A Model for the Stowage Planning of 40 Feet Containers at Container Terminals

Zhao Ning and Mi Weijian

Logistics Engineering School, Shanghai Maritime University, Shanghai, China

Received 19 January 2009; received in revised form 20 March 2009; accepted 15 May 2009

ABSTRACT

In container terminals, one of the most important factors driving the logistic efficiency in the yard is stowage planning for containers designated to be exported. The stowage plan and operations have to meet the requirement of the liner shipping company of ship stability on the one hand, and to ensure the smooth and orderly process of handling containers, deployment and movement of the yard cranes on the other. These criteria are often in conflict. This paper is concerned with the ship’s container stowage planning problem which is formulated as a multi-objective integer linear programming. For the sake of being practical, the model not only considers the conflict between ship stability and containers’ reshuffling operation but also first takes into account the moving frequency of yard cranes, the probability of wait by quay crane and the feasibility of multi-YC feeding one QC during the loading process. A wide variety of numerical experiments demonstrated that solutions by this formulation are useful and applicable in practice.

Keywords: multi-objective integer linear programming, container terminal, stowage planning, ship loading.

1. INTRODUCTION

Increased regional competition has put further pressure on port operators to stay competitive and relevant to their customers. Lower handling charge, shorter transit time, higher level of service, and wider connectivity to the rest of the world have been identified as the main goals to acquire international competitiveness.

It is therefore not surprising that a number of studies have been conducted in various aspects for optimization of the container terminal operations. As a result, various control policies for unloading, storing, and loading containers have been proposed based on simulation and mathematical formulations. One of the most prominent results is the application of object-oriented approach, in which terminal resources and entities are modeled as individual objects and solutions to the performance problem are found via operation research techniques.

However, as far as the throughput of container terminals is concerned, the service rate to meet the demand by mega vessels has yet to be achieved in the studies that concentrated on conventional storage yard, where containers are stacked on the ground, side by side and one on top of another.

The main disadvantage of the conventional stacking scheme is that the reshuffling operations, which incur additional unproductive moves, have to be performed in order to retrieve a container from a lower tier. The vehicle requesting the container will have to wait extra time which may cause delays in feeding to the quay cranes. The result could be as serious as lengthening the vessel’s turnaround time and consequently a downgrade of service level. Therefore, in order to reduce the chances of retrieving containers that are not on top of the stacks, and also due to the weight constraint of containers, the stacking height is usually restricted to not more than eight
(in practice even lower than eight). However, this practice implies a limited utilization of ground space that is scarce and previous.

In response to these observations, this work focus on stowage planning that assigns to each bay position a particular outbound container with a type matching the preliminary type-based stowage plan provided by shippers. It is normally done by assigning outbound containers in inverse order of ports to be visited by the ships and changes may be required from the shipping companies. Stowage plans are prepared a few hours in advance. We focus only on the 40 feet full containers stowage problem, since different type of containers should obey different rules of stowage, for instance, the empty containers' stowage rules are totally different from the full. However, it is applicable because the liner shipping company will designate the bay positions for each type of containers in the PSP (Preliminary Stowage Plan). And the model developed in this study is adaptable for the case with 20 feet containers without major modifications.

This paper is organized as follows. The next section reviews the related literature. In the third section the proposed algorithm is described. In the subsequent section, a variety of numerical experiments are carried out and presented, and the final section reports the paper's findings and conclusions.

2. LITERATURE REVIEW

Management of container terminal operations is essentially the allocation and scheduling of the expensive resources such as berths, quay cranes, storage space, yard cranes, and container carriers. Each type of these resources plays an indispensable role in the interlocking processes in a container terminal. A comprehensive review on various decision problems that arise in the planning of export containers’ stowage is given as followed in the literature. Some of the techniques introduced herein will be extended to evaluate the stowage planning.

Since the 1970s, researchers drawn from academic and commercial shipping organizations, have tried to examine and worked over the problem of stowage planning. As a category of the loading problem, stowage planning is well recognized in the literature and has become widely used in a variety of transportation operations. In the early stage, most of the studies were directed at the pre stowage planning in liner shipping companies. Those methods developed have been grouped into the following five main classes: (1) simulation based upon probability; (2) heuristic driven; (3) mathematical modeling; (4) rule-based expert systems; and (5) decision support systems. None of these approaches have provided a solution to the complete stowage-planning problem. Here follows a brief review of relatively recent research into automating stowage planning.

