

Multi objective optimization of ship spare parts maintenance based on Improved Genetic Algorithm

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Abstract. For ship equipment turnover spare parts, if the maintenance interval is too long, the safety and working ability will be reduced; if frequent maintenance is performed, it will cause much waste. Therefore, it is necessary to determine the appropriate maintenance interval for resource optimization. The article analyzes the factors of turnover spare parts maintenance resource optimization. It establishes an equipment parts maintenance time resource optimization model based on maintenance theory and multi-objective decision-making methods, which can ensure the familiar training environment, maintenance type, and update type preventive maintenance mode. The satisfaction is the largest, and group decision making and improved genetic algorithm are used to solve the optimal satisfaction. Finally, the effectiveness of the model is verified with examples of ship equipment spare parts.

1 Introduction

According to the maintenance attributes, equipment parts are divided into turnover parts, consumable parts, and life-limited parts. Turnover parts refer to the features that can be returned to the factory for maintenance, and they are generally large parts with a relatively high price; the consumable parts usually are some small parts, such as sealing ring, gasket, plug, etc., which are discarded when they are used up; the life-limited parts refer to the elements with life, which can be directly replaced after reaching a particular service time, such as the engine of an aircraft^[1].

For the ship turnover equipment spare parts, the maintenance time resource optimization is mainly to optimize the maintenance plan, determine the reasonable maintenance time, improve maintenance efficiency and equipment availability, and reduce the maintenance cost. Time resource optimization is mainly to select the appropriate maintenance cycle and carry out maintenance at a reasonable time, to minimize the downtime of equipment^[2]. Regular maintenance usually needs to choose the maintenance interval, which refers to replacing or maintaining equipment according to a specific break. It is suitable for the equipment with fixed distribution law and can predict the time interval of failure^[3]. If the maintenance interval is too long, the safety and working ability will be reduced. If the maintenance is carried out frequently, it will cause a lot of cost waste. Therefore, it is essential to determine the appropriate maintenance interval^[4].

The determination process of maintenance interval is complicated, which is usually determined by two

reference indexes: (1) refer to the equipment with the same model; (2) assess its initial value according to the manufacturer's instructions or the method recommended by the supplier^[5,6]. However, the two reference index parameters have a more human experience, extensive selection flexibility, and lack of strict logic. Besides, some scholars use the reliability of equipment, utilization rate, average interval between failures, failure consequences, maintenance costs and risks, depreciation life, and losses avoided by preventive maintenance to determine the maintenance interval. For example, in reference^[5], through analyzing the incomplete maintenance process of components, this paper examines the time weakening of repairable parts with the quasi renewal process method and takes the total maintenance cost as the objective function to obtain the purchased quantity and purchase time under the optimal economic condition. In this paper, the spare parts support model is established according to the different spare parts support rate. In reference^[8], the maintenance interval was determined by other optimization objectives, and the minimum variance control was used to reduce the mean square deviation of inventory, to minimize the robustness of the stock of aviation materials.

Besides, the maintenance cycle can not be considered from the perspective of a single factor and comprehensive calculation. The multi-objective decision-making is of great significance to improve the support rate, enhance reliability, and ensure its regular operation. In this paper, we improve the previous equipment maintenance support model, combine with the actual equipment parts procurement, based on the maintenance theory, consider the different maintenance model of equipment parts and

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maintenance time resource optimization model.

2 The basic theory of goal programming

Objective programming was proposed by A. Charnes and W. W. Cooper in 1961. Its fundamental idea is that multiple optimization objectives often contradict each other in the multi-objective optimization decision-making model. There are intense conflicts, and the measurement units are different, resulting in the optimization results of some unsatisfactory goals. To ease the competition and consider the benefits of multiple objectives, the decision-maker can set the expected value in advance according to the actual situation. By introducing the deviation variable, the objective function is transformed into a constraint condition, and a new constraint condition group is formed with the original constraint condition. By introducing the priority and weight coefficient of objectives, a new single objective function is constructed, and then the multi-objective problem is transformed into a single objective problem for solving^[9].

