# Optimal Design of Ship Multitasking Cabin Layout based on Interval Optimization Method

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## Abstract

Searching for the optimal cabin layout plan is an effective way to improve the efficiency of the overall design and reduce the ship's operation costs. Multitasking states of the ship is several statuses when facing different missions during voyage, such as the status of marine supply, emergency escape, etc. Human flow and logistics between cabins will change as the state changes. An ideal cabin layout plan, which directly impact upon the above two factors, can meet the different requirements of several statuses to a higher degree. There are inevitable deviations in the quantification of human flow and logistics, also, the uncontrollability exists in the flow situation during actual operation. Coupling of these deviations and uncontrollability shows typical uncertainties, which must be considered in the design process. It is vital to integrate demands of human flow and logistics in multiple states into an uncertainty parameter scheme. This research involves the uncertainty of adjacent strength and circulating strength obtained after quantifying the human flow and logistics. Interval numbers are used to integrate them, the two-layer nesting system of interval optimization is introduced, and different optimization algorithms are substituted for solving calculations. Comparing and analyzing the calculation results with deterministic optimization, the conclusions obtained can provide feasible guidance for cabin layout design.

**Keywords**: Cabin layout; Multitasking states; Uncertainty; Interval optimization; Human flow and logistics;

## Introduction

The issue of the ship cabin layout has always been an important research issue in the field of ship design. With the rapid development of computers in recent years, the intelligent requirements for cabin layout design are increasing. Scholars are doing more research in this field. A brief summary of recent research is shown in Fig. 1.

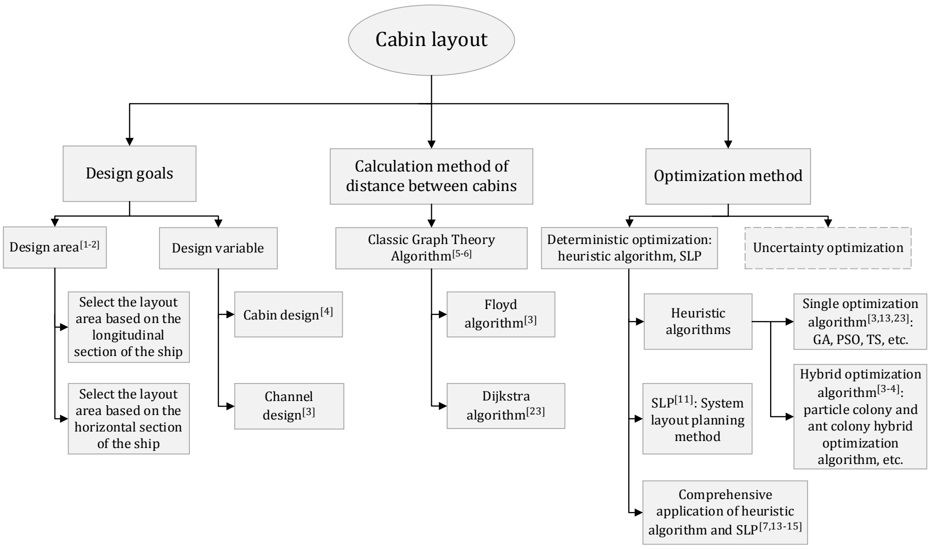


**Fig. 1** Brief summary of recent research

Most cabin layout designs draw on the thought of two-dimensional facility layout problems. The Facility Layout Problem (FLP) refers to minimizing the cost of material circulation between equipment by changing the location of equipment. Drira [9] summarized the research conducted by scholars and pointed out several research directions. Pourvaziri [10] proposed a new model of linear programming in FLP to optimize the width and number of passages and verify the effectiveness of the method through calculations. Shamsodin [11] proposed a new mathematical model for the Dynamic Facility Layout Problem, and solved the model by combining an improved genetic algorithm and a cloud model-based simulated annealing algorithm. Compared with FLP, the cabin layout problem has a more complicated system.

The cabin layout design refers to the reasonable determination of the cabins' distribution positions between the superstructure and each deck of the main hull, according to the specified performance indicators and requirements. For such problems, graph theory methods, heuristic algorithms, and system layout planning (SLP) methods are commonly used to solve them. Heuristic algorithms include genetic algorithm (GA), particle swarm optimization algorithm (PSO), and others. Among them, heuristic algorithms and SLP are more widely used in the marine field. Zhang [12] used SLP to optimize the layout of the ship meal system. Wang [13] applied an improved tabu search algorithm (TS) to optimize the design of ship cabins. In practical applications, it is more effective to combine several methods. Hu [14] and Zheng [15] comprehensively applied SLP and GA to the layout design of ship cabins and established mathematical models for an optimal solution; Li [16] introduced SLP to the problem of cabin equipment layout and combined it with GA to optimize the design.

There are multitasking states in the actual operation of ships, and there are different human flow and logistics requirements between cabins in different states. Optimizing the layout of cabins based on human flow and logistics in a state is unreasonable. The optimal plan must meet the needs of various states. It is vital to rationally integrate human flow and logistics in multitasking states into a parameter scheme. Wang [3] selected the battle state, damage control state, emergency escape state, and supply support state of the ship, and linearly weighted circulation demand in each state to solve the multi-objective model of the optimization of the ship channel layout.

Most optimization models of ship design are based on the idea of deterministic optimization, but in actual engineering problems, there are generally uncertain factors. In the optimization problem of cabin layout design, there is an error in artificially quantifying the adjacent and circulating requirements between cabins into parameters. Human flow and logistics between cabins are uncontrollable in actual operations, and the coupling shows typical uncertainties. In the multitasking state, there are a variety of human flow and logistics requirements, which makes the uncertainty more complicated.

To solve the cabin layout plan that meets the demand of human flow and logistics in the multitasking states, in the deterministic optimization method, the method of linear weighted summation is used to forcibly combine the requirements in different states, which do not have realistic interpretability. After many iterations, the uncertainty will be further coupled and amplified. The uncertainty optimization method is adopted, and the influence of uncertainty factors is fully considered in each iteration, so that the optimization process has higher stability and compatibility.

