Dispatching and Scheduling of the Lock Chamber of Three Gorges Lock

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Abstract—In order to maximize the navigation capacity of the Three Gorges and relieve the backlog of vessels, considering the regulation of navigation and the attributes of vessels of Three Gorges Hub, the concept of priority ship collection is introduced and the priority of dispatching is determined. Taking the utilization ratio of lock chamber and the mean latency of vessels at lockage as optimization target, an optimal scheduling algorithm for Three Gorge Lock chamber scheduling is proposed, which integrates two-dimensional strip packing heuristic algorithm and genetic algorithm. The proposed algorithm is tested on the vessels downlink data of Three Gorges Lock in August 2016 then compared with the manual arrangement strategy. The results show that the proposed algorithm has better performance in utilization ratio of lock chamber and the mean latency of vessels at lockage. The proposed algorithm can improve the carrying capacity of the Three Gorges ship lock to a certain extent.

1. INTRODUCTION
Traffic congestion of vessels at the dam area of the Three Gorges has been commonplace [1][2]. An effective strategy [3] to solve this problem at the hubs of the Three Gorge is improving the traffic capability of the navigation lock. The navigation lock works as a control node of inland water traffic networks, and its navigation capability is restricted [4] by the size of the lock chamber. The arrangement and dispatch of the lock chambers, which are the significant resources of vessel dispatching, can partly influence the navigation capability of the locks. Therefore, logical arrangement and dispatch of the lock chambers can greatly cut down the vessel latency at lockage and increase the utilization rate of the navigation lock chamber, thus improving the traffic ability [5] of the navigation locks.

The arrangement and dispatch of lock chamber refers to that, at the anchorage near the dam area, a collection of vessels are selected as per the lockage sequence [6]. As of now, the two-dimension packing heuristic algorithm has been frequently used to solve the problem of navigation lock chamber arrangement in the Three Gorges. Liu et al. [7] put forward the modified Depth-First-Search (DFS) algorithm in the light of actual operation. This algorithm solved the conflict between the utilization rate of lock chamber areas and the vessel priorities, consequently improving the operational efficiency. In accordance with the anthropomorphic strategy, Wu et al. [8] presented an optimized dispatching algorithm. Proved by the numerical examples, this algorithm could apparently increase the selected vessel quantity and the utilization rate of lock chamber areas. Deng et al. [9] proposed a genetic algorithm to handle the lock chamber arrangement. Through tests with practical data, this algorithm was verified to be effective and useful. The heuristic fast-arrangement algorithm proposed by Sun et al.
was built based on the sub-step dimension reduction ideology. It reduced the two-dimension packing problem of the lock chamber arrangement to a one-dimension problem and then solved it. This algorithm could perfectly solve the timetable coupling problems of scheduled arrangement and lock chamber arrangement. However, the algorithms mentioned above used the fuzzy comprehensive evaluation method, the analytic hierarchy process method, the expert researching method, etc. to assess the vessel dispatching priorities. All of these algorithms calibrated the priority weight of vessels by their respective attributes. In other words, the priority weights of above-mentioned algorithms were manually set and thus were susceptible to subjective factors. For vessel dispatching in actual arrangement, excessive parameters can also have an impact on the effect of arrangement.

According to the attributive characteristics of vessels and the regulations by the Three Gorges Navigation Administration, the priority vessel collection, the lockage sequence and other notions were introduced to build an arrangement and dispatch algorithm for the navigation lock chambers in the Three Gorges. This algorithm combined the advantages of the two-dimension packing heuristic algorithm and the genetic algorithm. Following the lockage principle of “first-in, first-out, the higher precedence passes first” advocated by the Three Gorges Navigation Administration, this algorithm designed the dispatching priority level and selected the preferential vessel collection. Next, taking the utilization rate of lock chamber areas and the vessel latency as the objectives of optimization, it used the heuristic recursive (HR) algorithm and the genetic algorithm to determine the optimal lockage sequence among the preferential vessel collection, and then generated the arrangement schedule for the lock chambers. Tests on the real data stream of vessels in the Three Gorges confirmed the advantages of the proposed algorithm.