The general form of multi-objective programming is as follows:

$$\min f(t, d^+, d^-) = \sum_{k=1}^n w_k (\lambda_k^+ d_k^+ + \lambda_k^- d_k^-)$$

$$s.t. \begin{cases} f_k(t) + d_k^- - d_k^+ = f_k^*(t > 0) \\ d_k^+ \geq 0 \\ d_k^- \geq 0 \\ \lambda_k^+ \geq 0 \\ \lambda_k^- \geq 0 \end{cases} \quad (1)$$

Where, f_k^* is the target value; t is the time; d_k^+, d_k^- is k -th the positive and negative deviation variable of the first goal, and $d_k^+ \cdot d_k^- = 0$; w_k is the weight of the k -th goal, and $\sum w_k = 1$; λ_k^+, λ_k^- is the weight of d_k^+, d_k^- of the k -th goal, and $\lambda_k^+ + \lambda_k^- = 1$.

3 Maintenance cycle model of ship equipment parts based on maintenance theory

The calculation of turnover process and maintenance cycle of repairable parts for warship equipment is as follows: starting from the collection of reliability data of equipment parts maintenance items, the life distribution model is determined through parameter estimation and hypothesis test, and the mathematical model of hypothetical maintenance mode is established, and the equipment parts maintenance interval is determined through simulation calculation. The optimal maintenance cycle of ship equipment parts is usually determined by the reliability of the mission, the system's effectiveness and cost, and the economy of fault loss.

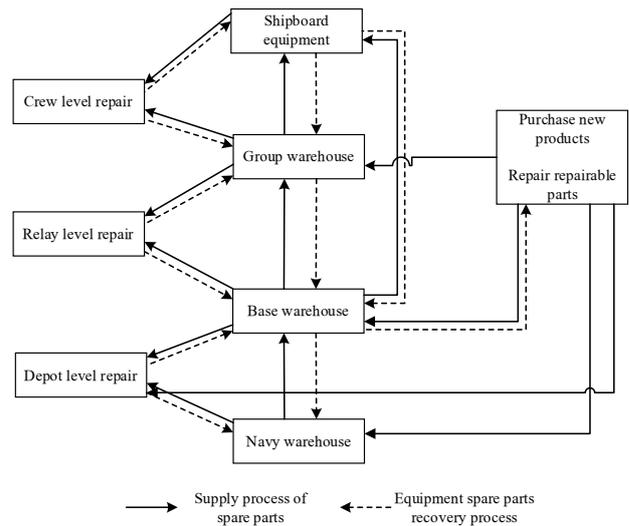


Fig1. Turnover process of repairable ship equipment parts

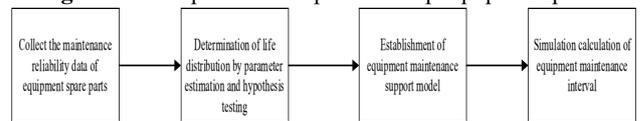


Fig2. Process of determining maintenance interval based on reliability data

3.1 Maintenance cycle of ship equipment parts considering mission reliability

The reliability of the equipment parts is as follows:

$$R(t + \Delta t | t) = \frac{R(t + \Delta t)}{R(t)} = e^{-\int_t^{t+\Delta t} \lambda(t) dt} \quad (2)$$

Where: $R(t + \Delta t | t)$ is reliability; maintenance cycle $T = \Delta t$; $\lambda(t)$ is failure rate.

3.2 Maintenance cycle of ship equipment materials considering maximum effectiveness

Before the preventive maintenance of equipment parts, there may be some parts that have not reached the maintenance time but has already broken down and needs to be repaired. Repair and maintenance are divided into maintenance type and renewal type[5]. These two kinds of repair and maintenance can restore the function of the system or equipment parts, but due to the different depth of recovery, the working time of the renewal type is calculated from zero; while the maintenance type, that is, the change of equipment failure rate function with time is not disturbed by minor repair, and the working time is not calculated from zero, but is calculated together with the period before the failure. As shown in Figure 3, preventative maintenance can also be divided into maintenance type preventative maintenance and renewal preventative maintenance, T_{pm} is preventative maintenance time, T_{cm} is repaired maintenance time, and $T_A + T_B = T$.

