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HYBRID QUANTUM ANT COLONY ALGORITHM FOR THE SHIP LOCK ARRANGEMENT PROBLEM

Ruijie LIU[1]*, Wenwu YU[2], Jingjing JIANG[3], Yao LI[4]

The ship lock is an important hydraulic engineering building to ensure navigation, and its smoothness has a very important impact on the whole inland waterborne transportation system. With the continuous development of river basin economy, the demand for shipping is also increasing, the problem of lock congestion and long waiting time is serious more and more, this has brought certain social, environmental and economic problems. Therefore, improving the passing ability of the ship lock can decrease the possibility of social problems, reduce environmental pollution, and improve economic benefits. This paper analysis the calculation formula of ship lock passing ability, proposes the concept of the arrangement problem of the ship lock and its constraints, designs hybrid quantum ant colony algorithm for the arrangement problem of the ship lock, and implements it. Through experiment and comparative analysis in two groups of data, its results demonstrate that the chamber utilization has been further improved, compared to the chamber utilization of using other algorithms.

Keywords: ship lock, passing ability, arrangement problem, hybrid quantum, ant colony algorithm

1. Introduction

From ancient to modern times, waterborne transport has always been an indispensable mode of transport, which uses ships, rafts and other floating to transport passengers and goods in the rivers, lakes, reservoirs, oceans and other waters. The waterborne transportation is usually characterized by low cost and large carrying ability, it has its own unique advantages compared with other modes of transportation such as air and railway. In China's total cargo volume, the proportion of the waterborne transportation is only second to that of railway and highway. According to the nature of the waterborne transportation, the waterborne transportation is divided into sea transportation and river transportation. In the river transportation, the ship lock (hereinafter referred to as lock) is a navigation facility, its passing ability is the main embodiment of the waterborne transportation ability. With the rapid growth of the river transportation

[1] Prof., Sch. of Info. Sci. & Tech., Dalian Univ. of Sci. & Tech., China, e-mail: hugmjjk@163.com
[2] Lect., Sch. of Info. Sci. & Tech., Dalian Univ. of Sci. & Tech., China
[3] Assist. Prof., Sch.. of Info. Sci. & Tech., Dalian Univ. of Sci. & Tech., China
[4] Lect., Sch. of Info. Sci. & Tech., Dalian Univ. of Sci. & Tech., China

volume year by year, the demand for shipping is also increasing, the problem of lock congestion and long waiting time is serious more and more. For instance, in 2011, after the TGP lock reached the design ability 19 years in advance, the TGP lock has been overloaded for 10 consecutive years, and the lock congestion has become increasingly serious. According to a report on the CPPCC website, in 2016, when the lock was not suspended for maintenance, there were 262 ships waiting for the lock every day, with a maximum of 489, the average time of the ship waiting for passing through the lock (hereinafter referred to as lockage) was 44 hours, with a maximum of 379 hours. In 2017, there were about 800 ships waiting for the lock every day, and the average time of the ship waiting for lockage was 106 hours, and it reached 150 hours in 2018. In 2020, the average waiting time exceeded 110 hours, the maximum waiting time was 1403 hours, and the maximum number of ships waiting for the lock reached 1171 ships, 2.5 times that of four years ago, without suspension of navigation for maintenance and affected by the COVID-19. In 2021, the average waiting time was more than 200 hours. A long time of waiting for the lock will cause a large number of ships and personnel to be overstocked, which increases the possibility of social problems. The domestic garbage will also pollute the environment, and the economic problems are more prominent. Take the Suez Canal grounding accident of the cargo ship "Ever Given" in March 2021 as an example, within six days of its stranding, more than 400 cargo ships of all kinds were blocked on the Suez Canal, with a loss of up to $400 million per hour. Therefore, it is meaningful to study how to improve the lock passing ability, decrease the possibility of social problems, reduce environmental pollution, and improve economic benefits.