Shields (1984) developed a container ship stowage computer-aided preplanning system. Here a small number of stowage plans are created which are then evaluated and compared by simulation of the voyage across a number of legs. The order in which loading heuristics are applied is determined using a limited number of different solutions. Since then further investigations have been carried out (Ratcliffe and Sen, 1987; Saginaw and Perakis, 1989) using expert systems and rule-based techniques to aid the stevedore in finding suitable configurations. Rule-based decision systems for dealing with MBPP are presented in Ambrosino and Sciomachen (1998), where a constraints satisfaction approach is used for defining and characterising the space of feasible solutions without employing an objective function to optimise, and in Wilson and Roach (2000), where the potential of applying the theory of artificial intelligence to cargo stowage problems is explored. Todd and Sen (1997) implemented a GA procedure with multiple criteria such as proximity in terms of container location on board and the minimization of unloading-related reshuffle, transverse moment and vertical moment. Their study examined the relationship between the reshuffle and the ship stability. Winter (1999) introduced the stowage planning in conjunction with load planning taking into account the equity of quay crane workload. This study also inspired issues of loading-related reshuffle and ship stability. However, although stability is an important factor of the pre stowage planning for the liners, but is not a key factor of the stowage in container terminals. Note that all the above studies do not assume that each vertical column in holds contains only containers of the same destination.

Botter and Brinati (1992), and Cho (1984) explored the application of mathematical models and linear programming to the problem, whereas too many simplification hypotheses were incorporated, which have made their approaches unsuitable for practical applications. Avriel and Penn (1993) and Avriel et al. (1998) addressed a stowage problem which formulated the problem as a 0-1 Integer Programming and applied it for loading onto a single hold, but only the unloading-related reshuffles was taken into consideration.

Some researchers explored the potential of applying the theory of artificial intelligence to cargo stowage problems. This class includes the work of Dillingham, Perakis, Wilson and Roach (1999-2001), and Sato. Ambrosino et al. (2004) addressed a stowage planning problem with the objective of minimizing the total stowage time where more practical constraints are taken into account such as different types of containers in length, weight limit being accepted for securing ship structure, etc. However, they do not explicitly take into account loading-related reshuffle.

Kim et al. analyzed rehandles of transfer crane and made a evaluation of the number of rehandles in container
yards (Kim, 1994, 1997; Kim and Kim, 1994; Kim et al., 2000, 2004). In 2004 they addressed a load-planning problem with an objective of proper arrangement of container stacks on board in light of smooth quay crane operation and the other of proper container retrieval sequence from container stacks in the yard in light of smooth transtainer operation. For this problem, they developed a beam search algorithm.

Imai et al. did a series of research on loading business in the container terminal (Imai and Miki, 1989; Imai et al., 2001, 2002, 2006). They formulated a multi-objective simultaneous stowage planning model for a container ship with container rehandle in yard stacks. They utilized the estimated number of rehandles in order to take the rehandle objective into account in the formulation. In this study, the rehandle is estimated based on the expected number of rehandles when retrieving each container in the block as the first one to be taken.

Sciomachen and Tanfani (2007) applied the theory of 3D-BPP approach to optimize stowage plans and terminal productivity. They evaluated how stowage plans can influence the performance of the quay so as to produce stowage plans that minimize the total loading time and allow an efficient use of the quay equipment. However, the performance of the yard crane and other factors are more important for the stowage planning in CT. The containership stowage and load-planning problem is much more difficult to solve than the three-dimensional bin packing problem due to the fact that the ship’s stowage plan has to consider the assignment of containers to a three-dimensional storage space in addition to the restrictions imposed in retrieving containers from the stacks in the field.

To sum up the points which we have just indicated, three sorts of elementary and crucial factors of this stowage problem were barely considered in most of the relevant research work. That includes (1) reshuffles in the stacks; (2) overweight stowage; (3) waiting by quay cranes; (4) move frequency of yard cranes; and (5) number of feeding blocks. In this paper we do take into account all the above factors comprehensively.

3. MODEL FORMULATION

3.1 Stowage Planning Description

As is well known, container terminals play a fundamental role in intercontinental cargo transportation by serving as an intermodal interface between the sea and the land carriers. Typically, they receive cargos in containers from various transportation devices like vessels or trucks, store them temporarily to account for the differences in arrival times of the sea and the land transport, and transfer them to other transportation devices to be delivered to their destinations. Fig. 1 is a schematic diagram showing the core operations in a container terminal. There is a typical cross-sectional view of a cellular ship. Each cell in the figure represents a slot where a container can be placed and the number in the cell implies the weight of the stowed container.

