# Multi-objective Optimization Based on Improved Genetic Algorithm for Containership Stowage on Full Route

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***Abstract*—In this paper, taking channel, shifts, ship stability, rolling period and trim of the river-sea-going containership as constraint conditions, the multi-objective optimal mathematical model of containership was established. Considering the minimum shift of the 20′ and 40′ containers mixed loading as object, with number of containers as a real coding, heuristic algorithm was used to generate the initial solution. With the trim and rolling period being targets, the initial solution was optimized by improved genetic algorithm. Six ports of the full route were selected and stowage result was calculated, and the computing time is about 8.042s. Result analysis showed that the fitness value were 0.049297, 0.048326, 0.000820, 0.039525, 0.010776, 0.047788, and the shift numbers were 0,6,0,0,0,0. The absolute value of trim was less than 0.05m, rolling period could be more than 9s. The obtained result can meet requirements of the transport efficiency and the safety of the ship. So the method is effective and could be applied for stowage of the actual navigation.**

***Key words-container transportation; shift; mixed loading; heuristic algorithm; full route stowage; genetic algorithm***

## I. INTRODUCTION

The container throughput of Yangtze river waterway continues to grow in recently years. How to improve the efficiency of containership handling operation and reduce ship waiting time in ports has become the problem that needs to be solved.

Containership commonly calls at series of ports on its route, containers can only be unloaded from the top in one row. If the destination of lower container is closer than the upper, then the upper container must be first removed. After unloading of the lower container, the upper container is loaded in ship again. This kind of action is called the shift. The shift is time-consuming work, therefore containership stowage is mainly to reduce the number of shifts on full route, and ensure the safety of the containership simultaneously. Operation research method, which contain 0–1 linear programming [1]-[3], mixed integer programming [4], constraint programming [5], etc., is used to solve the stowage problem. In order to improve the search capacity, some researchers developed intelligent algorithm and heuristic algorithm to solve the stowage problem. Wilson used a tabu search algorithm to solve the problem of stowage on multiple ports [6]. Dubrovsky used Genetic algorithm to obtain the stowage plan [7]. Sciomachen converted the stowage problem into the three-dimensional bin packing problem, and presented a heuristic method to solve stowage and crane productivity [8]. Monacowe dealt with the ship stowage planning problem based on that the objectives of the terminal management are related to the yard and transport operations, and proposed the binary integer program and a two-step heuristic algorithm [9]. Ding proposed a special heuristic algorithm for the stowage planning problem of a containership, and obtained the reasonable number of shifts [10].

The above were mostly confined to minimize the number of shifts, hardly considering the influence of the ship safety according to containers weight distribution. Actually, the stowage plan has great effects on the ship. This paper mainly focuses on the stowage of the river-sea-going containership, and used heuristic algorithm to generate the initial solution based on minimization of the number of shifts. Analyzing the impact of containers distribution on the safety of the ship in the initial solution, finally the initial solution is optimized by genetic algorithm with trim and rolling period as object of optimization.

## II. DESCRIPTION OF STOWAGE PROBLEM

### A. Definitions

*1) The container number.* The container number. Let P(i) = {0,1,2,3……, $n_t$}be the port that the containership will call at. Arabic numerals act as the order of the ports along the full route, and $n_t$ is the port of destination. Matrix T is used to indicate loading containers in the process of a voyage, $T_{ij}$ is the number of containers planned to be transported from port i to port j. The two size of containers is respectively 20′ and 40′, and matrix T is divided into two matrices: $t_{ij}$ represents numbers of 20′ container and $t_{ij}'$ represents numbers of 40′ container, $t_{ij}(k)$and $t_{ij}'(k)$ represents the unique number of the $k_{th}$ container is shipped from port i to port j, and $w(t_{ij}(k))$ and $w(t_{ij}'(k))$ are weights of containers.