The relevant research on the lock passing ability [1] mainly includes three aspects: the influencing factors of the lock passing ability, the design and building of waterborne transport facilities, such as locks and ships, and the lock management and operation. In aspect of the lock management and operation, the lock scheduling problem (LSP) is one of research contents, such as in [2], the LSP was introduced, and decomposed into three sub problems: lockage operation scheduling, chamber assignment and ship placement, and Jannes Verstichel et. al. developed several optimization methods for LSP. In [3], Noémie Le Carrer et. al. described a framework for ship scheduling and cargo loading optimization. In[4], a mathematical formulation was proposed by Tina Andersen et. al. to determine which vessels must wait in sidings for minimizing the passing through time. In[5], an optimized model and its solving method was used for the arrangement of the dispatch schedule in lock gate. Using this algorithm to arrange the scheduling plan can increase the average lock chamber utilization by more than 10%, and the calculation time is very short. In[6], scheduling by the optimal matching permutation strategy and sequential service permutation strategy was carried out, two classical operational research models were used to calculate the combination of passing ships and the gross tonnage of one-time passing, a simulation calculation software for the lock ability is developed. In [7], the improved layout model was proposed, and then the parameters were optimized by using PSO. Through the simulation comparison with the common layout model, the effect of the model was verified. In [8], the ship scheduling regulations based on the balance of fairness and efficiency were proposed, the lock chamber arrangement adopted the queuing algorithm based on “schedulable points”. In [9], the optimal arrangement algorithm of lock chamber based on ship comprehensive weight was used by the lock arrangement sub model. In [10], the ship breadth-first algorithm based on the lock chamber column was given. In the same group, ahead of the queue of ships had priority in the same queue service according to the priority and the arrival time for sorting, which was to ensure the fairness principle of lock. The length direction of the lock chamber known as column, and width larger ships had priority to be arranged in the front of the same column lock chamber.

This paper analysis the calculation formula of ship lock passing ability, proposes a simplified calculation formula of the actual gross load mass of lockage in one direction per year from the aspect of the lock actual operation, proposes the concept of the arrangement problem of the ship lock and its constraints, designs hybrid quantum ant colony algorithm for the arrangement problem of the ship lock, and implements the hybrid quantum ant colony algorithm for the arrangement problem of the ship lock. Through experiment and comparative analysis in two groups of data, its results demonstrate that the chamber utilization has been further improved comparing to the chamber utilization of using the BL algorithm, minimum horizontal line algorithm, simulated annealing algorithm, genetic algorithm, surplus rectangle mate algorithm, improved layout model[7] and ship breadth-first algorithm[10].

2. The arrangement problem of the ship lock

2.1. Lock passing ability

In the process of engineering design, the calculation formula [1] of the lock passing ability as follow.

$$N_1 = dDL \tag{1}$$

N_1 represents the gross load mass of lockage in one direction per year.

d represents the daily average number of lockage.

D represents the number of sailing days per year.

L represents the average load mass of one lockage.

$$N_2 = \left(d - d_0\right)\frac{vDL}{u} \tag{2}$$

N_2 represents the passenger and freight traffic volume of lockage in one direction per year.

d_0 represents the daily amount of lockage of non-passenger and cargo ships.

v represents the ship loading factor.

u represents the traffic volume unbalanced factor.

During the actual operation of the lock, parameters d_0, v and u are random values, because these parameters are determined when ships come to the lock and needs to pass the lock, their values can be considered to be given. Therefore, the lock passing ability can be improved by increasing d and L in one day. This can be described as follow.

$$N_3 = \sum_{k=1}^{dD} \max\left(L_k\right) \tag{3}$$

N_3 represents the actual gross load mass of lockage in one direction per year.

L_k represents the average load mass of lockage for the *k-th* times.

2.2. The arrangement problem of the ship lock

The average load mass of one lockage L can be calculated by (4).

$$L = t_a \frac{\gamma A}{f\left(t_a\right)} \tag{4}$$

t_a represents the ship average tonnage in lock chamber.

$f\left(t_a\right)$ represents the functional relationship of tonnage and area of inland ships.

A represents the effective lock chamber area.

γ represents the effective chamber utilization, i.e., the gross area of the ships entering the lock divided by the effective the lock chamber area.

Equation (4) describes, without considering the uncertainty of the combination and design ship type of the ships, the calculation relationship of the tonnage per unit area, the effective chamber utilization and the effective lock chamber area is the average load mass of one lockage. During the actual operation of the lock, the tonnage per unit area is determined when ships come to the lock and needs to pass the lock, the effective lock chamber area is also determined. Therefore, by improving the effective chamber utilization as much as possible, it will also improve the average load mass of one lockage, thus improving the lock passing capability.

So, how to improve the effective chamber utilization? Obviously, according to the meaning of the effective chamber utilization. Under the given condition of the lock, the larger the gross area of the ships entering the lock, the higher the value of the effective chamber utilization, here, which is called the arrangement problem of the ship lock. The constraints of the ship lock arrangement problem as follow.

The ships waiting for passing through the lock(hereinafter referred to as wait ship) cannot share the same space.

Wait ships must be in the space of the lock chamber.

Wait ships still maintains its normal operation direction, i.e., the body of the ship is parallel to the direction of entrance or exit.