The stowage planning is to assign a slot to each outbound container stacking in the yard according to the preliminary stowage plan provided by the liner shipping company. The PSP (preliminary stowage plan) is a kind of sketchy plan of slots for each type of containers classified by size, EF (empty or full), discharging port, dangerousness, particularity, and so on.

As has been elucidated in the foregoing, the stowage problem can be attributed to the decision-making of the relationship between the items of two sets. Set A is the containers in the yard, whereas set B should be the available slots from the PSP. The stowage between containers and slots in a ship is shown in Fig. 2.

As shown in the following figure, in conventional storage yard, containers are stacked by yard cranes side by side and one on top of another to form rectangularly shaped heaps called blocks, each of which consists of a number of rows in width, a number of bays in length and a number of tiers in height. Similarly, in each ship bay, there are also a number of rows in width and a number of tiers in height.

3.2 Evaluation of Unavoidable Reshuffling Containers

Although the loading sequence of containers in a
ship-bay is totally unknown before the stowage planning, but in the same row of a ship-bay the slots will be stowed in a certain order. The example illustrated in Fig. 3 showed the situation of unavoidable reshuffle. If container A is stowed in slot A and container B is stowed in slot B, then container A will definitely result in a reshuffle of container B because slot A should be loaded in advance of slot B.

To further calculate the reshuffles caused by a stowage planning, the following notations should be declared first.

Note: the notations with upper characters are unknown variables to be decided; the notations containing any lower characters are known parameters.

\[ i, x = \text{Index of containers to be loaded}; \]
\[ n = \text{Number of containers}; \]
\[ j, y = \text{Index of slots in the ship}; \]
\[ m = \text{Number of slots}; \]
\[ q = \text{Index of blocks in the yard}; \]
\[ tq = \text{Number of blocks}; \]
\[ w = \text{Index of yard-bays of the blocks}; \]
\[ tw = \text{Number of yard-bays}; \]
\[ b = \text{Index of ship-bays of the ship}; \]
\[ tb = \text{Number of ship-bays}; \]
\[ l = \text{Index of rows in the ship-bays}; \]
\[ tl = \text{Number of rows in a ship-bay}; \]
\[ STOWAGE_{ij} = \text{Binary variable indicating whether the container } i \text{ should be stowed in slot } j; \]
\[ Cud_{ix} = \text{Known binary parameter indicating whether container } x \text{ is stacked above container } i \text{ in the same row as container } i; \]
\[ Sud_{iy} = \text{Known binary parameter indicating whether slot } y \text{ is right above slot } j \text{ in the same row as slot } j; \]
\[ RESTOW_{ij} = \text{Binary variable indicating whether the container } i \text{ stowed in slot } j \text{ causes a reshuffle of other containers}; \]

To calculate the total number of reshuffles, the variable \( Uppos\_stowage_{ij} \) should be introduced to indicate the number of containers above container \( i \) which are stowed above slot \( j \). We can define this value by

\[
Uppos\_stowage_{ij} = \sum_{x=1}^{n} \sum_{y=1}^{m} Cud_{ix} \cdot STOWAGE_{ij} \cdot Sud_{iy}
\]  

Based on the analysis above, the unavoidable reshuffle occurs when \( Uppos\_stowage_{ij} \geq 1 \) and \( STOWAGE_{ij} = 1 \). So the reshuffle can be formulated as \( Uppos\_stowage_{ij} \cdot STOWAGE_{ij} \). Since the multiplication of two variables will make the model non-linear, we have to use a trick to make the evaluation of total reshuffles linear.

In order to make this formulation solvable as a mathematical programming, we introduce the binary variable \( RESTOW_{ij} \). By using this definition we may formulate the problem only with the minimization of the Total Reshuffles as follows:

[RS]

\[
\text{Minimize } \sum_{j=1}^{n} \sum_{i=1}^{m} RESTOW_{ij}
\]  

subject to,

\[
\sum_{i=1}^{n} STOWAGE_{ij} \leq 1 \forall j
\]  

\[
\sum_{j=1}^{m} STOWAGE_{ij} \leq 1 \forall i
\]  

\[
RESTOW_{ij} \geq Uppos\_stowage_{ij} / 10 + STOWAGE_{ij} - 1 \forall i, j
\]  

\[
STOWAGE_{ij} = \{0, 1\} \forall i, j
\]  

\[
RESTOW_{ij} = \{0, 1\} \forall i, j
\]  

where \( STOWAGE_{ij} = 1 \) if a container at position \( i \) of yard stacks is loaded in slot \( j \) of ship; \( = 0 \), otherwise and \( n \) is the number of containers to be loaded.