$$T=\begin{bmatrix} T_{01} & T_{02} & T_{03} & \cdots & T_{0n_t} \\ & T_{12} & T_{13} & \cdots & T_{1n_t} \\ & & T_{23} & \cdots & T_{2n_t} \\ & & & \ddots & \vdots \\ & & & & T_{n_{t-1}n_t} \end{bmatrix}=\begin{bmatrix} t_{01} & t_{02} & t_{03} & \cdots & t_{0n_t} \\ & t_{12} & t_{13} & \cdots & t_{1n_t} \\ & & t_{23} & \cdots & t_{2n_t} \\ & & & \ddots & \vdots \\ & & & & t_{n_{t-1}n_t} \end{bmatrix}+\begin{bmatrix} t'_{01} & t'_{02} & t'_{03} & \cdots & t'_{0n_t} \\ & t'_{12} & t'_{13} & \cdots & t'_{1n_t} \\ & & t'_{23} & \cdots & t'_{2n_t} \\ & & & \ddots & \vdots \\ & & & & t'_{n_{t-1}n_t} \end{bmatrix}$$

*2) The slot.* As shown in figure1, each container vessel is split into compartments which are termed as bay, and one 40′

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container takes up slots of two 20′ containers. Row is the position where the container is placed across the width of the ship. Tier denotes at which level the container is placed. Let b= {0, 1, …, $b_{max}$}be sequence number of bays from bow to stern, r= {0, 1, …, $r_{max}$} be sequence numbers of rows from portside to starboard, and t= {0, 1, …, $t_{max}$}be sequence numbers of tiers from bilge to deck. So through (b, r, t) the slot on the ship can be located. Let S (b, r, t) be the serial number of the slot, and its value equals the unique number of the container. If the slot is empty, the value is -1.

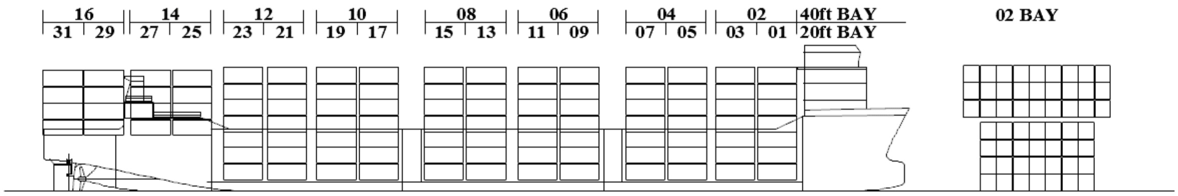


Figure 1. The arrangement of bays in containership

*3) Shift.* In the process of ship containers handling, containers can only be unloaded from the top, if the lower container port of destination within the same row is closer than the upper, and the upper container must be first removed, after unloading of the lower container, then the upper container is loaded in ship again, this kind of situation is called the shift.

*4) The calculation parameter of the ship.* $L_{pp}$ is the ship's length. B is the ship's breadth and d is the ship's draft. $\Delta$ is the displacement. $\Delta_1$ is the displacement before loading, $z_G$ is the vertical center of gravity before loading, and $z_{G1}$ is the vertical center of gravity after loading. $X_G$ is the longitudinal center of gravity before loading, and $X_{G1}$ is the longitudinal center of gravity after loading. $X_{B1}$ is the longitudinal center of buoyancy after loading. $\overline{BM}$ is metacenter radius, $\overline{GM}$ is transverse metacentric height，and $\overline{KB}$ is vertical center of buoyancy. $T_\theta$ is the rolling period. $M_T$ is trimming moment, MTC is curve of moment to change trim or centimeter, and t is the value of trim.

*5) Draft limitation of the route.* The Yangtze river waterway depth is limited by seasons and legs. In order to ensure safety when navigating in the shallow water, ships generally lightening cargo. So in different legs and seasons, ship can load the total weight of goods will be different. The draft limitation as shown in Fig. 2.