2. MATHEMATICAL MODEL

2.1. Descriptions of Symbols and Variations

The description of symbols and variables is shown in Table 1.

| Variations | Definition |
|------------|------------|
| $I$        | Vessels waiting at lockage $I = \{1, 2, ..., n\}$ |
| $K$        | Lockage set $K = \{1, 2, ..., n\}$ |
| $W, L$     | Size of lock chamber (width, length) |
| $\tau_k, \sigma_k$ | Cut-off time and running time of the $K$-the lockage |
| $w_{li}$, $l_i$ | Size of vessel $i$ (width, length) |
| $t_i$ | Moment when vessel $i$ arrives at the anchorage |
| $x_{ik}, y_{ik}$ | Coordinate of vessel $i$ at the $k$-th lockage (abscissa, ordinate) |
| $t_{ik}$ | Moment when vessel $i$ enters the $k$-th lockage |
| $s_{ij}$ | If vessel $i$ is moored to the left of vessel $j$, it is 1, otherwise 0 |
| $r_{ij}$ | If vessel $i$ is moored to the right of vessel $j$, it is 1, otherwise 0 |
| $b_i$ | If the vessel $i$ has passed lock chamber, it is 1. otherwise 0 |
| $f_k$ | If the vessel $i$ enters the $k$-th lockage, it is 1, otherwise 0 |
| $v_{ij}$ | If vessel $i$ and vessel $j$ are in the same lockage, it is 1, otherwise 0 |

2.2. Model Building

2.2.1. Optimization Variables and Objective Function

The utilization rate of lock chamber areas and the average latency of vessels at lockage were selected
as the optimization variables.

a). The utilization rate of lock chamber area was set as \( A_k \).

\[
A_k = \sum_{i \in I} \frac{w_i L_i f_{ik}}{W_k L_k}, \forall k \in K
\]  

(1)

The utilization rate of lock chamber area is the ratio of the general planar areas for single lockage to the planar lockage dimension of all vessels at the navigation lock. Now that the lock chamber area is limited, a higher utilization rate means more favorable spatial arrangement of lock chambers.

b). The average latency of vessels at lockage was set as \( T_k \).

\[
T_k = \frac{1}{I} \sum_{i \in I} (\tau_{ik} - t_i)(1 - B_i), \forall k \in K
\]  

(2)

The mean latency of vessels refers to the mean latency value of all vessels at lockage. This variable can reflect the service level of the navigation lock. For vessels at lockage, relatively lower latency indicates a higher level of service at the navigation lock. Regarding the utilization rate of lock chamber area \( A_k \), it is expressed by a percentage. The mean latency of vessels \( T_k \) is expressed by time. Equation (3) was used to normalize the mean latency of vessels.

\[
T'_k = \frac{\max(T_k) - T_k}{\max(T_k) - \min(T_k)}
\]  

(3)

A smaller \( T'_k \) indicates less latency, which is favorable to operation. Accordingly, a higher \( T'_k \) indicates a more favorable situation. After normalization, both variables possess the same dimension and same order of magnitude, and share the same purpose of obtaining the maximum value. The objective \( C \) is defined as:

\[
C = \alpha A_k + \beta T'_k
\]  

(4)

where \( \alpha \) and \( \beta \) are weighting factors and represent the relative importance of respective objectives.

2.2.2. Constraint Conditions

\( i \) and \( j \) represent any two vessels that dock in the same lock chamber. The constraint conditions (5) and (6) ensure them not to overlap each other.

\[
x_{ia} + l_i \leq x_{ja}, \forall i, j \in I, i \neq j, x_{ia} \leq x_{ja}, k \in K
\]  

(5)

\[
y_{ia} + w_i \leq y_{ja}, \forall i, j \in I, i \neq j, y_{ia} \leq y_{ja}, k \in K
\]  

(6)

The constraint conditions (7) and (8) ensure that all vessels dock within the plain size of lock chamber.

\[
x_{ia} + l_i \leq W, \forall i \in I, k \in K
\]  

(7)

\[
y_{ia} + w_i \leq L, \forall i \in I, k \in K
\]  

(8)

The constraint condition (9) ensures that, in the midst of single lockage dispatching, any vessel \( i \) passes through the navigation lock once only.

