Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2013, Article ID 593847, 8 pages
http://dx.doi.org/10.1155/2013/593847

Research Article

Performance Analysis on Transfer Platforms in Frame Bridge Based Automated Container Terminals

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Received 15 February 2013; Accepted 22 July 2013

Academic Editor: Gerhard-Wilhelm Weber

This paper studies a new automated container terminal (ACT) system which utilizes multistory frame bridges and rail-mounted trolleys to transport containers between the quay and the yard. Beside typical ACT systems use trucks or automated guided vehicles for transporting containers between quay cranes and yard cranes, the new design uses three types of handling machines, namely, ground trolleys (GTs), transfer platforms (TPs), and frame trolleys (FTs). These three types of handling machines collaborate with one another to transport containers. This study decomposes the system into several subsystems. Each subsystem has one TP and several FTs and GTs dedicated to this TP. Then, a Markov chain model is developed to analyze the throughput of TPs. At last, the performance of the new ACT system is estimated. Sensitivity analyzes the numbers, and the processing rates of trolleys are conducted through the numeric experiments.

1. Introduction

Port operators face challenges in handling large number of containers which growing fast when global trade increases. At the same time, it is difficult for terminal to expand its capacity fast enough due to insufficient land space, availability of initial investment, and environmental concerns [1]. Port operators also need to ensure that containers discharged from and loaded into vessels can be done quickly to meet the demand from customers that their vessels require to have a short port stay. Moreover, with the emergence of megavessels such as the Emma Maersk which can carry as many as 14,000 TEUs, port operators need effective operations to ensure that they can handle high throughput of containers. Given these trends, port operators try to find alternatives which can handle large surges of containers and at the same time are cost effective.

In many developed countries where labor cost is very high, we are seeing an increasing use of Automated Container Terminal (ACT) by port operators. For example, rail-mounted gantry cranes (RMGCs) are being used at the Hong Kong International Terminal (HIT) in Hong Kong. Automated stacking cranes (ASCs) are used at the European Combined of Terminal (ECT) in Rotterdam of the Netherlands. It was reported by the port operators that the use of ACT (e.g., Hong Kong International Terminal, Europe Container Terminal, Container Terminal Altenwerder, Thames port, Patrick Terminal, etc.) has helped them to contain direct cost and increase productivity. In most of ACTs, blocks are laid out vertically to the quay when yard cranes are used as the main handling machines in the yard. This layout has benefit from separating the area for seaside operations from land side operations. So, port operators can concentrate on controlling the automatic traffic of different machines for loading and unloading operations while the land side operation is almost impossible to be automated. However, under this yard layout, as the yard cranes need to perform the round-trip travel in a block, the travel time of yard cranes would affect the terminal productivity. In addition, in order to control Automatic Guided Vehicles (AGVs) efficiently, it is necessary to apply advanced operation technologies as well as the high-end hardware technologies.

Recently, Shanghai Zhenhua Port Machinery Company (ZPMC) introduced a new design of ACT which utilizes rail-mounted frame trolleys (FTs) and ground trolleys (GTs) to transport containers in quay and yard side, respectively. Figure 1 is an illustration (not to scale) of a Frame Bridge based Automated Container Terminal (FB-ACT). GTs travel