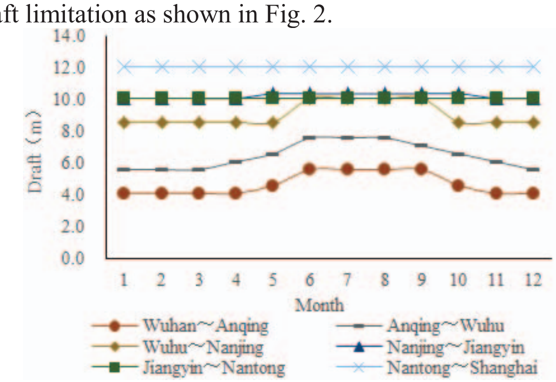


Figure 2. The water depth of the Yangtze river waterway in 2016

## B. The Basic Model of the Stowage Problem

According to the requirement of efficiency of cargo-handling and safety of containership, mathematical models are set put forward as followings.

$$\sum_{i=0}^{P(n)}\sum_{j=0}^{P(n_t)}(t_{ij}+2t_{ij}^{'})-\sum_{i=0}^{P(n-1)}\sum_{j=0}^{P(n-1)}(t_{ij}+2t_{ij}^{'})\le S_{\max},\quad 1<n<n_t \tag{1}$$

$$\sum_{i=0}^{\mathrm{P(n)}}\sum_{j=0}^{\mathrm{P(n_\mathit{t})}}\sum_{k=0}^{t_{\mathrm{P(n)P(n_\mathit{t})}}} w(t_{ij}{}^{(k)})-\sum_{i=0}^{\mathrm{P(n-1)}}\sum_{j=0}^{\mathrm{P(n_\mathit{t}-1)}}\sum_{k=0}^{t_{\mathrm{P(n-1)P(n_\mathit{t}-1)}}} w(t_{ij}{}^{(k)})+\Delta_1\le\Delta,\quad 1<n<n_t \tag{2}$$

$$\min C_s=\sum_{b=0}^{b_{\max}}\sum_{r=0}^{r_{\max}}C_{(b,r)} \tag{3}$$

$$z_{G1}=\frac{\Delta_1\bullet z_G+\sum_{b=0}^{b_{\max}}\sum_{r=0}^{r_{\max}}\sum_{t=0}^{t_{\max}}(\mathrm{w}(S_{(b,r,t)})\bullet S^z{}_{(b,r,t)})}{\Delta_1+\sum_{b=0}^{b_{\max}}\sum_{r=0}^{r_{\max}}\sum_{t=0}^{t_{\max}}\mathrm{w}(S_{(b,r,t)})} \tag{4}$$

$$\overline{GM}=\overline{KB}+\overline{BM}-z_{G1}\ge 0.3 \tag{5}$$

$$T_\theta=\frac{(0.55+0.07\frac{B}{d})\ B}{\sqrt{\overline{GM}}}\ge 9 \tag{6}$$

$$x_{G1}=\frac{\Delta_1\bullet x_G+\sum_{b=0}^{b_{\max}}\sum_{r=0}^{r_{\max}}\sum_{t=0}^{t_{\max}}(\mathrm{w}(S_{(b,r,t)})\bullet S^x{}_{(b,r,t)})}{\Delta_1+\sum_{b=0}^{b_{\max}}\sum_{r=0}^{r_{\max}}\sum_{t=0}^{t_{\max}}\mathrm{w}(S_{(b,r,t)})} \tag{7}$$

$$\mathrm{M_T}=(\Delta_1+\sum_{b=0}^{b_{\max}}\sum_{r=0}^{r_{\max}}\sum_{t=0}^{t_{\max}}\mathrm{w}(S_{(b,r,t)}))(x_{G1}-x_{B1}) \tag{8}$$

