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Simulation Model of a Rail-Road Container Terminal Described as a Queueing System

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Abstract

The subject of this study is a rail-road container terminal. The processes of the container handling and the downtime of the container trains and trucks in the terminal has been discussed in the study. The container terminal is considered as a M/M/n queueing system with incoming flow - the container trains and trucks. The container cranes in the terminal are the service facilities. The periods for loading and unloading of the container trains and trucks and additional handling of containers in the container yard have been considered in the study. A model of the container handling processes in the container terminal has been developed. The main technological options of container handling according to the type of container flow – import and export or transit and the type of handling - direct "train - truck" or vice versa or indirect "train - container yard - truck" or vice versa have been described in the model. The downtime of the container trains and trucks for loading and unloading in depend on the technological conditions of the terminal could be studied through the model. The downtime periods were calculated in the study considering the container flows, handling time of the containers, number of trains, number of handling equipment, duration of working time of the terminal, etc. The features and the influence of the studied parameters affect the downtime have been taken into account. The restrictions on the number of trains and the duration of the container terminal`s operation during the day have been determined through the results obtained in the study.
KEY WORDS: *Container terminal; Queueing system; Queueing theory; Container train*

1. Introduction

The rail-road container terminals are main elements of the intermodal transport system. They carry out the reloading of containers from container trains to road vehicles and vice versa. Yards of the container terminals provide the opportunity for temporary storage of containers. Container handling is performed according to the technology of the terminal and handling equipment [1]. In a various studies are considered issues related to the times of handling and downtime of the container trains and trucks in the container terminals.

The various container handling systems are used in the container terminals. In [2] the authors are described the main characteristics of in-terminal container handling systems. The main problems in the container terminals are crane scheduling and storage space allocation [3]. The effect factors of energy efficiency for container loading operations and develop a model to minimize the total handling time are analyzed by the authors in [4].

Studies of options for servicing trucks at the rail-road container terminal are published in [5, 6]. In the papers are presented the issues of container handling processes at a rail-road intermodal terminal. The purpose of authors is the assessment of the handling equipment utilization in the terminal and layout design of parking lots for external trucks.

The queueing theory [7, 8] is widely used to research and engineering different systems that could be represented as incoming requests serviced by devices. The main elements of queueing systems are incoming requests and service devices. The incoming requests enters the queueing system, where the requests are processed in service devices.

The different queueing systems are characterized by the type of incoming requests, queue discipline and service mechanism. The type of a queueing system could be described through Kendall's notation and classification of queueing systems developed by A. Lee [8, 9].

For determination of different technological, technical and financial parameters of container terminals – waiting time of container ships, trains and trucks, capacity of container yards, number of handling equipment, related costs, etc. could be used the queueing theory. Numerous studies related to the port container terminals, considered as a queueing system are described in the literature. Queueing theory has been used by the author in [10] to support the decision-making process by developing the container terminal infrastructure in the Alexandria seaport. The authors consider batch arrivals of containers at a port container yard that is modeled as a multi-server queue in [11]. In [12] the authors are used queueing theory for optimizing and decreasing the external trucks' waiting times, at the gate of the terminal and container yard, and the internal trucks' waiting times at the container yard.

The queueing theory is suitable for studying systems in which incoming requests are serviced by service devices. Handling processes in a rail-road container terminal are suitable for description and presentation through the principles of queue theory.

The purpose of the present study is to elaborate a model of the handling processes in a rail-road container terminal through applying the theory of queueing. The main technological and technical parameters related to the handling of containers and the downtime of the container trains and trucks in the terminal will be studied through the model.

2. Method of Research

The handling of the containers in a container terminal, according to the type of processing, could be divided into three technological groups:

Group 1 - handling of containers arriving and departing by container trains. This group includes the handling of containers in the terminal that are loaded onto or unloaded from container trains. Loading and unloading activities are performed in different periods of the terminal`s operation period during the day with a total duration T_R. The containers that are handled directly by the options "train – truck", "truck – train" and "train – train" or indirectly by the options "train – yard", "yard – train" and "train – yard – train" are included into this group.

