Critical Evaluation and Optimal Allocation Model of Ship Spare Parts

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Abstract. In the case of limited funding, in order to avoid the serious consequences of the shortage of critical spare parts on equipment, priority must be given to ensuring that critical spare parts are not in shortage. The assumption of the traditional equipment support model is that the criticality of spare parts is the same, which will lead to the priority of lower-priced spare parts rather than the critical ones under the constraints of limited funds. In order to overcome this shortcoming, an optimal allocation model based on the criticality of spare parts is established in this paper. The genetic algorithm software were used to solve the model. The practical case shows that under the circumstance of limited guarantee funds, the key-based spare parts allocation model can be adjusted according to the criticality of the spare parts, the priority is given to the highly critical spare parts, and the critical general spare parts are also considered.

Introduction

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The implementation of China's "Belt and Road" development strategy has given the Chinese Navy a new mission: to escort the "21st Century Maritime Silk Road", safeguard China's maritime rights and interests, and protect the safety of maritime passages. This requires the navy to move further into the deep blue and have a strong capacity for offshore operations. The increase in the frequency and intensity of the use of ship equipment leads to an increase in equipment failure rates, and the pressure on ship maintenance support is increasing. At present, during the voyage mission of the Navy, the maintenance of faulty equipment is carried out by means of replacement parts. Ships must not be equipped with too many spare parts. It is difficult for equipment managers to formulate a spare part configuration plan for the ship formation. At the same time, due to the criticality and complexity of the configuration of the ship's spare parts along with the ship, it is also a hot issue to carry out the maintenance of spare parts for the ship formation.

Experts at home and abroad have done a lot of research on the problem of spare parts allocation, and have achieved certain research results. In 1968, Sherbrook\cite{2} proposed a classic MERIC (A Multi-Echelon Technique for Recoverable Control) model in the field of equipment multi-level spare parts allocation, which divided the supply of spare parts into two levels: field and base, and first provided decisions for the configuration of spare parts for the US Air Force help. Because the
METRIC model has too many assumptions, some scholars have extended the model in order to use it for practical engineering problems [3-4]. The assumptions of the above studies are that the criticality of spare parts is the same, but in actual engineering practice, in order to avoid the shortage of critical spare parts affecting the operational performance of the equipment system, the criticality of spare parts must be considered when solving the optimization of spare parts allocation. Some scholars first studied how to determine the criticality of spare parts more accurately. Zhang Yi [5] carried out FMECA analysis of spare parts based on reliability, maintainability, economy and other factors to establish a critical evaluation system; Huang Jianxin et al. [6] proposed a method of importance evaluation based on Monte Carlo simulation, which is effective The impact of human subjective factors is reduced, and the accuracy of the evaluation is improved; Zuo Wenbo et al. [7] proposed a method for evaluating the importance of air defense and antimissile equipment units combining Vague sets and gray correlation analysis theory, which can objectively and accurately evaluate the importance of air defense and antimissile equipment units can also be used as a reference for other equipment. In the aspect of research on the optimal allocation of spare parts considering the critical differences of spare parts, Moon et al. [8] used the analytic hierarchy process to analyze the criticality of the Korean Navy's spare parts and studied the spare parts inventory based on the critical analysis. Jin Jiashan et al. [9] used fuzzy analytic hierarchy process and Monte Carlo simulation method to find the critical index of spare parts for repairable spare parts, and optimized the allocation of spare parts by marginal effect method; Zhou Liang et al. [10] took the criticality of spare parts as one of the constraints on the optimization of spare parts configuration, and established a spare parts configuration optimization model that constrained the cost of spare parts, volume of spare parts, and criticality of spare parts.

Based on the research of the above scholars, this article first comprehensively analyzes the critical factors of spare parts to construct a criticality evaluation system of spare parts, and uses TOPSIS to calculate the critical weight coefficients of spare parts based on the analytic hierarchy process to obtain the weights of each index. Then, with the spare parts guarantee funds as a constraint, a critical spare parts optimal allocation model is established, and the model is solved by using genetic algorithms. Finally, a practical case is used to compare the critical allocation scheme with the traditional allocation scheme, which proves that the model can Under the condition of limited guarantee funds, the storage amount of spare parts is adjusted according to the criticality of spare parts, and the spare parts with high criticality are prioritized, and the critical spare parts are also considered.

Evaluation of the Criticality of Spare Parts

Solving Process of Critical Weight Coefficient of Spare Parts

The criticality of the spare parts refers to the role played in the equipment and the degree of impact on the system performance after failure. The more critical the spare parts, the more critical the role of the equipment to form the operational integrity. Critical spare parts are often characterized by high prices, long supply cycles, and high process requirements. Therefore, shortages should be avoided as much as possible during the execution of tasks. This article quantifies the criticality of spare parts, and uses the size of the criticality coefficient of spare parts to indicate the critical difference of spare parts.