$$\mathrm{t}=\frac{M_T}{100MTC_1} \tag{9}$$

Equation (1) represents when the ship arrives at the $N_{th}$ port, the total numbers of containers are loaded in the ship does not exceed the total number of slots of the ship, and $S_{max}$ is the total number of 20′ slot. Equation (2) represents that the total weight of the ship less than the displacement of the ship after loading. Equation (3) represents number of the shift should be minimized, Cs is the total number of the shift and C (b, r) is the number of shifts in bay b and row r. Equation (4) is used to calculate the vertical center of gravity after loading, w(S(b, r, t)) is the weight of the container loaded on the slot(b, r, t), $S^z$(b, r, t) is the distance between centroid of the slot(b, r, t) and baseline. Transverse metacentric height can be calculated by (5), regulations require the value should not be less than 0.3 m. The rolling period can be obtained from Equation (6), it is advisable to not less than 9 seconds. Equation (7), Equation (8) and (9) are used to calculate the value of trim, $S^x(b, r, t)$ is the distance between centroid of the slot(b, r, t) and amidships. The value of trim is negative when ship trim by the bow and positive when ship trim by the stern. While the ship crosses the limit draught area, the trim should be approximated to zero.

## III. The Solution Approach

The solution approach consists of two main phases. In the first phase, minimum number of shift is considered as objective, and the initial solution would be generated by the heuristic algorithm. In the second phase, the ship's trim and rolling period are taken as the optimized object, and the initial solution is optimized through improved genetic algorithm. The main process as shown in Fig. 3.

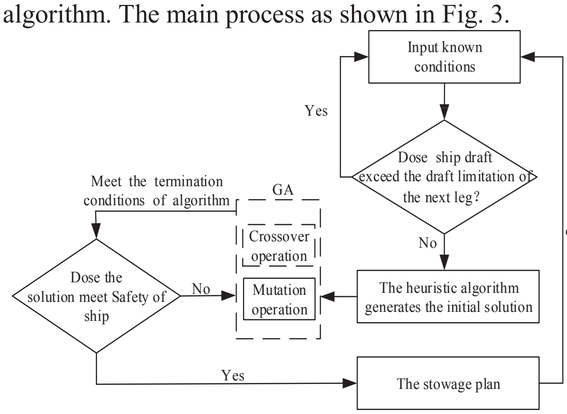


Figure 3. Algorithm flow

### A. Coding

In the algorithm, the number of slots are taken as real number coding is adopted.

$$P=\{g_1,\ g_2,\ g_3,\ g_4,\ \ldots\ldots,\ g_{Smax}\} \tag{10}$$

Equation(10) represents one stowage plan. The sequence contents in brackets is the number of the slot, and it corresponds to the unique container number. The unique container contains informaiton such as weight, size, port of destination, and so on. These information combines with the slot coordinates, mathematical models were proposed in Section II can be solved.

### B. The Heuristic Algorithm

The heuristic algorithm(HA) is divided into two parts, HA-a is loading algorithm, HA-b is the mixed loading algorithm.

The HA-a considers each of rows in the bay as loading objects. Containers reach the same destination are centralized layout. As shown in figure 4 (a), the number indicates the serial number of ports, the larger the number, the farther the destination. According to the destination, containers are loaded from left to right, from bottom to top. In the figure 4(b), after unloading at the port 1, rows contain empty slots are searched, and containers reach the next port are loaded in the empty slots firstly, as shown in the dotted box. After the empty slots are full, the rest of containers are loaded according to the destination from far and near. In the process of loading, containers reach the same destination are loaded in random order. A group of initial solutions are obtained by repeating the process several times, and solutions can be taken as the initial population of the genetic algorithm.

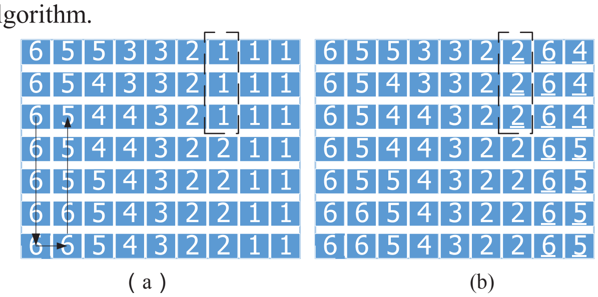


Figure 4. Ship bays

Actually, 20′ and 40′ containers are loaded in the same ship more often. When 40′ container is loaded in mixture with 20′ container, 40′ container span across two standard 20′ bays along the longitudinal direction of the ship, and 40′ container should be placed above the two 20’ containers. The mixed loading problem is solved by the HA-b as followings.