\[
f_{ik} = 1, \forall i \in I, k \in K
\]  

(9)

The constraint conditions (10) and (11) ensure the validity of voyage duration and lock chamber layout. The weight anchor time is ahead of cut-off time, and the lock-in time is later than the cut-off time.
The constraint condition (12) ensures all vessels to be moored in place. The vessel \(i\) can be moored on the port side or the starboard side of the other vessel; or on the float-type bollard at the left-bank or right-bank wharf.

\[
s_{r_{i,0}} + s_{l_{i,n+1}} + \sum_{j=1, j\neq i} s_{r_{ij}} + s_{l_{ij}} \geq 1, \forall i \in I
\]  

The constraint conditions (13) and (14) ensure that when the vessel \(i\) moors to the barge \(j\), they are adjacent to each other.

\[
y_{ij} = w_{ij} = y_{ij}, \forall i, j \in I, k \in K
\]

\[
y_{ij} = w_{ij} = y_{ij}, \forall i, j \in I, k \in K
\]

The constraint condition (15) ensures that when two vessels possess the same length, they will not be moored to each other.

\[
s_{r_{ij}} + s_{l_{ij}} \leq 1, \forall i \neq j, i, j \in I
\]

The constraint conditions (16) to (18) ensure that two vessels at respective lockage will not be moored to each other.

\[
f_{ik} - f_{jk} \leq V_{ij}, \forall i < j, i, j \in I, k \in K
\]

\[
f_{ki} - f_{kj} \leq V_{ij}, \forall i < j, i, j \in I, k \in K
\]

\[
s_{l_{ij}} + s_{r_{ij}} + s_{l_{ij}} + s_{r_{ij}} \leq (1 - V_{ij}), \forall i < j, i, j \in I
\]

The constraint conditions (19) to (22) present the limits of variables and their completion.

\[
h_{ij}, s_{r_{ij}}, s_{l_{ij}} \in \{0, 1\}, \forall i \neq j, i, j \in I
\]

\[
V_{ij} \in \{0, 1\}, \forall i < j, i, j \in I
\]

\[
x_{ik} \leq W, y_{ik} \leq L, \forall i \in I, k \in K
\]

\[
B_{ij}, f_{ik} \in \{0, 1\}, \forall i \in I, k \in K
\]
3. Dispatching Algorithm

3.1. Selection of Preferential Vessel Collection

![Diagram of Selection Process]

The preferential vessel collection refers to a group of vessels that meet the preferential requirements for current lockage. It consists of the vessels that wait at lockage for relatively longer time and that cannot stay at lockage for long time. The selected vessels in preferential collection are slightly more than the queuing vessels at single lockage. The quantity of queuing vessels at single lockage is estimated by considering the size of a typical vessel (with a length of 88 m and a width of 16 m) in the Three Gorges, and it is found that the lock chamber (planar collection vessel dimension: 266 m*32.8 m) has a capacity of six such type of vessels at a single time of lockage [11]. Based on the minimum vessel size in the statistics, the chamber can hold about ten vessels of the same model at most. The maximum number in preferential vessel collection is thus set as 10. Following the principle of “first-in, first-out, the higher precedence passes first”, the preferential vessel collection is adopted. The specific selection method is shown in Fig. 1.
3.2. Determination of the Lockage Sequence Based Upon HR Algorithm

After the determination of preferential vessel collection, the vessel collection at the same lockage was determined by the chosen preferential vessel collection in accordance with the geometric size and else constraint conditions of the lock chamber. This is part of the two-dimension packing issues, in which the rectangular packing was involved could be classified as two categories: the clearly structured hierarchical layout and the non-hierarchical layout that is interlaced and poorly structured. Under real vessel shifting operation, the non-hierarchical layout frequently increases the difficulty and takes more time for vessel docking, as well as lowers the docking safety. As a result, this thesis used the hierarchically layered two-dimension packing algorithm. Regarding the hierarchically arranged two-dimension packing issues, Zhang team has presented the HR algorithm. The specific procedure is as shown below:

Step 1: Place an article to be loaded in a corner of the container, which divides the space into two sections of space $S_1$ and $S_2$. It was shown in Fig.2 (a).

