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Modeling the mixed storage strategy for quay crane double cycling in container terminals

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ABSTRACT

A mixed storage strategy was proposed to improve the efficiency of yard operations and horizontal transportation to corporate with quay crane double cycling. The effects of the mixed storage strategy on terminal operations, including truck travel distance, yard crane operations and the number of required trucks, were analyzed. An approach based on cycle-time models, the queuing theory was proposed to evaluate the performances from long-term run. Results show using the mixed storage strategy, the truck travel distance can be decreased and the number of required trucks and yard crane's operation time can be reduced by 16% and 26% respectively.

1. Introduction

With the development of international trade, the volume of world sea cargo has rapidly increased. Since container terminals are important nodes in the international transport network, their efficiency affects the performance of the global supply chain. To attract more ships, port operators strive to decrease ship turnaround time by implementing new techniques. Double cycling has received increasing amounts of attention in recent years. Using this method, a quay crane (QC) can handle a pair of containers in a cycle, with this pair consisting of an inbound container and an outbound container that are stowed in the same ship bay (Goodchild and Daganzo, 2006). Meanwhile, a truck can carry an inbound container from the quay after delivering an outbound container to the quay. To ensure the efficiency of double cycling, the truck efficiency should be well coordinated with the QCs' efficiency.

Internal trucks transport containers in the terminal and serve as an interface between the quay operations and yard operations. The efficiency of these trucks is affected by the yard cranes (YC) and QCs. Any delay of yard operations will finally result in the delay of ships (Lee et al., 2009; Luo and Wu, 2015). Generally, inbound and outbound containers are stored separately in terminal yards. This storage strategy makes it more convenient for the terminal operators to make yard schedules and decrease the interferences between the internal and external operations (Tao and Lee, 2015; Zhen, 2014). However, with double cycling, the entire container handling system is more complex, consisting of seven stages, as shown in Fig. 1. The cycle time of trucks is longer, and the coordination of trucks and YCs becomes more important to maintain QCs' efficiency. Therefore, the use of YCs and trucks should be further planned.

To achieve a high productivity of double cycling operations, a mixed storage strategy in which outbound and inbound containers are stacked in the same bay but in different rows is proposed (Cheung et al., 2002). Using the mixed storage

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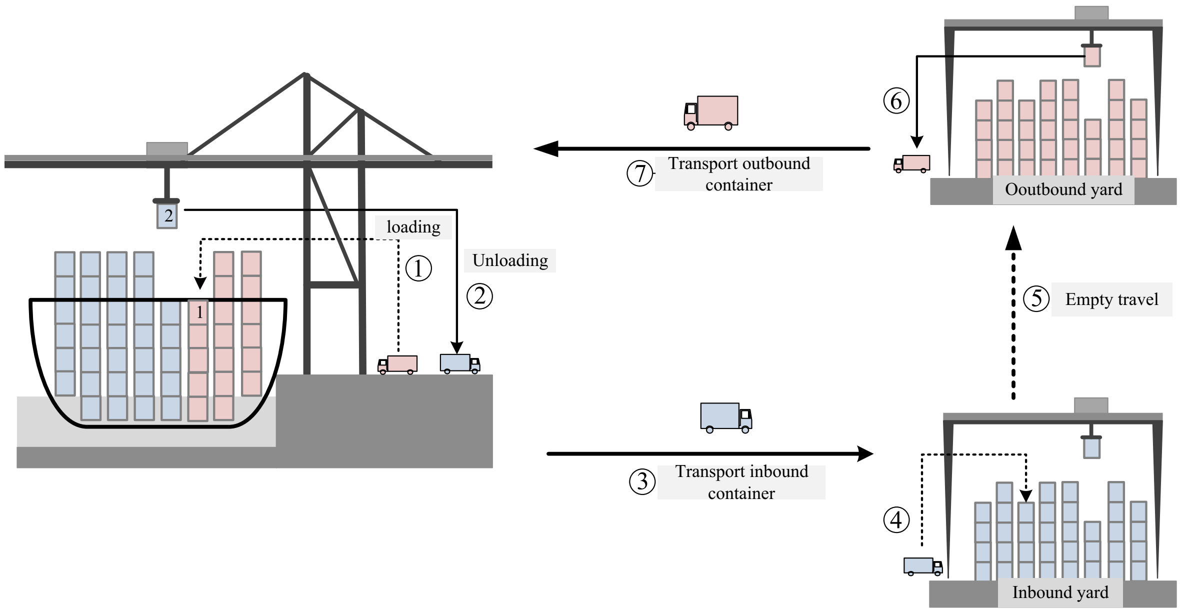


Fig. 1. The double-cycling handling system.

strategy, the unloaded travel of internal trucks between inbound and outbound blocks is eliminated (the fifth stage in Fig. 1). Meanwhile, double cycling operations of YCs are possible, which can increase the operation efficiency of YCs. The changes caused by a mixed storage strategy, such as the yard layout, the truck travel routes and YC operations, are obvious. However, the accurate effects of a mixed storage strategy on terminal operation costs and schedules must be addressed, and knowledge of these effects is necessary to gain insight into a long-term run at a general level.

In this study, the issues associated with modeling the mixed storage strategy for double cycling operations are addressed. The effects of a mixed storage strategy on the average truck travel distance, the required number of trucks and the YCs' operation efficiency are evaluated. Cycle-time models, queuing theory and simulation are used to quantify these effects. Furthermore, stacking strategies are proposed to achieve more benefits. The remainder of the paper is organized as follows. Section 2 provides a review of the existing literature. Section 3 provides a description of the mixed storage strategy, and its performance is evaluated in Section 4. Stacking strategies and lower bounds of YC's handling time are proposed in Section 5. A simulation study to test the validity of the models is provided in Section 6. Conclusions are given in Section 7.

2. Literature review

Container terminal operations have gained a substantial amount of attention from researchers. To increase terminal efficiency, new technologies and methods have been implemented, such as truck appointment system (Zhao and Goodchild, 2010; Chen et al., 2013), cross-docking at yards (Konur and Golias, 2013; Yu and Egbelu, 2008). Double cycling is one of the new techniques used in container terminals, serving to increase QCs' efficiency and optimize truck utilization. The effect of double cycling has been shown via practical implementation (e.g., in the ports of Los Angeles and Tianjin, China (TranSystmes, 2003)) and via theoretical research analysis (Goodchild and Daganzo, 2007). The results indicate that double cycling can reduce the cycling number of QCs by 20% and decrease the operation time by 10%. Furthermore, to increase the double cycling number, Goodchild and Daganzo (2006) optimized the sequence of QCs. Later, Zhang and Kim (2009) extended his model by considering the hatch. Lee et al. (2014) treated the quay crane sequencing model as a flow shop problem and used the Sidney algorithm to solve it. In addition to the effect on the QC's double cycling number, Goodchild and Daganzo (2007) analyzed the effect of double cycling on other operations in the terminal, including the truck travel distance, the number of required trucks and the loading sequence. To increase the operation efficiency, other operations should be incorporated with the quay crane double cycling (Kim and Kim, 1999; Luo and Wu, 2015).

Recently, studies on the integrated scheduling of QCs, trucks and YCs for single cycling have rapidly developed. For example, Kim and Park (2004) developed a dynamic programming model to optimize YC routing. Kaveshgar and Huynh (2015) formulated an integrated schedule of QCs, YCs and trucks as a hybrid flow shop scheduling problem. Cheung et al. (2002) proposed a storage space allocation method. Bish (2003) and Zhang et al. (2003) developed models to optimize the yard crane deployment. Bish et al. (2005) and Ng et al. (2007) studies the truck scheduling in container terminal. For QC's scheduling, many factors were considered to develop the models, such as safety clearance between the QCs (Kim and Park, 2004; Lee et al., 2008; Wen et al., 2010) and the moving time of QCs (Bierwirth and Meisel, 2009). To solve the model, the branch and bound method (Lim et al., 2007; Peterkofsky and Daganzo, 1990), proposed algorithms (Liu et al., 2006; Lee et al., 2008) and a simulation method (Kim and Park, 2004; Zhu and Lim, 2006) were developed.