Rule 1. Firstly, the number of 40′ (one 40′ container equal to two 20′ containers) and 20′ containers are calculated by matrix T on each leg, and $N_{bay}$ that represents total slots in one bay also could get form ship parameters.

Rule 2. The number of 20′containers and 40′ containers divide by $N_{bay}$ respectively and truncating, and bays that 20′ and 40′ container occupy can be gotten. Then the rest of bays are 40′ and 20′ containers mixed loading area. while the rest of bays are less than two, one of the 20′container loading area should be split to mixed loading area, and the 20′ containers in the split area also should be loaded in the mixed area. The mixed loading area should be adjacent two bays, and not across the bulkhead.

Rule 3. With HA-a, 20′ and 40′ containers are loaded in the corresponding bays. The rest of containers are loaded in the mixed area, and 20′ containers are loaded from portside firstly, then 40′ containers are loaded from starboard. Then the solution can be obtained.

Rule 4. When ship arrives one port and completes unloading work, selected from all of rows contain empty slots, and check types of rows. The types of rows are divided into two: fully empty and partly empty, and the former has no effect on following loading, the latter should be judged firstly. If rows do not belong to mixed loading area, containers are loaded by the HS-a. If rows belong to mixed loading area, the size of the top container in the row should be checked firstly. Both 20′ or 40′ containers can be loaded above on the top container if the top container is 20′ size, or only 40′ containers can be loaded above on the top container if the top container is 40′ size.

Rule 5. After all of partly empty rows are filled up, count up the rest slots on mixed loading area. If the amount of the rest slots is less than the number of 40′ containers will be loaded, go to Rule 2. If the amount of the rest slots meet requirement of 40′ containers demand, go to Step 3, and to calculate the solution of the next leg.

### C. *Improved Genetic Algorithm Optimized*

*1) The fitness function*

The fitness function. In the algorithm, trim and rolling period are main optimization objectives. The unit of trim is the meter, the unit of rolling period is the second, and the two parameters have not the same order of magnitudes. So the ratio between variables and target values are taken the as fitness value. Fitness function as following:

$$f_{fit} = \left(\frac{T-9}{T}\right) - \left(\frac{|t|}{d}\right) \tag{11}$$

Based on constraint conditions in the section II, the termination condition of the algorithm can be set as T > 9 and t < 0.05. In order to guarantee the safety of the ship, after each calculation, the value of ship stability also must be checked.

*2) The crossover operation*

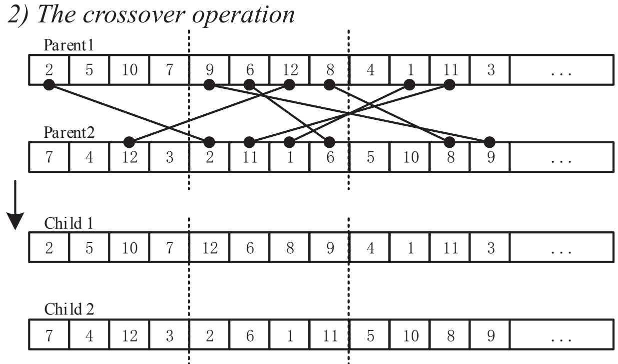


Figure 5. Crossover operation

Containers in the selected cross regions should have the same port of departure and port of destination. Two chromosomes are selected from the initial population by the roulette selection procedures. As shown in Fig. 5, suppose the serial number of containers is 1 to 12, and the order of containers are generated by HS. Parent1 and parent 2 are selected chromosomes，child1 and child2 are generated by crossover operation.

*3) The mutation operation*

The mutation operation is accomplished by containers interchange on the same chromosome. From the section II, it is found that stability and rolling period is related to the vertical distribution of containers, and trim is related to the longitudinal distribution of containers. Due to the large number of containers on the container ship, if every pair of containers interchange, it will cause slow convergence. To solve this problem, the interchange operation will be achieved by two ways, between two rows do not belong to the same bay and between two containers in the same row. The former operation is to change the longitudinal distribution of containers, while the latter is to change the vertical distribution of containers.

