Research on Dynamic Resource Allocation and Decision-making Model of Equipment Independent Maintenance

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Abstract: This paper defines the relevant concepts and research objects of equipment independent maintenance, and defines the basic framework of resource allocation and decision-making model of independent maintenance. The solution method and key technology of resource allocation and decision model of equipment independent maintenance under dynamic demand condition are studied. Finally, the model is solved and the results are compared and analyzed with an example, which provides a meta-heuristic intelligent optimization algorithm that does not depend on the problem itself, and provides a thought and reference for the independent maintenance of equipment.

1. The introduction

The equipment independent maintenance support system is a multi-layer, multi-level and multi-factor super network structure, and the optimization decision of maintenance support is unstructured and complex. For actual maintenance support activities, information integration and resource sharing among the nodes of the equipment use layer, the equipment maintenance layer and the resource supply layer is an important goal of the Autonomic Logistics System (ALS), driven by the evaluation information of the Remaining Useful Life (RUL). This paper takes the minimum transportation time, the lowest transportation cost and the satisfaction rate of spare parts as the goals to extend the resource allocation and decision of equipment independent maintenance under the conditions of static demand and dynamic demand. It Solve the best maintenance resource allocation scheme.

2. Configuration and decision process

There are two main features of ALS (Autonomic Logistics System) and JDIS (Joint Distributed Information System) when compared to traditional maintenance and maintenance support processes.

Therefore, in ALS, maintenance and support behaviors at different levels, such as equipment use, equipment maintenance and resource supply, also reflect different characteristics. For the equipment use-maintenance interlayer network, the purpose of ALS is to change the equipment maintenance strategy from the current ex post maintenance and preventive maintenance strategy to a state-based maintenance and a small amount of preventive maintenance (with the possibility of a small amount of ex post maintenance) with the help of PHM, and to promote the formation of a two-level maintenance assurance system.
As for the equipment supply-maintenance inter-layer network, the purpose of ALS is to realize the full integration of maintenance assurance information and the full sharing of maintenance resources with the support of JDIS. Due to the randomness of equipment performance degradation and failure, according to the rigid chain resource-maintenance support strategy, there may be an imbalance between equipment failure, maintenance capacity and resource supply capacity, leading to the shortage or surplus of local maintenance tasks and resource supply capacity in the maintenance support system. In order to optimize and balance the maintenance support capacity and resources, a cooperative spare parts supply strategy at the grass-roots level between the leap-level spare parts supply in the maintenance support network and the maintenance support link is considered.

The operation process of ALS is shown in Figure 2. Each equipment user shall conduct health assessment and tracking of equipment or components (collectively referred to as UUM) with appropriate state monitoring and detection and RUL assessment methods, and report maintenance requirements to ALSDC in real time. Maintenance units and inventory management units at all levels are responsible for collecting and managing their own maintenance support strength (including the ability and status of maintenance personnel, the type and quantity of spare parts inventory, etc.) and reporting to ALSDC; ALSDC is responsible for managing maintenance support requirements in the entire maintenance support system, assigning maintenance support tasks and supplying and scheduling
maintenance support resources according to the corresponding maintenance support response mechanism.

3. Build a model
Among the description models for the allocation and decision of independent maintenance resources, the multi-spare parts warehouse, multi-purpose loading unit and multi-spare parts supply model are the most common cases, which have generality. Therefore, we give the general form of the model for this case.

(1) Problem description
In the supply model of multiple warehouses for spare parts, multiple loading units and multiple types of spare parts, there are multiple loading units for spare parts. These spare parts are in multiple warehouses for spare parts, so it is necessary to coordinate transportation among multiple warehouses for the supply guarantee of spare parts.

(2) Build a model
According to the above problem description, the decision model of multiple loading units, multiple spare parts warehouses and multiple kinds of spare parts supply can be built.

\[
\begin{align*}
\text{min } & \sum_{h \in H} \sum_{j \in J} \phi_j \left( f^{(1)}(t) \right) dt + \int_{t_{j}}^{t_{j+1}} f^{(2)}(t) \, dt + \int_{t_{j}}^{t_{j+1}} f^{(3)}(t) \, dt + \cdots + \int_{t_{j}}^{t_{j+1}} f^{(n)}(t) \, dt \\
\text{s.t. } & \sum_{j=1}^{m} x_{ij} \leq a_{ih}, \quad h \in H \\
x_{ij} & \leq G_{ij}, \quad i \in I, \quad j \in J, \quad h \in H \\
\phi_{ij} & \leq f^{(1)}(t_{ij}), \quad l \in I, \quad j \in J, \quad h \in H \\
f^{(l+1)}(t) & = f^{(l)}(t) - x_{ij}, \quad l \in I, \quad j \in J, \quad h \in H \\
& x_{ij} \geq 0, \quad l \in I, \quad j \in J, \quad h \in H \\
f^{(l)}(t) & \geq 0, \quad l \in I, \quad j \in J, \quad h \in H \\
\phi_{ij} & \geq 0, \quad l \in I, \quad j \in J, \quad h \in H 
\end{align*}
\]