The mixed storage strategy has been used in some ports, such as the Hong Kong Port. Compared with the separated storage strategy, the mixed storage strategy has more advantages if the QCs are operated using the double cycling technique. Using this method, trucks can load an outbound container immediately after unloading an inbound container in the yard, thus improving the utilization of trucks. Meanwhile, double cycling of YCs can be used to increase the efficiency of yard operations. Researchers addressed the efficiency of different yard layouts. For example, Lee and Kim (2010a) developed various cycle-time models to analyse the cycle time of YCs under different yard layouts. Vidovic and Kim (2006) regarded the flow of containers in the terminal as a three-stage material handling system and estimated the cycle time of trucks. Lee and Kim (2010a,b) optimized the block size of yards. However, the cycle time of YCs with double cycling remains an open question. In addition, the total truck distance is affected by the yard layout (Kim et al., 2008), the berth location and the storage block. It is necessary to analyse the changes in the circular distance travelled by trucks using mixed storage strategies.

To our knowledge, no research has been performed to analyse the effect of the mixed storage strategy for QC double cycling. To fill this gap and to quantify the long-term effect of the mixed storage strategy, this study analyzed the mixed storage strategy from three aspects: the expected distance travelled by trucks, the number of trucks required and the yard crane operation time. Finally, this paper also suggests stacking strategies to increase productivity. The results can be used by port authorities to optimize the yard layout and to create yard operation schedules.

The contributions of this study are as follows: (1) Methods to evaluate the effect of the mixed storage strategy are proposed. A cycle-time model is developed to evaluate the time savings of YCs with double cycling. In addition, a queuing model is developed to evaluate the required number of trucks and truck travel distance. It provides an accurate evaluation and modeling method of the mixed storage strategy. (2) According to the changes in the storage strategies, stacking principles for mixed storage are designed. A lower bound of YC's handling time for unloading and loading a ship is derived. This provides an efficient tool to support decision making regarding implementation of the mixed storage strategy.

3. Descriptions of the mixed storage strategy

In the mixed storage strategy, outbound containers and inbound containers are stacked in the same block. The number of container handling stages is reduced. The related operations changes, such as trucks and YCs. The characteristics and effects of the mixed storage strategy are illustrated as follows.

3.1. Effects of the mixed storage strategy on YC's operations

With separated storage strategy, take unload operation as an example, the process of YCs is: pick up an inbound container from the truck, drop it off on the yard ground and pick up another inbound container from the next truck. However, with mixed storage strategy, the process of YCs is: pick up an inbound container from the truck, drop it off on the yard ground, pick up an outbound container from the yard ground and drop it off on the waiting truck. The fourth and the sixth stage in Fig. 1 are merged into one stage, as shown in Fig. 2. A yard crane can carry an outbound container after unloading an inbound container or vice versa, which doubles the number of containers served in one YC cycle. Thus, the efficiency of YCs can be improved, and ship turnaround time can be decreased. Compared with the traditional method, some of the empty moves are replaced by loaded moves in each cycle. Because the speed of the trolley when loading a container is different from that of an empty move, Goodchild and Daganzo (2006) has estimated the double cycling time of QCs, therefore it is also necessary to estimate the benefit of YC's double cycling using mathematical methods.

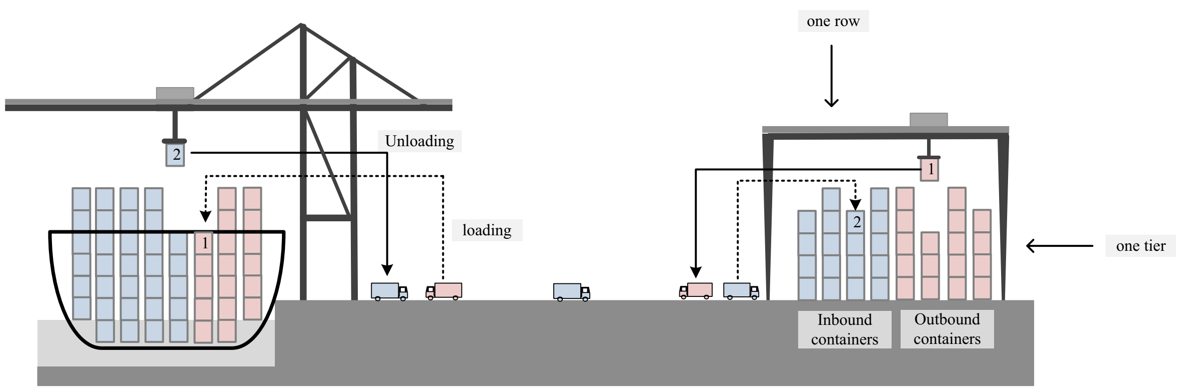


Fig. 2. Double cycling in container terminals.

3.2. Effects of the mixed storage strategy on internal trucks

The efficiency of internal trucks is affected by the turnaround time (total truck travel distance), which is determined by the target blocks, yard layout and the QC location. As shown in Fig. 3, there are two types of lanes in the yard: parallel lanes and vertical lanes. The parallel lanes are unidirectional and are only used for trucks to deliver or pick up containers from the block. The vertical lanes are used for trucks to move from one location to another, and these lanes are bi-directional. The travel route of a truck from quayside to yard and then back to the quayside is cyclic. The length of a cycle depends on the size of the block and the relative positions between the target blocks and the quay cranes. In a separated strategy, trucks travel from the inbound yard to the outbound yard after delivering an inbound container. Due to the directivity of the parallel lanes, the truck travel routes are complex. For example, the first scenario in Fig. 3 contains two short cycles in a task. To estimate the expected truck travel distance in a task, all the scenarios should be considered.

In mixed storage (Fig. 4), trucks load an outbound container immediately after unloading an inbound container. Although the truck utilization is higher, the expected truck travel distance is unknown due to the layout changes. Using the same method as the separated storage strategy, the expected travel of a truck in a task should be evaluated.

The overall efficiency of container terminals is determined by the efficiency of each process and their cooperation. The changes in the truck travelling time and the YC operation time may lead to a change in the number of required trucks. The mixed storage strategy affects the operation plan of trucks and YCs, therefore, next section will evaluate the changes caused by these effects.

4. Evaluation of the mixed storage strategy on terminal operations

4.1. Truck travel distance

Assuming that the storage block of containers and the berth location of ships are uniformly distributed, this section aims to analyse the expected truck travel distance in a cycle and determines the optimal yard configuration with minimum truck travel distance. The expected truck travel distance in a cycle with the mixed storage strategy and the separated storage strategy will be estimated separately. The assumptions are as follows:

- Trucks move in a clockwise direction.
- The width of the lanes is ignored.
- The berth location and block allocation follow a uniform distribution.
- The berth line is divided into several units whose length is equal to the block length.

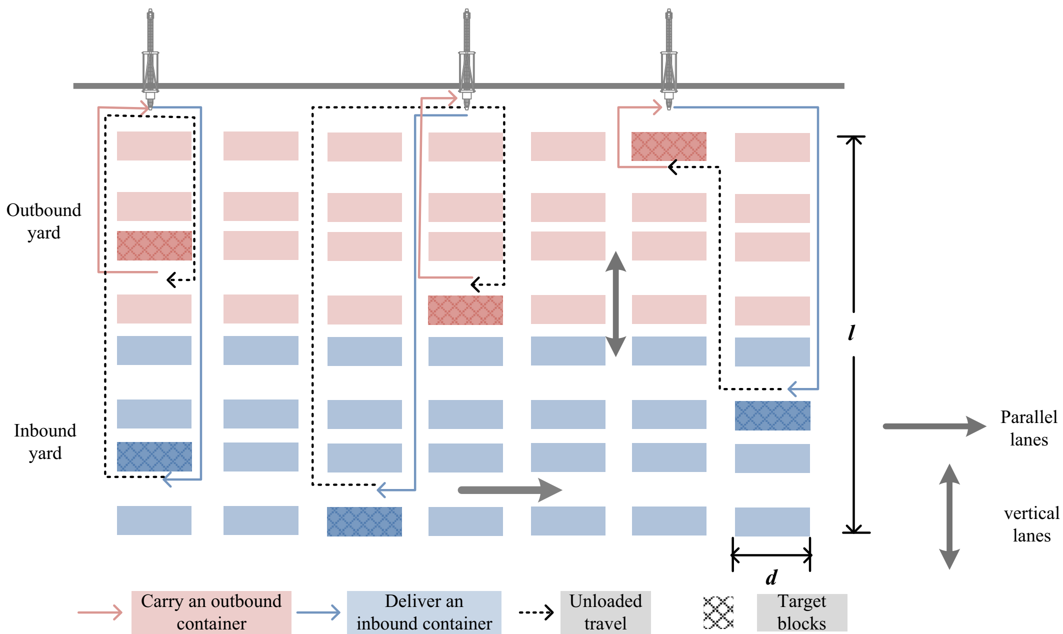


Fig. 3. The flow of trucks in a separated storage strategy.

