Layout Optimization of Yard Template Plan Considering Vessels’ Operational Time Requirements

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Abstract. In order to solve the problem of delayed departure of vessels in container ports and improve the efficiency of yard operation, a mathematical programming model of yard template planning based on vessels’ operation time was proposed to optimize the number of vessels loading points and put the operation time of vessels into constraints to avoid delayed departure of vessel. At the same time, transportation distance is put into the objective function to minimize transportation cost of containers. The numerical experiments are designed, which is solved by CPLEX solver to verify the validity of the model. The experimental results show that the mathematical model can deal with the problem of delayed departure of vessel.

1. Introduction

The scale of container transportation continues to expand, Driven by international trade activities and international multimodal transport. According to the forecast report of Drewry, the throughput of global ports will reach 943 million TEUs by 2023. The rapid growth of containers has deepened the contradiction between it and the land resources of terminal operations. Therefore, it is an emergency to improve the efficiency of port operations and accelerate the flow of port materials.

In recent years, the bottleneck of the container terminal has been transferred to the yard, and it is often seen that the container trucks are crowded on different channels of yard during peak operations and the seaside operation equipment is waiting for loading or unloading container. The situation that makes the vessels’ operation time in the port prolonged and cannot depart from port terminal on time. What’s worse, some unnecessary losses are caused, so yard management plays an important role in improving the operational efficiency of the port. The yard template planning is applied to the port to allocate storage space for vessels, which adopts the consignment strategy [1-3] to reserve the sub-blocks for vessels to meet their demand. The yard template planning determines the allocation of the sub-blocks, which can significantly reduce the shuffle of containers, the turnaround time of the vessels in the port and the invalid movement of the yard cranes [4]. The yard template planning not only determines the transportation distance of the containers, but also influences the traffic situation of yard.

The phenomenon of delayed departure of container vessel means that the vessel cannot complete the loading or unloading operations within its specified time, and departs later than the planned departure time. While this problem limits the efficiency of port operation, it also leads to a lot of consequences. In the yard, it may create conflicts of operation between adjacent sub-blocks and increase fright flow at pass lane aggravating traffic congestion. In the seaside, quay crane resources have been occupied, affecting the adjacent berths and subsequent berthing operations. In order to deal with the phenomenon of delayed departure of vessel, not only the spatial dimension of task allocation
should be considered, but also the time dimension of vessels operation should be added when generating the yard template planning. As the operation time demand of vessels and the number of loading points in block are mutually influenced. To a certain extent, it affects the traffic of the yard. Therefore, it is necessary to optimize the yard template planning by considering the operation time demand of vessels.

At present, there are many literatures about the optimal operation of container ports [5-7], such as berth allocation [8], optimization of truck routes [9], yard crane configuration and schedule [10], and yard space allocation [11-13]. Yard management has always been a key management point of container terminals. Especially for resource-constrained ports, yard management efficiency is particularly prominent. Carlo et al [14] provided a comprehensive overview of yard management in the study. Dekker et al [15] studied different stack storage strategies for automated blocks under the consideration of task balance to promote optimization of storage space, improving utilization and reduce shuffle. Moorthy and Teo [16] put forward a yard template concept when they made container terminal berth planning, and applied the template to yard management. Jiang et al [17] first proposed the concept of "sharing space "for consideration of the scarcity of space resources. Adjacent sub-blocks could take part of the space for mutual use, which alleviated the contradiction between land resources and the number of containers. On basis of "sharing space ", Zhen [18] considered vessels' fluctuation demand situation, studying the yard template planning. The minimum comprehensive cost of containers was for the main goal and yard traffic congestion was taken into mathematical programming model. Heuristic algorithm was designed to demonstrate the effectiveness of the model. Zhen [19] proposed considering reducing trucks transportation distance the mixed integer programming model. Arrival vessels was seen a sequence to get the initial yard template planning. Then he proposed an effective algorithm to improve the quality of the scheme. Woo and Kim [20] discussed the impact of space demand of export containers on loading and unloading efficiency, and proposed to consider not only the total space demand of vessels but also the impact of demand fluctuations on space allocation. He thought reserved space for vessels according to the arrival pattern of vessels and the number of containers. Tan et al [21] proposed a flexible yard template planning based on the yard operation bottleneck management, breaking through the limitations of the previous fixed yard template. Flexible template meant that the size of each sub-block was no longer a uniform fixed size that changes according to the storage demand of vessels. The mathematical model of space allocation could greatly improve the efficiency of space utilization and reduce the volume of overflowing containers in the yard.