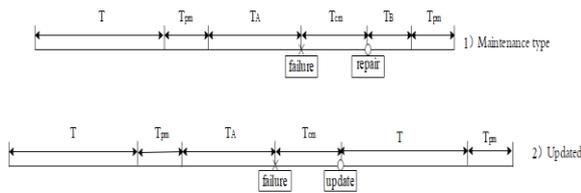


Fig3. Preventive maintenance mode

3.2.1 Maintenance type preventive maintenance:

$$EY = T \tag{3}$$

$$MTBR = \overline{T_{pm}} + \overline{T_{cm}} \int_0^T \lambda(t) dt \tag{4}$$

The effectiveness of the equipment parts is

$$A = \frac{EY}{EY + MTBR} = \frac{T}{\overline{T_{cm}} \int_0^T \lambda(t) dt + \overline{T_{pm}} + T} \tag{5}$$

Where: EY is the average available time in each cycle; $MTBR$ is the average shutdown time in each cycle; $\overline{T_{pm}}$ is the average preventive maintenance time; $\overline{T_{cm}}$ is the average repair and maintenance time.

3.2.2 Updated preventive maintenance:

$$\begin{aligned} EY &= T[1 - F(T)] + F(T) \int_0^T t dF(t) \\ &= R(T)T - \int_0^T t \frac{dR(t)}{dt} dt \\ &= \int_0^T R(t) dt \end{aligned} \tag{6}$$

Where: $\int_0^T t f(t) dt$ is the average value of working time before failure T_A ; $R(T)$ is the probability of working without fault for T hours.

$$MTBR = R(T)\overline{T_{pm}} + F(T)\overline{T_{cm}} \tag{7}$$

The effectiveness of the equipment parts is as follows:

$$A = \frac{EY}{EY + MTBR} = \frac{\int_0^T R(t) dt}{\int_0^T R(t) dt + R(T)\overline{T_{pm}} + \overline{T_{cm}}F(T)} \tag{8}$$

3.3 Maintenance cycle of ship equipment parts considering maintenance economy

The maintenance support economy mainly considers maintenance costs, including maintenance, replacement of spare parts, depreciation of maintenance equipment, consumption of maintenance labor, etc. Maintenance cost mainly includes preventive maintenance cost and repair maintenance cost. To ensure the reliability of equipment parts, a certain amount of maintenance funds are usually allocated. However, the more the maintenance support costs are, the better. If the maintenance support costs are too much, they will cause losses and waste, and if they are too small, they will not meet the support requirements. Therefore, it is necessary to constrain the cost allocation according to the relationship between the maintenance cycle and support cost.

3.3.1 Maintenance type preventive maintenance:

The average cost in a single period is:

$$C(T) = \frac{C_{pm} + C_{cm} \int_0^T \lambda(t) dt}{T} \tag{9}$$

Where: C_{pm} is the preventive maintenance cost; C_{cm} is the repair and maintenance cost; $\lambda(t)$ is the failure rate; $C(T)$ is the single cycle average cost.

3.3.2 Updated preventive maintenance:

The average cost per unit time is:

$$C = \frac{C_{pm}R(T) + C_{cm}[1 - R(T)]}{\int_0^T R(t) dt} \tag{10}$$

4 Weight determination of multi objective fuzzy group decision making

The factor set is $X = \{x_1, x_2, x_3\}$, x_1 means the maximum reliability, x_2 means the maximum availability and x_3 means the maximum economy (minimum cost). The fuzzy set of elements in X is determined, $w = \{w_1, w_2, w_3\}$. Through consulting the business personnel of equipment and equipment department and 20 experts of military academy, and combining their experience, fill in the questionnaire. According to the evaluation criteria, the weights of the three indexes are obtained. The expert's opinion can be expressed as $P = \{p_1, p_2, p_3 \dots p_{20}\}$.