Group 2 - handling of containers arriving and departing by trucks. This group includes the handling of containers in the terminal that are loaded onto or unloaded from trucks. Loading and unloading activities are performed in different periods of the terminal`s operation period during the day with a total duration T_T. The containers that are handled directly by the options "train – truck", "truck – train" and indirectly by the options "truck – yard" and "yard – truck" are included into this group. Direct handling of containers between the container trains and trucks takes place during different periods with a total duration $T_{T,1}\ \left(T_{T,1} \in T_R; T_{T,1} \in T_T; T_{T,1} \le T_R\right)$ and indirect handling during other periods with a total duration $T_{T,2}\ \left(T_{T,2} \in T_T\right)$. Some of the options are included in both of the groups – Group 1 and Group 2.

Group 3 – additional handling and repositioning of containers located on the container yard of the terminal. Loading and unloading activities are performed in different periods of the terminal`s operation period during the day with a total duration T_A.

When the containers in the container terminal are handled by one or several handling facilities, but it is done consistently during the periods $T_{T,2}$ and T_A, the minimum duration of terminal`s operation period during the day $\left(T_{CT}^{\min}, h\right)$ is given by:

$$T_{CT}^{min} = T_R + T_{T,2} + T_A,\ h, \tag{1}$$

where T_R − the total duration of the different periods during the day when loading and unloading activities with container trains are performed, h; $T_{T,2}$ − the total duration of the periods when indirect loading-unloading activities with trucks are performed, h; T_A − the total duration of the periods during the day when an additional (double) handling of the containers on the container yard is performed, h.

An additional handling of containers in the container yard and/or handling of trucks is performed during the periods when a container train (or a group of wagons) is moving on the freight track in the terminal before or after loading/unloading of containers. The average duration of the moving period of a container train (a group of wagons) on the railway freight track is T_{TM}. During this period loading and unloading of wagons is not able to be proceed. When the number of container trains $\left(N_{CT}\right)$ per a day has increased to values which the total duration of the periods for moving the wagons of all trains is $N_{CT}.T_{TM} > T_{T,2} + T_A$ the minimum duration of terminal`s operation period per a day T_{CT}^{min} is given by:

$$T_{CT}^{min} = T_R + N_{CT}.T_{TM},\ h, \tag{2}$$

where N_{CT} − the average number of container trains (groups of wagons) serviced in the terminal per a day, trains; T_{TM} − the average duration of a period for moving of a container train (a group of wagons) to/from railway freight track for loading/unloading, h/train.

The containers have to be handled in the terminal during a period with duration $T_{CT} \ge T_{CT}^{min}$ according restrictions:

$$\begin{cases} 0 < T_{CT} \le 24,\ h; \\ 0 < T_R \le T_{CT},\ h; \\ 0 < T_T \le T_{CT},\ h; \\ 0 \le T_A < T_{CT},\ h. \end{cases} \tag{3}$$

Restrictions for the number of the container trains (groups of wagons) are:

$$\begin{cases} N_{CT} \geq \dfrac{N_{WN}.K_W}{N_W}; \\ N_{CT} \geq 1, \qquad \qquad \textit{trains}; \\ N_{CT} \leq \dfrac{T_{CT} - T_R}{T_{TM}}, \end{cases} \tag{4}$$

where N_{WN} – the total number of wagons that are needed for transportation all containers handled at the terminal during the day, number; K_W – coefficient taking into account the presence of empty wagons in the container trains $(K_W \geq 1)$, coef.; N_W – the average number of wagons in a train, wagons.

When determining the minimum number of trains N_{CT} we are assumed that the trains for transit direct container traffic N_4 are situated simultaneous on the loading tracks in the terminal.

The main technological options for handling the containers during the terminal\`s operation period are shown in Table 1.

Table 1

Technological options for handling the containers

Technological option (TO)	**Description of the option**	**Technological group**	**Type of handling and container flow**	**Mode of transport**	**Total number of containers per a day**	**Average duration of a handling cycle, min**
TO-1	"Train – Truck" or "Truck – Train"	Group 1 and Group 2	Direct - Import and Export containers	Rail and Truck	N_1	T_1
TO-2	"Train – Yard" or "Yard – Train"	Group 1	Indirect - Import and Export containers	Rail	N_2	T_2
TO-3	"Truck – Yard" or "Yard – Truck"	Group 2	Indirect - Import and Export containers	Truck	$N_3 = N_2$	T_3
TO-4	"Train – Train"	Group 1	Direct – Transit containers	Rail	N_4	T_4
TO-5	"Train – Yard"	Group 1	Indirect – Transit containers	Rail	N_5	T_5
TO-6	"Yard – Train"	Group 1	Indirect – Transit containers	Rail	$N_6 = N_5$	T_6

The duration of the operating cycle $(T_1 \div T_6)$ for all technological options expressed the average period for executing one moving per one container.