Uncertainty optimization is a reliable method that considers the influence of uncertain factors on the optimization model on the basis of deterministic optimization problems. According to the characteristics of uncertain parameters, uncertainty optimization can be divided into stochastic programming, fuzzy programming, and interval programming [17]. Interval programming, that is, interval optimization, is used to express uncertain parameters with interval numbers, and it is necessary to obtain the endpoints of the interval numbers to find the midpoint and radius of the interval. In the optimization problem of ship design, it is difficult to obtain the probability distribution of uncertain parameters and the fuzzy membership function, while it is relatively easy to obtain the endpoints of interval numbers. The initial information of uncertain parameters is not affected by the interval number, so applying the interval optimization method to ship design has certain advantages.

Based on advantages of the interval optimization method, interval optimization has been widely used in the field of ship design in recent years. Li [18] applied the interval analysis method to the uncertainty and robust design optimization, used a bulk carrier as an example to optimize the existence of a single uncertain variable and the coexistence of multiple uncertain variables; Hou [19-20] used interval numbers to describe the uncertainty of the approximate model of the wave resistance coefficient constructed by the back-propagation neural network, constructed and solved the optimization model of the minimum total resistance. He also applied the interval optimization method to the minimum EEOI hull line design and verified its feasibility and superiority through calculation examples. Wen [21] developed an interval optimization method in the power system of a hybrid ship to determine the optimal size of the solar energy and Energy Storage System (ESS) in the ship power system to reduce fuel costs. The above research reflects the applicability and superiority of interval optimization in ship design, and it is feasible to try to apply this method to the layout design of ship cabins.

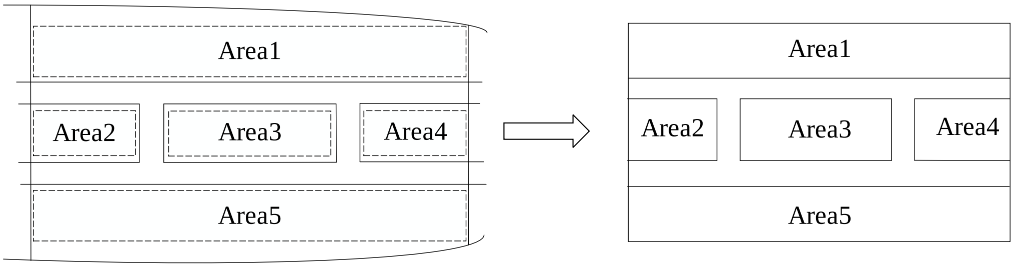
In this research, the interval optimization method is applied to the layout design of ship cabins, and the living area of the ship deck are taken as the research object while a simplified layout model is constructed. Based on the literature [22], a mathematical model is established with the cabin sequence as a design variable. Four task states are selected in the process of ship operation, and there are different adjacent and circulating strength coefficients in each state. First, deterministic optimization is carried out, and the improved genetic algorithm is used to optimize the calculation of the strength coefficient of the ship in one state and in multiple states. Then, the interval is optimized using interval numbers to represent the adjacent and circulating strength coefficients, and an optimization system of two-layer nested is applied. The outer layer uses an improved genetic algorithm to optimize the objective function, and the inner layer uses a simulated annealing algorithm to solve the interval of the objective function. Then, the results of interval optimization and deterministic optimization were compared and analysed, and the rationality and effectiveness of the interval optimization method were discussed.

## 1 Layout simplified model

To solve the optimal layout of the ship cabin layout, the two-dimensional FLP method is applied, combined with the method of multi-line layout, to simplify the cabin regions of the ship's living area.

Selecting the cabin regions of the living area to establish a simplified model is based on the regions having a neater structure, and there is less equipment in the cabin. It is assumed that the cabin layout of the living area has no effect on navigation performance, ship's weight distribution, hull's structure strength, and equipment performance [22]. The layout of stairways, doors, windows, and other accessories are not considered.

A rectangle was drawn based on the longest side and shortest side of the cabin area structure. The horizontal and longitudinal channels were used to enclose five areas inside the rectangle. The five areas are simplified into rectangles, and their layout positions remain unchanged. The simplified model of cabin layout is shown in Fig. 2.



(a) Structural frame of cabin layout (b) Simplified model of cabin layout

**Fig. 2** Simplified process of cabin layout

where: In Figure (a), the solid line represents the cabin area structure of the living area, and the dashed enclosed area represents the area to be deployed. In Figure (b), the solid line represents the simplified cabin area structure.

## 2 Mathematical model

In this research, the cabins sequence is used as a designed variable. The target's analysis is carried out from the perspective of the circulating relationship and the adjacent relationship between the cabins. The sub-objective evaluation functions are constructed separately and then linearly weighted to form the overall objective evaluation function to appraise the performance.

### 2.1 Design variable

The sequence of cabins is composed of the serial numbers of cabins in array according to the sequence of the layout positions of cabins. The cabins sequence X is expressed as:

$$X = \{x_1, x_2, x_3, \cdots, x_n\} \tag{1}$$

and

$$\begin{cases} x_k = \{x \mid x \in N^*, 1 \le x \le n\}, (k = 1,2,\cdots,n) \\ x_i \ne x_j, (i,j = 1,2,\cdots,n, i \ne j) \end{cases} \tag{2}$$

where: $n$ represents the total number of cabins to be deployed, and $x_k$ represents the serial numbers of the cabins corresponding to the location.

According to the cabins sequence $\mathrm{X}$, the distance between cabins is calculated on the basis of the simplified model that cabin layout.

Firstly, the network diagram is established with nodes and connecting lines. The cabin node is the cabin centroid. The intersection of the core and the vertical line between the channel center line and the cabin centroid is the channel node. The channel connecting line is composed of the vertical line between the channel center line and the cabin centroid and the channel center line. The deck after arranging the cabins can be abstracted as a network diagram, as shown in Fig. 3.

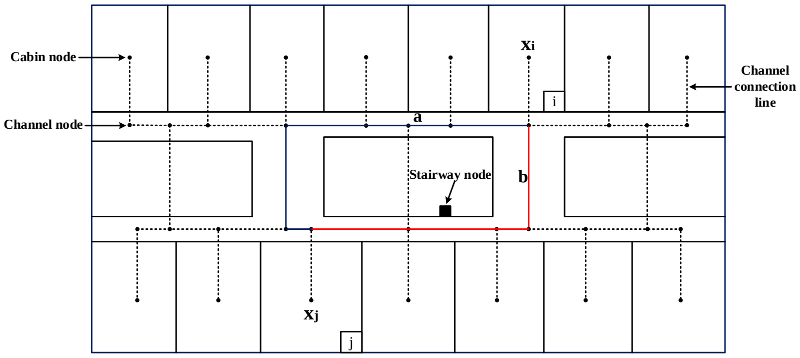


**Fig. 3** Simplified cabin network diagram

Where: stairway node is a connection node of the two decks. The shortest distance between cabin $i$ and cabin $j$ can be abstracted as the distance from point $x_i$ to point $x_j$ . There are two different paths $a$ and $b$ at the same time, and there will be up to 8 different paths between different floors of cabins.