## IV. Experiment and Result Analysis

The algorithm is achieved through VC ++ 2012, and the compiled program runs on 64-bit windows 10, Core i5-3210M, 8GB memory.

### A. *Experiment*

Taking an entire voyage as an example, the optimization stowage planning is analyzed: the number of shifts and impact on the ship scheme. Ports of call are indicated by the letters, figures in brackets are the amount of 40’ containers and those outside the brackets are the amount of 20’ containers, as shown in Table I.

TABLE I. Ports and Number of Containers

| Port of departure | Port of destination | | | | | |
|---|---|---|---|---|---|---|
| | B | C | D | E | F | G |
| A | 18(30) | 31(36) | 136(83) | 30(25) | 24(17) | 46(33) |
| B | | 0(0) | 7(6) | 8(4) | 6(2) | 9(12) |
| C | | | 12(7) | 15(4) | 8(5) | 14(9) |
| D | | | | 42(27) | 43(30) | 67(42) |
| E | | | | | 35(22) | 42(30) |
| F | | | | | | 8(13) |

### B. *Result Analysis*

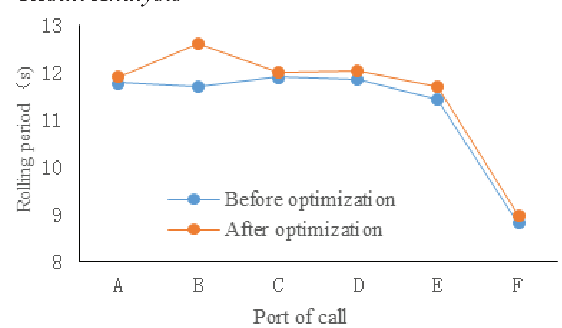


Figure 6. Rolling period optimization

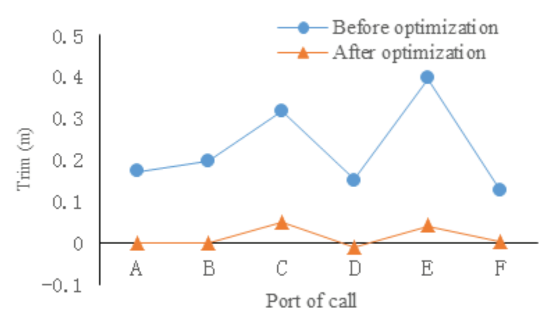


Figure 7. Trim optimization

In Table II, the number of shifts are zero except port B. Through the analysis of date, it is found the reason of shift is that the number of containers are shipped from port B to port C is 0, when partly empty rows are filled, containers reach the port D are loaded above on containers reach the port C, resulting in shifts. All of values are more than 0.3m, and meet the safety requirement. In the Fig. 6 and Fig. 7, the optimization result of rolling period and trim is obvious, all values of rolling periods are more than 9 seconds, and each of trim value is close to 0 m.

TABLE II. RESULT

| Port | Shift | Fitness value | $\overline{GM}$(m) | CPU time(s) |
|---|---|---|---|---|
| A | 0 | 0.049297 | 3.456 | 8.042 |
| B | 6 | 0.048326 | 3.482 | |
| C | 0 | 0.000820 | 3.475 | |
| D | 0 | 0.039525 | 3.446 | |
| E | 0 | 0.010776 | 3.795 | |
| F | 0 | 0.047788 | 7.62 | |

## V. CONCLUSION

In this paper, the river-sea-going containership is taken as the object, the mathematical model of stowage and constraints are proposed based on the analysis of the waterway and characteristics of the containership. For the stowage problem on the full route, a heuristic algorithm is put forward to generate the initial solution. With the aim of improving safety of the ship, rolling period and trim are selected as the optimization index, and the initial solution is optimized by genetic algorithm. Finally, an experiment is given to verify the method. Results show that this method can effectively reduce the number of shifts and ensure the safety of the ship.

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