The total duration of handling periods of the trains (T_R, h) and the trucks (T_T, h) in the terminal during the day could be calculated through:

$$T_R = \frac{\sum_{i=1,\,2,\,4}^{I} N_i.T_i}{60.N_{HE}.K_T}, h; \tag{5}$$

$$T_T = T_{T,1} + T_{T,2}, h; \tag{6}$$

$$T_{T,1} = \frac{N_1.T_1}{60.N_{HE}.K_T}, h. \tag{7}$$

In case of consecutive service of the trucks:

$$T_{T,2} = \frac{N_3.T_3}{60.K_T}, h. \tag{8}$$

In parallel service of trucks by more than one handling equipment $\left(N_{HE} \geq 2\right)$:

$$\frac{N_3.T_3}{60.N_{HE}.K_T} \leq T_{T,2} < \frac{N_3.T_3}{60.K_T},\ h, \tag{9}$$

where N_i − the average daily number of containers for a respective technological variant TO-1÷TO-6 $\left(i=1\div I\right)$, cont./day; T_i − the average duration of a handling cycle for a respective technological variant TO-1÷TO-6 $\left(i=1\div I\right)$, min; N_{HE} − number of handling equipment in the container terminal $\left(N_{HE} \geq 1\right)$, number; K_T − the coefficient taking into account the time of use of handling equipment during the daily operation`s period $\left(0 < K_T \leq 1\right)$, coef.; I − the number of the technological options $\left(I = 6\right)$.

In the case of direct handling "train – truck" and vice versa, the duration of the handling cycle T_1 is distributed equally between wagons and trucks.

The total duration of the period T_A is given by:

$$\frac{\sum_{i=2,5} N_i.K_{A,i}.N_{M,i}.T_{M,i}}{60.N_{HE}.K_T} \leq T_A \leq \frac{\sum_{i=2,5} N_i.K_{A,i}.N_{M,i}.T_{M,i}}{60.K_T},\ h, \tag{10}$$

where $K_{A,i}$ − the coefficient taking into account the part of the indirect containers by options TO-2 $\left(i=2\right)$ and TO-5 $\left(i=5\right)$, that are additionally handled in the yard of the terminal $\left(0 \leq K_{A,i} \leq 1, i = 2, 5\right)$, coef.; $N_{M,i}$ − the average number of moves in the yard for every indirect import, export and transit container handled by options TO-2 and TO-5, moves; $T_{M,i}$ − the average duration of one move in the yard of the terminal for indirect containers handled by options TO-2 and TO-5, min.

The container terminal is considered as a queueing system with Poisson distribution of incoming container flows transported by trains and trucks. The containers are served by one or more than one serving devices – handling facilities of the terminal. If the terminal is served by more than one handling equipment it is assumed that they are the same type and they are with the same productivity. The service period of the requests (incoming trains and trucks) is exponentially distributed. It is assumed the queueing system is without priority, without failure and with an unlimited queue.

The downtime of the container trains and trucks in the terminal in depends on the duration of the period for loading and unloading of containers and the waiting period in queue. The average downtime period of a train $\left(T_{TRAIN}, h\right)$ and a truck $\left(T_{TRUCK}, h\right)$ in terminal [13] is:

$$T_{TRAIN} = T_{TRAIN,1} + T_{TRAIN,2},\ h; \tag{11}$$

$$T_{TRUCK} = T_{TRUCK,1} + T_{TRUCK,2},\ h, \tag{12}$$

where $T_{TRAIN,1}$ − the average downtime period for a train loading and unloading in the terminal, h; $T_{TRAIN,2}$ − the average downtime period of a train in the queue until service of the train started (waiting in queue), h; $T_{TRUCK,1}$ − the average downtime period for loading or unloading of a truck, h; $T_{TRUCK,2}$ − the average downtime period of a truck in the queue until service of the truck started (waiting in queue), h.