Equation (1) is the objective function to minimize the total system loss; Equation (2) indicates that the supply of spare parts should be less than the maximum quantity available; Formula (3) indicates that the supply of spare parts should be less than the maximum capacity; Formula (4) indicates that the supply of spare parts at any time is less than the demand of spare parts; Formula (5) represents the spare parts demand function; Equations (6) and (7) indicate that the resource supply must be non-negative; Equation (8) indicates that the spare parts demand function is non-negative.

4. Modeling of independent maintenance resource allocation and decision optimization based on dynamic demand

4.1 An optimization model of independent maintenance resource network for dynamic equipment
Objective function 1: the minimum total cost of product supply, namely:

\[
\begin{align*}
\text{min } & C_1 = C_{\text{open}} + C_{\text{trans}} + C_{\text{invent}} + C_{\text{short}} 
\end{align*}
\]
Among them, $C_{ij}^{open}$ represents the opening cost of a transit point, $C_{ij}^{trans}$ represents transportation cost, $C_{ij}^{invent}$ represents the inventory cost of the product at the transit point, $C_{ij}^{short}$ represents missing part loss. Costs are calculated as follows:

$$C_{ij}^{open} = \sum_{j \in J} C_{ij}^{open} \cdot y_{ij}^t, \quad t = 1, 2, \cdots, T$$

$$C_{ij}^{trans} = \sum_{i \in I} \sum_{j \in J} C_{ij}^{trans} \cdot x_{ij}^t + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} C_{jk}^{trans} \cdot x_{jk}^t, \quad t = 1, 2, \cdots, T$$

$$C_{ij}^{invent} = \sum_{j \in J} C_{ij}^{invent} \cdot (\sum_{i \in I} x_{ij}^t - \sum_{i \in I} x_{ij}^n) \cdot x_{ij}^t, \quad t = 1, 2, \cdots, T$$

$$C_{ij}^{short} = \sum_{k \in K} C_{ij}^{short} \cdot d_{ij}^t - \sum_{j \in J} x_{ij}^t \cdot x_{ij}^t, \quad t = 1, 2, \cdots, T$$

Objective function 2: the shortest total time of product supply, namely:

$$\min \sum_{i \in I} \sum_{j \in J} C_{ij}^{trans} \cdot x_{ij}^t + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} C_{jk}^{trans} \cdot x_{jk}^t, \quad t = 1, 2, \cdots, T$$

The model meets the following constraints:

$$\sum_{i \in I} x_{ij}^t \leq y_{ij}^t \cdot U_{ij}, \quad t = 1, 2, \cdots, T$$

$$\sum_{k \in K} x_{ij}^t \leq y_{ij}^t \cdot U_{ij}, \quad t = 1, 2, \cdots, T$$

$$\sum_{j \in J} d_{ij}^t \leq 1, \quad t = 1, 2, \cdots, T$$

$$\sum_{k \in K} x_{ij}^t \leq \sum_{i \in I} x_{ij}^t, \quad t = 1$$

$$\sum_{k \in K} x_{ij}^t \leq \sum_{i \in I} x_{ij}^t + \sum_{i \in I} \sum_{j \in J} x_{ij}^t \cdot \sum_{k \in K} x_{ij}^n \cdot x_{ij}^t, \quad t = 2, 3, \cdots, T$$

$$\sum_{i \in I} x_{ij}^t \leq U_{ij}, \quad t = 1$$

$$\sum_{i \in I} \sum_{j \in J} (\sum_{i \in I} x_{ij}^t - \sum_{k \in K} x_{ij}^t) \leq U_{ij}, \quad t = 2, 3, \cdots, T$$

$$x_{ij}^t \in N^+, \quad x_{jk}^t \in N^+, \quad y_{ij}^t = \{0, 1\}$$

Among them, constraints (15) and (16) mean that unopened transit points cannot participate in the supply of products;

Constraint (17) specifies the product requirements that must meet the demand points;

Constraints (18) and (19) are flow balance constraints;

Equation (18) stipulates that if there is no inventory at the first stage transfer point, the output of the product shall not exceed the input;