The criticality of spare parts can not only rely on the equipment instruction manual provided by the research and development personnel. There are many influencing factors. It must be combined with the actual experience of using equipment and subjective and objective thinking to analyze, that is, on the one hand, the safety and tasks of spare parts Analysis of completeness, monitorability and maintainability; on the other hand, experts in the field of comprehensive support and operators of actual equipment on board the ship are invited to rate the weight of the critical evaluation indicators of the spare parts. Finally, a comprehensive balance is determined to determine the criticality of the spare parts. Therefore, this paper uses the analytic hierarchy process to divide each factor into ordered
levels, assign weights scientifically, and calculates the critical weight coefficients of spare parts in combination with the TOPSIS method.

**Evaluation System for Criticality of Spare Parts**

The determination of the criticality of equipment spare parts is a multi-level, multi-depth, and multi-factor problem. For a scientific and objective evaluation, a comprehensive index evaluation system needs to be established to make a large number of factors that affect and restrict each other clear, layered, complete and available. Based on the comprehensive and referenced existing experience, a critical spare parts evaluation index system as shown in Figure 1 was established based on the characteristics of the ship's spare parts. The evaluation system includes safety, mission completion, monitorability. The criticality of spare parts is evaluated in four aspects of maintainability.

![Figure 1. Evaluation index system of equipment spare parts importance.](image)

The criticality of spare parts is evaluated in four aspects of maintainability.

| Target layer | Criterion layer | standard floor |
|--------------|-----------------|----------------|
| Safety       | Impact on personnel and environmental safety $F_1$ |                     |
| Task completion | Impact on mission success $F_3$ |                     |
| Monitorability | Difficulty in monitoring faults $F_4$ |                     |
| Maintainability | Difficulty in maintenance $F_5$ |                     |

The impact on personnel and environmental safety refers to whether the equipment will cause danger or pollution to the personnel and the working environment after the failure of the spare parts. The scoring standards are shown in Table 1.

**Table 1. Scoring criteria for impact on people and the environment.**

| grade | Impact of failure on people and the environment | fraction |
|-------|-----------------------------------------------|----------|
| 1     | No effect                                     | 1        |
| 2     | Less effected                                 | 4        |
| 3     | Greater effected                              | 7        |
| 4     | Serious effected                              | 10       |

The impact on the equipment system safety refers to the degree of impact on the equipment system safety after the failure of the spare parts. The scoring standards are shown in Table 2.
Table 2. Scoring criteria for impact on equipment system.

| grade | Impact of failure on equipment system | fraction |
|-------|--------------------------------------|----------|
| 1     | No effect                            | 1        |
| 2     | Less effected                        | 4        |
| 3     | Greater effected                     | 7        |
| 4     | Serious effected                     | 10       |

The impact on task success is the degree of impact on the success of the task after the failure of the spare part.

Table 3. Scoring criteria for impact on success of mission.

| grade | Impact of failures on mission success | fraction |
|-------|--------------------------------------|----------|
| 1     | No effect                            | 1        |
| 2     | Less effected                        | 4        |
| 3     | Greater effected                     | 7        |
| 4     | Serious effected                     | 10       |

The difficulty of fault monitoring refers to the difficulty of monitoring before the failure of the spare parts. The scoring standards are shown in Table 4.

Table 4. Scoring criteria for difficulty of fault monitoring.

| Grade | Difficulty in monitoring faults | fraction |
|-------|---------------------------------|----------|
| 1     | Less difficulty                 | 1        |
| 2     | Moderate difficulty             | 4        |
| 3     | High difficulty                 | 7        |
| 4     | Extreme difficulty              | 10       |

Difficulty of maintenance refers to the ease with which the spare part can be repaired and replaced, which is limited by the technical level and number of maintenance personnel, maintenance equipment and levels, and facilities. They are divided into 4 categories according to their difficulty, and the scoring standards are shown in Table 5.

Table 5. Scoring criteria for difficulty of repair.

| Grade | Maintenance difficulty | fraction |
|-------|------------------------|----------|
| 1     | Less difficulty        | 1        |
| 2     | Moderate difficulty    | 4        |
| 3     | High difficulty        | 7        |
| 4     | Extreme difficulty     | 10       |
Calculation of Critical Weight of Spare Parts

Analytic Hierarchy Process (AHP) [11] was used to calculate the weight of each influencing factor in the evaluation index system. Because the AHP method is already a very mature method, this article does not specifically describe how the AHP method determines the index weight. It mainly introduces how to calculate the critical weight calculation of spare parts in combination with the TOPSIS method.