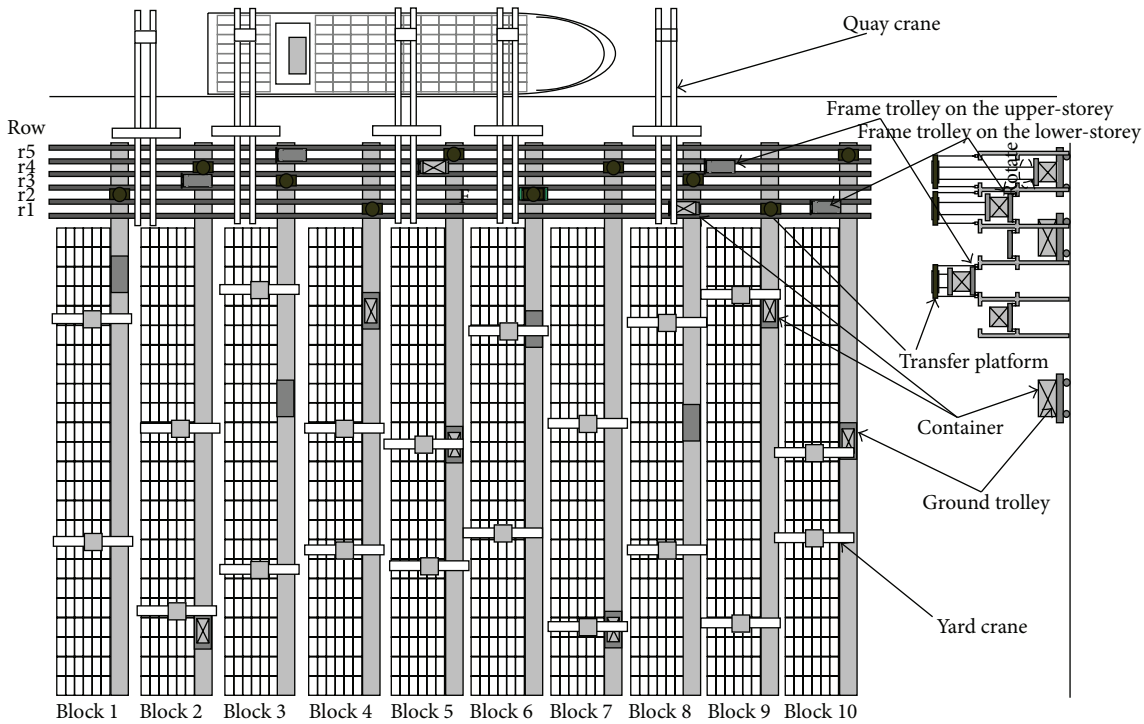

Figure 1: The configuration of the frame bridge based ACT.

on the rails along aside of a dedicated block; FTs travel on the rail of the stories in frame bridges located in the quay side; TPs transfer containers between the two types of trolleys. TP is a type of rail-mounted bridge crane and can move slowly on the rails of the highest story in frame bridges. These three types of handling machines collaborate with one another to transport containers. An example for unloading containers from vessels to the yard is as follows: containers are firstly unloaded from vessels by quay crane onto FTs mounted on frame bridges. The FTs transport the containers to TPs installed on certain locations of the frame bridges and the TPs lift and transfer the containers to GTs mounted on rails in the ground level; GTs deliver the containers to yard cranes to their allocated storage locations. Figure 1 shows an example of the FB-ACT system. In the realistic implementation, the frame bridges could be made with more than two stories and the ground rails for GTs could also be built with multistory structure.

FB-ACT has 4 handovers to deliver a container between vessels and yard, which are between quay crane (QC) and FT, FT and TP, TP and GT, GT and yard crane (YC). Each handover will take certain time to transfer a container from one machine to another. The time includes idle/waiting and processing time. However, in the traditional container terminal, there are only two handovers: one is between QC and truck; another is between truck and YC. The increased number of handovers in FB-ACT may decrease the performance of the system.

This study aims to develop a mathematical model for estimating the performance of an FB-ACT in order to assist the decision making of terminal operators who are considering automation as a solution. We try to answer these questions: what is the performance of this new design system with 2 additional handovers between trolleys and TPs? And how does it be affected by certain parameters, such as the number of the trolleys? So that port operators would estimate how many resources are required to achieve a desirable performance level such as annual containers throughput.

The remainder of this paper is organized as follows. Section 2 is the literature review. Section 3 proposes a mathematical model to estimate the capacity of TP by using Markov property. Section 4 shows the performance analysis of the single TP system. Section 5 gives the application of the single TP model for designing an FB-ACT system. The Conclusions are drawn in Section 6.

2. Literature Review

FB-ACT introduces a lot of challenges and opportunities for port operators. However, existing research efforts have been devoted to the conventional or AGV-based terminals. For the conventional terminals, Kim et al. recently proposed some analytical methodologies for optimizing the layout design [2, 3]. Li et al. studied the yard crane scheduling problem and developed a mathematical model considering intercrane interference, fixed yard crane separation distances and simultaneous container storage/retrievals [4]. Cao et al. proposed an integrated model for yard truck and yard crane scheduling problems for loading operations in container terminal [5]. Zhen et al. proposed a mixed-integer programming model to integrate the berth template and the yard template planning with the aim to minimize the service cost that is incurred by the deviation from vessels' expected turnaround time intervals and the operation cost that is related to the route length of transshipment container flows in

