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Performance Analysis and Planning for a Logistics System in a Free-Trade Port Area:

A Case Study

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Abstract

A free-trade port area is one of the important functional areas in international trade. This paper presents a performance analysis for planning a logistics operation system in a free-trade port area when a port is reformed from a traditional operation area to a free-trade port area. First, the new operation process of the system, including customs supervision operation at checkposts, the logistics operation process at container terminals and container yards, and the transport operation of trucks through the transport networks is analyzed. Then, the performance analysis model for the dynamic behaviour of the system is presented, especially the logistics process cycle of the container trucks between the outbound container yards and the inbound container terminals. Because of the complexity of the system activity, a simulation model has been adopted using discrete event system simulation to realize the system performance analysis method. Finally, an actual case in China is used to verify the performance analysis model, to analyze the operation performance, and to find the bottlenecks of the system operation according to the simulation results. According to the analysis results of the system operation performance, an improved planning scheme is proposed.

Key Words: Free-trade port area, Queue network, Logistics, Performance, Simulation

1. Introduction

A free trade port area (FTPA) or so-called bonded port, is being widely used in international trade, and its operation mode is similar to that of a free trade zone. Its functions include international cargo transit, distribution, stock, trade transferring, export processing, and so on. In China, FTPAs are still in the fledging stage. So, it is quite important to plan a well-performed logistics and transport operation network system from a conventional operation system to a FTPA system with customs supervision.

A FTPA has the characteristic of a regional logistics operation zone, where the different parts of the FTPA and container freight stations nearby have a mutual influence on each other. In the field of planning regional logistics zones, paper [1] (LI, 2004) presented a framework about a set of planning methods from macro-scale to micro-scale logistics operation zones. From the view of the analysis and design for logistics and traffic networks, graph theory in paper [2] (ZHANG, 2007), matrix analysis in paper [3] (HE, 2007) and [4] (Liu, 2007) were used to analyze the network structure of the logistics and transportation system from the

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aspect of theory. For practical purposes, paper [5] (Legato P., 2001) proposed a queuing network model to analyze the logistics activity in the planning of container terminals. The discrete event system simulation model has been widely used in planning the layout of road traffic network systems in container terminals and its nearby area in papers [6] and [7]. Paper [8] (David, 2007) adopted a multi-agent approach in analyzing and evaluating bus-network performance for diverse space and time scales.

At the same time, the research on traffic and logistics networks in FTPAs also belonged to the problem of regional multimode transport network in port areas. In this field, paper [7] (Dong, 2005) proposed a performance model and an analytic framework for analysis of integrated logistic chains. Paper [9] (Pablo Cortes, 2007) analyzed the freight transport process beginning with the movement through the whole estuary of the river and finishing with the vessels arriving at the port dependencies. Paper [9] (Francesco Parola, 2005) presented a discrete event simulation modeling approach related to the logistic chain as a whole in the northwestern Italian port system with the aim of evaluating a possible future growth of the container flows. Papers [11] and [12] (A. Ballis, 2004, 2002) proposed a modeling approach to evaluate and compare the facility's efficiency and operational effect in railroads and roads; similarly the effect of conventional and advanced technologies was also compared and evaluated. As stated above, in these research issues the performance analysis method of the logistics network of FTPAs considering the supervision of customs has not yet been a concern.

This paper focuses on the performance analysis and planning of logistics and transport operation systems on a FTPA. The modeling method is presented with graph theory and queuing theory, and the performance evaluation indexes are designed. An actual FTPA case in China is illustrated to verify the proposed model, to evaluate the queuing status and discover bottlenecks in the system, and to improve the system performance with feasible resource adjustments.