In the formulation, constraints (3) and (4) ensure that every container is stowed with one slot and every slot can only be taken by one container, whereas constraints (5) ensures \( Uppos\_stowage_{ij} \geq 1 \) and \( STOWAGE_{ij} = 1 \) when \( RESTOW_{ij} = 1 \).

### 3.3 Stability Factor: Overweight Stowage

The stowage planning has to satisfy the stability requirement of liner shipping company. Hence, it must be approved by the first mate of the ship before the loading process. And the primary concern for the mate is the issue of heavy container stowed on top of a lighter one. Although overweight stowage is not strictly forbidden, it should be as fewer as possible. Therefore, we ought to formulate it as a stability objective instead of a
constraint, and this objective should focus on the total number of containers that is stowed on a lighter one instead of the GM itself.

The following parameters are declared in order to formulate the overweight stowage objective.

\[ V_{ay} = \text{Known binary parameter indicating whether slot } y \text{ is on top of slot } j, \]
\[ C_{tn\_weight} = \text{Known parameter, the weight of container } i; \]
\[ SLOT\_WEIGHT_j = \text{Variable, the weight of container that is stowed in slot } j; \]
\[ WAV_j = \text{Variable, the weight of container that is stowed on top of slot } j; \]
\[ UVMB_j = \text{Variable, the weight that remains after the weight of container stowed on top of slot } j \text{ is subtracted from } SLOT\_WEIGHT_j; \]
\[ OVERWEIGHT_j = \text{Variable, if } UVMB_j > 0 \text{ then } OVERWEIGHT_j = 1, \text{otherwise, } 0; \]
\[ OVERWEIGHT\_STOWAGE = \text{Variable, the total number of containers that is overweight stowed.} \]

Based on constraint (3), \( SLOT\_WEIGHT_j \) can be evaluated by \( C_{tn\_weight} \), and \( STOWAGE_{ij} \).

\[
SLOT\_WEIGHT_j = \sum_{i=1}^{n} STOWAGE_{ij} * C_{tn\_weight_i} \tag{8}
\]
\[
WAV_j = \sum_{i=1}^{n} \sum_{y=1}^{m} V_{ay} * STOWAGE_{iy} * C_{tn\_weight_i} \tag{9}
\]
\[
UVMB_j = WAV_j - SLOT\_WEIGHT_j \tag{10}
\]
\[ OVERWEIGHT\_STOWAGE \text{ is the count of } UVMB_j \text{ which is positive. Therefore, a constraint and the variable } OVERWEIGHT_j \text{ and are introduced as follows to formulate it mathematically, resulting in the formulation } [OS]. \]

\[
\text{minimize } \sum_{j=1}^{m} OVERWEIGHT_j \tag{11}
\]
subject to (3)–(4), (6)–(7) and

\[
OVERWEIGHT_j >= UVMB_j / 100 \tag{12}
\]
\[
OVERWEIGHT_j = \{0, 1\} \forall j \tag{13}
\]

where number 100 ensures that \( UVMB_j/100 < 1 \).

3.4 Minimize the Probability of Wait

The wait by quay crane will directly lead to ineffi-

\[
\text{Minimize } \sum_{l=1}^{q} \sum_{q=1}^{m} L\_Q\_01_{liq} \tag{16}
\]
subject to (3)–(4), (6)–(7) and

\[
L\_Q\_01_{liq} >= (1 / \sum_{i=1}^{n} \sum_{a=1}^{m} 1) * L\_Q_{liq} \tag{17}
\]
\[
L\_Q\_01_{liq} = \{0, 1\} \forall l, q \tag{18}
\]

Fig. 4. A ship-bay stowed with containers from two blocks
where $L_{Q \_01_{lw}} = 1$ if one or more containers from block $q$ are stowed in ship-row $l$; $= 0$, otherwise, which is ensured by constraints (17)–(18).