The average handling duration of a container train or a group of wagons in the terminal during the day $T_{TRAIN,1}$ when the containers are served by N_{HE} loading machines that are the same type and are the same productivity [13] is:

$$T_{TRAIN,1} = \frac{T_R}{N_{CT}},\ \frac{h}{train}. \tag{13}$$

The average downtime period of a train in the queue is given [13] by:

$$T_{TRAIN,2} = \frac{\rho_R.T_{TRAIN,1}}{1-\rho_R},\ \frac{h}{train}, \tag{14}$$

where ρ_R − the average occupancy ratio from the container flows by rail in the terminal $\left(0 < \rho_R < 1\right)$, coef.

$$\rho_R = \frac{T_R}{T_{CT}}, coef \ . \quad (15)$$

The average handling duration of a truck in the terminal $T_{TRUCK,1}$ when the indirect export and import containers are handled is given by:

$$T_{TRUCK,1} = \frac{N_3.T_3}{60.N_T}, \frac{h}{truck}, \quad (16)$$

where N_T − the average daily number of trucks that are needed to transport the indirect import and export containers handling in the terminal, number.

When determining the period of downtime in the queue of a truck $T_{TRUCK,2}$, we consider the container terminal as a N_{HE} parallel service channel queueing system. Average waiting time of an arrival truck [13] is given by:

$$T_{TRUCK,2} = \frac{P.T_{TRUCK,1}}{N_{HE} - \rho_T}, \frac{h}{truck} \ . \quad (17)$$

Probability of having a truck to wait for service [13] is given by:

$$P = \frac{(\rho_T)^{N_{HE}}.P_0}{(N_{HE}-1)!.(N_{HE}-\rho_T)} . \quad (18)$$

The probability a handling equipment to be idle [13] is given by:

$$P_0 = \left(\sum_{i=0}^{N_{HE}-1} \frac{(\rho_T)^i}{i!} + \frac{(\rho_T)^{N_{HE}}}{(N_{HE}-1)!.(N_{HE}-\rho_T)} \right)^{-1}, \quad (19)$$

where ρ_T − the average occupancy ratio from the indirect container flows by trucks in the terminal, coef.

The value of ρ_T depends on pattern of arrivals of the trucks and opportunity to be used more than one handling equipment at the same time (parallel service of two or more trucks).

$$\frac{N_3.T_3}{60.N_{HE}.T_{CT}} \le \rho_T \le \frac{N_3.T_3}{60.T_{CT}}, coef \ . \quad (20)$$

The average occupancy of the system from trucks for a steady-state solution is given by $\frac{\rho_T}{N_{HE}} < 1$.

The average occupancy of the container terminal\`s system from additional (double) handling of the indirect containers in the yard ρ_A $(0 \le \rho_A < 1)$ is given by:

$$\rho_A = \frac{T_A}{T_{TC}}, coef \ . \quad (21)$$

To be the container terminal\`s system in a steady-state $\rho_R + \rho_T + \rho_A < 1$.

3. Results and Discussion

A numerical experiment was performed according to the proposed simulation model. The research was conducted for handling of 20-foot export and import containers in the terminal. Containers are handled at the terminal by two cranes. On one 60-foot wagon it is possible to be placed up to 3 containers.

The basic assumptions for the research are shown in Table 2.

Table 2

Assumptions for the research

Parameter	Value	Dimension	Parameter	Value	Dimension
N_1	50	cont./day	T_1	4	min
N_2	100	cont./day	T_2	5	min
N_3	100	cont./day	T_3	4	min
N_4	0	cont./day	T_4	5	min
N_5	40	cont./day	T_5	5	min
N_6	40	cont./day	T_6	4	min
K_T	0,9	coef.	N_W	15	wagons/train
K_W	1,1	coef.	T_{TM}	20	min

The values of the period $T_{T,2}$ and occupancy ρ_T are determined as an average value between maximum and minimum value calculated through Eq. (9) and Eq. (20).

The results of the conducted numerical experiment are shown in Figs. 1-4.

