Optimal Planning on Gate System on Container Terminals Based on Simulation Optimization Method and Case Study

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Abstract: A simulation optimization method is presented to realize the optimal planning on the gate system on container terminals. At first, the formulation of mathematical programming model is established including the planning objectives and constraints according to the analysis on the operation requirement of the gate system. The optimal objective is to minimize the total cost of construction and ensure the desired operation efficiency. Then, considering the uncertain and stochastic activities in the system, the discrete-event system simulation model is built. To solve the optimal planning problem, the requirement for optimization algorithm suit for the simulation model is discussed and the approach of simulation optimization is presented. The optimization method is presented that combines genetic algorithm with the discrete-event system simulation model of the gate system. At last, an actual case is analyzed to illustrate the validity and effectiveness. The results from simulation optimization method are compared with traditional planning method and the advantage of this method is shown. Moreover, the sensitivity of this planning result is analyzed.

Keywords: Gate system, Genetic algorithm, Simulation modeling, Simulation optimization, System planning,

1. Introduction

The gate system on container terminals is the operation channel for trucks to carry containers to move into or out of the container yard. With the rapid development of maritime logistics, the demand of improving the operation performance of the gate system of container terminals is becoming higher and higher. If the planning on the configuration of gate system, such as the number of truck lanes, is unreasonable, the congestion by trucks’ waiting and queuing outside the terminal gate becomes quite serious in the rush hours, and it will influence the whole service performance of the container terminal. Therefore, it is necessary to carry out the feasible planning on the terminal gate. But as the ratio of construction cost of terminal gates to that of the whole port is far lower, and as the bad operation performance of the gate system does not bring the direct punishment charges, the planning on the terminal gate system has been not considered much. So far, researches on planning of container terminals focused mainly on the berth and yard, while the gate system is only researched as an accessorial part of them. Legato and Mazza (2001) described processes of vessels at a container terminal and the berth planning system, presented the simulation approach with SLAM \(^1\). Nishimura, Imai, and Papadimitriou (2001) addressed the problem of a dynamic planning on ships, described the model formulation and solution procedure using the genetic algorithm (GA) \(^2\). Kim, Lee and Hwang (2003) considered the problems of delivery of container, proposed a dynamic programming model and a learning-based method according to static sequencing problem and dynamic situation \(^3\). Sgouridis, Angelides (2003) focused on the handling of incoming containers transported on trucks and simulated the system \(^4\). Jansen, Swinkels and et al (2004) described the planning system that performed the automatic planning of transport orders on trains and trucks in Germany \(^5\).

Actually, the performance of the gate system plays an important role in enhancement of service quality of ports. An optimal planning on the gate system of the container terminal will not only cut down construction cost but also reduce the service time for customers.

This paper presents the optimal planning on the gate system based on simulation optimization method. Section 2 establishes the mathematical programming model of the gate system planning. Section 3 describes the system simulation model. Section 4 presents the methodology of simulation optimization. Section 5 analyzes an actual case to illustrate the proposed method.

2. Formulation of optimization model

2.1 Operation flow of gate system

The layout and the operation flow on the terminal gate system are shown in Fig.1. When a loaded truck arrives at the gate system, if there is at least one entrance lane that is idle, the truck enters the lane and receives the service operation from the gate system; if all entrance lanes are busy, the truck has to wait in queue until one lane becomes idle. Then, the truck moves to the container yard, where the containers on truck are unloaded. After this, the unloaded truck returns to the exit lanes, where receives service operation, departs from the exit lanes, and leaves the port.

The operation process of unloaded trucks is nearly the same as that of loaded trucks, but the difference is that containers is loaded onto the truck on the container yard, then the truck becomes loaded and leaves the port.

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2.2 Definition of model parameters

- \( n_1 \): the number of entrance lanes.
- \( n_2 \): the number of exit lanes.
- \( N \): the number of total lanes, \( N = n_1 + n_2 \).
- \( C_1, C_2 \): the total investment cost of one entrance lane and exit lane, respectively. The cost mainly includes the investment of construction, communication facilities and other auxiliary facilities.

The factor we consider mostly that influences the service efficiency of a gate lane is the service time of a truck in a gate lane. Suppose:

- \( f_1(t) \) and \( f_2(t) \): the distribution functions of service time at an entrance lane for loaded trucks and unloaded trucks, respectively.
- \( f_3(t) \): the distribution function of service time at exit lanes of loaded trucks and empty trucks. It is assumed that the service time at exit lanes for all trucks is the same.

\( a, b, c \): the expected values of distribution functions \( f_1(t), f_2(t), \) and \( f_3(t) \), respectively, which denote different service efficiency for three kinds of services of lanes.