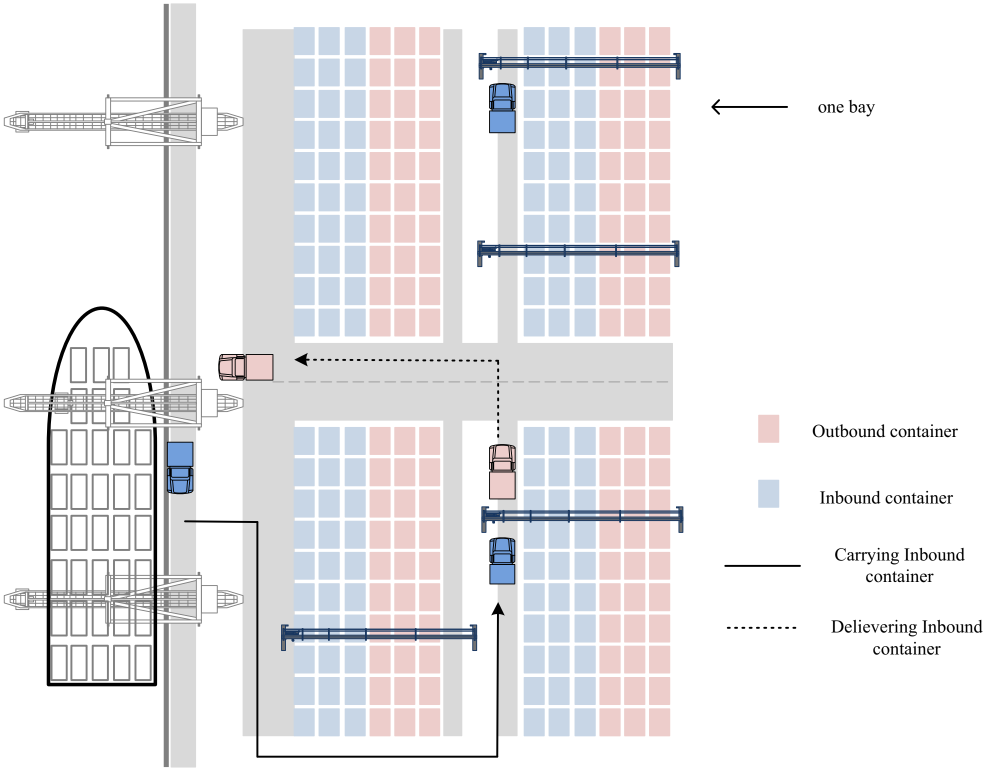


Fig. 4. Mixed storage strategy in a container yard.

Let n be the number of blocks in the horizontal direction; d represents the length of each block and l represents the width of the entire inbound storage zone (labeled in Fig. 3). Suppose the layout of the inbound and outbound yards is the same. The expected truck travel distance equals the sum of the probability of each case multiplied by the travel distance in each case.

4.1.1. Expected truck travel with the mixed storage strategy

When $n = 1$, the expected truck travel distance is $D = 2d + 2l$.

When $n > 1$, there are only two cases to consider. One case is that the ship berth location and the target blocks are vertical, and the other is that they are not vertical (Fig. 5).

In the first case, the truck travel distance is $E(D_1^1) = 2d + 2l$, and the probability is $P(D_1^1) = 1/n$. Thus, the expected truck travel distance can be calculated as follows:

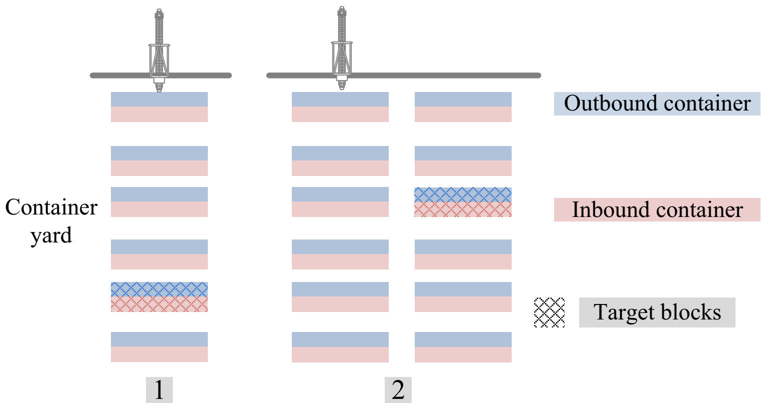


Fig. 5. Relative positions of quay cranes and target blocks in the mixed storage strategy.

$$E(D_1) = E\left(D_1^1\right) \cdot P\left(D_1^1\right) = \frac{2}{n} \cdot l + \frac{2}{n} \cdot d$$

In the second case, the truck travel distance is $E\left(D_2^1\right) = 3d + 2l$ if there is no column between blocks, and the probability is $P\left(D_2^1\right) = 2(n-1)/n^2$. If there is one column between inbound and outbound blocks, then the travel distance is $E\left(D_2^2\right) = 5d + 2l$, and the probability is $P(D_2^2) = 2(n-2)/n^2$. If there are two columns between inbound and outbound blocks, then the travel distance is $E\left(D_2^3\right) = 7d + 2l$, and the probability is $P\left(D_2^3\right) = 2(n-3)/n^2$. Similarly, the following can be derived: the truck travel distance is $E\left(D_2^{n-1}\right) = (2n-1)d + 2l$, and the probability is $P\left(D_2^{n-1}\right) = 2/n^2$. Thus, the following can be derived:

$$E(D_2) = E\left(D_2^1\right) \cdot P\left(D_2^1\right) + E\left(D_2^2\right) \cdot P\left(D_2^2\right) + \ldots + E\left(D_2^{n-1}\right) \cdot P\left(D_2^{n-1}\right) = \frac{2n-2}{n} l + \frac{2n^2+3n-5}{3n} \cdot d$$

Then, the expected truck travel distance is determined as follows:

$$E(D^n) = \sum_{i=1}^{2} E(D_i) = 2l + \frac{2n^2+3n+1}{3n} \cdot d$$

4.1.2. Expected truck travel distance with the separated storage strategy

When $n = 1$, the truck travel distance is $S = 4d + 4l$.

When $n > 1$, as shown in Fig. 6, there are 13 possible QC locations for the target inbound and outbound blocks. Then, the truck flows in each situation can be obtained. Based on this information, the truck travel routes with probabilities can be estimated.

In the first case, the truck travel distance is $E\left(S_1^1\right) = 4d + 4l$, and the probability of this scenario is $P\left(S_1^1\right) = 1/n^2$. Thus, the expected travel distance is as follows:

$$E(S_1) = E\left(S_1^1\right) \cdot P\left(S_1^1\right) = \frac{4}{n^2} \cdot l + \frac{4}{n^2} \cdot d$$

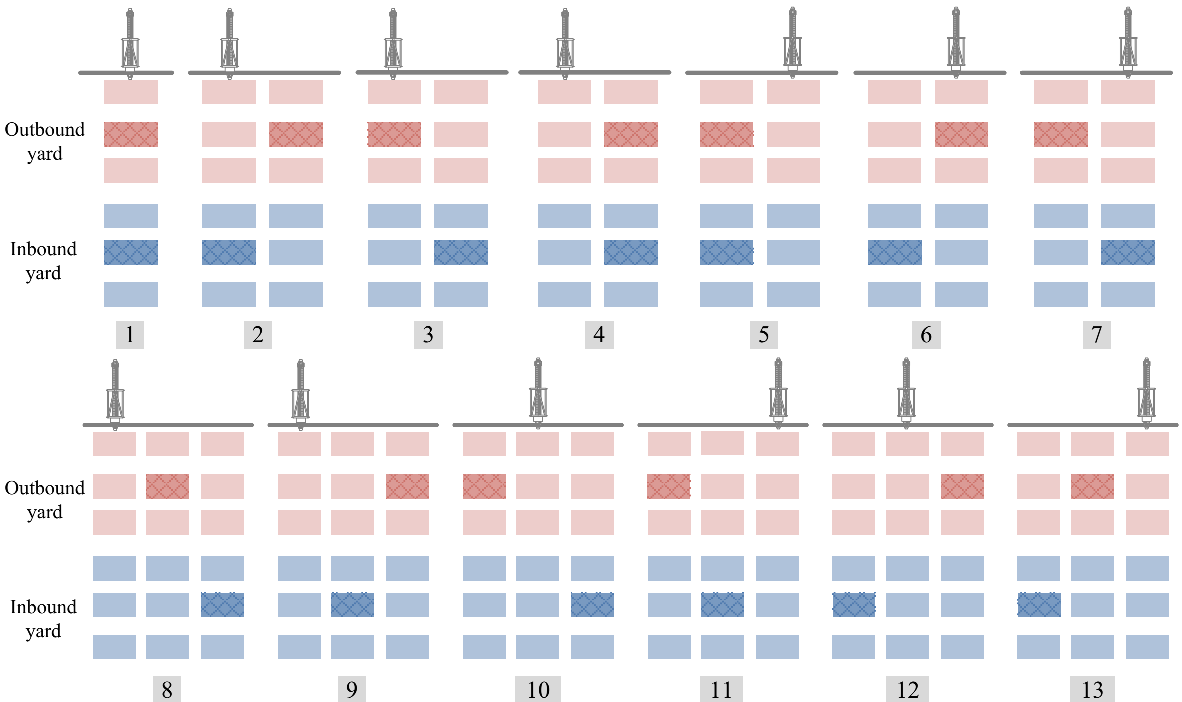


Fig. 6. Relationship between quay cranes and target blocks in the separated storage strategy.