3. Hybrid quantum ant colony algorithm for the ship lock arrangement problem

The hybrid quantum ant colony algorithm [11-12] combines ant colony algorithm with quantum computing.

3.1. Quantum state

The quantum bit(hereinafter referred to as qubit) is the concept in quantum computing, the qubit is the basic information unit, it has two basic states in a two-states quantum system, such as selected state and unselected state, except for this, the qubit has a superposition state. The arbitrary linear superposition of the selected state and unselected state is called superposition state of the qubit in quantum mechanics, which can be represented as:

$$|\tau\rangle = \xi|x\rangle + \delta|y\rangle \tag{5}$$

Where $|\ \rangle$ represents the symbol for the quantum state.

$|\tau\rangle$ represents the qubit superposition state.

$|x\rangle$ represents the basic state of the qubit, such as unselected state.

$|y\rangle$ represents the basic state of the qubit, such as selected state.

ξ and δ represent probability amplitude in unselected state and selected state respectively, they are a complex number in quantum mechanics. $|\xi|^2$ and $|\delta|^2$ represent the probability in unselected state and selected state respectively. ξ and δ satisfy $|\xi|^2 + |\delta|^2 = 1$.

Whereas a classical n-bits binary number can represent one of 2^n values at the same time, a n-qubits can represent all 2^n values at the same time. Therefore, a hybrid quantum approach can improve the diversity of information expression. In the hybrid quantum ant colony algorithm for the ship lock arrangement problem, use qubits to represent pheromones on the wait ship.

3.2. Ant colony algorithm

The ant colony algorithm[13] is a probabilistic algorithm achieved by the pheromone on the path by the ant agents leaved. It is based on observation and inspiration of ants' foraging behavior in the real world, i.e. ant colony can find shortest path to food, not because one ant is commanding, by relying on the information transmission mechanism in the whole colony. This information is a certain material called pheromone leaved on their path by ants. The higher the pheromone, the more ants. Therefore, the ant colony algorithm is characterized with a parallel, distributed computing, positive feedback and so on. Next, by solving the ship lock arrangement problem, the hybrid quantum ant colony algorithm will be further described.

3.3. Hybrid quantum ant colony algorithm for the ship lock arrangement problem

In the hybrid quantum ant colony algorithm for the ship lock arrangement problem, use qubits to represent pheromones on the wait ship as follows:

$$\varpi_a(g) = \begin{pmatrix} \xi_a(g) \\ \delta_a(g) \end{pmatrix} \tag{6}$$

Where $\varpi_a(g)$ is the quantum pheromone of wait ship a in *g-th* loop.

a represents the number of wait ship, $1 \le a \le p$, p represents the gross quantity of wait ships.

g represents the times of loop, $1 \le g \le n$, n represents the gross times of loops.

$\xi_a(g)$ and $\delta_a(g)$ represent the probability amplitude of wait ship a in unselected state and selected state respectively, and $|\xi_a(g)|^2 + |\delta_a(g)|^2 = 1$. $|\xi_a(g)|^2$ and $|\delta_a(g)|^2$ represent the probability of wait ship a in unselected state and selected state respectively.

Ant agent selects a wait ship according to the rule (7).

$$\eta_a^e(g) = \begin{cases} \dfrac{[h_a]^{\chi} \cdot \left[|\delta_a(g)|^2\right]^{\beta}}{\sum\limits_{b \in allowed_e} [h_b]^{\chi} \cdot \left[|\delta_b(g)|^2\right]^{\beta}} & if\ a \in allowed_e \\ 0 & otherwise \end{cases} \tag{7}$$

Where a, g, $\delta_a(g)$, and $|\delta_a(g)|^2$ have the same meaning as above.

$\eta_a^e(g)$ represents the probability that the *e-th* ant agent selects wait ship a in *g-th* loop, $0 \le \eta_a^e(g) \le 1$.

e represents the ant agent number, $1 \le e \le m$, m represents the gross quantity of ant agents.

b has the same meaning as a, $1 \le b \le p$.

h_a and h_b represent the heuristic information of the wait ship a and the wait ship b respectively, which associated with the chamber utilization.

$\left|\delta_b(g)\right|^2$ is the probability of wait ship b in selected state.

χ is the update parameter of the heuristic information, $\chi \ge 0$.

β is the update parameter of the pheromone, $\beta \ge 0$.

$allowed_e$ represents the wait ship set, in which the wait ship can be selected by the *e-th* ant agent.