There have been a lot of relevant studies about storage space allocation, such as considering the uncertain environment, the scarce resource and space storage strategy and so on. They minimize the storage space to meet the container vessel needs and improve the yard space utilization. There are also many researchers who take the traffic condition of the yard into consideration in the yard template planning to solve the yard bottleneck problem, while the study on optimizing the yard template planning considering the operation time requirement of the vessels in the port is relatively weak. This paper mainly studies the operation time requirements of vessels, generates the yard template planning, and optimizes the number of loading points in block to deal with the problem of delayed departure of vessel.

2. Problem Description
Consignment strategy where containers in the same sub-block will be loaded to the same vessel, is applied in the yard template planning to allocate sub-blocks for vessels. The yard template planning divided yard into many blocks that contains the four or five sub-blocks, and considers vessels' preferred berths and arrival laws. Nowadays, the main bottleneck of port operation has turned to the yard. The traffic condition of the yard affects the operation of containers. In serious cases, vessels cannot complete the loading or unloading operation as planned, causing the delay departure of vessel. So as to alleviate the problem of delayed departure of vessel and improve the service efficiency of the yard, when making the yard template planning, the impact of the operation time requirements of
vessels in the port is taken into account, and a reasonable number of storage sub-blocks and loading points in blocks should be allocated for arrival vessels.

![Figure 1. Illustration of the loading points of vessel](image)

In the storage yard template planning, the number of loading points determines the vessel's turnover time in the port, which affects the efficiency and service quality. As shown in figure 1, vessel and vessel 2 have the same amount of containers, but different operating time requirements. Four loading points is allocated for vessel 1, while six loading points for vessel 2. The number of reserved sub-blocks and loading points can be allocated to vessels according to the operation time requirements of vessels, which can optimize the yard template planning and improve the service efficiency of ports.

In this paper, the yard template planning is implemented based on the sharing strategy. Jiang [17] first pointed out that the storage space (such as sub-block) allocated to vessels would no longer be fully reserved, a part of the sub-block would be shared with its adjacent sub-blocks in certain periods, which could greatly improve the utilization efficiency of the yard.

Based on this strategy, this paper will allocate the storage space for vessels visiting port periodicity. Considering the size of the container volume of vessels and the arrival law, to a large extent, it will allocate adjacent sub-blocks to the vessels that can share space with each other.

3. Yard Template Model Formulation

As for the model establishment, this paper refers to the practice of Yu et al [22] and He et al [23]. Yu et al proposed the concept of loading clusters in the blocks, and He et al proposed a modeling method about resilient yard template. On basis of them, the mathematical model of yard template planning is presented as follows:

3.1. Assumptions

The model is formulated based on the following assumptions: (1) Vessels’ arrival time, departure time, storage demand, berth plan and quay crane scheduling plan are known; (2) The storage capacity of each block of the yard, and the number of available yard crane in each period are known; (3) Only export containers and transit containers are considered, not import containers. (4) Within the same time period, a yard crane can only serve one block, and once occupied, it cannot be assigned to other blocks;
(5) The vessel will depart from the port immediately after loading or unloading; (6) There is only one yard crane for loading operation in one block.

3.2. Set Definitions

$R$: the set of all lanes in the yard, the index is $r$. $B$: the set of all blocks in the yard, the index is $b$. $V$: the set of all vessels visiting port periodicity, the index is $v$. $SB$: the set of all sub-blocks in the yard, the index is $s$. $T$: the set of all time steps in the planning horizon, the index is $t$. $N$: the set of all adjacent sub-block ($s$), the index is $s'$. $N_b$: the set of sub-block of block ($b$). $R$: the set of blocks using lane $r$.