2. Description of Operation Process

The research range includes the logistics and transport operations of a FTPA and the container freight stations (CFS) inside and outside the FTPA, which is shown in Figure 1. The whole system is divided into two parts by the enclosed fence line of the customs supervision: the inside part possesses the trade free functions, and the outside part does not have those functions. So, the total operations in the research include the customs supervision operation, port operations, inbound and outbound CFS operations, and the traffic operation. In all these operations, the entities of activities are vehicles or mainly container trucks.

(1) Customs supervision operation. This consists of the closed customs fence line and the checkposts or customs stations for customs supervision. The checkpost is an important point connecting a FTPA and an outside area. There are several checkposts in a FTPA. All freight trucks inboard and outboard through a FTPA have to be checked to handle the procedures of tax declaration or export tax drawbacks when passing the checkpost. One checkpost consists of some independent entrance-lanes and exit-lanes that serve specified type of vehicles and perform supervision operations for one vehicle at one time.

(2) Port operation. This includes three types of operations: container terminal gate operations for trucks, container yard operations for containers and berth operations

for ships. The container is handled to load or unload among ships, berth, yard, container truck, and container terminal gate. The main factor impacting the traffic status in a FTPA is the port gate operation. When entering or departing from the container terminal, the container truck has to pass the port gate. The operation process at the gate is similar with those of checkposts. They also include some lanes that serve those container trucks arriving at or departing from the port.

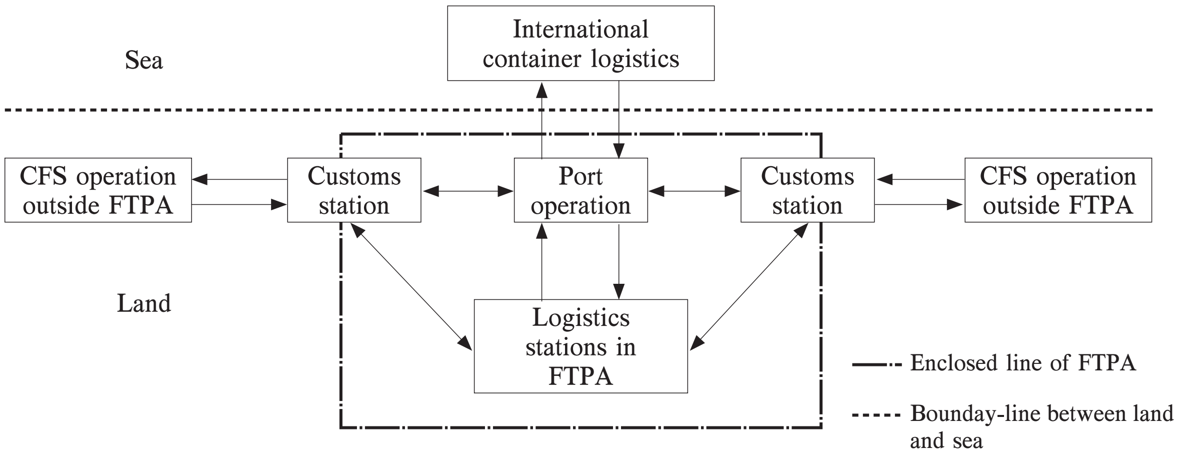

Figure 1 The structure of a FTPA

(3) CFS operations. These include those enterprises for manufacturing and warehousing inside a FTPA and those outside a FTPA for CFS operation. As these enterprises are similar in operation process, they are all considered CFS station operations.

(4) Traffic operations. This means the traveling process of vehicles. As it takes time for a vehicle to travel from one point to another, so, the congestion status of roads affects the traveling time of vehicles in a FTPA, and then impacts the operation efficiency of the vehicle, and that of the whole system.

The typical logistics operation cycle process is shown in Figure 2 for a container truck from outside a CFS to a FTPA and then from a FTPA to outside a CFS. In Figure 2, the number sequence from 1 to 12 represents the operation sequence. The operations around number 14 represent the CFS operation in a FTPA, and the operations around number 18 represent the ship operation. For the FTPA operation performance analysis and planning, it is necessary to consider the following characteristics:

(1) Types of entities. There are six types of vehicles: empty container trucks, container trucks with an unloaded container, container trucks with a loaded container, unloaded bulk cargo trucks, loaded cargo trucks, administration vehicles. The five former types need customs supervision procedures. Here, variable u ($u = 1, 2, \ldots, 6$) is used to represent the type of vehicles.