yard [6]. For AGV-based terminals, Hoshino et al. proposed a methodology for evaluating vertical and horizontal AGV based ACTs [7]; Liu et al. utilized simulation method to compare four types of ACTs, for example, AGV system, linear motor conveyance system, grid rail system, and automated storage and retrieval system [8]. Kim and Bae proposed a look-ahead dispatching method of AGVs under the dual cycle operations of assigned quay cranes [9]. Angeloudis and Bell studied job assignments for AGVs in an ACT by settings various conditions of uncertainty [10]. They developed a new AGV dispatching approach suitable for real-time control of AGVs under uncertain conditions. Qiu and Hsu presented a bidirectional path layout and an algorithm for routing AGVs to route the vehicles without conflicts and to minimize the space requirement of the layout [11].

The FB-ACT system can be described as a closed-loop material handling system since the three types of machines transport container with one another as described in Section 2. There are some available works on closed-loop systems. Dallery and Towsley illustrated that for the single closed-loop line, the throughput increases as the trolley number increases from 0 to an optimal number, while throughput decreases as the trolley number increases from the optimal number to the total quantity of buffers [12]. Performance evaluation of a multiloop closed line is more difficult than that of the single loop closed line. Levantesi published a primary work on the multiloop closed systems by decomposition method [13]. Han and Park studied the optimal carrier number of a production line and indicated that the carrier number taken at about half of the total buffers is efficient for the production line [14]. Biller et al. used the Bernoulli reliability model to analyze the closed production lines and selected the smallest number of carriers and the empty carrier buffers [15]. Lee and Kim proposed analytic expressions for estimating the expectation and the variance of the cycle time for various types of operation of YCs in container terminals [16]. For the details of performance measures, we would like to refer the summary by Li et al. [17]. Most of studies for production systems have buffer spaces in machines. However, the FB-ACT has no storage spaces for containers waiting for the TP. So, the trolleys have to wait at the TP when it is busy.

Recently, Zhen et al. also studied the FB-ACT system [18]. They divided the whole system into several subsystems: each subsystem has several TPs in the same bridge row, and each TP is dedicated to one block. An M/M/c queueing system, in which GTs in a block are treated as the c parallel servers and FTs are regarded as customers, was applied to analyze the FB-ACT. However, they did not consider the loading/unloading rate of a TP, which may have great impact on the performance of the whole system.

In this paper, we also divide the whole system into several subsystems. However, we divide the system according to the number of TP. And each subsystem has two closed loops for trolleys and is connected by one TP. Instead of an M/M/c queuing system, we use a Markov chain model to analyze the performance of each subsystem. We also focus on the impact of throughput of TP on the whole system's performance.

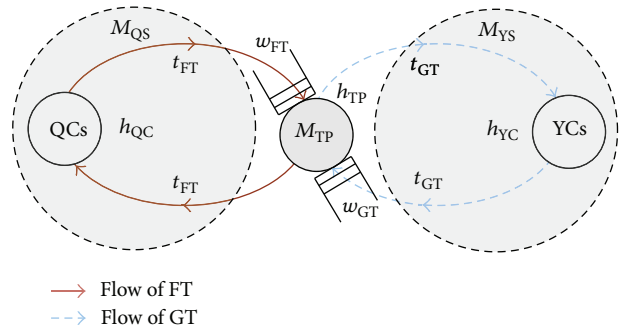

Figure 2: Model for the single TP system.

3. Problem Description and Modeling

In this paper, we take the same assumptions as mentioned in Zhen et al.'s study [18], such as the following.

(1) The pickup and delivery locations of these activities follow the uniform distribution along the quay in horizontal directions and along a side of a block in vertical directions, respectively. This assumption is commonly made in some analytical studies on container terminals [2].

(2) The number of TPs is the same to the number of blocks, which means a TP is dedicated to a block during a relatively long period. It is also assumed that FTs are dedicated to a TP during a relatively long period.

(3) The handling operation of quay cranes (or yard cranes) is represented as the average handling and waiting time of quay cranes (or yard cranes) which is denoted by h_{QC} (h_{YC}). It is a typical way to represent them as the average time in some studies on conventional terminals [3, 7].