2.3 Objective function

The aim of planning on the terminal gate system is to minimize the overall investment cost of the terminal gate by determining the number and service efficiency of entrance lanes and exit lanes, which is on the preconditions of satisfied the operations requirement of the terminal gate.

The decision variables constitute a decision vector \( X \) that is shown in equation (1).

\[
X = (x_1, x_2, x_3, x_4, x_5)
\]

Where, \( x_1 = n_1, x_2 = n_2, x_3 = a, x_4 = b, x_5 = c; x_i \in [1, m_i], i \) is an integer from 1 to 5, and \( m_i \) is the upper bound value for \( x_i \).

The objective function of the gate system planning \( f(X) \) is shown in formula (2).

\[
\min f(X) = C_1 x_1 + C_2 x_2
\]

2.4 Constraints

Constraint conditions are described as follows.

(1) The annual throughout of gate \( Q \) is equal to expected quantity \( Q_0 \) of berth operation.

\[
Q = Q_0
\]

(2) The utilization rates of entrance lanes and exit lanes are denoted as \( \rho_1, \rho_2 \), respectively. \( \rho_1 \) and \( \rho_2 \) are fall in the range of \( [\rho_{\text{min}}, \rho_{\text{max}}] \).

\[
\rho_{\text{min}} \leq \rho_1 \leq \rho_{\text{max}}
\]

\[
\rho_{\text{min}} \leq \rho_2 \leq \rho_{\text{max}}
\]

(3) The permitted maximum number of lanes for the gate system is \( N_m \).

\[
2 \leq x_1 + x_2 \leq N_m
\]

\[
1 \leq x_1 \leq N_m, 1 \leq x_2 \leq N_m
\]

(4) The relationship between single-lane’s investment cost and the lane’s service efficiency is expressed in equations (7) and (8).

\[
f = g(x_3, x_4)
\]

\[
f = h(x_5)
\]

Where, \( g \) is the function that computes the investment cost of single entrance lane, which has a relationship with \( x_3 \) and \( x_4 \). Similarly, \( h \) is the function that denotes the relationship between investment cost of single exit lane and its service efficiency \( x_5 \).

Therefore, the formulation of the optimization model is composed of the objective function by equation (2) and the constraint functions by formulas (3)-(8). The operation process of terminal gate system is a typical discrete event dynamic system, in which there are many random, uncertain factors, such as the trucks arrival, the service time of gate lanes, and so on. For such a dynamic complex system, as it is hard to describe and analyze with analytic model, so the simulation model based on discrete event dynamic system is suitable for this purpose. Shabayek (2002), Kia (2005) presented their application of a simulation model to ports, respectively. In section 3, the simulation model for gate system is described.

The solution to this optimization model is attributed to a combination optimization problem whose state space of solutions is \( \prod_{i=1}^{5} m_i \), according to its decision vector listed in equation (1), and the combination quantity increases in exponential tendency with the increasing of the \( m_i \). At the same time, in this problem, as the complex simulation model is used that the difference of the objective function does not exit, so it is necessary to find an effective search method suit for this feature. In order to solve the optimization problem like this, the approach of simulation optimization is proposed in section 4.

3. Simulation model

The operation process of the terminal gate system is attributed to a dynamic multi-classes queuing process. So, the simulation model based on the queuing theory is established as shown in Fig.2.
The main factors are described as follows.

1. Arrival process. The arrivals of unloaded and loaded trucks are regarded as the random process, and the probable distributions are used.

2. Queuing rule. The service rule is FIFO for three queues. If the service station is busy, customers will wait in the queue until the station becomes idle.

3. Service process. The entrance lanes, container yard and exit lanes are regarded as multi-class service stations with multi-server units. Each service unit deals with one customer at a time, and the service time is random.

When a truck reaches the entrance lanes (as first-class service station), if the entrance lane of gate system is idle, it will receive the service; and if the entrance lane is busy, it has to wait in a waiting Queue 1 as shown in Fig. 2. After the service has finished, the truck moves to the yard (as second-class service station) to load and unload containers. Then, it returns to the exit lane, if the lane is idle, the truck moves into the gate and receives service; otherwise it has to wait in a waiting Queue 3 in Fig.2. Finally, the truck departs from the terminal gate and finishes all activities in the system.

The following factors are also considered.

1. The operation time per workday is $T_w$;
2. The annual operation days are $T_{op}$;
3. All the quantity of containers on berth side is equal to the quantity of terminal gate side;
4. It is assumed that the service time for loaded trucks is the same as unloaded trucks at the exit lane.