After every loop, the quantum pheromone update rule is as follow.

$$\varpi_a(g+1) = \kappa \cdot \varpi_a(g) + \Delta\varpi_a \tag{8}$$

In rule (8), κ is the evaporation coefficient of the pheromone, $0 \le \kappa < 1$.

$\Delta\varpi_a$ represents the quantity of the quantum pheromone, calculated by (9).

$$\Delta\varpi_a = \sum_{e=1}^{m} \varpi_a^e \tag{9}$$

ϖ_a^e calculated by (10).

$$\varpi_a^e = \begin{pmatrix} \xi_a^e = 0 \\ \delta_a^e = \begin{cases} W \cdot f(c^e) & if\ wait\ ship\ a\ selected \\ 0 & unselected \end{cases} \end{pmatrix} \tag{10}$$

W is the parameter. $f\left(c^e\right)$ is the feasible solution produced by the *e-th* ant agent, which is associated with the chamber utilization.

Next, calculate the value of the probability amplitude of the wait ship a in unselected state.

$$\xi_a(g+1) = \sqrt{1 - \left|\delta_a(g+1)\right|^2} \tag{11}$$

After applying the rule (8), the quantum pheromone is updated by employing quantum rotation gate as follow.

$$\begin{pmatrix}\xi_a(g+1)\\ \delta_a(g+1)\end{pmatrix}=\begin{pmatrix}\cos(\rho_a) & -\sin(\rho_a)\\ \sin(\rho_a) & \cos(\rho_a)\end{pmatrix}\begin{pmatrix}\xi_a(g)\\ \delta_a(g)\end{pmatrix} \tag{12}$$

Where ρ_a represents a rotation angle, and calculated by (13).

$$\rho_a = f(\xi_a,\delta_a)\cdot\Delta\rho_a \tag{13}$$

Where $f(\xi_a,\delta_a)$ represents the ρ_a sign, it indicates the rotation direction of rotation angle. $\Delta\rho_a$ indicates the value of rotation angle. the value of $\Delta\rho_a$ and $f(\xi_a,\delta_a)$ are shown by Table 1.

Table 1

$\Delta\rho_a$ **and** $f(\xi_a,\delta_a)$

c_a	l_a	$u_c \ge u_b$	$\Delta\rho_a$	$f(\xi_a,\delta_a)$			
				$\xi_a = 0$	$\delta_a = 0$	$\xi_a\cdot\delta_a < 0$	$\xi_a\cdot\delta_a > 0$
Y	Y	T	π/40	0	±1	-1	+1
Y	Y	F	π/200	0	±1	-1	+1
Y	N	T	π/40	0	±1	-1	+1
Y	N	F	π/100	±1	0	+1	-1
N	Y	T	π/20	±1	0	+1	-1
N	Y	F	0	0	0	0	0
N	N	T	0	0	0	0	0
N	N	F	0	0	0	0	0

u_c is the chamber utilization associated with current feasible solution, u_b is the chamber utilization associated with best feasible solution. c_a represents whether the wait ship a is contained in the current feasible solution or not(Y/N). l_a represents whether the wait ship a is contained in the best feasible solution or not(Y/N).

3.4. Parameters

In the hybrid quantum ant colony algorithm for the ship lock arrangement problem, the parameters as follow.

$$m = p,\ \varpi_a(0)=\begin{pmatrix}1/\sqrt{2}\\ 1/\sqrt{2}\end{pmatrix},\ \kappa = 0.98,\ \chi = 2.0,\ \beta = 1.0.$$

3.5. Computational results

This paper designs and implements the hybrid quantum ant colony algorithm for the ship lock arrangement problem by Microsoft Visual C++ in

Windows10, analyzes with other lock arrangement algorithms in two groups of data. When the experiment and comparative analysis, this paper regards the lock chamber and wait ship as the rectangle, and the digit in the figure represents the number of wait ship.

The first group data is taken from section 3.5 given in [7], a queue of 12 wait ships. The chamber utilizations without priority of the BL algorithm, minimum horizontal line algorithm, surplus rectangle mate algorithm, genetic algorithm and improved layout model [7] are shown in Table 2.

Table 2

Comparison of 1st experimental results

Algorithm	chamber utilization	
	190×23	270×28
Genetic Algorithm	75.34	76.73
Surplus Rectangle Mate Algorithm	84.53	85.18
Minimum Horizontal Line Algorithm	73.31	71.47
BL Algorithm	59.10	66.93
Improved Layout Model	83.96	84.76
Hybrid Quantum Ant Colony Algorithm	86.36	89.13

Table 2 shows that the comparison results of the hybrid quantum ant colony algorithm with the BL algorithm, minimum horizontal line algorithm, surplus rectangle mate algorithm, genetic algorithm and improved layout model. Experimental results demonstrate that the hybrid quantum ant colony algorithm for the ship lock arrangement problem is better than other algorithms.