Let N be the number of blocks, R the number of rows of frame bridges, M_{TP} the number of TPs in each row of frame bridges, M_{GT} the number of GTs in each block, and M_{FT} the number of FTs on one bridge and dedicated to one TP. For the example of FB-ACT in Figure 1, $N = 10$, $R = 5$, $M_{TP} = 2$, $M_{GT} = 1$, $M_{FT} = 1$. As we assumed that the number of TPs is the same to the number of blocks in FB-ACT, $N = R \times M_{TP}$. Thus, this study decomposes the whole system into N subsystems and each subsystem has a TP, M_{GT} GTs, and M_{FT} FTs.

3.1. Model Description for the Single TP System. In order to study the performance of the sub system, first of all, the behaviors of the trolleys are analyzed. There are two types of operation cycles related to FTs and GTs, respectively, for loading and unloading activities. Those two types of cycles are linked up by TPs as in Figure 2. The cycle time of a GT contains four elements, for example, the cycle time for the loading activity includes (1) the waiting and handling time of a YC (h_{YC}) to load a container onto the GT, (2) the travel time (t_{GT}) of the GT from the pickup location to a TP,

Table 1: Transition rates of the system form X_i to X_j.

Event	Condition	$X_i \rightarrow X_j$	q_{ij}
A FT moves a container from M_{QS} to M_{TP}.	$s = 0^-$	$(0^-, 0, N_{GT}) \rightarrow (-1, 0, N_{GT})$	$m\mu_{QS}$
	$s \neq 0^-$	$(s, N_{FT}, N_{GT}) \rightarrow (s, N_{FT}+1, N_{GT})$	$(m - N_{FT})\mu_{QS}$
M_{TP} takes a container from a FT	$N_{GT} = 0$	$(-1, N_{FT}, 0) \rightarrow (0^+, N_{FT}-1, 0)$	μ_{TP}
	$N_G > 0$	$(-1, N_{FT}, N_{GT}) \rightarrow (1, N_{FT}-1, N_{GT})$	μ_{TP}
M_{TP} puts a container to a GT	$N_{FT} = 0$	$(1, 0, N_{GT}) \rightarrow (0^-, 0, N_{GT}-1)$	μ_{TP}
	$N_{FT} > 0$	$(1, N_{FT}, N_{GT}) \rightarrow (-1, N_{FT}, N_{GT}-1)$	μ_{TP}
M_{YS} takes a container from a GT	$s = 0^+$	$(0^+, N_{FT}, 0) \rightarrow (1, N_{FT}, 1)$	$n\mu_{YS}$
	$s \neq 0^+$	$(s, N_{FT}, N_{GT}) \rightarrow (s, N_{FT}, N_{GT}+1)$	$(n - N_{GT})\mu_{YS}$

(3) the waiting time (w_{GT}) of a GT at the TP and the handling time of the TP (t_{TP}), and (4) the travel time (t_{GT}) of the GT from the TP to the next pickup location. Similarly, the cycle time of an FT contains also four time elements for loading activity: (1) the waiting time of an FT (w_{FT}) at a TP and the handling time of the TP (t_{TP}), (2) the travel time (t_{FT}) of the FT from the TP to the drop-off position under a quay crane, (3) the waiting and handling time of a quay crane (h_{QC}), and (4) the travel time (t_{FT}) of the FT to return back to a TP.

As TP is the machine which transfers the container between a GT and an FT, this study first analyzes the performance of a TP which is dedicated to a block and serving the constant numbers of FTs and GTs. We introduce a two-loop closed line as drawn in Figure 2 to model the single TP system.

Figure 2 shows the queuing network model for the single TP system. The TP has two queues for FTs and GTs and is modeled as a single server. The quayside operations and the block operations are modeled as delays. The notations for the queuing network model are as followings.

M_{QS}: an infinite capacity machine representing the delay of FTs at the quay side (QS). The delay possesses loading/unloading containers by QCs and travelling between QCs and TP. The processing rate of M_{QS} is μ_{QS}, which is equivalent to the delay rate of an FT. It can be estimated as $\mu_{QS} = 1/(2t_{FT} + h_{QC})$.