Step 2: Select either section of space, $S_1$ for instance, use the method in step 1 to implement recursion packing until the space cannot load any more articles. It was shown in Fig. 2(b).

Step 3: Set $S_2$ as $S_1$, continue the calculation in Step 2 until the whole space cannot load any more articles. It was shown in Fig.2 (c).

Step 4: The sum aggregate of all solutions is the solution of the original question. It was shown in Fig.2(d).

The HR algorithm works to place all eligible vessels at the appropriate positions according to the constraint conditions. However, this can only bring feasible solution that cannot be optimized subsequently. In fact, the vessel entry sequence through the lock chamber is an essential factor that influences the quality of solution. Accordingly, the concept of lockage sequence was introduced. The lockage sequence refers to the vessel entry sequence through the navigation lock. The HR algorithm can first go through the front-ranked vessels in sequence. It then judges whether the planar dimension accords with present loading space. If yes, the vessel will be placed in the space; otherwise, the algorithm will go through the information of next vessel.

3.3. The Genetic Algorithm in Preferential Consideration of the Vessel Collection and the Lockage Sequence

On basis of HR algorithm, it aimed at solving the actual arrangement issues at navigation locks. Meanwhile, it appropriately modified the HR algorithm and combined it with the genetic algorithm in the midst of solving the lock chamber arrangements. The genetic algorithm was used in iteration to generate new progeny, thus replacing the sequence order at lockage. The generated sequence was input in the HR algorithm to produce the lock chamber layout. Then it used the fitness function of the genetic algorithm to decide the advantages and disadvantages of lock chamber layout, and thus obtaining relatively more favorable lock chamber arrangement.

1). Generating the initial solution: use the greedy principle to arrange the lockage sequence in descending order as per areas; then input the sequence in the HR algorithm to generate the initial arrangement of lock chamber.

2). Encoding: Integer coding was used on the chromosome. The gene bits referred to the serial
number from vessel to the anchor. Take [021045081008041] for example, in it, every three adjacent bits represent the code of a vessel. The first three bits “021” represent the vessel \(i_{21}\) (i.e. the 21st. vessel to the anchor); next “045” represent the vessel \(i_{45}\) (i.e. the 45th. vessel to the anchor), and the like.

3). Fitness function: Use the fitness function \(\text{fitness} = 1/c\) in calculation. The function indicates that the fitness of some chromosome is the reciprocal of the objective function value. In it, \(\text{fitness}\) refers to the fit level, \(c\) refers to the value of objective function.

4). Selection: Use the roulette method in selection.

5). Overlapping: Use partial mapping method in overlapping. Implement regular two-point crossover on the parent; then revise the respective gene value out of the overlapping area in accordance with the mapping relations of various gene values within the overlapping area.

6). Variation: Implement variation on random bits.

7). Elite retention strategy: Substitute the solutions that possess better fitness for the unfavorable solutions to ensure the astringency of genetic algorithm.

The solution steps of the algorithm: Firstly, as per the vessel priority rule set, select a preferential vessel collection which total quantity was slightly larger than the vessel quantity at single lockage. Use the greedy principle to generate an initial sequence; then input it to the HR algorithm and obtain an initial solution. After that, use the genetic algorithm to handle the initial sequence and generate various priority vessel sequences. Next, keep using HR algorithm to rank these sequences until the practicable lock chamber arrangement was created. Once it achieves the maximum number of iterations, stop calculation. Finally, compare the fitness of generated lock chamber layouts and select out the relatively more favorable arrangement of lock chamber. The specific algorithm procedure was shown in Fig. 3.

```
Start

Input the vessel lockage table

Generate the preferential vessel collection by priority from the lockage table

Use greedy principle to generate the initial priority lockage sequence

Input the sequence into the HR algorithm to generate the planar layout of lock chamber

Record the layout details and parameters

Dispatch the genetic algorithm to generate new priority lockage sequence

Obtain the optimal lockage chamber arrangement and output it as present lockage sequence schedule

Reach the maximum iteration times?

Y

N

End
```