The distance between cabins varies with paths, and choosing different path has a direct impact on the human flow and logistics between cabins. The distance between the cabins with adjacent requirements is farther. The layout efficiency and the effectiveness of the overall layout plan are even worse. Therefore, the shortest distance between cabins is an important indicator to evaluate the pros and cons of the layout plan, and it is very important to find the shortest path and distance.

Classic graph theory algorithms for solving the shortest distance include Dijkstra's algorithm, Floyd's algorithm, etc. Among them, Dijkstra algorithm is the most stable shortest path algorithm, while having the advantage of low complexity [23]. The process is shown in Fig. 4.

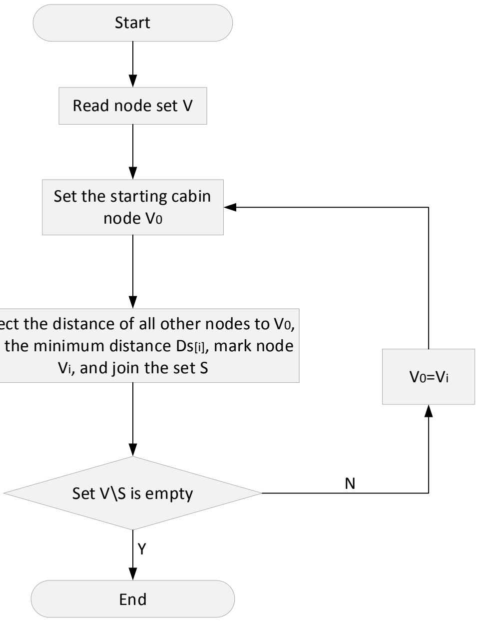


**Fig. 4** Dijkstra algorithm flow chart

The shortest distance calculated by Dijkstra algorithm is stored in the matrix $D$.

$$D = \left[d_{ij}\right]_{n\times n}, (i, j = 1,2,\cdots,n, i \neq j) \tag{3}$$

Where: $d_{ij}$ represents the shortest distance between the cabin $i$ and the cabin $j$ .

### 2.2 Sub-objective evaluation function

In the research, starting from the adjacent relationship and the circulating relationship between cabins, quantify the degree of association between cabins, and establish the adjacent sub-objective and the circulating sub-objective function.

#### 2.2.1 The target of adjacent strength

The strength of the adjacency between cabins, is the degree of adjacent requirements between two cabins to be deployed based on functional and usage requirements. Quantify it and express it in parameterized form [22]. The coefficient is represented by the number 0-1. The larger the value, the higher the adjacent demand. Storing the coefficients' value in the matrix $B$

$$B = \left[b_{ij}\right]_{n\times n}, (i, j = 1,2,\cdots,n, i \neq j) \tag{4}$$

where: $b_{ij}$ represents the value of adjacent strength coefficients between the cabin $i$ and the cabin $j$ .

Establishing adjacent strength sub-objective function $F_1(X)$ :

$$F_1(X) = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} B \times D(X) \tag{5}$$

Where:$D(X)$ represents the shortest distances' matrix between cabins.

#### 2.2.2 The target of circulating strength

The strength of the circulation between cabins mainly considers the strength of the circulating relationship between the crews in the cabin, during the daily activities of crews on the ship [22]. The coefficient is represented by the number 0-1. The larger the value, the higher the circulating demand. The coefficients' value is stored in the matrix $F$

$$F = \left[f_{ij}\right]_{n\times n}, (i, j = 1,2,\cdots,n, i \neq j) \tag{6}$$

where: $f_{ij}$ represents the value of circulating strength coefficients between the cabin $i$ and the cabin $j$ .

Establishing circulating strength sub-objective function $F_2(X)$ :

$$F_2(X)=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}F\times D(X) \tag{7}$$

### 2.3 Constraints

Constraints include location and available areas.

### 2.3.1 location

Regarding the location constraint of the cabin, this research defines it as the distance between the two cabins and the requirement that the cabin is suitably arranged in a specific position. The degree to which a cabin needs to be far from another cabin is quantified. The coefficient obtained after quantization is represented by the number 0-1. The coefficient is stored in the matrix $A$ .

$$A=\left[a_{ij}\right]_{n\times n},(i,j=1,2,\cdots,n,i\neq j) \tag{8}$$

where: $a_{ij}$ represents the value of strength coefficients between the cabin $i$ and the cabin $j$ .

The requirements for the suitable arrangement of the cabin in a specific position should be determined based on the layout of the mother ship and combined with layout standards. For example, cabin 1 and cabin 11 are suitable to be arranged in the middle of the upper deck; cabin 7, cabin 33 and cabin 44 are suitable to be arranged on the lower deck, etc.

$$\begin{cases}\{x_1,x_{11}\}\in\{1\}\\\{x_7,x_{33},x_{44}\}\in\{2\}\end{cases} \tag{9}$$

where: 1,2 represents the upper and lower decks.

### 2.3.2 Available areas

Based on the basic framework of the cabin area to be deployed, the usable area $S_i$ $(i=1,2\cdots,m)$of each row and the minimum areas' reference of each cabin $\alpha\left(x_j\right)$ $(j=1,2\cdots,n)$are obtained. The cabins sequence $X$ is sequentially arranged in the cabin area. The minimum area of the cabin arranged in each row is required to be no more than the usable area of the row.

$$\begin{cases}\alpha(x_1)+\alpha(x_2)+\alpha(x_3)\leq S_1\\\alpha(x_4)+\alpha(x_5)+\alpha(x_6)+\alpha(x_7)\leq S_2\\\cdots\\\alpha(x_{n-2})+\alpha(x_{n-1})+\alpha(x_n)\leq S_m\end{cases} \tag{10}$$

where: $m$ represents the maximum number of rows divided by the longitudinal channel, and $\alpha\left(x_j\right)$ represents the minimum areas' reference of the cabin corresponding to the location.