M_{YS}: an infinite capacity machine representing the delay of GTs at the yard side (YS). The delay possesses stacking/retrieving containers by YCs and travelling between YCs and TP. The processing rate of M_{YS} is μ_{YS}, which is equivalent to the delay rate of a GT. It can be represented as $\mu_{YS} = 1/(2t_{GT} + h_{YC})$.

M_{TP}: a single machine representing the transferring process of a TP. The processing rate of the TP for an FT is same to that for a GT, which is denoted by $\mu_{TP} = 1/h_{TP}$.

The handling and transportation activities are performed by three machines proposed in the network model. The unloading operation, for example, can be described by using the network model terms as follows: At first, an FT moves to QS to receive a container. The container is loaded onto the FT by M_{QS} and its processing rate is μ_{QS}. Secondly, FT takes the container to M_{TP}. M_{TP} takes the container from FT and the processing rate is μ_{TP}. If there is a GT at M_{TP}, M_{TP} then transfers the container to GT with the processing rate μ_{TP}. If a GT is not arrived yet, then the TP holds the container and needs to wait until a GT is arrived; lastly, a GT takes a container to M_{YS}. And M_{YS} unloads the container from GT with processing rate μ_{YS}. Note that finite numbers of FTs (m) and GTs (n) are used in order to transport containers in the single TP system.

This system includes three machines and forms two closed loops with finite numbers of trolleys. In the following sections, an analytical model based on the Markov chain is developed to estimate the throughput of the single TP system.

3.2. Mathematical Analysis for the Single TP System. In this section, we analyze the two closed-loop systems as a Markov chain in which the containers are transferred from M_{QS} to M_{YS} (i.e., the unloading operation). The state of the system is described as $X = (s, N_{FT}, N_{GT})$, where s is the state of M_{TP}, N_{FT} is the number of FTs at M_{TP}, and N_{GT} is the number of GTs at M_{TP}. There are four kinds of states of M_{TP}: $s = 0^-$ means M_{TP} is idle and waits for an FT; $s = -1$ means M_{TP} is unloading container from an FT; $s = 0^+$ means M_{TP} handles container and waits for a GT; and $s = 1$ means M_{TP} is unloading container to a GT.

Due to the fact that the total number of FTs is m, the number of FTs at M_{QS} is $m - N_{FT}$. Similarly, the number of GTs at M_{YS} is $n - N_{GT}$. The system states can be enumerated as follows. When $s = 0^-$ (M_{TP} is idle and waits for an FT), there is no FT at M_{TP} and the system states will be $(0^-, 0, 0), (0^-, 0, 1), (0^-, 0, 2), \ldots, (0^-, 0, n)$. When $s = -1$ (M_{TP} is unloading container from an FT), there is at least one FT at M_{TP} and the system states will be $(-1, 1, 0)$,$(-1, 1, 1)$, $(-1, 1, 2)$,$\ldots$,$(-1, 1, n)$;$(-1, 2, 0)$,$(-1, 2, 1)$, $(-1, 2, 2)$,$\ldots$, $(-1, 2, n)$; $\ldots$; $(-1, m, 0)$, $(-1, m, 1)$,$(-1, m, 2)$, $\ldots$, $(-1, m, n)$. When $s = 0^+$ (M_{TP} handles container and waits for a GT), there is no GT at M_{TP} and the system states will be $(0^+, 0, 0)$, $(0^+, 1, 0)$, $(0^+, 2, 0), \ldots, (0^+, m, 0)$. When $s = 1$ (M_{TP} is unloading container to a GT), there is at least one GT at M_{TP} and the system states will be $(1, 0, 1), (1, 0, 2), \ldots$, $(1, 0, n)$;$(1, 1, 1)$,$(1, 1, 2)$, $\ldots$, $(1, 1, n)$; $\ldots$;$(1, m, 1)$, $(1, m, 2)$, $\ldots$, $(1, m, n)$. There are $(n+1) + m(n+1) + (m+1) + (m+1)\ n = 2\ (nm + n + m + 1)$ states in the system.

Set $\pi = \{\pi_1, \pi_2, \pi_3 \ldots, \pi_{2(nm+n+m+1)}\}$ as the stationary probability vector of the states, and $Q_{2(nm+n+m+1),2(nm+n+m+1)}$ is the transition matrix for the Markov chain, where q_{ij} is

the transition rate of the system from X_i to X_j, and $q_{ii} = -\sum_{j=1,\ldots,2,(nm+n+m+1)}^{j\neq i} q_{ij}$. By considering the behavior of the system, q_{ij} can be enumerated as in Table 1.