4. Methodology of simulation optimization

The methodology of simulation optimization is a kind of optimization technology combining with simulation. The relationship among optimization algorithm, decision vector or variables, and simulation model is shown in Fig. 3. The decision variables of optimized problem serve as the input parameters of simulation model. The optimization procedure uses the outputs from the simulation model to evaluate the inputs to the model, and analyzes this evaluation and previous evaluations. And then, the optimization algorithm selects a new set of input values. The process continues until it meets some termination criterion, then the outputs of optimization algorithm are the optimal solutions of this optimization problem. It is easier for this technology to solve the problem of combination optimization with large numbers of stochastic parameters. Kochel, Nieland (2005) presented that the simulation optimization was applied to define optimal policies in very general multi-echelon inventory systems and an example illustrated the usability of the approach [8]. Angelis, Felici, and et al (2003) presented the simulation optimization methodology to plan the configuration of the services and facilities in complex health care systems by minimizing the average server time [9]. Jin, Ren, Higuchi, and et al (1999) used the simulation optimization technology to plan berths facilities on container terminals [10][11]. Paul and Chanev (1998) applied GA to the problem of optimizing an existing simulation model [12].

We use the simulation optimization method to plan the terminal gate system, following the approach as shown in Fig. 3. Here, genetic algorithm (GA) is adopted as the optimization algorithm that conducts the optimal solution without evaluating all possible solutions. GA changes the combinations of values of the decision variables of $X = (x_1, x_2, x_3, x_4, x_5)$ directly that provides the most desirable $f(X)$ from the simulation model. The result of a simulation run returns to the model, and it decides what new parameter changes to enhance performance. The performance measure is $f(X)$. The expected value of the objective function $f(X)$ is estimated by the model’s simulation output over multiple replications.

From the view of the simulation, the simulation optimization problem for the optimal planning shown in equation (2) is transferred into the following expression (9).

$$\text{Min}[E[f(X)]]$$  \hspace{1cm} (9)

Where, $E[f(X)]$ denotes the expected value of the objective function. The outputs of GA, when the simulation cycle is over, are the optimal solution of this decision-making problem, from which we can obtain the optimal values of decision vector $X$. 

![Fig.2 Simulation model based on queuing theory](Image)

![Fig.3 Methodology of Simulation optimization](Image)
5. Case study

5.1 System description and main parameters

An actual case is studied to illustrate the effectiveness and feasibility of our method. The terminal gate system of the container terminal is in northern China. The main parameters of this gate system are shown in Tab.1.

According to the statistical analysis of historical data, the different distributions of external operation factors are determined. The distribution of annual quantity of container arrivals is shown in Fig.4 with TEUs per month during one year. It is known from Fig.4 that the peak occurs in August. And the distribution of container TEUs per day during August is shown in Fig.5. The distribution of loaded and unloaded trucks arrival at the gate during one day is shown in Fig.6 with truck arrival numbers to hour, respectively. In this simulation model, empirical distributions are used for these external factors.

The different service distributions $f_1(t), f_2(t), f_3(t)$ of truck service time in the gate follow Normal distribution shown in Tab.2. Here, $\mu$ is the mean value, and $\sigma$ is the standard variance. The values range within $[\mu - 3\sigma, \mu + 3\sigma]$.

The empirical distribution of operation time for a truck at the container yard is expressed as follows.

$$f_4(t) = \text{DISC}((0.9, 9), (0.95, 21), (0.99, 36), (1, 60))$$  \hspace{1cm} (10)

Where, $f_4(t)$ includes four double groups, for each double group, the first one is the cumulated percentage, the second one is the mean operation time. For example, $(0.95, 21)$ indicates that the probability of mean operation time of 21 minutes is 5 percent ($0.95 - 0.9 = 0.05$).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_n$ (10^3 TEU)</td>
<td>3000</td>
<td>$L_{max1}$ (number)</td>
<td>5</td>
</tr>
<tr>
<td>$N_m$ (lane)</td>
<td>20</td>
<td>$L_{max3}$ (number)</td>
<td>5</td>
</tr>
<tr>
<td>$\rho_{min}$ (%)</td>
<td>20</td>
<td>$W_{T_{max1}}$ (min)</td>
<td>5</td>
</tr>
<tr>
<td>$\rho_{max}$ (%)</td>
<td>90</td>
<td>$W_{T_{max2}}$ (min)</td>
<td>5</td>
</tr>
<tr>
<td>$C_1(10^3 \text{RMB})$</td>
<td>1450</td>
<td>$T_d$ (hour)</td>
<td>24</td>
</tr>
<tr>
<td>$C_2(10^3 \text{RMB})$</td>
<td>1150</td>
<td>$T_{d}$ (day)</td>
<td>360</td>
</tr>
</tbody>
</table>

5.2 Model validation

For this case, the simulation model is realized with visual simulation software Arena. To validate this model, the results from simulation model are compared with actual operation data in one day as shown in Fig.7. And it indicates that this simulation model is valid.
5.3 Results and analysis

The function of simulation optimization for this model is realized with OptQuest as an optimization tool in Arena.