In the second case, the truck travel distance is $E\left(S_2^1\right) = 5d + 4l$ if there is no column between blocks, and the probability is $P\left(S_2^1\right) = (n-1)/n^3$. If there is one column between the inbound block and the outbound block, then the travel distance is $E\left(S_2^2\right) = 7d + 4l$, and the probability is $P\left(S_2^2\right) = (n-2)/n^3$. If there are two columns between the inbound block and the outbound block, then the travel distance is $E\left(S_2^3\right) = 9d + 4l$, and the probability is $P\left(S_2^3\right) = (n-3)/n^3$. If there are n-2 columns between the inbound block and the outbound block, the truck travel distance is $E\left(S_2^{n-1}\right) = (2n+1)d + 4l$, and the probability is $P\left(S_2^{n-1}\right) = 1/n^3$. Thus, the following can be derived:

$$E(S_2) = \sum_{i=1}^{n-1} E\left(S_2^i\right) \cdot P\left(S_2^i\right) = \frac{2(n-1)}{n^2} \cdot l + \frac{2n^2 + 9n - 11}{6n^2} \cdot d$$

Similarly, the truck travel distance under other scenarios are given in Appendix A. Thus, the expected truck travel distance is as follows:

$$E(S^n) = \sum_{i=1}^{13} E(S_i) = \frac{32n^2 - 91n + 84}{n^3} \cdot l + \frac{20n^3 + 66n^2 - 386n + 456}{3n^3} \cdot d$$

The expected truck travel distance using different storage strategies is compared. First, suppose that the length and the width of the block have fixed values. Let $d = 250$ m and $l = 140$ m; then, the expected truck travel distances are $E(S^n) = \frac{32n^2-91n+84}{n^3} \cdot 140 + \frac{20n^3+66n^2-386n+456}{3n^3} \cdot 250$ and $E(D^n) = 280 + \frac{2n^2+3n+1}{3n} \cdot 250$, respectively. Let $\phi = E(S^n) - E(D^n)$; then, the curve of ϕ as n changes is shown in Fig. 7.

The result shows that when $n<10, \phi > 0$, the expected truck travel distance using the separated storage strategy is longer than that using the mixed storage strategy.

The mixed storage strategy changes the layout of the container yard and then the effect of the yard layout on the truck travel distance is analyzed. The width of each block is determined by the width of the YCs. The common layout of each block is six rows in a bay, and the width is approximately 16.6 m. The width of the vertical lanes is 25 m and the width of the horizontal lanes is 16.4 m. Therefore, the size of the container yard can be expressed as $S = \left(16.6\text{ m} + \frac{m}{2} * 16.4\right)((n-1) \cdot 25 + n \cdot d)$, where m represents the number of blocks in the vertical direction. Then, the truck travel distance can be expressed as $E(D^n) = \sum_{i=1}^{3} E(D_i) = 24.8\text{ m} + \frac{2n^2+3n+1}{3n} \cdot \left(\frac{S}{24.8\text{ m}\cdot n} + \frac{25}{n} - 25\right)$. A yard with a size of 700,000 m^2 is selected, and the result is shown in Fig. 8.

The results presented in Fig. 8 indicate that the truck travel distance is the shortest when $n = 10$ and $m = 12$. However, the large number of blocks may lead to a lower utilization of the container yard because the driving lanes are larger. Therefore, it is important for the container terminal operator to balance the truck travel distance and the yard utilization.

Because the locations of inbound and outbound containers affect the truck travel routes and YC scheduling, the following principle is used when planning the space allocation:

Principle 1 (*Store containers close to the ship berthing location*). As demonstrated, the truck travel distance is determined by the QC location (ship berthing location) and target blocks. Principle 1 presents a method to reduce the truck travelling

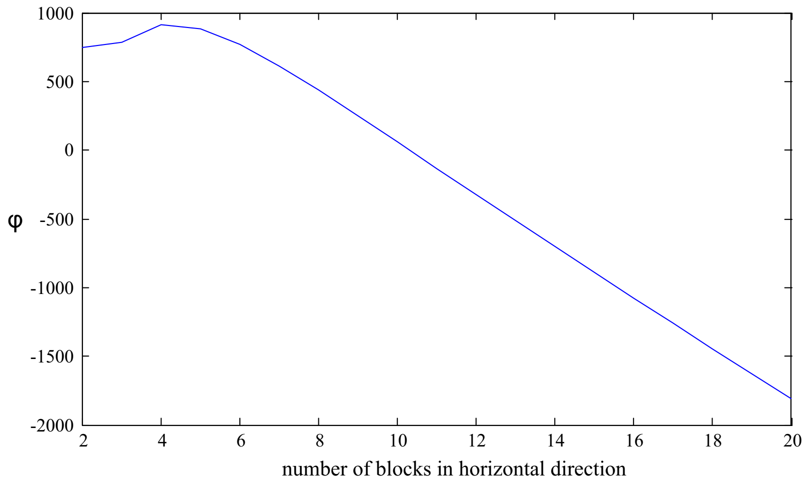


Fig. 7. Comparison of the expected truck travel distances using the mixed and separated storage strategies.

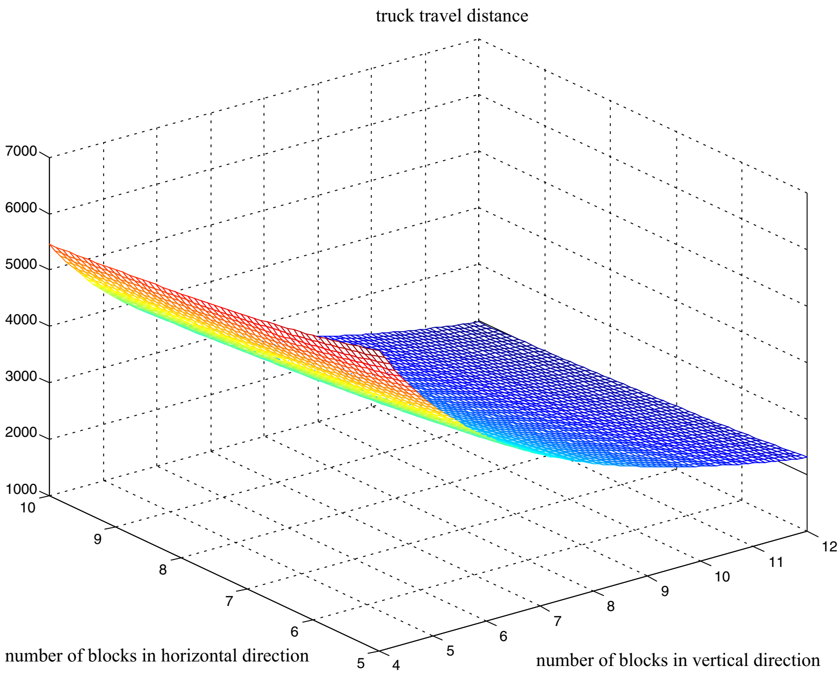


Fig. 8. Truck travel distance with different yard layouts.

distance between the yard and the quayside. However, if the ship berthing location changes or the ship delay for berthing, more efforts should be done. For example, if the ship delays for berthing, containers in the bottom may be loaded first, thus the number of rehandling will increase. If the ship berthing location changes, longer truck travel distance may be resulted.