The factor set is $X = \{x_1, x_2, x_3\}$. x_1 means the maximum reliability, x_2 represents the full availability and x_3 indicates the maximum economy (minimum cost). The fuzzy set of elements in X is determined as $w = \{w_1, w_2, w_3\}$. By consulting the equipment and equipment department's business personnel and 20 experts of the military academy, and combining their experience, fill in the questionnaire. According to the evaluation criteria, the weights of the three indexes are obtained. The expert's opinion can be expressed as $P = \{p_1, p_2, \dots p_{20}\}$.

Average weight of equipment index:

$$a_1 = a(x_1, P_j) = \frac{1}{20} \sum_{j=1}^{20} a(x_1, P_j)$$

$$a_2 = a(x_2, P_j) = \frac{1}{20} \sum_{j=1}^{20} a(x_2, P_j)$$

$$a_3 = a(x_3, P_j) = \frac{1}{20} \sum_{j=1}^{20} a(x_3, P_j)$$

a_1, a_2 and a_3 were normalized from the mean value of the questionnaire:

$$w_1 = w(x_1) = \frac{a_1}{a_1 + a_2 + a_3} = 0.3$$

$$w_2 = w(x_2) = \frac{a_2}{a_1 + a_2 + a_3} = 0.4$$

$$w_3 = w(x_3) = \frac{a_3}{a_1 + a_2 + a_3} = 0.3$$

The scoring criteria are shown in Table 1.

Table1. expert evaluation criteria

Score	Evaluation criteria
1	Slightly important
3	More important
5	Obviously important
7	Obviously important
9	Strongly important
2,4,6,8	The Importance is between the two
10	Must be guaranteed

5 Multi-objective decision making of equipment parts maintenance based on Improved Genetic Algorithm

Modern naval warfare requires that the maintenance interval of warship equipment parts should be more task-oriented reliability and system effectiveness, and the maintenance support cost should also meet the constraint of mission support cost. The task's reliability usually determines the maintenance interval, the system's energy and value, and the economy of the failure loss. These three factors are generally mutually balanced and restricted: when the higher reliability of the task and the effectiveness of the system are required, the more significant maintenance and maintenance cost is needed, and the reliability of the equipment parts task and the usefulness of the system will be achieved when the maintenance support cost is reduced Degree can not meet the requirements. In general, different tasks are executed, and the target weight is often additional. High intensity and short-term combat tasks require higher mission reliability and system effectiveness; on the contrary, low-intensity, long-term combat tasks put forward higher requirements for saving support costs [7].

Traditional mathematical programming and biological evolution are the main methods to solve multi-objective optimization problems. Traditional methods decompose the multi-objective optimization problem into a single objective situation, which requires high-quality solutions. The algorithm has low searchability and cannot find specific location points; the biological evolution algorithm has a robust global optimization search ability by simulating the natural law to search the optimal solution. The traditional genetic algorithm has low local searchability in the later stage, so it is not easy to improve the operation speed and convergence accuracy.

In this paper, three operators in the traditional genetic algorithm are improved to improve the algorithm's optimization ability.

1) Improved selection operator: improved roulette method, changed to direct panning

The individuals with small fitness should be eliminated, and the excellent individuals should be inherited to the next generation. According to the individual fitness, all

individuals in the population are sorted from small to large, and then the population is divided into four parts from small to large. The first individual is eliminated, and the middle two copies are copied and left to the next generation. The last individual replicates two documents and goes it to the next generation. The population number and parent generation of the next generation remain unchanged.