For the cabins sequence $X$ that meets the available areas' constraints, each row may have a remaining area, which is equally distributed to each cabin. The revised cabin area is used to determine layout parameters corresponding to cabins sequence $X$.

$$\begin{cases}\beta(x_1)+\beta(x_2)+\beta(x_3)=S_1\\\beta(x_4)+\beta(x_5)+\beta(x_6)+\beta(x_7)=S_2\\\cdots\\\beta(x_{n-2})+\beta(x_{n-1})+\beta(x_n)=S_m\end{cases} \tag{11}$$

where: $\beta\left(x_j\right)$ represents the area of the cabin after correction.

### 2.4 Overall objective evaluation function

The overall objective function $F(X)$ for optimization that cabin layout contains two sub-objective functions. In view of the uncertain importance of sub-objective functions, this research adopts linear weighting processing, and the overall objective function is expressed as follows:

$$min\,F(X)=min\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left(w_1\times b_{ij}\times d_{ij}+w_2\times f_{ij}\times d_{ij}\right) \tag{12}$$

and

$$\sum_{h=1}^{2} w_h = 1, X = \{x_1, x_2, x_3 \cdots, x_n\} \tag{13}$$

where: $w_1$ is the weighting coefficient of adjacent strength, and $w_2$ is the weighting coefficient of circulating strength. They are determined according to the importance of the sub-targets, and the sum of the two weighting coefficients is 1. The optimization goal of this research is to obtain the minimum value of the overall objective function $F(X)$ in the feasible region of the cabins sequence $X$, that is, to obtain the optimal cabins sequence $X$ that satisfies constraints. The adjacent strength and circulating strength sub-objectives can reach comprehensive optimum.

## 3 Deterministic Optimization

### 3.1 Deterministic optimization in a single task state

Before performing optimization, we must determine the initial parameters value and the initial variable for layout design.

**Table 1** Initial values of design variables and layout parameters

**Design variables:**

- Cabin sequence: X

**layout parameters:**

- Minimum area of cabin ($m^2$): $\alpha(x_j) \in \{10,12,13,15,16,17,18,19,20,26,30\}$
- Total length of the deck area (m): 40
- Total width of the deck area (m): 20
- Height between decks (m): 2.3
- Number of horizontal channels: 2
- Number of longitudinal channels: 2
- Channel width (m): 1.5

**Table 2** Initial values of strength in each state

| Task states | State 1 | State 2 | State 3 | State 4 |
|---|---|---|---|---|
| The coefficient of adjacent strength | 0.4（1-7） | 0.4（2-11） | 0.6（9-15） | 0.7（2-11） |
| | 1（33-46） | 0.3（17-27） | 0.3（35-39） | 0.5（35-39） |
| | 0.5（56-60） | 0.5（56-60） | 0.4（56-60） | 0.7（66-79） |
| | 1（66-79） | 0.5（66-79） | 0.9（66-79） | 0.5（77-78） |
| The coefficient of circulating strength | 0.6（1-4） | 0.8（9-10） | 1（41-46） | 1（13-31） |
| | 0.7（9-10） | 0.5（27-67） | 0.4（44-55） | 0.6（44-55） |
| | 0.5（41-46） | 0.5（44-55） | 0.9（50-60） | 0.4（50-60） |
| | 0.7（50-60） | 0.3（50-60） | 0.4（70-80） | 0.2（72-73） |

where: the intensity requirement is quantified as an intensity coefficient, which is represented by 0-1. The larger the value, the higher the requirement. The numbers in brackets indicate a group of cabins with strength requirements. For instance, 0.4 (1-7) means that the strength coefficient of cabin 1 and cabin 7 is 0.4.

**Table 3** Calculation cases

| Case | Optimization method | Algorithm | States |
|---|---|---|---|
| C1# | Deterministic optimization | GA | State 1 |
| C2# | Deterministic optimization | GA | State 1-4 |
| C3# | Interval optimization | GA+SA | State 1-4 |

where: C1#, C2#, C3# represent three different calculation cases.

Genetic algorithm (GA) provides a general framework for solving complex optimization problems. It does not depend on the specific field of the problem, can be flexibly improved, and has strong robustness [20].

This paper has made some improvements to the basic genetic algorithm in practical applications. For example, in the initial population generation method, the individual in the solution space of the optimization problem is directly encoded, and the decoding step is omitted, which is more convenient and feasible than the binary encoding method adopted by the basic genetic algorithm. Based on the general framework, an improved genetic algorithm suitable for solving the cabin layout model is constructed.

C1# selects state 1 for the calculation case and applies an improved genetic algorithm to calculate. The optimal solution is searched through iteration, and the optimal result of deterministic optimization is obtained after 10,000 iterations, as shown in Fig. 5. The optimal result is obtained in the 8536th calculation, represented by a red rectangle, with a value of 0.405.

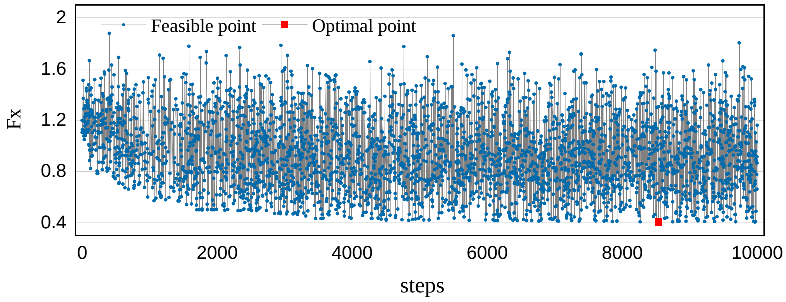


**Fig. 5** Optimization curve of overall objective function for C1#

A cabin layout result diagram is then generated after calculation, as shown in Fig. 6. The diagram shows the number of feasible solutions and optimized solutions generated by continuous calculations, and displays the fitness value of the objective function and the layout of cabins on the two decks.