4. Throughput Analysis of the Single TP System

This section provides a systematic way to estimate the throughput of a TP and its relevant analyses including the impact of the delay rates of trolleys and the numbers of trolleys on the throughput of a TP.

With $\begin{cases}\pi Q=0\\ \sum \pi=1\end{cases}$, π can be derived. Thus, the mean utilization of M_{TP} for FTs (when the state of M_{TP} is $s = -1$, the TP unloads a container from an FT) is represented as $U_{\mathrm{FT}} = E_{t->+\infty}(s = -1) = \sum_{i=1}^{m}\sum_{j=0}^{n}\pi_{i(n+1)+j+1}$. Similarly, the mean utilization of M_{TP} for GTs (when the state of M_{TP} is $s = 1$, the TP loads a container onto a GT) is represented as $U_{\mathrm{GT}} = E_{t->+\infty}(s = 1) = \sum_{i=0}^{m}\sum_{j=1}^{n}\pi_{(n+2)(m+1)+in+j}$. Hence, the mean throughput of M_{TP} is represented as $H_{\mathrm{TP}} = \mu_{\mathrm{TP}} \times U_{\mathrm{GT}} = \mu_{\mathrm{TP}} \times U_{\mathrm{FT}}$. Following sub-sections deal with analyzing the throughput of a TP with different delay and processing rates and numbers of trolleys.

4.1. Impacts of the Delay Rates of Trolleys on the Throughput of the Single TP System with One FT and One GT. When there is one FT and one GT in the single TP system, the system states are $S = \{(0^-, 0, 0), (0^-, 0, 1), (-1, 1, 0), (-1, 1, 1), (0^+, 0, 0), (0^+, 1, 0), (1, 0, 1), (1, 1, 1)\}$, and the transition matrix of the Markov chain consequently is

$$Q = \begin{bmatrix} -\mu_{\mathrm{YS}}-\mu_{\mathrm{QS}} & \mu_{\mathrm{QS}} & \mu_{\mathrm{YS}} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\mu_{\mathrm{YS}} & 0 & \mu_{\mathrm{YS}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\mu_{\mathrm{TP}}-\mu_{\mathrm{QS}} & \mu_{\mathrm{QS}} & \mu_{\mathrm{TP}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\mu_{\mathrm{TP}} & 0 & 0 & \mu_{\mathrm{TP}} & 0 \\ 0 & 0 & 0 & 0 & -\mu_{\mathrm{YS}}-\mu_{\mathrm{QS}} & \mu_{\mathrm{YS}} & \mu_{\mathrm{QS}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\mu_{\mathrm{QS}} & 0 & \mu_{\mathrm{QS}} \\ \mu_{\mathrm{TP}} & 0 & 0 & 0 & 0 & 0 & -\mu_{\mathrm{YS}}-\mu_{\mathrm{TP}} & \mu_{\mathrm{YS}} \\ 0 & 0 & \mu_{\mathrm{TP}} & 0 & 0 & 0 & 0 & -\mu_{\mathrm{TP}} \end{bmatrix}. \quad (1)$$

Table 2: Throughput of TP with different delay rates of trolleys and the processing rate of TP.

Case	μ_{QS}	μ_{YS}	μ_{TP}	H_{TP} (containers/hour)
1	30	20	60	12.7
1	30	25	60	14.1
1	30	30	60	15.0
1	30	35	60	15.7
1	30	40	60	16.1
2	30	30	50	13.9
2	30	30	55	14.5
2	30	30	60	15.0
2	30	30	65	15.4
2	30	30	70	15.8
3	20	30	60	12.7
3	25	30	60	14.1
3	30	30	60	15.0
3	35	30	60	15.7
3	40	30	60	16.1

Let $\mu_{\mathrm{YS}} = a$, $\mu_{\mathrm{TP}} = b$ and $\mu_{\mathrm{QS}} = c$. By solving $\begin{cases}\pi Q=0\\ \sum \pi=1\end{cases}$, the mean throughput of M_{TP} can be derived as $H_{\mathrm{TP}} = (ab^2c(b^2(a^2 + ac + c^2) + b(a + c)^3 + ac(a + c)^2))/((b^2(a^2 + c^2) + 2a^2c^2)(a + c) + 2abc(a^2 + ac + c^2))$.