2) Improved crossover operator: crossover mode is divided into single-point crossover and multiple crossovers

In this paper, point crossing is a single point crossover is selected to carry out cross-exchange among individuals. When the similarity s is less than r , the crossover is conducted. When the similarity s is not less than r , the crossover is not allowed. Because in the initial stage of population evolution, the difference between individuals will be more massive, and the contrast of similarity will be smaller. By making the crossover threshold smaller, the convergence speed can be improved. With the development of evolution, the differences between individuals are reduced, and the similarity is increased. By increasing the cross threshold, the convergence performance is improved.

Assuming that there are two binary coded parent individuals, the two children's similarity is defined as:

$$s = \frac{c}{n} \tag{11}$$

Where: s is the similarity; c is the maximum length of the common substring of two individuals; n is the length of chromosome coding.

Assuming that the chromosome code of an individual is 10101011 and that of chromosome b is 10101000, then the common substring of two individuals is 101010 with the maximum length of $c = 6$ and $n = 8$. According to the similarity formula, $s = 3 / 4$ and dynamic crossover threshold r , as the evolution algebra increases, the formula is as follows:

$$r = \frac{1 + g \times G^{-1}}{3} \tag{12}$$

Where: g is the current evolution algebra; is the set total evolution algebra.

3) Improved mutation operator: using modified adaptive mutation algorithm: When the fitness value of the individual before mutation is less than the average fitness of the population, the mutation probability is adjusted to a more considerable amount, and through the transformation, the individual fitness value gradually approaches the excellent individual; when the personal fitness is greater than the average fitness of the population, the mutation probability is adjusted to a smaller value [11].

$$P_m = \begin{cases} P_{\max} - (P_{\max} - P_{\min}) \times \frac{f - f_{avg}}{f_{\max} - f_{avg}}, & f \geq f_{avg} \\ P_{\max}, & f < f_{avg} \end{cases}$$

Where: P_m is the mutation probability; P_{\max}, P_{\min} are the maximum and minimum mutation probability; f is the fitness before the mutation, f_{avg} is the average fitness of each population, and f_{\max} is the fitness of the largest individual in the population.

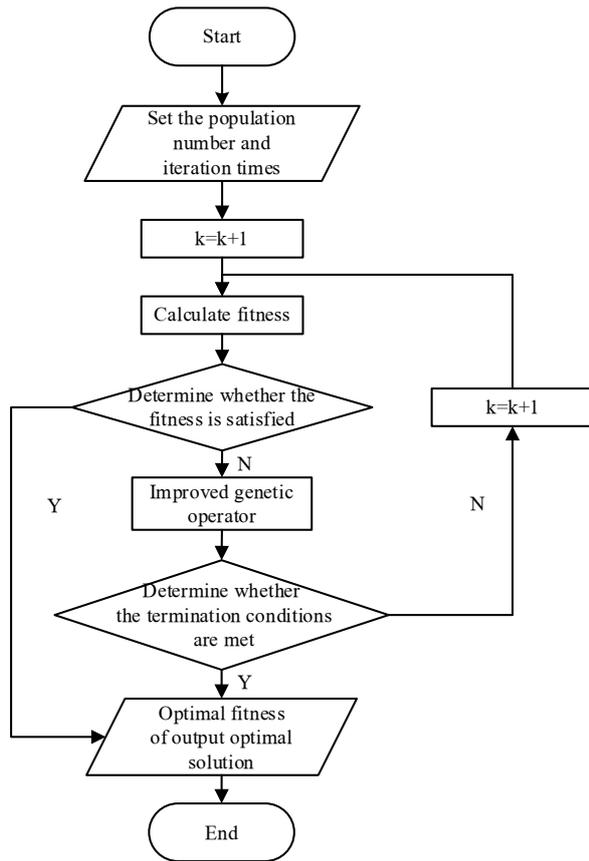


Fig4. Flow chart of improved genetic algorithm

6 Case Calculation

Taking the failure data of the flap system of carrier based aircraft in reference^[10] as an example, the determination model of maintenance task interval is verified. The functional inspection data of equipment are shown in Table 2.