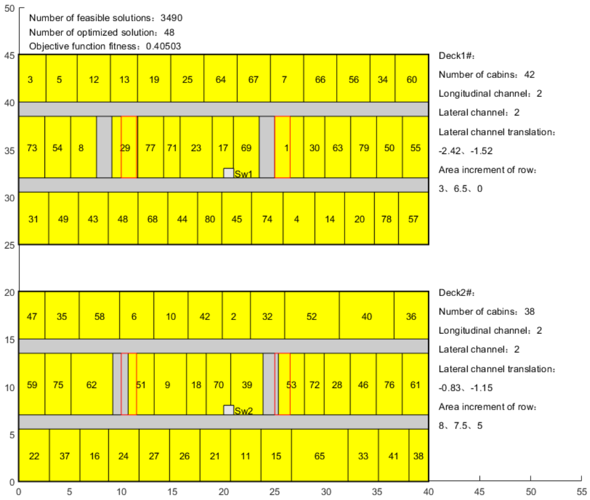


**Fig. 6** The diagram of cabin layout for C1#

where: the yellow rectangular frame in the figure represents the cabin, the number in it represents the serial number of the cabin, the grey area represents the horizontal passage and the longitudinal passage, and Sw1 and Sw2 indicate the entrance and exit of the stairway. The red rectangular frame is the originally given position of the horizontal passage, which needs to be moved due to the specific situation of the cabin layout. After movement, it is represented by the grey rectangular frame. The translation amount of the horizontal passage in the figure is caused by this. The area of each cabin in the figure is the revised cabin area $\beta\left(x_j\right)$ that satisfies the available area constraint.

### 3.2 Deterministic optimization in multitasking state

Deterministic optimization is performed in the multitasking state, and the linear weighted sum method is selected to integrate the human flow and logistics requirements in the four task states into a plan. To ensure the effectiveness of the comparison with the interval optimization results, the weight coefficient of each state $\lambda_k$ takes the weight coefficient $k_i$ used in the interval optimization below, $\lambda_i = \{0.33,0.16,0.28,0.23\}$。

In C2#, after linear weighting, the strengths of adjacency and circulation coefficients are obtained, and the improved genetic algorithm is used for calculation. The optimization curve of the overall objective function is obtained by 10,000 iterations, as shown in Fig. 7, where the 8941st calculation obtains the optimal result, represented by a red rectangle with a value of 0.4219.

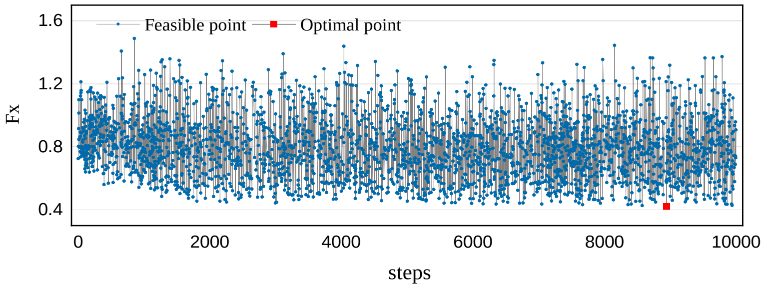


**Fig. 7** Optimization curve of overall objective function for C2#

After calculation, the layout result diagram is generated, as shown in Fig. 8.

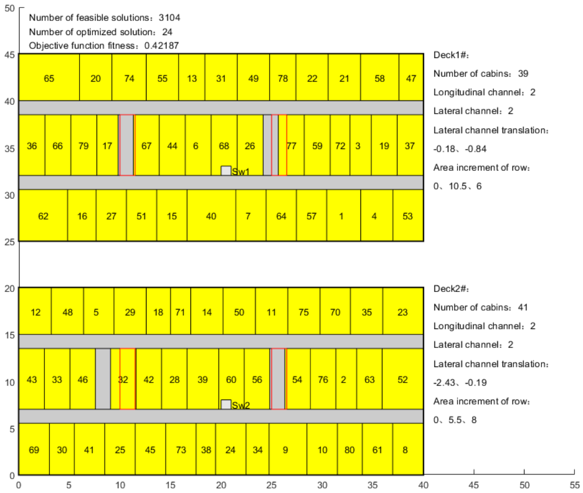


**Fig. 8** The diagram of cabin layout for C2#

# 4 Interval Optimization

## 4.1 Determination of the number of intervals

Based on the superiority of the interval optimization method in the field of ship design, the method is selected to optimize the cabin layout in a multitasking state. The interval number is a kind of numerical value represented by the interval, which can be expressed as [24],

$$A^I = [A^L, A^R] \tag{14}$$

where:$A^L, A^R$ represent the upper and lower limits of the interval number, $A^L, A^R \in R$ and $A^L \leq A^R$, when $A^L = A^R$, $A^I$ is a real number.

The number of intervals is determined by the coefficient values of the adjacent strength and circulating strength in multitasking states combined with the weight of its state. The weight of each state is determined by integrating the proportion of the state in the entire operating life cycle and experts' opinions.

$$k_i = \frac{w_i \bar{w}_i}{\sum_{i=1}^{n} w_i \bar{w}_i} \tag{15}$$

and

$$\sum_{i=1}^{n} k_i = 1 \tag{16}$$

where: $w_i$ represents the proportion of the state in the entire operating life cycle, $\overline{w}_i$ represents the proportion of experts' opinions, $k_i$ represents the weight of the target state, and $n$ represents the number of target states.

Combining the weights of multitasking states to determine the end point of the interval number.

$$p_s = \left[a_i, a_j\right] \tag{17}$$

and

$$o = \frac{a_1 + a_s}{2}\ , a_j > a_i$$

$$\begin{cases} m = num\{a_w < o \mid w \in [1, s]\} \\ n = num\{a_u > o \mid u \in [1, s]\} \\ m + n \leq s \end{cases} \tag{18}$$

$$\begin{cases} a_i = o - (a_s - a_1) \times \dfrac{\sum_{i=1}^{m} k_i}{\sum_{i=1}^{s} k_i} \\ a_j = o + (a_s - a_1) \times \dfrac{\sum_{i=s-n+1}^{s} k_i}{\sum_{i=1}^{s} k_i} \end{cases}$$

where: $p_s$ represents the number of intervals of adjacent and circulating strength coefficients in various states. $a_i$ , $a_j$ represent the upper and lower limits of the interval, and $a_i < a_j$. $s$ indicates that the coefficient exists in several states. $o$ represents the midpoint of the interval. $num$ represents the number of elements in the set. $m$ represents the number of coefficient values less than the midpoint, $n$ represents the number of coefficient values greater than the midpoint. $k_i$ represents the weight of the target state. $\{a_1, a_2, \cdots, a_s\}$ represent the coefficient values in different states, and it is assumed that they are arranged in $1 - s$ from small to large.