(2) Closed local operation. It is usual for the functions of FTPA to be transferred from an original conventional logistics and transport operation area without customs checkposts and operational supervision. For the construction of a closed fence line settled by the customs supervision requirement, all operations are limited in a specified region. So the operational performance and the planning scheme of a FTPA is influenced by the conventional operation layout and road network.

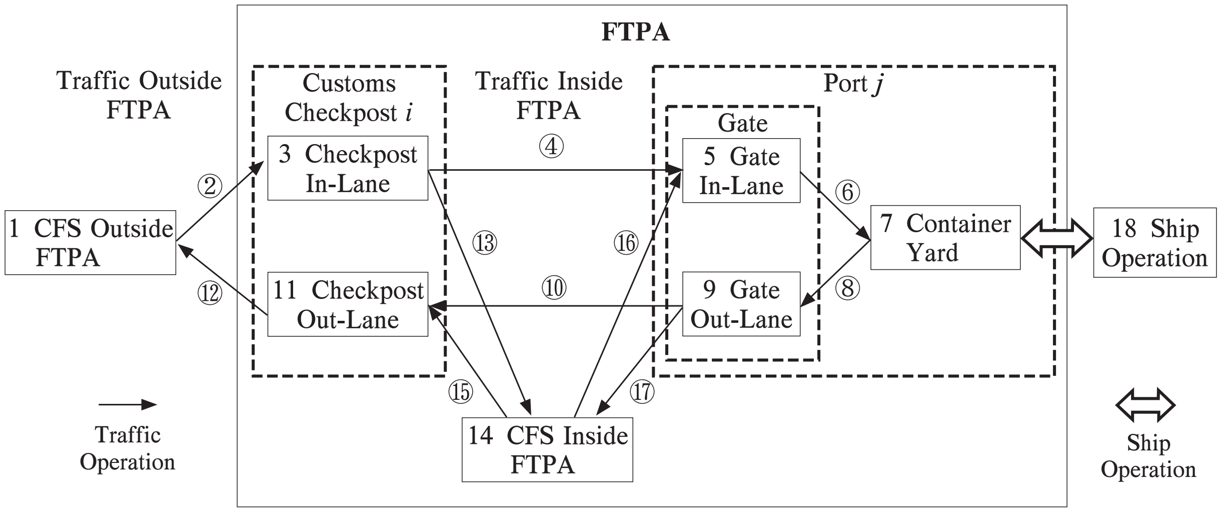

Figure 2 The operation process of a FTPA

(3) Business-oriented route. The arrival ratio of different types of vehicles depends on the logistics quantity of different functional areas in a FTPA. The container trucks aim for the operation at the container terminals; and the cargo trucks aim for the CFS operations inside a FTPA. The vehicle routes are also determined according to the starting position, the business destination, and the road network. In addition, all vehicles have to pass through the checkposts twice in one operation cycle.

(4) Cycle operation. The total process cycle of vehicles is divided into two parts: forward processes and reverse processes. A vehicle repeats a similar operation cycle in turn. If a vehicle stays in the system too long in one operation cycle, it will influence the next operation cycle. Therefore, the overall operational efficiency will become lower. That will cause a series of impacts on the other system performances such as ship loading/unloading operation, CFS operations, road and gate congestion, and so on.

3. System Modeling

3.1 System Network Structure Model

The key resource elements impacting logistics operation in a FTPA system are determined by the analysis on business processes. They include checkposts, container terminal gates, CFS stations, and road networks. These resource elements constitute a resource network. A directed network system is described with graph theory, as shown in Figure 3, where the part within the dotted line stands for the FTPA, and the solid arrow stands for the road and its direction.