3.3. Parameter Definition

$a_v$: plan arrival time of vessel $v$. $d_v$: plan departure time of vessel $v$. $G$: maximum number of trucks that can simultaneously pass lane $r$. $o_v$: handing parameter of vessel $v$ at step $t$. Set to 1, if step $t$ is in the handling time window of vessel $v$; and set to 0, otherwise. $N_s$: the number of containers of vessel $v$. $Q$: the number of quay cranes assigned to vessel $v$. $p_v$: the capacity of each yard crane (teus/t). $\theta$: the maximum number of yard cranes that can simultaneously operate in one block. $\mu^{min}_v$: the maximum coefficient of yard cranes to meet quay cranes assigned to vessel $v$. $\mu^{min}_v$: the minimum coefficient of yard cranes to meet quay cranes assigned to vessel $v$. $CP$: the capacity of each sub-block ($s$). $\lambda$: the sharing space coefficient of all sub-blocks, and $\lambda \in [0,1]$. $l_v$: the distance from sub-block ($s$) to operation berth of vessel $v$. $CC_v$: the unit transportation cost of per container of vessel $v$. $Y$: The total number of yard cranes. $M$: a big positive number.

3.4. Decision Definitions

$x_v$: set to 1, if sub-block ($s$) is allocated to vessel $v$, and set to 0 otherwise. $c_v$: the complete time of vessel $v$. $TD$: the total delayed time of vessel $v$. $K_v$: the number of containers vessel $v$ that allocate to sub-block ($s$). $z_v$: loading point of vessel $v$ in block ($b$); set to 1, if sub-block ($s$) in block ($b$) is reserved for vessel $v$; set to 0, otherwise.

3.5. Mathematical Model

Objective: 

$$\text{min } f = CC_v \sum_{s \in SB} x_v l_v CP_v$$  \hspace{1cm} (1)

Subject to:

$$\sum_{s \in SB} x_v \leq 1, \quad \forall s \in SB$$  \hspace{1cm} (2)

$$\sum_{s \in SB} x_v CP_v (1+\lambda) \geq N_s, \quad \forall v \in V$$  \hspace{1cm} (3)

$$K_v \leq CP_v (1+\lambda), \quad \forall v \in V, s \in SB$$  \hspace{1cm} (4)

$$K_v \geq N_s, \quad \forall v \in V$$  \hspace{1cm} (5)

$$\sum_{v \in V} x_v o_v \leq \theta, \quad \forall t \in T, b \in B$$  \hspace{1cm} (6)

$$\sum_{b \in B} \sum_{t \in T} z_v o_v \leq G_r, \quad \forall t \in T, r \in G$$  \hspace{1cm} (7)

$$M(1-\sum_{v \in V} x_v o_v) \geq \sum_{v \in V} \sum_{s \in SB} x_v o_v CP_v \quad \forall s \in SB, t \in T$$  \hspace{1cm} (8)

$$\sum_{b \in B} z_v \geq Q_v \mu^{min}_v, \quad \forall v \in V$$  \hspace{1cm} (9)
\[ \sum_{i=0}^{d} z_{iv} \leq Q \cdot \mu_v^{\text{min}}, \quad \forall v \in V \]  

\[ \sum_{i=0}^{d} \sum_{j=0}^{d} z_{ijv} \leq YC, \quad \forall t \in T \]  

\[ TD_v \geq C_v - d_v, \quad \forall v \in V \]  

\[ C_v \geq o_v t, \quad \forall v \in V, t \in T \]  

\[ \sum_{i=0}^{d} z_{iv} \cdot \sum_{j=0}^{d} \alpha_{ij} \geq N_v, \quad \forall v \in V \]  

\[ K_v = \frac{N_v}{\sum_{i=0}^{d} z_{iv}}, \quad \forall v \in V, s \in SB \]  

\[ \sum_{i=0}^{d} x_{iv} \geq z_{iv}, \quad \forall v \in V, \quad b \in B \]  

\[ \sum_{i=0}^{d} x_{iv} \leq z_{iv} M, \quad \forall v \in V, \quad b \in B \]  

\[ K_v \geq x_v, \quad \forall v \in V, s \in SB \]  

\[ K_v \leq M x_v, \quad \forall v \in V, s \in SB \]  

\[ x_v \in \{0,1\}, \quad \forall v \in V, s \in SB \]  

\[ K_v \geq 0, \quad \forall v \in V, s \in SB \]  

\[ z_{vb} \in \{0,1\}, \quad \forall v \in V, b \in B \]  