The main idea of determining the end point of the interval number is to move the end point based on the weight of the midpoint according to the task state, as shown in Fig. 9.

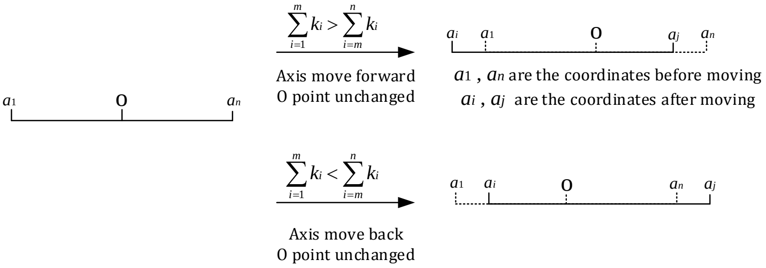


**Fig. 9** Determining end points of the interval number

### 4.2 Theory of interval optimization

This research uses interval numbers to describe uncertain variables. The main idea is to use the midpoint and radius of the objective function to judge the pros and cons of different design variables, thereby obtains a deterministic objective function.

$$opt\ \ minf_p = min\left\{(1-\beta)\mu\big(f(X, p_m)\big) + \beta\omega\big(f(X, p_m)\big)\right\} \tag{19}$$

and

$$\begin{cases} \mu\big(f(X, p_m)\big) = \frac{(min\, f(X, p_m) + max\, f(X, p_m))}{2} \\ \omega\big(f(X, p_m)\big) = \frac{(min\, f(X, p_m) - max\, f(X, p_m))}{2} \end{cases} \tag{20}$$

where: $\beta$ is the weight coefficient, which satisfies $0 \leq \beta \leq 1$ ,and generally takes 0.5, $\mu\big(f(X, p_m)\big)$ is the midpoint of the objective function, and $\omega\big(f(X, p_m)\big)$ is the radius of the objective function.

The above optimization model is an optimization problem with interval numbers, and its corresponding objective function is not a specific real number in the optimization iteration, but an interval number. Therefore, the interval analysis method needs to be integrated into the entire optimization process to realize the calculation of interval numbers. Without considering the optimization strategy, the optimization problem is transformed into a two-layer nested optimization problem. A two-layer nested optimization system is used for uncertainty optimization [25], and the structure is shown in Fig. 10.

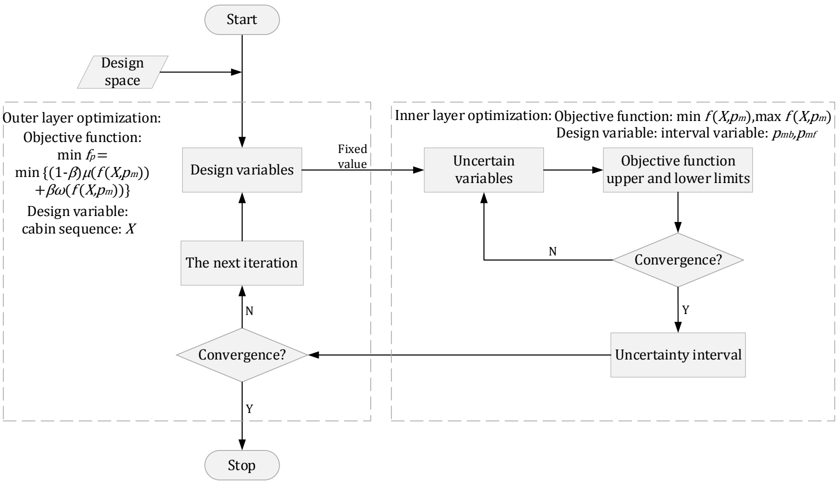


**Fig. 10** Two-layer nested structure

The outer layer optimization is used to search for design variables, and the inner layer optimization is used to calculate the interval of uncertain objective function. That is, the individual design variables are generated through outer layer calculations. Each individual uses the inner algorithm to obtain the uncertain objective function and constraint interval. Then it is transformed into the objective function of deterministic optimization.

The task of outer layer optimization is to generate individual design variables with wide coverage in the global scale. The algorithm used is required to have a strong traversal search ability. The improved genetic algorithm is based on the general framework of GA, and combined with some improvements in the issue of cabin layout. It has fast random search capability and strong robustness, and can be better adapted to the issue of cabin layout optimization after improvement.

Inner layer optimization is the core of the uncertain optimization system. It has high requirements on the local search capability and computational efficiency of the algorithm. The simulated annealing algorithm (SA) [26] has been proved to be strict and effective by long-term research and application. Compared with other intelligent algorithms, it has the advantages of wide application range, simple algorithm and easy realization. Its search method can effectively avoid falling into local optimal solution and obtain a global optimal solution with high reliability, which is more suitable for the calculation of cabin layout optimization.

Before optimization, we must determine the end points of the interval number, and apply formula (15) to calculate the weights of the four task states, $k_i = \{0.33,0.16,0.28,0.23\}$.

The number of intervals is determined by the values of the intensity coefficient under each state, combined with the weight occupied.

**Table 4** Interval values of adjacent strength and circulating strength

| Number of intervals | Values | Corresponding cabins group |
|---|---|---|
| Number of adjacent strength | [0.427,0.727] | （2-11） |

| | | |
|---|---|---|
| intervals $p_{mb}$ | [0.29,0.49] | （35-39） |
| | [0.414,0.514] | （56-60） |
| | [0.555,1] | （66-79） |
| Number of Circulating strength intervals $p_{mf}$ | [0.683,0.783] | （9-10） |
| | [0.48,0.98] | （41-46） |
| | [0.39,0.59] | （44-55） |
| | [0.366,0.966] | （50-60） |

C3# applies the interval optimization method. The outer optimizer selects an improved genetic algorithm and sets 10,000 iterations. The inner optimizer selects the simulated annealing algorithm, sets the initial temperature of 10000C, the end temperature of 0.01C, and the temperature attenuation coefficient of 0.9. The optimal result of interval optimization is obtained after iterative optimization, as shown in Fig. 11. Among them, the optimal result is obtained in the 8663rd calculation, which is represented by a red rectangle alone with a value of 0.4920.