According to Figure 3, the whole resource network of a FTPA is described with a set with a triple group $P_0 = (V, E, D)$, where, V stands for a set of all vertexes including V_c, V_g, V_y, V_w, V_s, $V = \{V_c, V_g, V_y, V_w, V_s\}$, and the total number of each vertex set is l, p, q, r, s, respectively. For the checkpost set, $V_c = \{v_{ci} \mid i = 1, 2, \ldots, l\}$, other vertex sets are similar to it. The total number of vertexes is respresented by $N_v = l+p+q+r+s$. E stands for the set of directed road edges in the network graph, $E = \{e(v_i, v_j) \mid v_i, v_j \in V\}$; $e(v_i, v_j)$ is the edge from vertex v_i to v_j. D stands for the set of weighted values of edges or road lengths, $D = \{d(v_i, v_j) \mid v_i, v_j \in V\}$; $d(v_i, v_j)$ is the weighted value of edge $e(v_i, v_j)$.

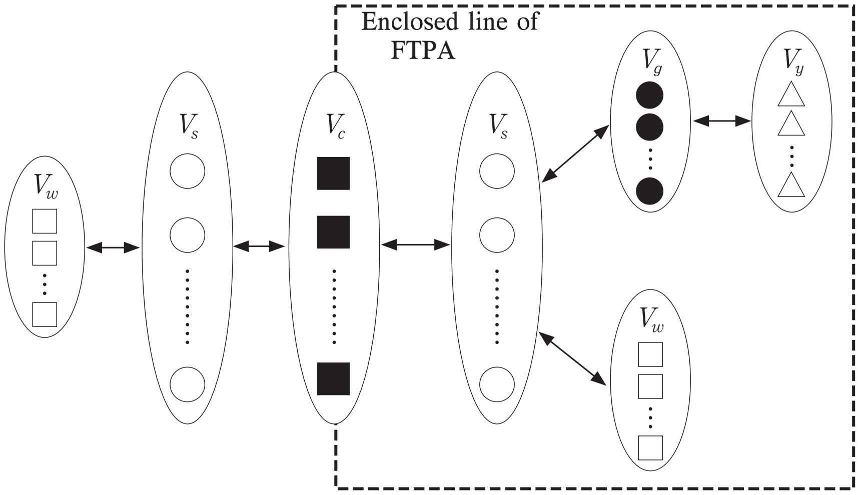

Figure 3 Graph-based resource network structure of a FTPA

3.2 Queue Network Model for System Activities

System activity means a process where an entity (vehicle) receives series of services by passing through the node of resources in sequence in the system. The whole process contains input processes describing the entities' arrival according to a certain distribution, traffic process, queuing process for entities' waiting for seizing service resources, service process for logistics operations, and departure processes for going back to its original place. Hence, the activity in a FTPA system belongs to a multi-stage, multi-server queuing network system.

For the purposes of this research, this issue aims to analyze the service process, evaluate operation effect and the utility of system resources, and does not address the largest flow problems or minimum cost flow problems of transport networks. Therefore, system modeling and performance analysis is based on a discrete event system model for the queue network model.

In order to describe the queue network activities model, the set P_0 is expanded to a sextuple set $P = (V, E, D, A, R, F)$ and is used to describe the activity process of system entities (vehicles). In set P, subset A is defined as the set of resource attributes of each vertex in the system. Namely, it is the service time distribution of resources for entities as shown in formula(1).

$$A = \{A_c, A_g, A_y, A_w, A_s\} \qquad (1)$$

In formula(1), A_c expresses checkpost resource, $A_c = \{T_{ci} | i = 1, 2, \ldots, l\}$, where, T_{ci} is the mean service time of checkpost i; it is different for different kind of truck entities. $A_c(u) = \{T_{ci}(u) | i = 1, 2, \ldots, l; u = 1, 2, 3, 4, 5, 6\}$ represents the mean service time for trucks of type u at a checkpost. The service time for other resources can be expressed by the same method.