Here, μ_{QS} is the processing rate for an FT to transfer a container between the QC and TP including the FT's traveling time to the QC, waiting time for a QC to load/unload a container, and traveling time back to the TP. And μ_{YS} is the processing rate for a GT to transfer a container between the YC and TP including the GT's traveling time to the YC, waiting time for a YC to load/unload a container, and traveling time back to the TP. A QC's/YC's top handing rate is typically 45 lifts per hour. Considering the travelling time of FT/GT between QC/YC and TP, μ_{QS} and μ_{YS} should be below 45 containers/hour. And μ_{TP} is the processing rate of loading/unloading containers by TP from/to an FT or GT. Based on the technical specification data provided by the ZPMC Company, μ_{TP} is around 60 containers/hour.

Table 3: Throughput of TP when $\mu_{\mathrm{YS}} + \mu_{\mathrm{QS}} = 60$ container/hour and $\mu_{\mathrm{TP}} = 60$ container/hour.

μ_{QS}	μ_{YS}	μ_{TP}	H_{TP} (containers/hour)
20	40	60	13.3
22	38	60	13.9
24	36	60	14.4
26	34	60	14.7
28	32	60	14.9
30	30	60	15.0
32	28	60	14.9
34	26	60	14.7
36	24	60	14.4
38	22	60	13.9
40	20	60	13.3

In order to analyze the impact of the delay rates of trolleys (μ_{YS} and μ_{QS}) and the processing rate of the TP (μ_{TP}) in detail, three different cases are compared: Case 1 = $\{\mu_{\mathrm{QS}} = 30$ containers/hour, $\mu_{\mathrm{TP}} = 60$ containers/hour and μ_{YS} is changed

Table 4: Results of sensitivity analysis on different quay length.

Quay length (meters)	Expected number of blocks	Number of FTs per TP	Number of GTs per TP	Terminal throughput (containers/hour)
300	4	1	1	51.0
600	8	1	1	101.9
900	12	1	1	152.9
1200	16	1	1	203.9

Table 5: Results of sensitivity analysis on different levels of resource requirement.

Quay length (meters)	Expected number of blocks	Number of FTs per TP	Number of GTs per TP	Terminal throughput (containers/hour)
900	12	1	1	152.9
900	12	2	1	168.4
900	12	3	1	169.4
900	12	1	2	205.3
900	12	2	2	269.3
900	12	3	2	279.1
900	12	1	3	214.8
900	12	2	3	308.6
900	12	3	3	331.4

from 20 containers/hour to 40 containers/hour}; Case 2 = {$\mu_{YS} = \mu_{QS} = 30$ containers/hour and μ_{TP} is changed from 50 container/hour to 70 container/hour}; and Case 3 = {$\mu_{YS} = 30$ containers/hour, $\mu_{TP} = 60$ containers/hour, and μ_{QS} is changed from 20 containers/hour to 40 containers/hour}, the throughput of a TP (H_{TP}) is estimated as in Table 2. The results show that H_{TP} increases as μ_{QS}, μ_{YS}, or μ_{TP} increases. Furthermore, the throughput of M_{TP} is symmetrical with the delay rate of an FT at YS (μ_{YS}) and the delay rate of a GT (μ_{QS}) at QS, which means that $H_{TP}(\mu_{YS}, \mu_{TP}, \mu_{QS}) = H_{TP}(\mu_{QS}, \mu_{TP}, \mu_{YS})$. For example, $H_{TP}(30, 20, 60) = H_{TP}(20, 30, 60) = 12.7$ containers/hour. This is because the proposed network consists of two equivalent closed loops.

In order to further analyze the impact of μ_{YS} and μ_{QS}, the sum of μ_{YS} and μ_{QS} is given as constant and H_{TP} is investigated. Table 3 shows the results under $\mu_{YS} + \mu_{QS} = 60$ containers/hour and $\mu_{TP} = 60$ containers/hour. It is found that the maximum H_{TP} is achieved when $\mu_{YS} = \mu_{QS} = 30$ containers/hour. It means that in order to achieve the maximum throughput of TP, the port operator should balance the arriving rate of FTs and GTs by optimizing the traveling speed and workload of FTs and GTs. This is because the proposed network is consisted of two equivalent closed loops. When the delay rate of FTs is higher than that of GTs, FTs have to wait at the TP. Otherwise, GTs have to wait at the TP when the delay rate of GTs is higher than the FTs. Only when the delay rates of FTs and GTs are the same, the two closed traveling loops of FTs and GTs become balance. Then, the TP achieves the maximum throughput.