Figure 3. The genetic algorithm flow of lockage sequence

4. EXPERIMENTS

The data of downstream vessels passing through the navigation lock alongside the southern line of the
Three Gorges in August 2016 was selected as the test data. Supposed the vessel collection size in navigation lock chamber was $266m \times 32.8m$; the target weight $\alpha = 0.5$, the utilization rate of navigation lock chamber $A = 70\%$. In accordance with the sizes of vessels at lockage as well as the mean interval of water discharging in the Three Gorges, it presumed that every day the total discharging times $k = 18$, and the interval of discharging was 1.5 hours. Taking into account the arrangement of navigation lock alongside the southern line of the Three Gorges, it calculated the preferential vessel lockage sequence. Meanwhile, the lock chamber arrangement was generated by HR algorithm; then it generated the layout schedule of lock chamber by using genetic algorithm and iteration. The arrangement schedule within 0:00 and 12:00 on August 10, 2016 was shown in Table 2.

Table 2. The arrangement schedule within 0:00 and 12:00 on August 10, 2016 that was generated by the proposed algorithm

| Lockage order | Opening Time | Vessels at this lockage |
|---------------|--------------|-------------------------|
| 1             | 00:00        | ↓Yufa988↓↓Shijihuihuang↓↓Jinyun867↓↓Weiduoliya3↓ |
| 2             | 01:30        | ↓Yuhai61↓↓Zongtongbahao↓↓Changan118↓↓Changlong6↓ |
| 3             | 03:00        | ↓Minggu666↓↓Jiangjiyun1239↓↓Xiangling866↓↓Chuanji35↓ |
| 4             | 04:30        | ↓Yichangjinghang↓↓jimie2↓↓Yunanhai8↓↓Ejinzhou↓↓Zhengfeng66↓ |
| 5             | 06:00        | ↓Dawei809↓↓Taohui636↓↓Xingyuanwang1↓↓Xiexia998↓ |
| 6             | 07:30        | ↓Xingyi13↓↓Changxun19↓↓Taipingyang08↓↓Yifa5↓ |
| 7             | 09:00        | ↓Xinpingjiang1006↓↓Dayang5↓↓Dongqi↓↓Xinpingjiang108↓↓Santong80↓↓Jialun905↓ |
| 8             | 10:30        | ↓Yuwenhang906↓↓Qinhe838↓↓Yichanghuifeng9↓↓Jianglun01↓ |
| 9             | 12:00        | ↓Juhang18↓↓Xilexia718↓↓Hangshun606↓↓Changshun22↓ |

Studying the daily statistics of the arrangement schedule, it obtained the mean utilization rate of the lock chamber and its average latency during August 5 and August 20. In light of the presented algorithm and practically manual arrangement (this manual layout data was obtained from the investigation by the Navigation Administration of the Three Gorges), it acquired the utilization rate of the lock chamber areas and its mean latency alongside the southern line of the Three Gorges, which was shown in Fig. 4 and Fig. 5.
Observed from Fig. 4 and Fig. 5, in comparison of the manual arrangement, the utilization rate of lock chamber areas calculated by the proposed dispatching algorithm was relatively higher, with an average increase by 7.86%; additionally, the mean latency of vessels at lockage was relatively sooner, with an average decrease by 9.67%. As a result, the presented dispatching algorithm can greatly cut down the latency of vessels at lockage, thus improving the utilization rate of lock chambers.

CONCLUSIONS
This thesis researched the navigation lock arrangement and dispatching at the Three Gorges hub. Under the real navigating scenarios, it built a linear mathematical model. Again, a new arrangement and dispatching algorithm was built on basis of the two-dimension packing heuristic algorithm and the genetic algorithm. The algorithm was tested based on real vessel data in the Three Gorges and the following conclusions were reached:

1). The proposed algorithm is accessible to arrange and dispatch the vessels at lockage under the lockage principle of “first-in, first-out, higher precedence passes first” by the Navigation Administration of the Three Gorges. Moreover, the designed algorithm is logical and safe in arranging and dispatching the lock chambers.

2). Compared with manual arrangement, the proposed algorithm is more favorable to improving the utilization rate of lock chamber and cutting down the mean latency of vessels at lockage. Accordingly, it partly improved the traffic capacity of the navigation lock in the Three Gorges.

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