In set P, subset R is defined as the travel time distribution set for truck entities traveling on the roads in the system. Take road links between checkposts and crossover for example, matrix $R_{cs} = (T_{csij})_{l \times s}$ is defined to express the travel time distribution in the process from checkpost to crossover, which is related to the road matrix D and the truck's limit speed. When T_{csij} is 0, the checkpost i is not adjacent to the crossover j or there is no access. Matrix $R_{sc} = (T_{scij})_{s \times l}$ is defined as the travel time distribution for truck entities heading to the checkpost. Similarly, there are also other road matrixes. Thus, R is expressed as formula(2).

$$R = \{R_{cs}, R_{gs}, R_{ys}, R_{ws}, R_{sc}, R_{sg}, R_{sy}, R_{sw}\} \quad (2)$$

In set P, subset F is defined as an arrival distribution set for truck entities in the system, Note F_{uy} as the arrival distribution for trucks type u to the container yard, and F_{uw} as the arrival distribution to a CFS. Here, we consider the operation cycle t which is divided into z segments, $t = \{t_1,\dots,t_i,\dots,t_z\}$, so the total truck arrival distribution is expressed as $F(t) = (F_1(t_1),\dots,F_i(t_i),\dots,F_z(t_z))$, where, $F_i(t_i)$ is the arrival distribution at time segment t_i, expressed in formula(3).

$$F_i(t_i) = \sum_u (F_{uyi}(t_i) + F_{uwi}(t_i)) \quad (3)$$

3.3 Sub-models of the System Model

(1) Checkpost model

A checkpost $v_{ci} \in V_c$ has some check channels for entrance and exit roads. Each channel is regarded as a service element. So, a checkpost model is attributed to a two-direction, multi-server queue model $G_1/G_2/n_{ci}/m_{ci}$. The service rule is FIFO (First In, First Out). The vehicle arrival distribution G_1 is determined by $F_{uy}(t)$ and $F_{uw}(t)$ in equation(3), and the service time distribution G_2 is determined by equation (1). The total number of channels is n_{ci}. Because of the limited road area, the checkpost has a limited value m_{ci} on service area capacity. If the number of waiting vehicles has reached the value m_c, the arriving vehicles afterward have to wait in the queuing line along the road.

(2) Container terminal gate model

The operation of a container terminal gate $v_{gi} \in V_g$ is regarded as a $G_1/G_2/n_{gi}/m_{gi}$ queue model, similar with a checkpost model. The distribution G_1 of the vehicle arrival is decided by $F_{uy}(t)$, the distribution G_2 of gate service time can be decided as that of a checkpost. The total number of gate servers is n_{gi}, the maximum number of waiting container trucks on the gate i is m_{gi}. Moreover, for container yard operation, considering that this research focuses on the integrated function in logistics and transport operation on the FTPA, we mainly consider the yard capacity myi containing container trucks inside the yard area. If the number of vehicle inside the yard is more than m_{yi}, these container trucks have to wait outsider the gate. Therefore, the traffic status will be impacted.

(3) CFS station operation model

This is similar to the gate operation model. The operation model of a CFS station $v_{wi} \in V_w$, is a $G_1/G_2/n_{wi}/m_{wi}$ queue model. The vehicle arrival distribution G_1 is decided by $F_{uw}(t)$; the service time distribution G_2 is decided by the same method as the checkpost model.

(4) Crossover process model

The model of a crossover process $v_{si} \in V_s$, is defined as a queue model $G_1/G_2/n_{si}/m_{si}$. The service rule is FIFO. As all crossover nodes are connected with roads and other crossovers, so arrival distribution G_1 depends on the number of departing vehicles from the adjacent crossover nodes. Service time distribution G_2 depends on the vehicle's speed through the crossover, lane number and traffic rule. The number of service elements n_{si} is decided by the number of lanes; the service capacity m_{si} is decided by the number of lanes m_{si}.