Table2. fault data d

Serial number	life span	Serial number	life span	Serial number	life span
1	10	14	524	27	265
2	34	15	1160	28	11
3	90	16	232	29	94
4	423	17	234	30	270
5	233	18	241	31	426
6	240	19	523	32	523
7	527	20	526	33	529
8	97	21	93	34	1860
9	1143	22	30	35	235
10	1890	23	272	36	13
11	94	24	430	37	35
12	97	25	1157	38	529
13	11	26	529	39	1876

After K-means clustering, the parameters of reliability function are estimated and tested for the data of cluster center points, and the reliability follows exponential distribution^[10]:

$$R(t) = e^{-\lambda t}, \lambda = \frac{1}{330.58}$$

Life distribution function:

$$F(t) = 1 - R(t) = 1 - e^{-\frac{t}{330.58}}$$

6.1 Maintenance type preventive maintenance

Let $f_1(t)$, $f_2(t)$ and $f_3(t)$ denote reliability, availability and economy respectively: $f_1(t) = R(t) = e^{-\frac{t}{330.58}}$

Substituting formula $f_1(t)$ into equation (5), we get the following results:

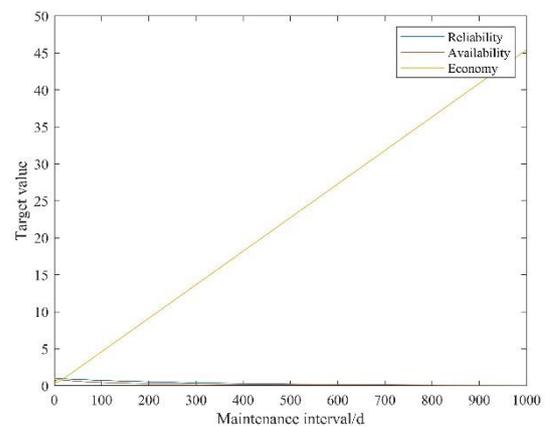
$$f_2(t) = \frac{T}{T + \bar{T}_p + \bar{T}_c} \frac{t}{330.58}$$

Substituting formula $f_1(t)$ into equation (9), we get the following results:

$$f_3(t) = \frac{C_{pm} + C_{cm} \frac{t}{330.58}}{T}$$

The maintenance interval is determined by comprehensively considering the reliability, availability and economy. Assuming that the average repair maintenance cost C_{cm} is 60 times of the preventive maintenance cost C_{pm} , the average repair maintenance time \bar{T}_{cm} is 8 times of the average preventive maintenance time \bar{T}_{pm} , $C_{pm} = 10,000$ yuan, $\bar{T}_{pm} = 0.5$ day, then $C_{cm} = 600,000$ yuan, $\bar{T}_{cm} = 4$ day. $w_1 = 0.30$, $\lambda_1^+ = 1$, $\lambda_1^- = 0$; $w_2 = 0.40$, $\lambda_2^+ = 1$, $\lambda_2^- = 0$; $w_3 = 0.30$, $\lambda_3^+ = 0$, $\lambda_3^- = 1$. The reliability and availability are required to be as large as possible, and the economy is getting higher and higher, that is, the target value is required.

According to the calculation, the equipment adopts the maintenance type preventive maintenance. Under the normal training environment, the maintenance type: the optimal regular inspection interval $T = 39.8066d$, $f_1^* = 0.8866$, $f_2^* = 0.6670$, $f_3^* = 0.9017$. The results are shown in Figure 5.