The chamber utilization is 86.36% by the hybrid quantum ant colony algorithm for the ship lock arrangement problem, the lock chamber size is 190 m (L)$\times$23 m (W), the simulation diagram is showed by Fig. 1. In [7], the lock chamber size is 270 m (L)$\times$28 m (W), the ship combined priority utilization and the chamber utilization can reach 88.61% and 76.94% respectively. The chamber utilization is 89.13% by the hybrid quantum ant colony algorithm for the ship lock arrangement problem without priority, the simulation diagram is showed by Fig. 2.

Fig.1. Simulation diagram of the ship lock arrangement (190×23)

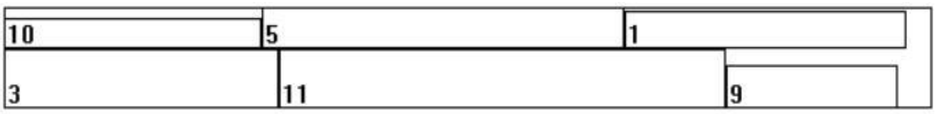

Fig.2. Simulation diagram of the ship lock arrangement (270×28)

The next group data is taken from first column of appendix 4 given in [10], a queue of 50 wait ships. The chamber utilizations of the BL algorithm, minimum horizontal line algorithm, simulated annealing algorithm, genetic algorithm and ship breadth-first algorithm [10] are shown in Table 3. Table 3 shows that the comparison results of the hybrid quantum ant colony algorithm with the BL algorithm, minimum horizontal line algorithm, simulated annealing algorithm, genetic algorithm and ship breadth-first algorithm. Experimental results demonstrate that the hybrid quantum ant colony algorithm for the ship lock arrangement problem is better than other algorithms.

Table 3

Comparison of 2nd experimental results

Algorithm	chamber utilization	
	180×23	320×32
Genetic Algorithm	78.50	77.77
Simulated Annealing Algorithm	81.50	79.10
Minimum Horizontal Line Algorithm	74.44	71.60
BL Algorithm	65.46	68.53
Ship Breadth-First Algorithm	80.10	83.79
Hybrid Quantum Ant Colony Algorithm	91.55	90.62

The chamber utilization is 91.55% by the hybrid quantum ant colony algorithm for the ship lock arrangement problem, the lock chamber size is 180 m (L) $\times$ 23 m (W), the simulation diagram is showed by Fig. 3. The chamber utilization is 90.62% by the hybrid quantum ant colony algorithm for the ship lock arrangement problem, the lock chamber size is 320 m (L) $\times$ 32 m (W), the simulation diagram is showed by Fig. 4.

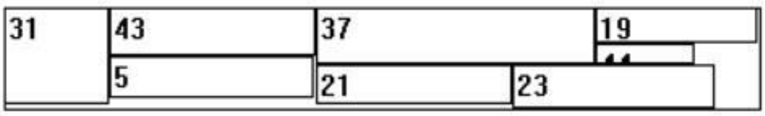

Fig.3. simulation diagram of the ship lock arrangement (180×23)

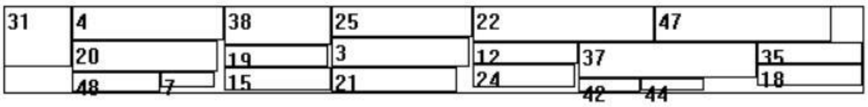

Fig.4. simulation diagram of the ship lock arrangement (320×32)

4. Conclusions

This paper analysis the calculation formula of ship lock passing ability, proposes a simplified calculation formula of the actual gross load mass of lockage in one direction per year from the aspect of the lock actual operation, proposes the concept of the ship lock arrangement problem and its constraints, designs the hybrid quantum ant colony algorithm for the ship lock arrangement problem, and implements the hybrid quantum ant colony algorithm for the ship lock arrangement problem. Through experiment and comparative analysis in two groups of data, its results demonstrate that the chamber utilization has been further improved comparing to the chamber utilization of using the BL algorithm, minimum horizontal line algorithm, simulated annealing algorithm, genetic algorithm, surplus rectangle mate algorithm, improved layout model and ship breadth-first algorithm. The realization of the hybrid quantum ant colony algorithm for the ship lock arrangement problem can provide reference for the management and operation of the lock.

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