3.5 Minimize the Move Frequency of YC

The move of yard crane from one yard-bay to another can decrease efficiency with a cost of fuel. As is shown in Fig. 5, two different stowage plans within a ship-bay stowed with containers from two yard-bays of one block. In most cases, there is one yard crane working in one block. For Stowage I, in most rows of the ship-bay containers stowed are from different bays. As is illustrated in Fig. 5, the loading process is divided into five phases according to the four moves of the yard crane from bay to bay like $N \rightarrow M \rightarrow N \rightarrow M \rightarrow N$, whereas for Stowage II, the yard crane only has to move once from bay $N$ to bay $M$.

Therefore, the problem can be formulated with the minimization of the total number of yard-bays in each row of the ship-bay as follows:

\[
L_{Wlw} = \text{Variable, the number of containers from yard-bay } w \text{ stowed in ship-row } l;
\]

\[
L_{W\_01_{lw}} = \text{Binary variable, whether there are any containers from yard-bay } w \text{ stowed in ship-row } l; \tag{19}
\]

subject to (3)–(4), (6)–(7) and

\[
L_{W\_01_{lw}} > = (1 / \sum_{n=1}^{n} \sum_{i=1}^{m} SLTAGE_{ij} * Rwc_{nw} * Rrs_{jl}) \tag{20}
\]

\[
L_{W\_01_{lw}} > = (1 / \sum_{n=1}^{n} \sum_{i=1}^{m} SLTAGE_{ij} * Rwc_{nw} * Rrs_{jl}) \tag{21}
\]

\[
L_{W\_01_{lw}} = \{0, 1\} \forall l, w \tag{22}
\]

where $L_{W\_01_{lw}} = 1$ if one or more containers from yard-bay $w$ are stowed in ship-row $l$; $= 0$, otherwise, which is ensured by constraints (21)–(22).

3.6 Maximize the Number of Feeding Blocks

The work rate of QC is generally faster than that of YC, especially during the loading process. One of the most important factors influencing the loading efficiency is the feeding process in yard. Therefore the feeding yard cranes for one ship-bay should be more than one if possible, and this possibility depends on the stowage planning.

Fig. 6 is a schematic diagram showing a stowage plan with containers from block $X$ and block $Y$. It is evident that to maximize the number of feeding blocks is to maximize the number of blocks in each ship-bay.

Accordingly, we may formulate the problem with the maximization of the total number of blocks in each ship-bay as follows:

\[
BAYQ_{bq} = \text{Variable, the number of containers from block } q \text{ stowed in ship-bay } b; \tag{23}
\]

\[
BAYQ\_01_{bq} = \text{Binary variable, whether there are any containers from block } q \text{ stowed in ship-bay } b; \tag{24}
\]

subject to (3)–(4), (6)–(7) and

\[
BAYQ\_01_{bq} <= BAYQ_{bq} \tag{25}
\]
If_ondeck = Known parameter representing High_container_limit

If_high = Known parameter indicating whether slot is on deck or not;

High_container_limit = Known parameter representing the limitation of the number high containers stowed in a row;

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \text{STOWAGE}_{ij} \cdot \text{Ctn_weight}_{ij} \cdot \text{Rrs}_{ij} \leq L_{weight_{limitation}} \]  

\[ \sum_{j=1}^{m} \text{OVERWEIGHT}_{ij} \cdot \text{If_ondeck}_{ij} = 0 \]  

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \text{STOWAGE}_{ij} \cdot \text{If_high}_{ij} \cdot \text{Rrs}_{ij} \leq \text{High_container_limit} \]

3.7 Formulation

Besides the five objectives above, the port operators have to do the stowage planning under the following three constraints.

- There is a weight limitation for each row of the ship-bay. So that the sum of stowed containers’ weight for each row must be less than or equal to the limitation.
- For the containers stowed on deck of the ship, over-weight stowage is strictly forbidden, which means each container on deck must be on the top of a heavier one or the first tier of the ship-bay.
- The general height of container is 8.4 feet, while the high container’s height is 9.6 feet. So there is a limitation for the number of high containers in each row of ship-bay.