4.2. Time savings of YCs

To calculate the operation time savings of YCs using double cycling, the variables are denoted as follows:

h: the maximum stacking height in the storage yard;
d: the width of each block, which is determined by the YC width;
V_h^u: hoist speed of the trolley when carrying a container;
V_h^l: hoist speed of the trolley when not carrying a container;
V_d^l: horizontal travel speed of the trolley when carrying a container;
V_d^u: horizontal travel speed of the trolley when not carrying a container;
t_a: time required to grasp or drop off a container.

Suppose the location of the containers follows a uniform distribution and the rehandling time is ignored. Consider the time required to load a container from the storage yard or to unload a container from the truck using single cycling. For each cycle, the time can be calculated as follows (the detail deviation is given in Appendix C):

$$T_s = \frac{3h}{2V_h^u} + \frac{3h}{2V_h^l} + \frac{d}{2V_d^u} + \frac{d}{2V_d^l} + 2t_a$$

With double cycling, the time required to unload a container from the truck and load a container onto the truck is as follows (the detail deviation is given in Appendix C):

$$T_d = \frac{3h}{V_h^l} + \frac{h}{V_h^u} + \frac{d}{V_d^l} + \frac{d}{2V_d^u} + 4t_a$$

Thus, the time saved by YC double cycling in a cycle is as follows:

$$T_c = 2T_s - T_d = 2\frac{h}{V_h^u} + \frac{d}{2V_d^u}$$

Let D_c represent the double cycles of YCs, and then, the total time saved by applying double cycling with YCs is as follows:

$$T_t = D_c \cdot T_c = D_c \cdot \left(2\frac{h}{V_h^u} + \frac{d}{2V_d^u}\right)$$

The parameter values used to estimate the operation time of YCs are given in Table 1.

The lower and upper bounds of the calculated operation time of YCs with single cycling are 132 s and 151.5 s, respectively; the values with double cycling are 222.5 s and 253.5 s, respectively. Therefore, the lower and upper bounds of the time savings with double cycling are 41.5 s and 49.5 s, respectively.

In practical operations, the average operation time of YCs using a single cycle ranges from 2 min to 2.5 min, and the average time using double cycling is 3 min. Thus, double cycling can save approximately 1 min to 2 min per pair of containers.

However, the total decreased time achieved using double cycling depends on the number of the double cycles, which is determined by the locations of the inbound and outbound containers carried by the same truck. In practical operation, the loading plan and the storage space allocation should be well planned.

4.3. Required number of trucks

The service time of YCs and the truck travel distance in the mixed storage strategy are different from those in the separated storage strategy, leading to different required numbers of trucks. This section will examine the required number of trucks per QC of mixed and separated storage strategies.

The flow of internal trucks is modeled as a closed queuing network, which consists of two stations and many customers (Fig. 10). The QCs, YCs and trucks compose of a closed queuing system in which the QCs and YCs are regarded as servers, and the trucks are regarded as customers. In the separated storage strategy, the truck picks up an outbound container and delivers an inbound container at different locations; thus, the trucks must serve three times in the system. The two yard locations are regarded as part of the same station, and the service time is the sum of each operation time (Goodchild and Daganzo, 2007). The variables are as follows:

μ_g: the service rate of the quay crane with double cycling;
μ_y: the service rate of YCs with single cycling;
$\hat{\mu}_y$: the service rate of YCs with double cycling;
N_g: number of trucks waiting under a quay crane;
N_y: number of trucks waiting under a yard crane;
N_r: number of trucks in transit;
N: the total number of trucks in the system;
T: the truck travel time in a cycle.

Suppose the queue of trucks waiting under the QCs always exists; then, the number of trucks in transit is $N_r = \mu_g \cdot T$. Therefore, the arriving rate at the yard is steady and is equal to the service rate of QCs. Assume that the arriving interval between two trucks follows an exponential distribution and the service rate of YCs follows an exponential distribution. Then, the storage yard sub-system acts as an M/M/1 queuing system. Therefore, the average number of waiting internal trucks can be obtained by the following equations:

$$E(N_y) = \frac{2\rho^3}{(1-\rho)^2} \cdot \pi_0 + \frac{\lambda}{\mu} \tag{1}$$

$$\mathrm{var}(N_y) = \frac{\lambda^2}{\mu^2} + \frac{4\rho^4(1-\rho-\rho^2 \cdot \pi_0) \cdot \pi_0}{(1-\rho)^4} \tag{2}$$

$$\rho = \frac{\lambda}{\mu} \tag{3}$$

Table 1
Parameter values of YCs. *Source:* investigation from Tianjin port.

Parameters	Value	Parameters	Value
h (containers are stacked 4 or 5 tiers)	15 m	h (containers are stacked 5 or 6 tiers)	18 m
d (containers are stacked 6 rows)	23 m	d (containers are stacked 8 rows)	27 m
V_h^u	60 m/min	V_h^l	30 m/min
V_d^u	60 m/min	V_d^l	30 m/min
t_a	15 s		

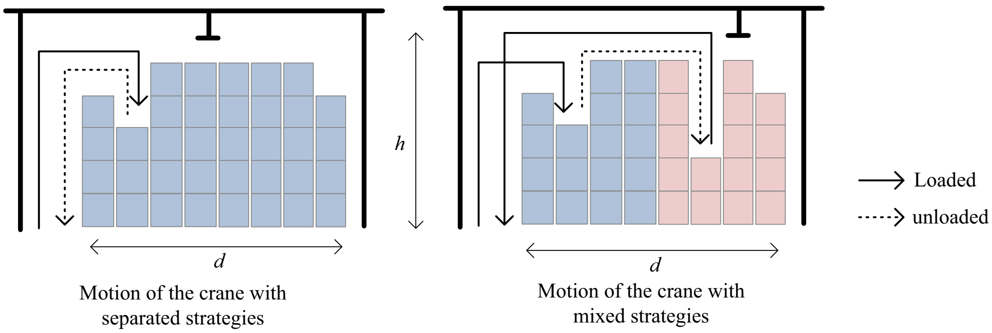


Fig. 9. Motion of the yard cranes.

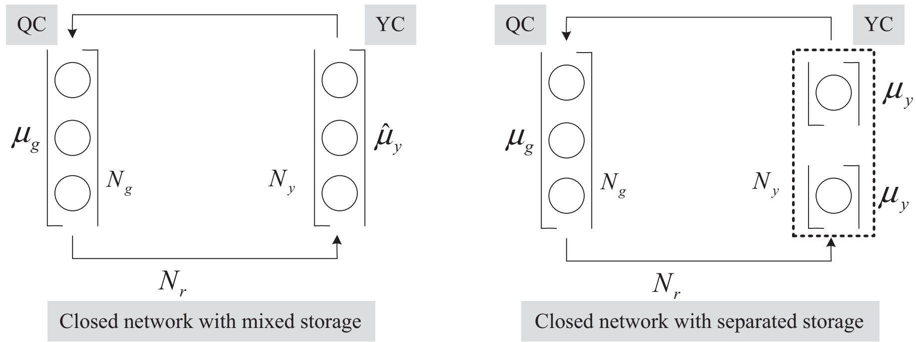


Fig. 10. Closed network in a container terminal.

$$\pi_0 = \left(1 + 2\rho + 2\rho^2 + \frac{2\rho^2}{1-\rho}\right)^{-1} \tag{4}$$

Eq. (1) gives the expected number of waiting trucks under the YCs, and Eq. (2) is its variance. The parameter λ is the arrival rate of trucks, which is also the service rate of QCs, and μ is the service rate of the YCs. Eq. (3) represents the service intensity of the storage queuing system, while Eq. (4) is the busy probability of the system. The number of trucks under the quay crane can be derived from $N_g = N - N_r - N_y$; thus, the expected number of trucks and its variance are as follows:

$$E(N_g) = N - T \cdot \mu_g - E(N_y) \tag{5}$$

$$\mathrm{var}(N_g) = \mathrm{var}(N_y) \tag{6}$$

Assume the expected number of waiting trucks under the quay crane rarely deviates from its mean by two standard deviations, as shown in Eq. (7):

$$E(N_g) = 2\sqrt{\mathrm{var}(N_g)} + 1 \tag{7}$$

Using the results in Section 4.1, let d = 250 m, l = 140 m and $n = 8$; then, $E(S_n) = 2310$ m and $E(D_n) = 1874$ m. The truck speed is set to 30 km/h. From Section 4.2, the service time of the yard crane with double cycling is approximately 3 min, and then, $\mu_y = 1/3$. With single cycling, the operation time is approximately 2.25 min, but the service time is doubled (loading and unloading operations), so $\hat{\mu}_y = 2/9$. The service time of the quay crane with double cycling is 2 min and 50 s, so $\mu_g = 6/17$. Therefore, 7.6 trucks are required with single cycling of YCs, and 6.4 trucks are required with double cycling of YCs. Double cycling with YCs can reduce the required number of trucks by 15.9%.