5. Application of the Single TP Model for Analyzing Configurations of an FB-ACT

In Section 4, the proposed single TP model is used to estimate the TP throughput. It can be approximately extended to help the port operators to design an FB-ACT. This section aims to discuss ways to conduct the sensitivity analyses and analyze the results from the perspective of terminal design.

Under the given quay length denoted by B, suppose W is the width of a block including the space allowance between adjacent blocks, and then $\lfloor B/W \rfloor$ is the expected number of blocks. With the given process rate of rates μ_{QC}, μ_{YC}, and μ_{TP}, the throughput of each block can be calculated based on different number of trolleys. And then the whole system performance can be estimated by summing up the throughputs of TPs for all blocks.

Tables 4 and 5 show comparisons of the terminal throughput for different quay lengths and numbers of trolleys. It is assumed that W is 70 meters since the FB-ACT needs wide space between blocks for installing rail-tracks for YCs and frame structures for GTs. According to Zhen et al.'s study [18], the delay and processing rates are assumed to be 30 containers/hour, 20 containers/hour, and 60 containers/hour for μ_{QC}, μ_{YC}, and μ_{TP}, respectively.

The results demonstrate the follows. (1) the terminal throughput increases as the quay length increases. In the same manner, (2) the throughput of system increase as the number of trolleys per TP increases. However, increasing rate is not proportional to the numbers of trolleys. For example, the terminal throughput under the strategy {two FTs, two GTs} is less than the double of the terminal throughput under the strategy {one FT, one GT}. (3) The number of GTs affects the terminal throughput rather than the number of FTs. The reason lies that the delay rate of a GT is smaller than that of an FT. (4) the terminal throughput is influenced by the number of TPs rather than the number of QCs. Suppose that the expected number of QCs is three per berth and the berth length is 300 meter as they are typically known in a conventional container terminal. The estimate terminal throughput is less than the throughput calculated

by multiplying the number of QCs and the processing rate of QS (the delay rate of an FT). The results underpin the underlying conjecture of this study in which the TPs are bottlenecks for the operation processes of container flows in FB-ACTs instead of QCs.

6. Conclusions

This paper introduces a new type of ACT system and makes an explorative study to identify the challenges for the FB-ACT system. It is assumed that a TP is dedicated to a block and the system consists of several single TP systems which serve certain numbers of FTs and GTs. A Markov chain model is developed to analyze the performance of a single TP system in terms of the throughput of a TP. This study further analyzed the number of resources and the terminal configurations by using the developed Markov model. The results show that the throughput of TP increases as its processing rates or the delay rates of the trolleys at quay side and yard side increase. In order to achieve the maximum throughput of TP, the port operator should balance the arriving rate of FTs and GTs by optimizing the traveling speed and workload of FTs and GTs. The terminal throughput increases as the quay length increases or the number of trolleys increases. However, the increasing rate is not proportional to the numbers of trolleys per TP.

This study simplifies the system under the assumptions that there are enough numbers of QCs and YCs. In the future study, it may be necessary to consider the performance of this new system under the certain numbers of QCs and YCs. Different dispatching strategies among FTs, TPs, and GTs are needed to be analyzed. Moreover, uncertain factors in the port operations in ACTs will be investigated in the future [19–21].

Acknowledgments

This research is supported by the National Natural Science Foundation of China (no. 71201099, no. 71101090), Shanghai Pujiang Program (no. 13PJC066), the Ministry of Transport Research Projects (no. 2012-329-810-180), Doctoral Fund of the Ministry of Education Jointly Funded Project (20123121120002, 20123121120004), Shanghai Municipal Education Commission Project (no. 12ZZ148, no. 12ZZ149, and no. 13YZ080), Science and Technology Commission of Shanghai Municipality (no. 10PJ1404700) Shanghai Top Academic Discipline Project-Management Science & Engineering, the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning, and the Maritime and Port Authority, Singapore (MPA).

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