These three constraints can be formulated as follows:

\[ L_{weight_{limitation}} = \text{Known parameter representing the weight limitation for each row of the ship-bay;} \]

\[ \text{If_ondeck}_{ij} = \text{Known parameter indicating whether slot is on deck or not;} \]

\[ \text{If_high}_{ij} = \text{Known parameter indicating whether container i is a high container or not;} \]

\[ \text{High_container_limit} = \text{Known parameter representing the limitation of the number high containers stowed in a row;} \]

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \text{STOWAGE}_{ij} \cdot \text{Ctn_weight}_{ij} \cdot \text{Rrs}_{ij} \leq L_{weight_{limitation}} \]  

\[ \sum_{j=1}^{m} \text{OVERWEIGHT}_{ij} \cdot \text{If_ondeck}_{ij} = 0 \]  

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \text{STOWAGE}_{ij} \cdot \text{If_high}_{ij} \cdot \text{Rrs}_{ij} \leq \text{High_container_limit} \]

with weights, we obtain the following formulation:

\[ \text{Minimize } Z = \alpha \sum_{i=1}^{n} \sum_{j=1}^{m} \text{RESTOW}_{ij} \]

\[ + \beta \sum_{j=1}^{m} \text{OVERWEIGHT}_{ij} + \chi \sum_{j=1}^{m} \sum_{q=1}^{n} \text{L}_{Q_{01}} \]

\[ + \delta \sum_{l=1}^{n} \sum_{w=1}^{m} \text{L}_W_{01} - \epsilon \sum_{b=1}^{n} \sum_{q=1}^{m} \text{BAY}_{Q_{01}} \]  

subject to (3)–(7), (12)–(13), (17)–(18), (21)–(22) and (25)–(29), where \( \alpha, \beta, \chi, \delta \) and \( \epsilon \) are weights for the objectives of [RS], [OS], [PW], [MF] and [FB], respectively. Note that \( \epsilon \) is set negative because of the maximization of [FB].

3.8 Solution Procedure Using the Genetic Algorithm

We develop a heuristic algorithm by using the genetic algorithm (GA) in Aimms language. The sets we defined in the model include yard positions, yard blocks, yard bays, positions in the ship, stacks in the ship and bays of the ship. The relationships described between the sets are also given as constant parameters or decision variables. The stowage-planning problem is designed as a minimization mathematical program with all the above constraints and the multi-objective formulated in (30).

GAs are widely applied for plenty of practical problems of mathematical programming, which are difficult to solve in terms of polynomially-bounded computational time. It is solved for each scenario to find the optimal solution under each scenario, and then the robust model is solved to find the robust solution. Although we can solve the model with solver “XA”, but the calculation is too much slow when the number of containers in the same group is increasing or when the initial feasible solution lags far behind the optimal one. Thus, to accelerate the calculation, we introduced selection operator and mutation operators into the solving process. To minimize the objective function, the selection operator and mutation operators are designed as followed.

Selection operator:

\[ \text{fitness } (x) = \frac{1}{10} \wedge \frac{y(x)}{\sum_{s=1}^{n} y(s)} \]  

(31)

\( Y(x) \) denotes the objective function value. Fitness(\( x \)) stands for the probability of Gene X being selected.

The mutation operators are designed with a certain purpose. For example, to minimize the possibility of restow, the Gene X (\( \text{STOWAGE}_{ij} \)) mutates when Max(\( \text{Uppos}_{\text{stowage}} \cdot \text{STOWAGE}_{ij} \cdot \text{STOWAGE}_{xy} \cdot \text{STOWAGE}_{xy} \cdot \text{STOWAGE}_{xy} \) >= 1, and the mutation operator is to change the value of \( \text{STOWAGE}_{ij} \), \( \text{STOWAGE}_{xy} \) and \( \text{STOWAGE}_{xy} \) into their opposite way (0→1, 1→0).
4. NUMERICAL EXPERIMENTS

The solution procedures were coded in “Aimms” language on the PC with Core(TM) 2, T5600 (1.83GHz) CPU. Problems used in the experiments were read from the database of container terminal management information system for Tianjin port. Values of weights $\alpha$, $\beta$, $\gamma$, $\delta$ and $\epsilon$ in Equation (30) used in the numerical experiments are respectively 1, 1, 2, 2, 1.

Table 1 demonstrates the numerical cases of different ship size, number of containers to be stowed, the result of reshuffles, overweight stowage and the solving time.