5. Stacking strategies and the lower bound

The real benefit of the mixed storage strategy for yard cranes is the reduced operation time. This section provides the stacking strategies that can increase the number of double cycles and the lower bound of the double cycles of the yard crane.

5.1. Stacking strategies

Studies (Goodchild and Daganzo, 2007; Zhang and Kim, 2009; Lee et al., 2014) have aimed to optimize the QC sequence to increase the double cycling of QCs. For simultaneous double cycling and mixed storage operation, a truck carries an inbound container to the yard and then carries an outbound container to the quayside. To obtain the advantage of the mixed storage strategy, the YCs must complete the transfer of an inbound and an outbound container in the same cycle.

Principle 2 (*Store the outbound container and the inbound container carried by the same truck in the same bay at the yards*). This principle minimizes the movement of YCs after delivering an inbound container to the yard. As demonstrated, a truck carries an outbound container after delivering an inbound container, and the two containers are regarded as a pair of containers. Thus, the number of double cycles can be increased, and thereby the operation time is decreased.

Suppose there are 5 trucks and 1 yard crane serving one quay crane. The red containers are outbound containers, and the blue containers are inbound containers. The loading and unloading sequences with QC double cycling are shown in Fig. 11. If a truck delivers No. 1 inbound container (blue) to the yard, and then it will carry No. 6 outbound container (blue) in the next cycle. It can be easily observed that the No. 6 inbound container (blue) and the No. 5 outbound container (red) will be handled by the QC in a cycle. Therefore, the truck will carry No. 5 outbound container back to the quayside after delivering No. 1 inbound container to the yard. According to Principle 2, No. 5 outbound container and No.1 inbound container should be stacked in the same bay at the yard.

The stowage plan of a ship affects the location of the inbound containers at yards and the location of outbound containers on the ship. To increase the number of YC double cycles, the loading sequence of the outbound containers should be changed according to the locations and the unloading sequence of inbound containers. If no outbound container is available in the target bay, then decisions should be made to decrease the moving and rehandling of the yard cranes. Therefore, according to Principle 2, stowage planning should be changed if the ship and container information is given in advance.

5.2. A lower bound of the handling time of YCs

The handling time of YCs consists of loading or unloading time and moving time. Loading or unloading time of YCs is derived in Section 4.2, which is also a constant value given the configuration of yards. The moving time of YCs varies with the loading sequence and the locations of containers. This section derives the lower bound of the moving time of YCs.

Let $\boldsymbol{S}$ be the set of outbound containers and $\boldsymbol{P}$ be the set of inbound containers; l_i is the bay number of the ith loaded outbound container in the yard and u_i is the bay number of the ith unloaded inbound container in the yard. Suppose all the outbound containers are stacked in the same block and are loaded on trucks by one YC. Similarly, all the inbound containers from a ship are stacked in the same block and are unloaded from trucks by one YC. If YC is applied with single cycling, the moving distance of loading all the outbound containers on trucks in sequence is $L_s = \sum_2^s |l_i - l_{i-1}|$. To unload the inbound containers from trucks in sequence, the moving distance of the YCs is $U_p = \sum_2^p |u_i - u_{i-1}|$. When using YC's double cycling, an outbound container is loaded on the truck immediately after an inbound container is unloaded. Therefore, the moving distance to complete loading outbound containers and unloading inbound containers is $D_n = \sum_{i=2}^n (|l_{i-1} - u_{i-1}| + |u_i - l_{i-1}|)$. If there are more outbound containers than inbound containers, then the moving distance is $D = D_p + L_s - L_p$. If there are more inbound containers than outbound containers, then the moving distance is $D = D_p + U_p - U_s$.

Theorem 1. $D \geqslant \min\{U_p + L_{s-1} - L_p + |l_p - u_p|, L_{s-1} + |l_1 - u_1|, U_{p-1} + |l_s - u_s|, L_s + U_{p-1} - U_s + |l_1 - u_1|\}$.

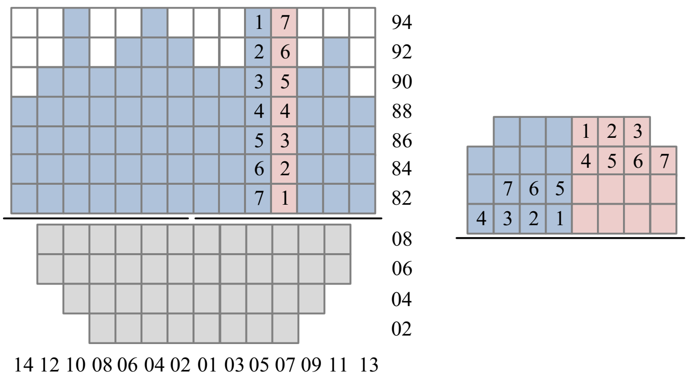


Fig. 11. The loading sequence and yard location of containers.

Proof. If there are more outbound containers than inbound containers, then $D \geqslant U_p + L_{s-1} - L_p + |l_p - u_p|$ or $D \geqslant L_{s-1} + |l_1 - u_1|$; therefore, $D \geqslant \min\{U_p + L_{s-1} - L_p + |l_p - u_p|, L_{s-1} + |l_1 - u_1|\}$. If there are more inbound containers than outbound containers, then $D \geqslant U_{p-1} + |l_s - u_s|$ or $D \geqslant L_s + U_{p-1} - U_s + |l_1 - u_1|$; therefore, $D \geqslant \min\{U_{p-1} + |l_s - u_s|, L_s + U_{p-1} - U_s + |l_1 - u_1|\}$.

Suppose that the bay number of each container is uniformly distributed. Because $l_{i+1} - l_i$ and $u_{i+1} - u_i$ are independent and are identically distributed random variables, $\sum_i (l_{i+1} - l_i)$ and $\sum_i (u_{i+1} - u_i)$ can be regarded as diffusion processes with the p*th* or *sth* container completed. Therefore, U_p and L_s can be regarded as the absolute diffusion of these processes. □

The drift of $\sum_i (l_{i+1} - l_i)$ is as follows:

$$d = \frac{E[\sum_i (l_{i+1} - l_i)]}{S} = E(l_{i+1} - l_i) = \frac{N^2 - 1}{3N} \tag{8}$$

Its variance rate is as follows:

$$R = \frac{\mathrm{var}[\sum_i (l_{i+1} - l_i)]}{S} = \mathrm{var}(l_{i+1} - l_i) = \frac{(N-1)(17N-7)}{12} + \frac{(N-1)^3(N+1)}{18N^3} - \frac{(N^2-1)^2}{9N^2} \tag{9}$$

where N is the total number of bays in a block at yards. According to Feller (1950) and Goodchild and Daganzo (2007), the expected total moving distance of the yard crane is as follows:

$$E[L_s] = \int_0^\infty dz \int_0^S \frac{z}{\sqrt{2\pi R y^3}} e^{\frac{-(z-dy)^2}{2Dy}} dy = \frac{2R}{d}\left[\varphi\left(\frac{d\sqrt{S}}{\sqrt{R}}\right) - \frac{1}{2} + \int_0^{\frac{d\sqrt{S}}{\sqrt{D}}} z\varphi(z)dz\right] \tag{10}$$

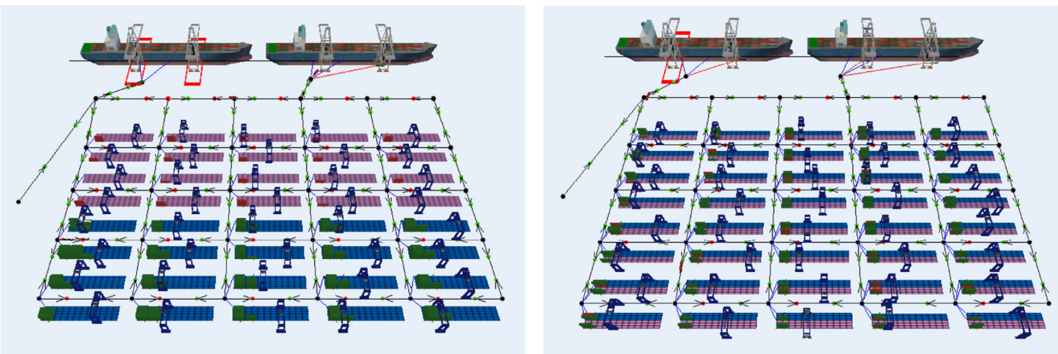
$$\varphi(x) = \int_{-\infty}^{x} \frac{e^{-\frac{w^2}{2}}}{\sqrt{2\pi}} dw \tag{11}$$

For the long-term run, with single cycling of YCs, the expected travel distance of yard cranes to load all the outbound containers can be obtained by Eqs. (10) and (11). Similarly, it is easy to obtain the expected travel distance of yard cranes to unload all the inbound containers with the same estimation. Theorem 1 gives the lower bound of YCs' travel distance with YCs' double cycling. Combined with the estimates obtained by Eq. (10), the expected lower bound of the YCs' travel distance can be approximated. It gives a concise approximated result of the travel distance of YCs' double cycling.