Formula (19) stipulates that when there is inventory at the transfer point of each stage starting from the second stage, the output of the product shall not exceed the sum of the input and the stock;

Constraints (20) and (21) are capacity limiting constraints;

Equation (20) stipulates that if there is no inventory at the first stage transfer point, the input quantity of the product shall not exceed the maximum capacity;

Formula (21) stipulates that in the case of inventory, the sum of product input quantity and inventory quantity shall not exceed the maximum capacity;

Constraint (22) specifies the type of decision variable.
4.2 Calculation examples and experimental Settings

An equipment independent maintenance network consists of 2 supply points, 4 transfer points and 6 demand points. The product supply task can be completed in 5 stages. The product demand, missing parts loss and transportation costs at different demand points in different stages are different. The specific relevant information is shown in Table 1 to Table 2.

Table 1 Transportation cost of unit product between nodes (100 yuan)

| Transit point 1 | Transit point 2 | Transit point 3 | Transit point 4 |
|----------------|----------------|----------------|----------------|
| s.p. 1         | 20/25/30/40/50 | 30/35/40/45/50 | 26/32/40/45/35 |
| s.p. 2         | 30/35/45/50/30 | 12/15/16/20/22 | 35/38/40/45/55 |
| Demand point 1 | 2/2.5/3/3.2/3.8 | 1/1.5/1.6/1.9/2.2 | 1.5/1.8/2/2.6/3 |
| Demand point 2 | 1.5/2.2/5/3.3/3.2 | 1.6/1.8/1.8/2.3/3 | 0.5/0.8/1/1.1/1.2 |
| Demand point 3 | 0.6/1.1/2/1.6/2 | 3/2.3/3.5/3.8/4 | 1.2/1.5/2/2/2.3 |
| Demand point 4 | 2.6/2.8/3/3.6/4 | 3/2.6/4.8/5/3.5 | 2.2/2.6/3.2/3.5 |
| Demand point 5 | 2.2/2.6/3/3.2/3 | 1/2.5/3/3.5/4 | 1.2/1.6/1.5/2.3 |
| Demand point 6 | 2.2/3.2/6/3/3.2 | 1/2.5/3.5/3.6/4 | 1/1.2/1.2/2.3/5 |

Note: The data in each column from left to right are the transportation costs from the first stage to the fifth stage.

Table 2 Transportation time of unit product between nodes (hours)

| Transit point 1 | Transit point 2 | Transit point 3 | Transit point 4 |
|----------------|----------------|----------------|----------------|
| s.p. 1         | 5/6/8/10/15    | 5/8/10/12/6    | 6/7/8/9/10     |
| s.p. 2         | 10/12/14/16/18 | 4/5/6/8/10    | 6/7/9/10/12    |
| Demand point 1 | 0/4/0.5/0.8/1.2 | 0.6/0.7/0.6/1.1 | 0.5/0.8/1.1/1.2 |
| Demand point 2 | 0.5/0/0.6/0.7/0.8 | 0.2/0.3/0.3/0.5/0.6 | 0.5/0.8/1.1/1.2 |
| Demand point 3 | 0.6/0.8/0.8/1.2 | 0.3/0.2/0.5/0.8/0.9 | 0.2/0.5/0.6/0.8/1 |
| Demand point 4 | 0.5/0.8/1/1/1   | 0.4/0.6/0.4/0.8/1 | 0.2/0.3/0.3/0.5/0.5 |
| Demand point 5 | 0/2.4/0.5/0.6/0.8 | 0.2/0.2/0.3/0.4/0.5 | 0.8/0.9/1.1/2.2 |
| Demand point 6 | 0/2.3/0.6/0.8/1 | 0.3/0.5/0.6/0.6/0.7 | 1/1.2/1.2/3.1/5 |

Note: The data in each column are the delay time from the first stage to the fifth stage from left to right.

The experiment uses MATLAB 2014b for programming on Windows 7 operating system, and the platform is a personal notebook (Intel Core i5-6300HQ (2.3GHz/L3) CPU and 4.00GB RAM). The relevant experimental parameters are set as follows: population size \(N = 100\), maximum number of iterations \(\text{max}_\text{iter} = 500\), number of stages \(\text{period} = 5\), the environment changes once every 100 generations, environmental change counter: \(t = \left\lfloor \frac{\text{iter}}{\text{max}_\text{iter} / \text{period}} \right\rfloor \), \(t_0 = 1\), initial environmental change detection factor \(\text{Detector} = 0\), initial constraint violation penalty coefficient \(M_o = 10000\), initial variation rate \(F_0 = 0.9\), and crossover rate \(CR = 0.8\).