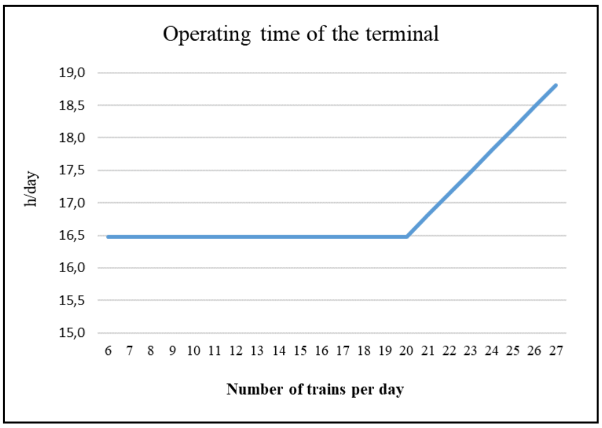

Fig. 1 Operating time of the terminal

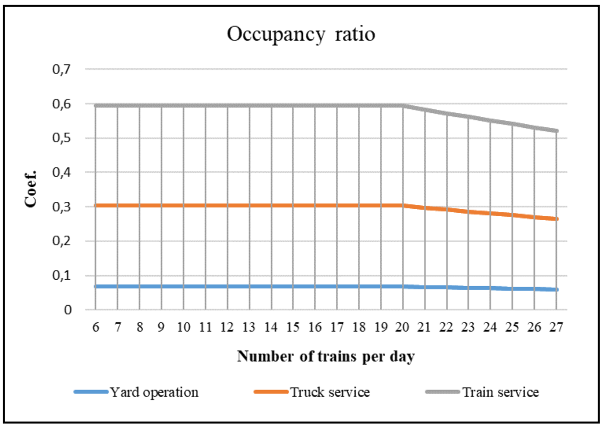

Fig. 2 Occupancy ratio

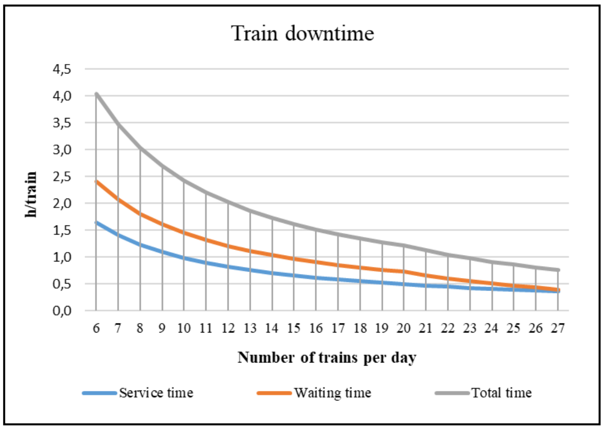

Fig. 3 Train downtime

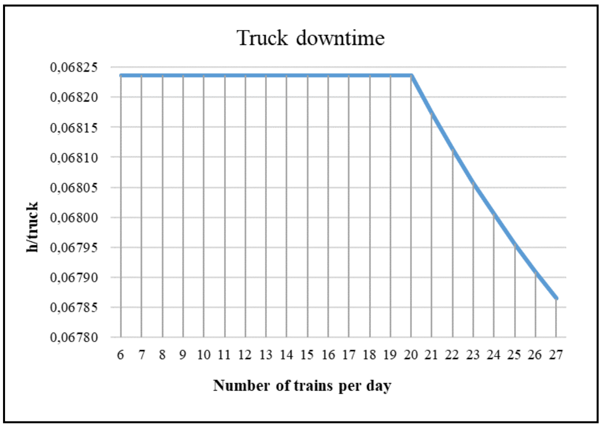

Fig. 4 Truck downtime

The results show that if the number of the container trains in the terminal increase above 20 trains per day, it is necessary to be increased the terminal`s operation period. At least six trains per day are required for transportation of the daily container turnover. An interval up to 27 container trains (groups of wagons) served in the terminal per a day was studied. The minimum operating time of the terminal is shown in Fig. 1. The maximum downtime in the terminal of a train varies between 240 and 48 minutes (Fig. 3). The results show (Fig. 4) a small impact of the number of trains on the truck`s downtime period, when the number of trains increases over 20 trains per a day.

4. Conclusions

In the study has described an improved model of a rail-road container terminal, which is considered as a queueing system type M/M/n. The model reflects the processes of loading and unloading of the container trains and trucks, taking into account the system occupancy from the additional (double) operations with the containers that are stored in the yard of the container terminal. Incoming requests are the container trains and trucks, and service devices are the handling facilities (container cranes).

The main characteristics of the container terminals related to the loading and unloading processes - container turnover of the terminal, number of handling equipment, technological options for handling of containers, number of container trains, duration of operating cycles, duration of the technological period for double operations, etc. are described in the model.

The model allows to be studied the processes related to handling of the containers, to determine the expected periods of waiting and service of the container trains and trucks and to determine the required duration of operation period of the terminal. The trains downtime in the terminal is one of the main parameters related to the organization of the timetable of the container trains.

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