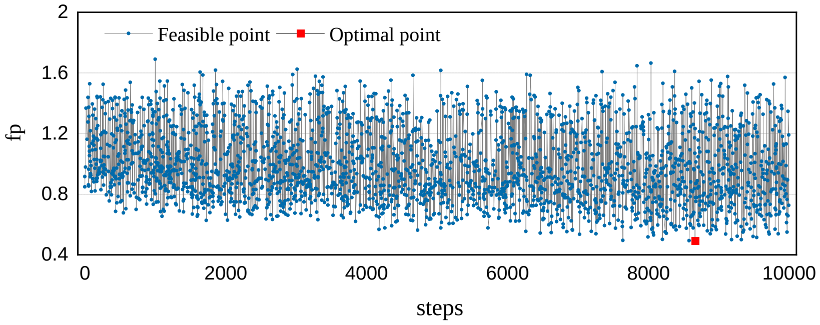


**Fig. 11** Optimization curve of overall objective function for C3#

When the optimal solution is obtained, the curve of the minimum value $min\, f(X, p_m)$ and the maximum value $max\, f(X, p_m)$ of the objective function in the inner optimizer is as shown in Fig. 12. Generating a layout diagram of the interval optimization results, as shown in Fig. 13.

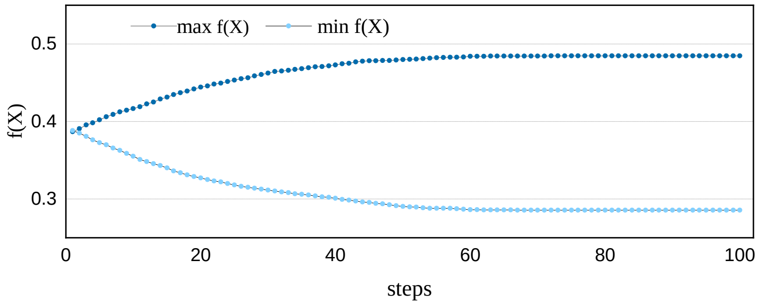


**Fig. 12** Optimization curve of maximum value and minimum value

where: The two curves represent the change curve of $\min f(X, p_m)$ and $\max f(X, p_m)$. As the number of SA iterations increases, the values tend to be stable. The minimum and maximum values of the objective function in the inner optimizer are obtained.

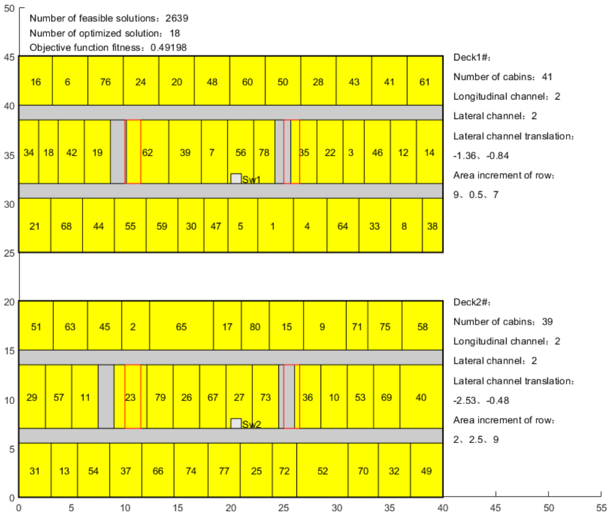
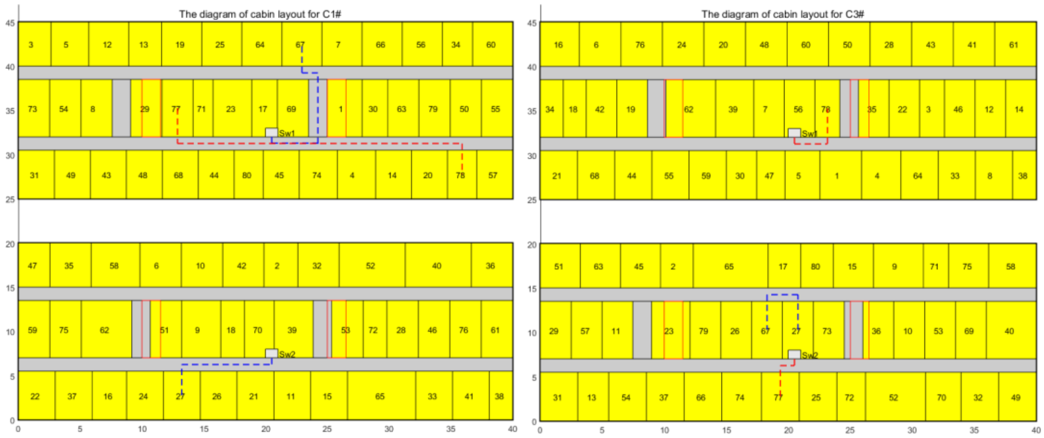


**Fig. 13** The diagram of cabin layout for C3#

## 4.3 Results and analysis

According to the calculated results, compare the advantages and disadvantages of interval optimization and deterministic optimization.

### 4.3.1 Comparing the shortest paths



(a) Shortest paths in C1#　　(b) Shortest paths in C3#

**Fig. 14** Comparison of distance between C1# and C3#

where: selecting the cabin groups (27-67), (77-78) to compare its shortest path and shortest distance. The red dotted line represents the shortest path between cabin groups (77-78), the blue dotted line represents the shortest path between cabin groups (27-67).

It can be seen that the distance between the two paths in Fig. 14 (b) is significantly smaller than in Fig. 14 (a), and the two sets of cabins are more closely arranged. Interval optimization can better meet the needs of proximity between cabins. These two groups of cabins have adjacent and circulating requirements in states 2 and 4, respectively. Compared with deterministic optimization, which only considers state 1, interval optimization fully considers the influence of various states, which can better meet the layout requirements of cabins.

(a) Shortest paths in C2#　　　　(b) Shortest paths in C3#

**Fig. 15** Comparison of distance between C2# and C3#

where: selecting the cabin groups (9-15), (72-73) for comparison. The red dotted line represents the shortest path between cabin groups (9-15), the blue dotted line represents the shortest path between cabin groups (72-73).

From the comparison of (a) and (b) in Fig. 15, it can be seen that the distance between the two sets of cabins under the two methods is relatively small, which can better meet the needs of proximity between the cabins. Under the cabin layout obtained by the interval optimization, the distance between the two groups of cabins is smaller, and the obtained cabin layout is more reasonable. Compared with deterministic optimization considering multiple states, interval optimization has higher applicability and effectiveness for cabin layout problems in multitasking states.