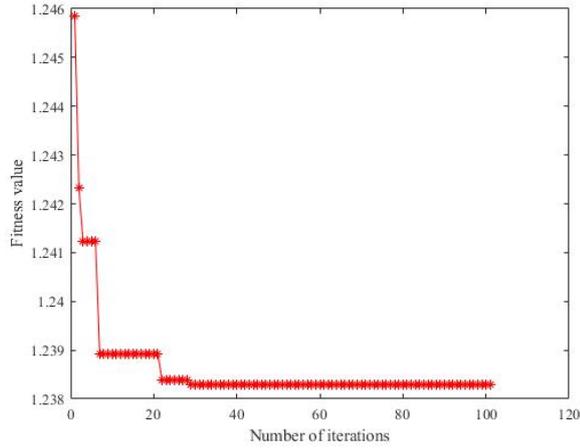


Fig5. Maintenance preventive maintenance interval (traditional genetic algorithm)

6.2 Updated preventive maintenance

Similarly, the model of renewal preventive maintenance is as follows:

$$\min f(t, d^+, d^-) = \sum_{k=1}^3 w_k (\lambda_k^+ d_k^+ + \lambda_k^- d_k^-)$$

$$s.t \begin{cases} f_1(t) + d_1^- - d_1^+ = f_1^* \\ f_2(t) + d_2^- - d_2^+ = f_2^* \\ f_3(t) + d_3^- - d_3^+ = f_3^* \\ d_k^+ \geq 0, d_k^- \geq 0 \\ t \geq 0 \end{cases}$$

$$f_1(t) = R(t) = e^{-\frac{t}{330.58}}$$

Substituting formula $f_1(t)$ into equation (6), we get the following results:

$$f_2(t) = \frac{\int_0^T e^{-\frac{t}{330.58}} dt}{\int_0^T e^{-\frac{t}{330.58}} dt + e^{-\frac{t}{330.58}} T_{pm} + T_{cm}} \left[1 - e^{-\frac{t}{330.58}} \right]$$

Substituting formula $f_1(t)$ into equation(10), we get the following results:

$$f_3(t) = \frac{C_{pm} e^{-\frac{t}{330.58}} + C_{cm} \left[1 - e^{-\frac{t}{330.58}} \right]}{\int_0^T e^{-\frac{t}{330.58}} dt}$$

As a result of $f_1(t)$ is an exponential function, the derivation of $f_3(t)$ shows that when the optimal economy is reached, the optimal maintenance interval does not exist. Due to the derivation of $f_3(t)$, it is found that $f_3(t)$ decreases monotonically. When the optimal economy is reached, the optimal maintenance interval does not exist. The reliability, availability and economy are also considered, and the weight coefficients. $w_1 = 0.30, \lambda_1^+ = 1, \lambda_1^- = 0; w_2 = 0.40, \lambda_2^+ = 1, \lambda_2^- = 0;$

$w_3 = 0.30, \lambda_3^+ = 0, \lambda_3^- = 1.$ According to the calculation, the equipment adopts the renewal preventive maintenance, and the optimal regular inspection interval under the usual training environment $T = 16.0467 d,$ $f_1^* = 0.9526, f_2^* = 0.9213, f_3^* = 0.0761.$ The results are shown in Figure 6.

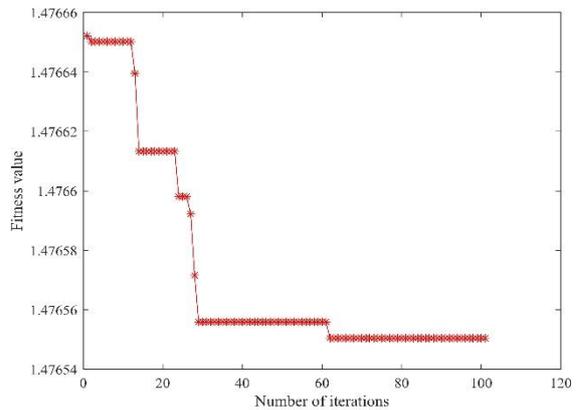
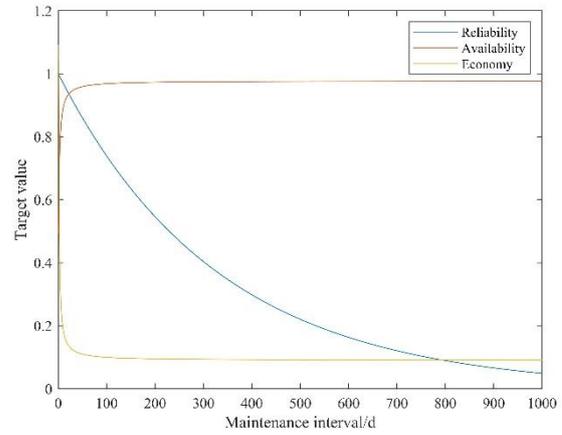