4. Performance Analysis

The system operation performance in the dynamic operation activities is evaluated based on the analysis on the road network, service nodes and the system operating activities. In the following analysis, we focus on the vehicle staying time in the system to evaluate operation efficiency, and the queuing status of the checkposts and container terminal gates to assess the utilization status of the critical service resources. The relationship between operation cost and resource scale is analyzed to discuss the planning of checkposts.

4.1 Vehicle Staying Time in System for One Cycle

In one cycle of the n-th vehicle from arriving at the system to departing from the system, it is assumed that the vehicle route is determined on the basis of the vehicle type and designed process; set $H(n)$ expresses the vehicle route sequence, $H(n) = \{h_1(n), \ldots, h_i(n), \ldots, h_{N_h}(n)\}$,where, $h_i(n) \in V, N_h < N_v$, $h_i(n)$ is a vertex in the vehicle route. The waiting time of the n-th vehicle at a service node is represented with vector $Q(n)$, $Q(n) = \{T_{qi} \mid i = 1, 2, \ldots, N_h\}$. For route $H(n)$, the vehicle's processing time $T_{hi}(n)$, waiting time $T_{qi}(n)$, and traveling time $T_{mi}(n)$ from service node $h_i(n)$ to node $h_{i+1}(n)$ can be determined by a statistical method, so then the n-th vehicle's total staying time $T(n)$ in its one cycle is expressed as expression (4).

$$T(n) = \sum_{i=1}^{N_h} (T_{hi}(n) + T_{qi}(n) + T_{mi}(n)) \tag{4}$$

4.2 Performance Indices of Service Nodes

By analyzing the operation performance of service nodes in the queue network system with performance indexes such as utilization rates and queuing length, the bottlenecks of the system can be found out and a judgment can be made whether the allocation of all kinds of resources is feasible. In a FTPA system, these service nodes include checkposts, gates, terminal yards, CFSs and road crossovers. In the following, take the checkpost as an example to determine its service performance index. Similarly, other service nodes are determined by the same method.

The service process at the checkpost is a dynamic stochastic queuing process. In the period of t_i, the distribution of the vehicle arrival at node j is $F_j(t_j)$. When the service node meets the flow balance condition, it is assumed that C_{jk} is the number of vehicles having passed through the k-th channel in the checkpost V_{cj}. It is assumed that , in the period t_i, the state is $Y_j(n, t_i)$ when the number of total vehicles is equal to n at checkpost j, and when the system status changes from the state $Y_j(n, t_i)$, the duration time of state $Y_j(n, t_i)$ is $T_j^{l(n)}(n, t_i)$; $l(n)$ is the change times of status $Y_j(n, t_i)$. Then the mean queue length $L_j(t_i)$ and the mean staying time $M_j(t_i)$ at checkpost j are formulated in expressions (5) and (6).

$$L_j(t_i) = \frac{\sum_{k=1}^{n} \sum_{l=1}^{l(k)} T_i^{l}(k, t_i)}{t_i} \tag{5}$$

$$M_j(t_i) = \frac{\sum_{k=1}^{n} \sum_{l=1}^{l(k)} T_i^l(k, t_i)}{\sum_{r=1}^{n_{cj}} C_{jr}} \quad (6)$$

5. Case Study

In this section, an actual case of a FTPA in northern China is illustrated with the proposed performance evaluation model, and the performance analysis is carried out with a simulation model in ARENA. By performance analysis, the planned scheme is improved through revising the bottleneck points, and from the case study, the effect and feasibility of this performance analysis model is validated.