Equation (1) is the objective function and represents the cost of transportation. Constraint (2) means that a sub-block in the yard can only be allocated to one vessel. Constraint (3) means that the sub-blocks assigned to each vessel should meet its storage demands. Constraint (4) means that the containers in each sub-block shall not exceed its maximum capacity. Constraint (5) ensures that the number of containers allocated to resaved sub-blocks of one vessel equals to its storage demand. Constraint (6) means that the number of sub-block operating simultaneously in each block shall not exceed its maximum number of yard cranes. Constraint (7) represents the traffic flow limitation among the blocks of the yard, in order to avoid road traffic congestion. Constraint (8) ensures that operation conflicts in adjacent sub-blocks are avoided. Constraints (9) and (10) respectively ensure that the number of yard cranes in shall meet the minimum and maximum number of demands required by the quay cranes. Constraint (11) means that the number of yard cranes in each period shall not exceed the number of available yard cranes. Constraint (12) represents the calculation of the total time of delayed vessel departure. Constraint (13) represents the relationship between the completion time of the vessel and the operation time. Constraint (14) means that the yard cranes must meet the total operation demand of a vessel. Constraint (15) means that the containers of each vessel are evenly distributed in the reserved sub-blocks to ensure the balance of operation in the yard. Constraints (16) and (17) represent the logical relationship between \( x_v \) and \( z_{iv} \). Constraints (18) and (19) represent the logical relationship between \( x_v \) and \( K_v \). Constraints (20) to (22) respectively represent the range of \( x_v \), \( K_v \), and \( z_{vb} \).

In the above constraints, equation (15) contains a nonlinear expression \( \sqrt{\sum_{i=0}^{d} x_{iv}} \). In order to facilitate the linearization of the solution, the nonlinear constraint is transformed into linear constraints. equation (17) is converted into the following formula:

\[ K_v - K_v \leq (1 - x_v) \cdot \alpha_{CP}, \quad \forall v \in V, s, s' \in SB \]  

Set \( \beta_{sv} = x_v x_{sv} \) is an auxiliary decision variable, when \( x_v \) is equal to 1 as \( x_{sv} \), \( \beta_{sv} \) is 1, otherwise set to 0. The logical relationship among auxiliary decision variable \( \beta_{sv} \), \( x_v \), and \( x_{sv} \) are as follows:

\[ \beta_{sv} \leq x_{sv}, \quad \forall v \in V, s \in SB \]
\[
\beta_n, \leq x_{v^\prime}, \quad \forall v \in V, s^\prime \in SB
\]
\[
\beta_n, \geq x_{v^\prime} + x_s - 1, \quad \forall v \in V, s, s' \in SB
\]  

4. Computational Experiments

In order to verify the effectiveness of the designed yard template proposed in this paper, a series of experiments with different scales are used for computational validation. All the experiments were done by the ILOG CPLEX 12.2 solver, and the experimental computing environment was Intel Core i5-5200u CPU@2.20 GHz processor and 64-bit operation system. The constant parameters are shown in table 1 and experimental results with two cases are as shown in table 2 and table 3.

| Table 1. Parameters. |
|----------------------|
| parameter | \( G \) | \( yP \) | \( \theta \) | \( \mu_c^{\text{max}} \) | \( \mu_c^{\text{min}} \) | \( \lambda \) |
| value | 6 | 140 | 2 | 3 | 2 | 10% |

| Table 2. Experimental results with case 1. |
|------------------------------------------|
| \( n(V) \) | \( n(SS)/n(B) = 5 \cdot n(SS) = 40 \) | results of case 1 |
| \( N \) | \( Q \) | \( n(O_v) \) | \( n(x_v) \) | \( n(LP) \) |
| 1 | \( N \in [640,660] \) | \( Q \in [1,2] \) | 1 | 5 | 5 |
| 2 | \( N \in [1040,1080] \) | \( Q \in [2,3] \) | 1 | 8 | 8 |
| 3 | \( N \in [400,440] \) | \( Q \in [1,2] \) | 1 | 4 | 4 |
| 4 | \( N \in [820,860] \) | \( Q \in [2,3] \) | 1 | 6 | 6 |
| 5 | \( N \in [820,860] \) | \( Q \in [1,2] \) | 1 | 6 | 6 |
| 6 | \( N \in [640,660] \) | \( Q \in [1,2] \) | 2 | 4 | 4 |