4.3 The calculation results

DSMODEA algorithm is used to solve the model, and the optimal supply scheme at each stage is obtained. Due to space problems, all supply schemes obtained at all stages cannot be presented, so this paper only illustrates the supply scheme with an optimization result. Table 3 shows an example of a
supply scheme, and the opening of transit points and the supply quantity of products between nodes can be obtained by combining the coding method of DSMODEA algorithm. Results analysis is mainly based on the fitness function and objective function corresponding to each scheme.

| Model Phase III Supply Scheme |
|--------------------------------|
| $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 17    | 8     | 15    | 16    | 0     | 3     | 4     | 9     | 0     |
| $x_{10}$ | $x_{11}$ | $x_{12}$ | $x_{13}$ | $x_{14}$ | $x_{15}$ | $x_{16}$ | $x_{17}$ | $x_{18}$ |
| 8     | 4     | 0     | 2     | 0     | 5     | 0     | 3     | 0     |
| $x_{19}$ | $x_{20}$ | $x_{21}$ | $x_{22}$ | $x_{23}$ | $x_{24}$ | $x_{25}$ | $x_{26}$ | $x_{27}$ |
| 3     | 0     | 2     | 5     | 1     | 6     | 0     | 5     | 6     |
| $x_{28}$ | $x_{29}$ | $x_{30}$ | $x_{31}$ | $x_{32}$ | $x_{33}$ | $x_{34}$ | $x_{35}$ | $x_{36}$ |
| 1     | 8     | 5     | 5     | 0     | 1     | 1     | 1     | 1     |

Then $x_1 \sim x_4$ refers to the product supply from supply point 1 to four transfer points in turn, and $x_5 \sim x_8$ refers to the product supply from supply point 2 to four transfer points in turn. $x_9 \sim x_{14}$, $x_{15} \sim x_{20}$, $x_{21} \sim x_{26}$ and $x_{27} \sim x_{32}$ respectively refer to the product supply from four transfer points to six demand points; $x_{33} \sim x_{36}$ represents the opening of the four transfer points, 1 represents the opening and 0 represents the closing, so all the four transfer points under this scheme are open.

Fig. 3 is the distribution of the optimal solution obtained at each stage in the target space. The horizontal axis is fitness function 1, and the vertical axis is fitness function 2. One optimal solution is obtained in the first stage, nine optimal solutions are obtained in the second stage, four optimal solutions are obtained in the third stage, and one optimal solution is obtained in both the fourth and fifth stages. It can be seen that the optimal solution set in each stage is not governed by each other.

![Figure 3 Pareto front of optimal solution at each stage](image)

| Table 4 Solving results of DSMODEA algorithm |
|---------------------------------------------|
| Fitness function 1 | Fitness function 2 | Cost (100 yuan) | Time (h) |
|---------------------|---------------------|-----------------|----------|
| The first stage     |                      |                 |          |
| 2105.5              | 343.5               | 2105.5          | 343.5    |
| 2607.8              | 580.1               | 2607.8          | 580.1    |
| 2531.8              | 599.1               | 2531.8          | 599.1    |
| 2707.8              | 553.1               | 2707.8          | 553.1    |
| 2600.8              | 596.1               | 2600.8          | 596.1    |
| 2651.8              | 575.1               | 2651.8          | 575.1    |
| 2503.8              | 610.1               | 2503.8          | 610.1    |
| 2654.8              | 566.1               | 2654.8          | 566.1    |
| 2435.8              | 614.1               | 2435.8          | 614.1    |

The second stage
Table 4 gives the fitness function and objective function values of each optimal solution. It can be seen from Table 4 that the fitness function of all optimal solutions is equal to the corresponding objective function. According to the fitness function expression in 1.4, the constraint value corresponding to all optimal solutions is zero, that is, all solutions are feasible solutions. At the same time, the two fitness function values of the optimal solution are compared to verify that the optimal solution is not dominated by each other at each stage.

In order to study the influence of the change of the optimal environment (the change of supply stage) on the algorithm, the convergence of the fitness function of the elite individuals under the following two population environmental change response strategies was compared. The results are shown in Fig. 4 (a) and Fig. 4 (b), respectively. Fig. 4 (a) shows the results of randomly initializing the population after environmental changes, denoted as Strategy 1. Fig. 4 (b) is the result of inheriting the previous generation population and entering the next environment for optimization after environmental changes, denoted as Strategy 2. It can be seen that the change rule of the two fitness functions is the same, and the fluctuation of the inherited population is much smaller than that of random initialization when the environment changes. This is because the new population uses the information of the previous population and can converge quickly. Therefore, DSMODEA algorithm adopts the environmental change response strategy inherited from the previous generation population.