5.1 Main Parameters

In this case, the structure of the FTPA, including road networks, is shown in Figure 4, where there are two container terminals V_{p1}, V_{p2}, and three checkposts V_{c1}, V_{c2}, V_{c3}. The main parameters of the system resources are shown in Table 1. The main parameters of the system node service time are shown in Table 2. The distribution from trucks arrivals to the container terminal in hours in one day are shown in Figure 5.

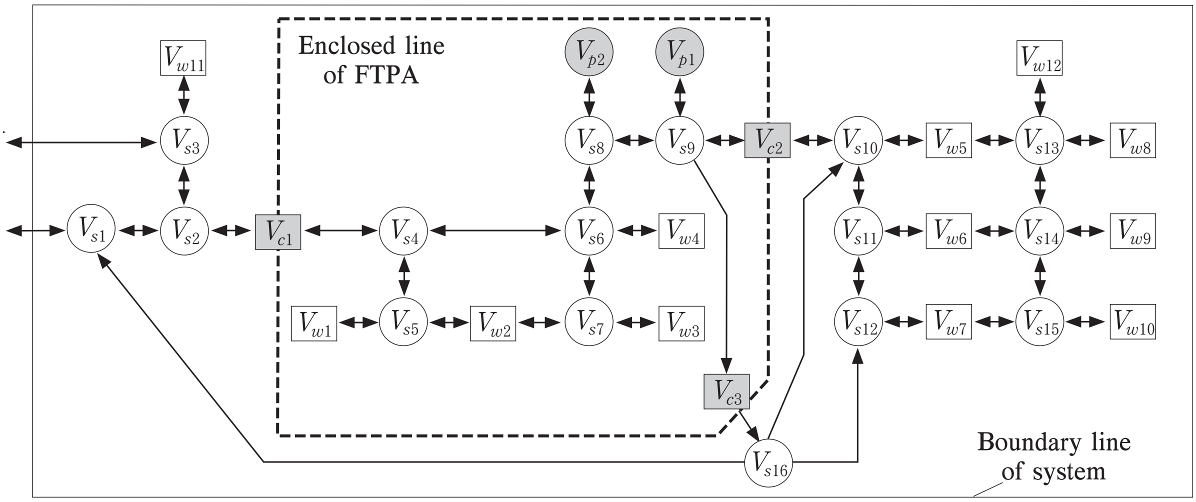

Figure 4 The road network of the FTPA

Table 1 Main parameters of the system resources

Parameters	Values	Parameters	Values	Parameters	Values
l	3	n_{c1} (In/Out)	7/8	n_{g1} (In/Out)	8/5
p	2	n_{c2} (In/Out)	3/3	n_{g2} (In/Out)	9/7
q	2	n_{c3} (In/Out)	0/4	m_{g1}	100
r	12	m_{c1}	60	m_{g2}	80
s	16	m_{c2}	30	m_{y1}	300
N_v	35	m_{c3}	16	m_{y2}	200

Table 2 Main parameters of the system service times

Parameters	Values	Parameters	Values	Parameters	Values
T_{ci} (1)	30 *s*	T_{gi} (1)	20 *s*	T_w (1)	30 *min*
T_{ci} (2)	60 *s*	T_{gi} (2)	60 *s*	T_w (2)	30 *min*
T_{ci} (3)	60 *s*	T_{gi} (3)	60 *s*	T_w (3)	30 *min*
T_y (*u*)	40 *min*	T_w (5)	20 *min*	T_w (4)	20 *min*

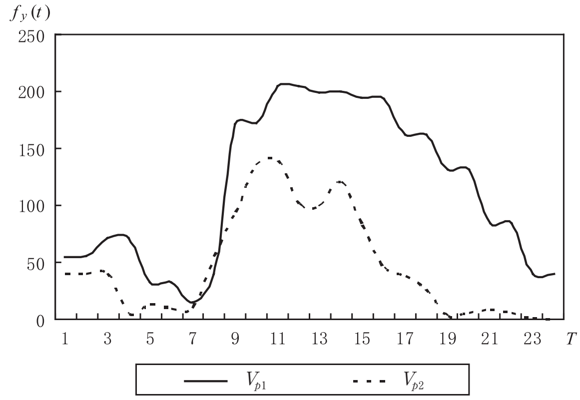

Figure 5 Truck arrival to container terminal distribution in hours per day

5.2 Result Analysis and Comparison

A simulation on the FTPA for one day's operation was executed and the results are shown as the following.