![Fig. 7. The stowage of bay 18h and 22d in case 1](image1)

![Fig. 8. The stowage from two yard-bays to one ship-bay in case 8](image2)

<table>
<thead>
<tr>
<th>Case</th>
<th>Ship size</th>
<th>Container volume</th>
<th>Reshuffle</th>
<th>Overweight</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S</td>
<td>50</td>
<td>0</td>
<td>3</td>
<td>142</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>125</td>
<td>2</td>
<td>4</td>
<td>152</td>
</tr>
<tr>
<td>3</td>
<td>S</td>
<td>150</td>
<td>3</td>
<td>7</td>
<td>176</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>175</td>
<td>2</td>
<td>5</td>
<td>235</td>
</tr>
<tr>
<td>5</td>
<td>S</td>
<td>200</td>
<td>3</td>
<td>5</td>
<td>248</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>200</td>
<td>4</td>
<td>9</td>
<td>268</td>
</tr>
<tr>
<td>7</td>
<td>S</td>
<td>200</td>
<td>4</td>
<td>2</td>
<td>335</td>
</tr>
<tr>
<td>8</td>
<td>S</td>
<td>250</td>
<td>4</td>
<td>11</td>
<td>503</td>
</tr>
<tr>
<td>9</td>
<td>L</td>
<td>300</td>
<td>2</td>
<td>7</td>
<td>654</td>
</tr>
<tr>
<td>10</td>
<td>L</td>
<td>325</td>
<td>7</td>
<td>9</td>
<td>752</td>
</tr>
<tr>
<td>11</td>
<td>L</td>
<td>345</td>
<td>3</td>
<td>9</td>
<td>809</td>
</tr>
<tr>
<td>12</td>
<td>L</td>
<td>350</td>
<td>2</td>
<td>10</td>
<td>856</td>
</tr>
<tr>
<td>13</td>
<td>L</td>
<td>365</td>
<td>2</td>
<td>1</td>
<td>918</td>
</tr>
<tr>
<td>14</td>
<td>L</td>
<td>375</td>
<td>2</td>
<td>13</td>
<td>1,006</td>
</tr>
<tr>
<td>15</td>
<td>L</td>
<td>400</td>
<td>3</td>
<td>12</td>
<td>1,073</td>
</tr>
<tr>
<td>16</td>
<td>L</td>
<td>400</td>
<td>0</td>
<td>14</td>
<td>1,207</td>
</tr>
<tr>
<td>17</td>
<td>L</td>
<td>450</td>
<td>1</td>
<td>7</td>
<td>1,357</td>
</tr>
<tr>
<td>18</td>
<td>L</td>
<td>450</td>
<td>5</td>
<td>7</td>
<td>1,511</td>
</tr>
<tr>
<td>19</td>
<td>L</td>
<td>501</td>
<td>5</td>
<td>9</td>
<td>1,857</td>
</tr>
<tr>
<td>20</td>
<td>L</td>
<td>553</td>
<td>7</td>
<td>15</td>
<td>2,050</td>
</tr>
</tbody>
</table>

Note that each case of experiment consists of several types of containers classified by their discharging ports. For each type, it is solved separately. So the computation time in the last column of Table 1 is the sum of each type’s solved time.

5. CONCLUDING REMARKS

This paper addressed the problem of obtaining a non-inferior solution set for the container ship stowage planning in the container terminals. The problem was defined as a multi-objective integer programming, for bay “A110” of block “A1” and yard-bay “A348” of block “A3”.

As is illustrated in Fig.8, in each row of the ship-bay, the stowed containers are from one block which perfectly accord with the objective of [PW] to minimize. The fourteen containers stowed on ship-bay “14d” are from only one yard-bay of “A348”, although there are other bays in block A3, which proves the model can well minimize the move frequency of YC (objective of [MF]). And according to the above figure 8, we can imagine the deployment of yard cranes during the loading process of ship-bay “14d”. Evidently, the containers can be loaded by two feeding flows, which well meet the requirement of objective [FB].
which we obtained a set of non-inferior solutions by using the weighting method. For the sake of being practical, the model not only considers the conflict between ship stability and containers’ reshuffling operation but also first takes into account the moving frequency of yard cranes, the probability of wait by quay crane and the feasibility of multi-YC feeding one QC during the loading process. A wide variety of experiments demonstrated that the solutions by this formulation were acceptable for practical use.

ACKNOWLEDGMENTS

The authors wish to thank the terminal management office of the terminal SMCT for the fruitful support. Special thanks are to the anonymous referee for the valuable remarks and helpful comments and suggestions.

REFERENCES