| Table 3. Experimental results with case 2. |
|------------------------------------------|
| \( n(V) \) | \( n(SS)/n(B) = 5 \cdot n(SS) = 40 \) | results of case 2 |
| \( N \) | \( Q \) | \( n(O_v) \) | \( n(x_v) \) | \( n(LP) \) |
| 1 | \( N \in [760,780] \) | \( Q \in [2,3] \) | 1 | 6 | 6 |
| 2 | \( N \in [1120,1140] \) | \( Q \in [2,3] \) | 2 | 8 | 5 |
| 3 | \( N \in [400,440] \) | \( Q \in [1,2] \) | 1 | 3 | 3 |
| 4 | \( N \in [820,860] \) | \( Q \in [3,4] \) | 1 | 6 | 6 |
| 5 | \( N \in [820,860] \) | \( Q \in [2,3] \) | 1 | 6 | 6 |
| 6 | \( N \in [760,780] \) | \( Q \in [2,3] \) | 2 | 6 | 4 |

In table 2 and able 3, \( n(V) \) represents the total number of vessels. The demand \( (N) \) of vessels and quay cranes distribution \( (Q) \) are generated by the uniform distribution function given in table 2. \( n(O_v) \) represents the total time requirement of vessel \( v \), \( n(x_v) \) denotes the number of sub-block allocated for vessel \( v \), and \( n(LP) \) denotes the number of loading points allocated for vessel \( v \). The objective function is the minimum transportation distance \( (f) \) of containers. It is easy to see from the relationship among sub-blocks, loading points and vessel’s operation time in table 2 and table 3, which indicates that the sub-blocks allocation model proposed in this paper can
deal with the number of allocations about loading points and sub-blocks of vessels very well when operation time of vessels are taken into constraints. From the experimental results, we can also see that:

(1) The impact of container vessels’ loading points and operating time requirements. It can be seen from the comparison between vessel \( V_i \) and vessel \( V_j \) in table 2 that when the number of containers is the same with the corresponding quay cranes, the operation time requirement of vessel \( V_i \) is higher than vessel \( V_j \). In order to ensure the smooth completion of the operation, 6 sub-blocks and 6 loading points are allocated for the vessel \( V_i \), while the other gets 6 sub-blocks and 4 loading points.

(2) The impact of container vessels’ loading points and quay cranes distribution. It can be seen from the comparison between vessel \( V_i \) and vessel \( V_j \) in table 2 that the number of quay cranes of vessel \( V_i \) is less than vessel \( V_j \) when the number of container and the operation time in the port are same. To ensure the smooth completion of the operation in the port, the number of loading points of vessel \( V_j \) can be increased to reach the same number of loading points as vessel \( V_i \).

(3) The impact of allocation of loading points and sub-blocks of container vessels. It can be seen from the comparison between vessel \( V_i \) and vessel \( V_j \) in table 2 and table 3. In table 2, a loading point corresponds to a sub-block, and in table 3, there is a loading point matching with a sub-block and a loading point matching with two sub-blocks. For example, there are six sub-blocks and six loading points for the vessel \( V_i \) in table 2, a sub-block in a block matches with a loading point, while in table 3, there are six sub-blocks respectively in four blocks and four loading points for the vessel \( V_j \). There are two blocks respectively with a sub-block, and the other two blocks respectively are with two sub-blocks.

5. Conclusions
In this paper, the yard template optimization under considering the operation time requirement of vessels is studied, and the CPLEX solver is used to solve the yard space allocation model. At the same time, the validity of the model is verified by small-scale numerical experiments. This model can provide a template optimization strategy for port operators, which can solve the phenomenon of delayed departure of vessels and deal with the optimization of loading points when operation time of vessels are considered well, improve the operation efficiency of the yard, and alleviate the operation bottleneck of the yard.

However, there are some limitations in this paper. The storage demand of container vessels generally fluctuates, which is limited by the fact that this paper takes it as a certain value that can be estimated, and the calculation example in this paper is in small scale.

In the future research, we will pay more attention to the impact of vessel demand fluctuation on the number of loading points of vessels.

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