For the simulation execution, the simulation length is 8640 hours (the number of hours in one year), and the number of replications per simulation is 6 to 10, this is the number of times that the model will be run in every simulation, and the “inferior solution” test constructs a 95% confidence interval.

The optimal solution of the terminal gate system planning is shown as follows.

\[ X^* = (8, 6, 40, 30, 20) \]  

From expression (11), the number of entrance lanes is \( x_1 = 8 \), and that of exit lanes is \( x_2 = 6 \), respectively.

In traditional planning method, the following expression (12) is used.

\[ N = \frac{Q}{(1 - K_b)K_{bv}} \]  

Where, \( K_b \) is the percentage of marine operation quantity and railroad operation quantity, \( K_{bv} \) is the imbalance coefficient of container vehicles arrival at the container terminal, \( P_d \) is the number of trucks per hour through a single lane, \( q_c \) is the average number of container loaded for one truck, \( T_{yd} \) is annual workdays, and \( T_d \) is the operation time in one day of gate lanes.

In this case, \( K_b \) is equal to 33%, \( K_{bv} \) is 2.5, \( T_{yd} \) is 360 days, \( T_d \) is 12 hours, \( P_d \) is 40 vehicles/hour, and \( q_c \) is 1.45. With expression (12), the number of entrance lanes is \( n_1 = 10 \), and that of exit lanes is \( n_2 = 10 \), respectively.

The comparison of results from the optimal solution (Method A) with the results from the traditional planning method (Method B) is shown in Tab.3.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Method A</th>
<th>Method B</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of lanes</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Number of exit lanes</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Total cost</td>
<td>18500</td>
<td>26000</td>
<td>10^7 RMB</td>
</tr>
<tr>
<td>Average cycle time of trucks</td>
<td>26.8</td>
<td>24.0</td>
<td>minute</td>
</tr>
<tr>
<td>Utilization rate</td>
<td>Aver. 23.1</td>
<td>12.7</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Max. 100.0</td>
<td>90.0</td>
<td>%</td>
</tr>
<tr>
<td>Waiting time</td>
<td>Aver. 13.2</td>
<td>10.7</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Max. 100.0</td>
<td>90.0</td>
<td>%</td>
</tr>
<tr>
<td>Queue1 Waiting time</td>
<td>Aver. 1.2</td>
<td>0.0</td>
<td>minute</td>
</tr>
<tr>
<td></td>
<td>Max. 3.0</td>
<td>0.0</td>
<td>minute</td>
</tr>
<tr>
<td></td>
<td>Aver. 1.5</td>
<td>0.0</td>
<td>minute</td>
</tr>
<tr>
<td></td>
<td>Max. 3.5</td>
<td>0.0</td>
<td>minute</td>
</tr>
<tr>
<td></td>
<td>Aver. 0.15</td>
<td>0.0</td>
<td>minute</td>
</tr>
<tr>
<td>Length of queue</td>
<td>Max. 4.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aver. 0.2</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max. 2.0</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

From Fig.8, it is clear that the average waiting time of trucks decreases with lanes increasing. It is found that both the number of gate lanes and the service efficiency influence the average waiting time, but the number of lanes has a much greater impact than the service efficiency of lanes.

5.4 Sensitivity analysis

The sensitivity of the optimal solution from simulation optimization method to the variable throughput \( Q_n \) of terminal gate system is analyzed when \( Q_n \) is varying in the range of ±20%. The varying process of the optimal solution is shown in Fig.9.

From Fig.9, it is known that when \( Q_n \) increases or decreases by 10%, the entrance gate lanes should increase or decrease one lane, correspondingly, while \( Q_n \) increases or decreases by 20%, the exit gate lanes should increase or decrease one lane, correspondingly.
6. Conclusions

We have presented the optimal planning of gate system on container terminals with the simulation optimization method. The conclusions are summarized as follows:

At first, the mathematical programming model is established for the optimal planning on the terminal gate system. With this model, the decision variables, objective function and constraints are formulated.

Secondly, this optimization problem is involved with two key problems: system modeling and optimization method. For the system modeling, as there are uncertain and stochastic activities in the terminal gate system, the discrete-event system simulation model for the multi-class queuing process is built. For the optimization method, we propose a simulation optimization method that combines genetic algorithm with this simulation model.

Thirdly, a case study is presented to verify the validity and effectiveness of proposed method. The results show that it is available and feasible to determine the optimal planning of terminal gate system. By comparing the optimal results with the traditional one, the advantage of this method is represented.

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References