However, the real travel distance of YCs is affected by the loading and unloading plan, which also affects the double cycle number of YCs. Therefore, Principle 2 provides a practical strategy to increase the double cycle number (decrease the travel distance during operations).

6. Simulation study

A simulation study is conducted to evaluate the accuracy of the cycle-time model and the validity of the proposed principles. The simulation is conducted using Flexsim CT software on a personal computer with a 3.20 GHz Inter Core i5-4570 CPU and 4.0 GB RAM. Flexsim CT software is an extension of the Flexsim and specially applied in the simulation of container terminals (Kavakeb et al., 2015). It provides a good 3D vision and simulation outputs. A simple running chart of the simulation is shown in Fig. 12.



(a) Separated storage strategy (b) Mixed storage strategy

Fig. 12. A running chart of the simulation.

6.1. Accuracy of the proposed model

A simulation model based on the Flexsim CT is developed for the trucks transporting containers between the QCs and the yard blocks. The input parameters are as follows:

- The locations of QCs are random, and the probabilities for each location are the same;
- The containers' locations in the yard are uniformly distributed, and each truck is randomly assigned to deliver containers;
- The specification of the YCs and QCs and the size of the blocks are the same as the specifications assumed in Section 4.1;
- The containers are stacked 4 or 5 tiers in height and 6 rows in width at the yards (the height of YCs is 15 m and the width is 23 m);
- The number of blocks in the horizontal direction is assumed to be 10 and the number of quay cranes is 4;
- The expected value of the speed of the trilogy sets as Section 4.2, and the variance is set to 0.1;
- The number of outbound containers and inbound containers is 2000 respectively.

The simulation is conducted 10 times, and the comparison results are shown in Table 2. The expected values of the truck travel distance according to the simulation method and the proposed model are separately obtained. The variance of the simulation results is analyzed. The deviation equals the difference between the simulation value and the model value divided by the model value.

The deviation between the values from the simulation and the values by the proposed model is less than 3%. Thus, the proposed model can accurately estimate the truck travel distance and the cycle-time of YCs.

6.2. Validity of the proposed principles

The proposed principles are used to gain a greater benefit. To test the validity, the simulation results with and without the principles applied are compared. By implementing Principle 1, the containers are stacked in the block closest to the handling QC. The only difference between the two simulation models is the containers' location at the yard. The input parameters of simulation are as follows:

- The QC, YC and truck specifications and the configuration of the yard blocks are the same as in Section 6.1.
- The expected speed of the YCs is assumed to be 60 m per minute with normal distribution, and the variance is 0.2.
- The total number of containers to unload and load is 300 twenty-foot equivalent units (TEU) with one YC.

Each simulation model is run 10 times, and the average results are shown in Table 3. The deviation equals the difference between the results with and without the principles applied divided by the value without the principles applied. Then, the benefit of applying these principles is clearly observed.

Table 3 shows the average truck travel distance in a cycle. By applying Principle 1, the truck travel distance is decreased by 29.8%. However, the real benefit of Principle 1 depends on the container locations in the yards. Therefore, terminal operators should devise a reasonable yard plan according to the QC allocation to each ship. The total completion time of YC is decreased due to Principle 2. Principle 2 reduces the movement of YCs during the handling operations. The lower bound calculated in Section 5.2 is 469 min. The gap refers to the simulation result divided by the difference between the lower bound and the simulation result. Greater benefit can be further gained by implementing Principle 2.

6.3. Efficiency analysis of container terminal

Although the direct effects of Principles 1 and 2 are different, however, both of them affect the whole operation efficiency, such as total completion time of ships, utilization of quay cranes, waiting time of trucks for QCs and waiting time of trucks for YCs. The number of QCs, YCs, trucks, is set to 4, 8 and 24 respectively. Trucks travel at a speed of 30 km/h. The number of inbound and outbound containers is 2000 respectively. Table 4 shows the results of container terminal's efficiency with four different combinations of the two principles, for example, with Principle 1 and 2(w P1, w P2), with Principle 1 and without Principle 2(w P1, w/o P2), without Principle 1 and *with principle 2*(w/o P1, w P2), *without principle 1* and 2(w/o P1, w/o P2).

Table 2
Comparisons between the simulation results and the approximates.

		Mixed storage strategy		Separated storage strategy	
		Truck travel distance (m)	Cycle time of YCs (sec)	Truck travel distance (m)	Cycle time of YCs (sec)
Expected values	Simulation method	2189	218.7	2226	128.3
	Proposed models	2205	222.5	2265	132.0
Variance of simulation		0.09	0.18	0.11	0.21
Deviation		0.73%	1.71%	1.72%	2.8%

Table 3
Comparison results by simulation method with and without principles.

	Truck travel distance (m)		Total completion time of YC(min)	
	With Principle 1	Without Principle 1	With Principle 2	Without Principle 2
Simulation results	1537	2189	518	683
Variance of simulation	0.10	0.09	0.18	0.15
Deviation	29.8%		14.9%	
Lower bound	–		469	469
Gap	–		9.46%	31.3%

Table 4
Required truck number with different combinations of the two principles.

Combinations of principles	QCs	Trucks		YCs	Total completion time(h)
	Rate of idle time (%)	Rate of waiting time at quayside (%)	Rate of waiting time at yard (%)	Rate of travel time (%)	
(w P1, w P2)	19.8	4.3	6.2	18.7	15.3
(w P1, w/o P2)	25.4	4.7	7.1	24.8	17.6
(w/o P1, w P2)	29.8	5.7	6.8	18.4	16.9
(w/o P1, w/o P2)	34.7	5.2	7.9	25.6	19.8

Principle 1 contributes to reducing truck travel time. Therefore, the turnaround time of trucks is decreased. Principle 2 contributes to decreasing travel time of YCs and thus affects the truck waiting time at yards. From the analysis above, the rate of idle time of QCs is affected most by the two principles. The changes of truck waiting time at both quayside and yard are affected least.

7. Conclusions

The mixed storage strategy is already used in some ports, such as in Hong Kong port. Its advantages are more obvious when QC double cycling is used. Therefore, this paper analyzed the effect of the mixed storage strategy on QC double cycling operations and developed tools to quantify these effects from a long-term run. The considerations primarily include the truck travel distance, the operation time of YCs with double cycling and the required number of trucks per quay crane. An approach based on cycle-time models, the queuing theory and its simulation is developed. The results indicate that when the number of blocks in the horizontal direction is less than 10, the truck travel distance using the mixed storage strategy is shorter than that using the separated storage strategy. In addition, the operation time of YCs can be reduced by 26% with double cycling, and the number of trucks per quay crane can be reduced by 16%. Thus, the proposed stacking principles can be used as an efficient tool to support decision making when using the mixed storage strategy.

Before the mixed storage strategy is widely used in container terminals, additional efforts should focus on incorporating this new technique with the current methods. The layout of the yard and the storage should be well designed. Meanwhile, the outbound containers and the inbound containers have different storage characteristics, which is a challenge for YC double cycling and storage schedules. These are interesting topics for further studies.

