truck strategy is applicable as this is the most natural and convenient way for YC operators. Once the shipping lines proffer the requirement of reducing vessel turnaround time or there are more vessels waiting for berths than normal, the terminal operator might prefer the strategy that can greatly improve GCR in order to achieve a desirable service level (the average waiting time of vessels/the average service time of vessels) and remain competitive among other regional CTs. In short, YC dispatching strategies have a remarkable influence on terminal operational cost and GCR, and the selection of which strategy to use should be deliberated and determined by the terminal operator as per the practical situation.

6. Conclusion

This paper introduced a cost estimation model for container terminal operations and a simulation model to investigate the effects of various YC dispatching strategies on terminal operational cost and GCR in the long term. To validate the simulation model, we derived mathematical formulas for the variables in the cost model, such as expected handling time of QC/YC, expected YC gantry travel distance, expected truck waiting time in yard, expected YT waiting time under QC, and expected YT/ET travel distance. A comparison of results between simulation and calculation confirmed the validity of the simulation model. In total, four YC dispatching strategies under two stacking strategies and two different vessel schedules were examined.

The main conclusions obtained from the results are as follows. First, YC dispatching strategies and stacking strategies indeed have a significant influence on terminal operational cost and GCR, and the differences of GCR among

various YC dispatching strategies are more apparent for the scattered stacking strategy. Second, the nearest truck strategy yields the lowest operational cost but achieves the lowest GCR under any combination of the proposed stacking strategy and vessel schedule scenario, which corroborates the effectiveness of the current practice as terminal operators usually aim to operate a terminal with the minimum cost. Third, the earliest YT strategy yields the highest GCR with more vessels at the expense of high operational cost, and the nearest YT strategy yields the highest GCR with fewer vessels at a relatively lower operational cost. Finally, under any of the proposed YC dispatching strategies, the separate stacking strategy remarkably outperforms the scattered stacking strategy in terms of GCR, while no dominant advantage is gained in the aspect of operational cost. Although the experiments are not exhaustive enough to cover all scenarios at manually controlled CTs, they do provide a comprehensive analysis on the performance of various YC dispatching strategies under different tactical-level stacking strategies. The results in this study may be used by terminal operators for selecting a proper YC dispatching strategy as per the practical situation and the specific objective.

The management level at terminals is improving rapidly with the great advance of Internet and information technologies, and ET appointment system which has a significant influence on YC operations has been gradually accepted at some terminals. Future research will focus on investigating the effects of ET appointment systems on the performance of various YC dispatching strategies for NTCTs.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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