On the whole, interval optimization can consider the layout requirements of multitasking states, and at the same time, it can efficiently obtain a cabin layout plan that meets the demands of the immediate vicinity as much as possible. The method of interval optimization is used to solve the problems of cabin layout in various states, which has high applicability and stability.

### 4.3.2 Comparing the optimization results

**Table 5** Comparison of optimization results of three cases

| Calculation cases | Fitness values | Number of iterations |
|---|---|---|
| C1# | 0.405 | 8536th |
| C2# | 0.4219 | 8941st |
| C3# | 0.492 | 8663rd |

According to table 5, the fitness curves are drawn as shown in Fig. 16.

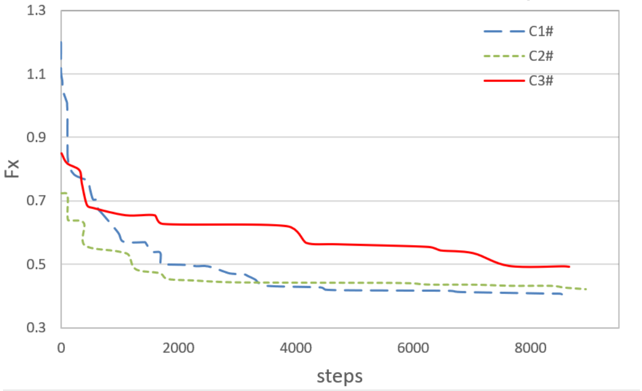
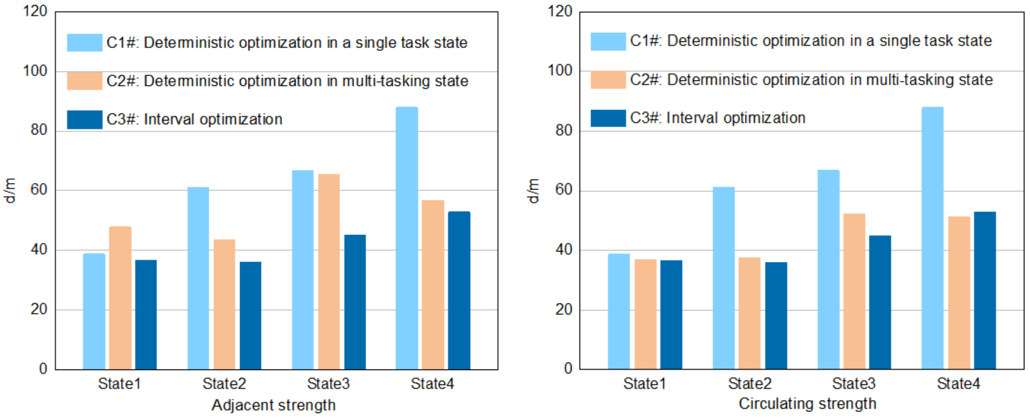


**Fig. 16** The curve of optimal adaptive value of three methods

From Table 5 and Fi. 16, C1 # and C2 # curves tend to be stable faster, while C3 # curves tend to be stable slower. Compared with interval optimization, deterministic optimization has better robustness. The fitness value of deterministic optimization is lower than those of interval optimization. In contrast, deterministic optimization can better meet requirements of design objectives.

In order to better compare the advantages and disadvantages of the three methods, the distance

$d$ between cabins with adjacent requirements is summed according to the state, as shown in Fig. 17.



(a) The sum of cabins' distances with adjacent strength (b) The sum of cabins' distances with circulating strength

**Fig. 17** The sum of cabins' distances with adjacent and circulating strength

As shown in Fig. 17, the sum of distances of C1# in State 1 is small, while the sum of distances in other states is relatively large. It only considers the requirements in State 1, so the compatibility of requirements in States 2, 3, and 4 is extremely poor.

C2# fluctuates greatly in the sum of the cabins' distances under each state of the adjacent strength, and its distance is higher than C1# in State 1, while the distances under State 2, 3, and 4 are all smaller than C1#. The sum of the cabins' distances in each state under the circulating strength is relatively even, and the distance in each state is less than C1#. The smaller the distance between the cabins on demand, the better the adjacent and circulating requirements between the cabins can be met, and the higher the degree of completion of the layout of cabins. Therefore, the linear weighted sum method is used to integrate the requirements of multiple states, which is highly effective and can better consider the multitasking states of the ship.

In C3#, the sum of the cabins' distances under each state of adjacent strength and circulating strength is relatively average, and its distance value is less than C1# in each state. Compared with C2#, although the distance is not much different in a small part of the state, the distance is smaller in most of the states. The smaller the distance, the more able to meet the adjacent and circulating needs between the cabins, and the higher the completion of the cabin layout.

Although deterministic optimization has higher robustness, the interval optimization method is used to solve the problem of cabin layout in various states, which has extremely high applicability and effectiveness, and has a high degree of compatibility for multitasking states in the ship operation process.

## 5 Conclusions

Considering the different intensities and uncertainties of human flow and logistics under different states, the methods of deterministic optimization and interval optimization are respectively adopted, and after a series of calculations, analysis, and comparison, the following conclusions are obtained:

(1) Based on multitasking states, compared to deterministic optimization that only considers the demands of the immediate vicinity in a single state, the use of interval optimization can better consider the demands of multiple states. Compared with the method of linear weighting to integrate the demands under multitasking states, the representation of interval numbers can effectively obtain a better cabin layout plan. Applying the method of interval optimization to the cabin layout problem can effectively solve the problem of layout optimization and has high applicability, stability, and compatibility.

(2) In deterministic optimization, an improved genetic algorithm is applied to obtain a more reasonable plan of cabin layout after calculations. The algorithm has good applicability in the field of cabin layout. In the interval optimization, a two-layer nesting system is used: the outer layer optimization and the inner layer optimization have different optimization goals, and the improved genetic algorithm and the simulated annealing algorithm are selected, respectively. After calculation

and analysis, reasonable and reliable optimization results are obtained, so applying GA and SA algorithms to interval optimization has high applicability and applying different optimization algorithms in the two-layer nested system can improve the effectiveness and reliability of the optimization process.

(3) In the research, interval numbers are used to represent uncertain factors, then fuzzy numbers and random numbers can be used to quantify uncertain factors, and uncertainties can be analysed to further explore and solve their influence.

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