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Appendix A. expected distance under other scenarios

$$E(S_3) = \sum_{i=1}^{n-1} E\left(S_3^i\right) \cdot P\left(S_3^i\right) = \frac{3(n-1)}{2n^2} \cdot l + \frac{n^2+3n-4}{3n^2} \cdot d$$

$$E(S_4) = \sum_{i=1}^{n-1} E\left(S_4^i\right) \cdot P\left(S_4^i\right) = \frac{2(n-1)}{n^2} \cdot l + \frac{2n^2+9n-11}{6n^2} \cdot d$$

$$E(S_5) = \sum_{i=1}^{n-1} E\left(S_5^i\right) \cdot P\left(S_5^i\right) = \frac{2(n-1)}{n^2} \cdot l + \frac{2n^2+9n-11}{6n^2} \cdot d$$

$$E(S_6)=\sum_{i=1}^{n-1}E\left(S_6^i\right)\cdot P\left(S_6^i\right)=\frac{2(n-1)}{n^2}\cdot l+\frac{2n^2+9n-11}{6n^2}\cdot d$$

$$E(S_7)=\sum_{i=1}^{n-1}E\left(S_7^i\right)\cdot P\left(S_7^i\right)=\frac{3(n-1)}{2n^2}\cdot l+\frac{n^2+3n-4}{3n^2}\cdot d$$

$$E(S_8)=\sum_{i=1}^{n-2}E\left(S_8^i\right)\cdot P\left(S_8^i\right)=\frac{3(n-2)^2}{n^3}\cdot l+\frac{2n^3+3n^2-38n+48}{3n^3}\cdot d$$

$$E(S_9)=\sum_{i=1}^{n-2}E\left(S_9^i\right)\cdot P\left(S_9^i\right)=\frac{4(n-2)^2}{n^3}\cdot l+\frac{4n^3+18n^2-124n+144}{3n^3}\cdot d$$

$$E(S_{10})=\sum_{i=1}^{n-2}E\left(S_{10}^i\right)\cdot P\left(S_{10}^i\right)=\frac{3(n-2)^2}{n^3}\cdot l+\frac{2n^3+6n^2-50n+60}{3n^3}\cdot d$$

$$E(S_{11})=\sum_{i=1}^{n-2}E\left(S_{11}^i\right)\cdot P\left(S_{11}^i\right)=\frac{3(n-2)^2}{n^3}\cdot l+\frac{2n^3+3n^2-38n+48}{3n^3}\cdot d$$

$$E(S_{12})=\sum_{i=1}^{n-2}E\left(S_{12}^i\right)\cdot P\left(S_{12}^i\right)=\frac{4(n-2)^2}{n^3}\cdot l+\frac{2n^3+6n^2-50n+60}{3n^3}\cdot d$$

$$E(S_{13})=\sum_{i=1}^{n-2}E\left(S_{13}^i\right)\cdot P\left(S_{13}^i\right)=\frac{4(n-2)^2}{n^3}\cdot l+\frac{4n^3+18n^2-124n+144}{3n^3}\cdot d$$

Appendix B. Derivation of Eqs. (8) and (9)

Because the location of the containers in the yards is uniformly distributed, the expected distance travelled by the yard crane to handle two adjacent containers (Eq. (8)) is as follows:

$$E(l_{i+1}-l_i)=(N-1)\frac{2}{N^2}+(N-2)\frac{4}{N^2}+(N-3)\frac{6}{N^2}+\cdots+(N-(N-1))\frac{2(N-1)}{N^2}$$

$$E(l_{i+1}-l_i)=\frac{2}{N^2}[N-1+2(N-2)+3(N-3)+\cdots+(N-1)]$$

$$E(l_{i+1}-l_i)=\frac{2}{N^2}[N-1+2(N-2)+3(N-3)\cdots(N-1)(N-(N-1))]$$

$$E(l_{i+1}-l_i)=\frac{N^2-1}{3N}$$

The variance of the distance travelled by the yard crane to handle two adjacent containers (Eq. (9)) is as follows:

$$\mathrm{var}(l_{i+1}-l_i)=(N-1-E)^2\frac{2}{N^2}+(N-2-E)^2\frac{4}{N^2}+(N-3-E)^2\frac{6}{N^2}+\cdots+(N-(N-1)-E)^2\frac{2(N-1)}{N^2}$$

$$\mathrm{var}(l_{i+1}-l_i)=\frac{2}{N^2}[(N-1-E)^2+2(N-2-E)^2+3(N-3-E)^2+\cdots+(N-1)(N-(N-1)-E)^2]$$

$$\begin{aligned}\mathrm{var}(l_{i+1}-l_i)=&\frac{2}{N^2}[(N-1)^2+2(N-2)^2+3(N-3)^2+\cdots+(N-1)(N-(N-1))^2+E^2+2E^2+\cdots+(N-1)E^2(N-1)E^2\\&-2E(N-1+2(N-2)+3(N-3)+\cdots+(N-1)(N-(N-1)))]\end{aligned}$$

$$\mathrm{var}(l_{i+1}-l_i)=\frac{2}{N^2}\left[E^2\frac{N(N-1)}{2}-E\frac{N(N^2-1)}{3}+\frac{N^3(N-1)}{2}-\frac{N^2(N-1)(2N-1)}{3}+\frac{N^2(N-1)^2}{4}\right]$$

$$\mathrm{var}(l_{i+1}-l_i)=\frac{(N-1)(17N-7)}{12}+\frac{(N-1)^3(N+1)}{18N^3}-\frac{(N^2-1)^2}{9N^2}$$

Appendix C. Derivation of T_s and T_d

Notations used in the formula are as follows:

T^u_{lift}: time spent lifting by the hoist of the YC without carrying containers;
T^l_{lift}: time spent lifting a container by the hoist of the YC;
T^u_{move}: time spent moving horizontal of the trolley without carrying containers;
T^l_{move}: time spent moving horizontal of the trolley;
T^u_{fall}: time spent falling down the hoist of the YC without carrying containers;
T^l_{fall}: time spent falling down the hoist of the YC;

With single cycling, YCs handle an outbound or an inbound container per cycle. The expected cycle time of handling an outbound container and an inbound container are the same. Therefore, this paper takes inbound containers as an example. The process of unloading an inbound container from the truck to the yard ground is: grasping the inbound container, lifting it to the highest height, moving horizontally, falling down the container, dropping off the container, lifting empty, moving horizontally empty and falling down empty (as shown in the left of Fig. 9). It can be expressed as follows:

$$T_s = t_a + T^l_{lift} + T^l_{move} + T^l_{fall} + t_a + T^u_{lift} + T^u_{move} + T^u_{fall}$$

To calculate the expected cycle time, this paper assumes that the locations of the containers at yards are random. Therefore, the following can be derived:

$$T^l_{fall} = \frac{h}{2V^l_h}$$

$$T^u_{lift} = \frac{h}{2V^u_h}$$

Similarly, $T^l_{move} = \frac{d}{2V^l_d}$ and $T^u_{move} = \frac{d}{2V^u_d}$ can be derived. Thus, the expected cycle time is:

$$\begin{aligned} T_s &= t_a + T^l_{lift} + T^l_{move} + T^l_{fall} + t_a + T^u_{lift} + T^u_{move} + T^u_{fall} = t_a + \frac{h}{V^l_h} + \frac{d}{2V^l_d} + \frac{h}{2V^l_h} + t_a + \frac{h}{2V^u_h} + \frac{d}{2V^u_d} + \frac{h}{V^u_h} \\ &= \frac{3h}{2V^l_h} + \frac{d}{2V^l_d} + \frac{3h}{2V^u_h} + \frac{d}{2V^u_d} + 2t_a \end{aligned}$$

With double cycling, YCs handle an outbound and an inbound container per cycle. The process of YCs is: grasping the inbound container, lifting it to the highest height, moving horizontally, falling down the inbound container, dropping off the container, lifting empty, moving horizontally empty to the outbound container's location, falling down empty, grasping the outbound container, lifting it to the highest height, moving horizontally, falling down the outbound container, dropping off the container (as shown in the right of Fig. 9). It can be expressed as follows:

$$T_d = t_a + T^l_{lift} + T^l_{move} + T^l_{fall} + t_a + T^u_{lift} + T^u_{move} + T^u_{fall} + t_a + T^l_{lift} + T^l_{move} + T^l_{fall} + t_a$$

The locations of the outbound containers and inbound containers at yards are also random. The method used are the same as the derivation of T_s, thus the following can be derived:

$$\begin{aligned} T_s &= t_a + T^l_{lift} + T^l_{move} + T^l_{fall} + t_a + T^u_{lift} + T^u_{move} + T^u_{fall} + t_a + T^l_{lift} + T^l_{move} + T^l_{fall} + t_a \\ &= t_a + \frac{h}{V^l_h} + \frac{d}{4V^l_d} + \frac{h}{2V^l_h} + t_a + \frac{h}{2V^u_h} + \frac{d}{2V^u_d} + \frac{h}{2V^u_h} + t_a + \frac{h}{2V^l_h} + \frac{3d}{4V^l_d} + \frac{h}{V^l_h} + t_a = \frac{3h}{V^l_h} + \frac{d}{V^l_d} + \frac{h}{V^u_h} + \frac{d}{2V^u_d} + 4t_a \end{aligned}$$

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