(1) Performance indexes. It is known from Figure 6 that the peak period of mean queue lengths of container terminal V_{p1} and customs checkpost V_{c2} occurs from 11:00 to 17:00; that accords basically with trucks arrivals distribution. As time goes on, the queue length of the container terminal and custom checkpost will decrease, because the number of arriving trucks decreases. So, the cumulative effect will not occur, that is to say, this system possesses stability in the service process. If the number of out lanes of container terminal V_{p1} and the lanes of customs checkpost V_{c2} is increased by 2 lanes respectively, the mean queue lengths decrease clearly as shown in Figure 7, and that can meet the requirements of the system operation.

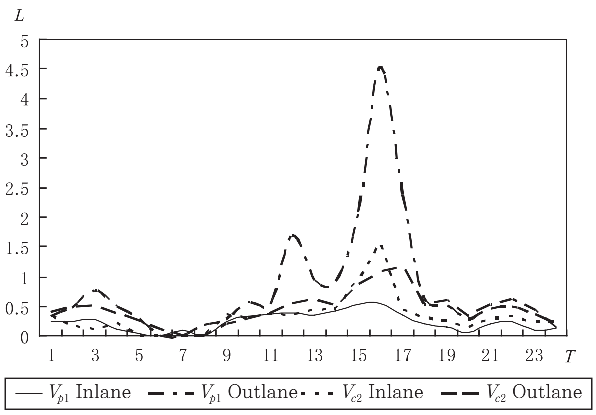

Figure 6 The mean queue length on V_{p1} and V_{c2}

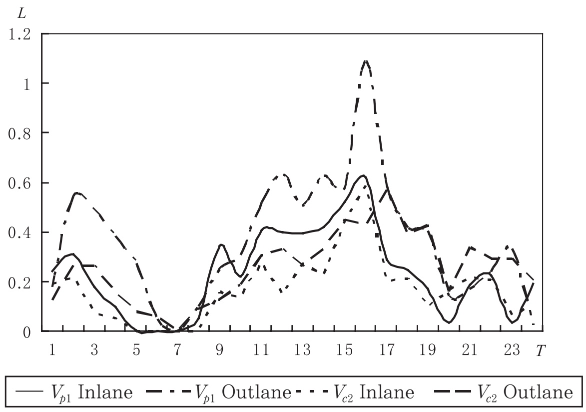

Figure 7 The improved mean queue length on V_{p1} and V_{c2}

6. Conclusions

We have proposed a performance analysis method based on a queue network model for a FTPA system. For an actual FTPA case, our proposed method was validated with a discrete event simulation model. The conclusions are summarized as follows:

（1） As the conventional logistics and transport operation at container terminals become complicated under the condition of customs supervision within a FTPA area, it is necessary and difficult to evaluate its operational performance in a FTPA;

（2） The graph structure is used to define the resource network of a FTPA, and the queue network model, based on the queuing theory is established to describe the operation process. The operational performances, such as the queue length, waiting time, and operation cycle for trucks is analyzed, and their accumulative effect along with time processes is analyzed.

（3） Since there are a lot of stochastic factors, a performance analysis on the whole system is implemented with a simulation model based on a discrete event system simulation. According to the simulation results, the bottlenecks are pointed out and improvements are proposed to construct a better planning scheme according to the trade-off analysis on the capacity of the resources and the operational cost.

Acknowledgements

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