The algorithm under response strategy 2 is equivalent to decomposing the dynamic optimization problem into multiple single-stage static optimization problems, and then optimizing them separately. It can be seen from Figure 2 that static optimization needs to be initialized and re-optimized at each stage respectively, which is of great computational cost. The dynamic optimization makes use of the information of the previous stage, and the fluctuation is small when the environment changes, and the dynamic optimization can quickly converge. Since response strategy 2 mainly optimizes the initial population when the environment changes each time and replaces random initialization with the inherited population of the previous generation, this process does not increase the amount of calculation and does not change the framework of the algorithm, so it will not affect the complexity of the algorithm. The advantage of this strategy is that the initial population after optimization is closer to the optimal solution set, so the optimization process can be accelerated. The overall optimization cost of the dynamic optimization algorithm is far less than that of the static optimization algorithm, and with the increase of the number of stages, this advantage becomes more obvious.
In order to verify the effectiveness of the adaptive flight strategy proposed in this paper in solving the dynamic multi-objective optimization problem, the model in this paper was solved respectively when the Levy flight strategy was not adopted and when the Levy flight was performed with full probability, and the results were compared with those of DSMODEA algorithm. Table 5 shows the solution results without Levy flight strategy. It can be seen from the table that the fitness function value of the desired result is much larger than the target value, that is, the constraint violation degree is large and it is an infeasible solution. And the cost and time of each optimal solution in Table 5 are much greater than the results in Table 4. This is because when Levy flight is not taken, the diversity of the population is poor, and the algorithm is easy to fall into local optimal. Table 6 is the result of Levy flight with full probability, and the results of all stages are also infeasible solutions, but the constraint violation degree is relatively small. At the same time, the cost and time spent are also greater than the results in Table 6. This is due to the full probability Levy flight, the algorithm in the later period is not conducive to convergence.

Table 5 does not take Levy flight solution results

|                | Fitness function 1 | Fitness function 2 | Cost (100 yuan) | Time (h) |
|----------------|-------------------|-------------------|----------------|---------|
| The first stage| 8.1470×10⁶        | 8.1412e+06        | 7017.8         | 1200.8  |
| The second stage| 7.9989×10⁶       | 7.9915e+06        | 8896.8         | 1492.3  |
| The third stage| 7.9708×10⁶        | 7.9618e+06        | 10764          | 1824.4  |
| The fourth stage| 7.9924×10⁶       | 7.9822e+06        | 12430          | 2154.1  |
| The fifth stage | 7.9434×10⁶        | 7.9325 e+06       | 13406          | 2490.0  |

Table 6 Solving results of full probability Levy flight

|                | Fitness function 1 | Fitness function 2 | Cost (100 yuan) | Time (h) |
|----------------|-------------------|-------------------|----------------|---------|
| The first stage| 22704.2           | 20623.5           | 2704.2         | 623.5   |
| The second stage| 12585            | 10672             | 2584.5         | 671.8   |
| The third stage| 23159            | 20903             | 3159.3         | 903     |
| The fourth stage| 23467            | 21022             | 3466.8         | 1021.7  |
| The fifth stage | 23594            | 21151             | 3594.1         | 1151.3  |

5. Conclusion
Firstly, this paper defines the relevant concepts and research objects of equipment independent maintenance, and defines the basic framework of resource allocation and decision-making model of independent maintenance. The solution method and key technology of resource allocation and decision
model of equipment independent maintenance under dynamic demand condition are studied. Finally, the model is solved and the results are compared with an example. The effectiveness and efficiency of the algorithm are verified.

Reference
[1] Lu Ch, Zhang Mf. (2019) Research on maintenance and support mode of network-based measurement and control equipment. J. Electronic test, 17: 59-60.
[2] Xu Yg, Qiu J, Liu Gj. (2013) Joint optimization of maintenance and inventory for equipment independent maintenance support. J. Journal of aviation, 34(08): 1869873.
[3] Xu Yg. (2012) Research on key technology of equipment independent maintenance support. D. National University of Defense Technology.
[4] Wang Qj, Zhang J. (2021) Research on Ordnance Equipment Support Capability of the Navy under the Background of Civil-Military Integration. J. China Equipment Engineering, 03: 239-240.
[5] Chen Sj. (2011) Decision-making Technology and System of Maintenance Resource Optimization Based on Fault Prediction Information. D. National University of Defense Technology.
[6] Lei N, Cao Jp. (2020) Review of research on optimal allocation of equipment maintenance support resources. J. Naval electronic engineering, 40(06): 9-12.