Fig6. Updated preventive maintenance interval (traditional genetic algorithm)

According to the needs of users, the best periodic replacement interval is customized under certain use conditions. For example, if a unit carries out combat readiness duty task for a long time, the weight of availability can be increased; if a unit carries out long-distance transportation task for a long time, the weight of reliability can be increased; if the maintenance cost is too high due to unreasonable maintenance planning in the past, the weight of maintenance cost can be increased.

6.3 Comparison between improved genetic algorithm and traditional genetic algorithm

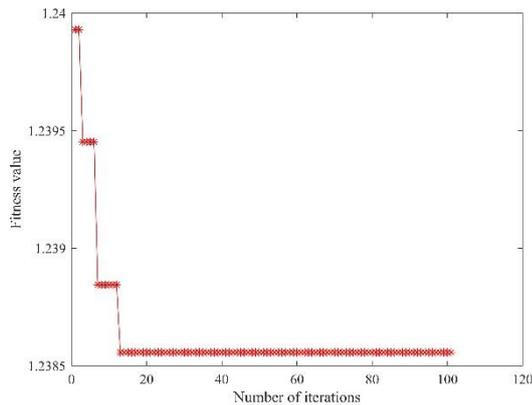


Fig7. Calculation of maintenance preventive maintenance interval efficiency by improved genetic algorithm

Maintenance type: optimal $T = 39.0884 d$, $f_1^* = 0.8885$, $f_2^* = 0.6629$, $f_3^* = 0.9182$.

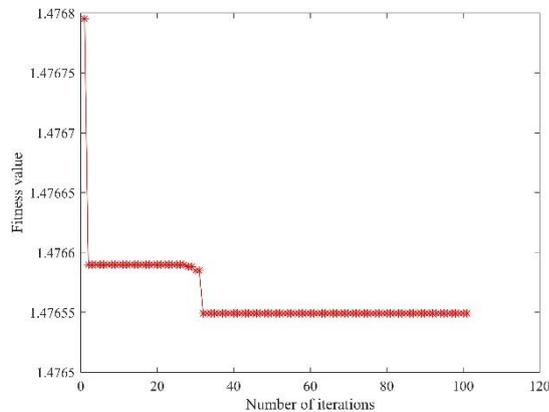


Fig8. Calculation of maintenance interval efficiency by improved genetic algorithm

Renewal type: optimal $T = 15.0760 d$, $f_1^* = 0.9554$, $f_2^* = 0.9178$, $f_3^* = 0.0783$.

The improved genetic algorithm calculates the preventive maintenance efficiency of maintenance type and renewal type, as shown in Fig. Seven and Fig. 8. Through the comparison, it is found that the improved genetic algorithm has more vital searchability than the traditional genetic algorithm, the operation speed and convergence accuracy are improved, and it is more convenient to find the optimal solution of the model.

7 Concluding Remarks

The maintenance time resource optimization model of equipment parts is established based on the maintenance theory and multi-objective optimization decision-making method. The K-means clustering is used to cluster the life of maintenance items, and the maximum likelihood estimation of clustering points is carried out to obtain the reliability function of maintenance items. The multi-objective fuzzy group decision-making method is used to determine the weight, and the improved genetic algorithm is used to solve the multi-objective decision-making model. Under different task environments, the maintenance type preventive maintenance mode and the renewal type

preventive maintenance mode have the maximum satisfaction degree of equipment parts maintenance. The optimal maintenance interval is obtained through the simulation calculation, which has a specific value for making a reality maintenance plan. It has guiding significance.

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