The TOPSIS method is a commonly used multi-objective decision analysis method for finite schemes. [12] This article replaces the type of the scheme with the spare type of the equipment system. Using this method to calculate the relative closeness between the spare part and the ideal solution, and then calculate the critical weight coefficient of the spare part according to the closeness.

1. The equipment system has m type spare parts: \( A_1, A_2, \cdots, A_m \) and the indicator system has n indicators: \( F_1, F_2, \cdots, F_n \). The initial score matrix \( P \) can be obtained based on the evaluation values of the spare parts for different indicators.

\[
P = \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} & r_{22} & \cdots & r_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix}
\]

2. Normalize the initial judgement matrix. The types of indicators in the matrix \( P \) are divided into benefit-type indicators and loss-type indicators. The standardized calculation formulas are different, respectively:

- **Benefit indicators**:
  \[
b_{ij} = \frac{r_{ij} - \min_j r_{ij}}{\max_j r_{ij} - \min_j r_{ij}}, \quad i = 1, 2, \cdots, m; \quad j = 1, 2, \cdots, n
\]

- **Loss indicators**:
  \[
b_{ij} = \frac{\max_j r_{ij} - r_{ij}}{\max_j r_{ij} - \min_j r_{ij}}, \quad i = 1, 2, \cdots, m; \quad j = 1, 2, \cdots, n
\]

3. Multiply the index weight value \( w_i \) calculated by the analytic hierarchy process with matrix \( B \) to obtain a weighted standardized decision matrix \( R \)

\[
R = \begin{bmatrix}
w_1 b_{11} & w_2 b_{12} & \cdots & w_n b_{1n} \\
w_1 b_{21} & w_2 b_{22} & \cdots & w_n b_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
w_1 b_{m1} & w_2 b_{m2} & \cdots & w_n b_{mn}
\end{bmatrix}
\]

4. Determine positive ideal solution and negative ideal solution

Benefits-type and loss-type indicators have their respective positive ideal solutions and negative ideal solutions. \( j \) stands for benefit-type indicators set, and \( j' \) stands for loss-type indicators set.

\[X^+ = \{ \max_i w_i b_{ij} | j \in j | \min_i w_i b_{ij} | j \in j' \} = \{ X_1^+, X_2^+, \cdots, X_n^+ \}\]

\[X^- = \{ \min_i w_i b_{ij} | j \in j | \max_i w_i b_{ij} | j \in j' \} = \{ X_1^-, X_2^-, \cdots, X_n^- \}\]

5. Calculate the distance from each type of spare part to the positive and negative ideal solutions.
\[
d_i^+ = \sqrt{\sum_{j=1}^{n} (X_i^+ - w_i b_{ij})^2}.
\]

(3)

\[
d_i^- = \sqrt{\sum_{j=1}^{n} (X_i^- - w_i b_{ij})^2}
\]

(4)

(6) Calculate the relative proximity \( c_i^* \) and calculate the critical weight of spare parts \( I_{Si} \).

\[
c_i^* = \frac{d_i^-}{d_i^++d_i^-}.
\]

(5)

\[
I_{Si} = \frac{c_i^*}{\sum_{i=1}^{m} c_i^*}.
\]

(6)

The size of the critical weight coefficient \( I_{Si} \) indicates the criticality of the spare parts. The larger the critical weight coefficient, the more critical the role of the spare part in the equipment system, and the greater the impact of the shortage on the equipment system.

**Spare Parts Allocation Model Based on Criticality of Spare Parts and Solving Algorithm**

When ships are performing tasks independently or in formations, they are far away from the shore, have a long mission period, and are highly independent. The quality of the ship's spare parts allocation plan is the key to successfully completing the task. Considering the special conditions of ship maintenance, when the equipment fails, its performance can usually only be restored by replacing parts. Due to the limitations of the size, weight, cost, and actual support capabilities of the ship, it is impossible to meet the needs of all ship-based spare parts directly from the ship or from other ships in the formation. Therefore, under the constraints of limited support funds, it is necessary to consider highly critical spare parts, especially when wartime or logistical support costs are tight, the supply of highly critical spare parts must be guaranteed first, while taking into account the general Spare parts.

**Spare Parts Allocation Model Based on Criticality of Spare Parts**

The traditional spare parts support model [2] assumes that the criticality of each spare part is the same. When the spare parts support funds are limited, in order to achieve the goal of high overall availability of equipment, the traditional allocation model will preferentially allocate spare parts with lower costs, which will lead to the result that the priority is given to the price rather than to the critical spare parts, so there are certain limitations. Aiming at the problem that the criticality of spare parts has an impact on the configuration of spare parts, but is difficult to model directly, considering that priority should be given to meet critical spare parts without shortage when resources are limited, a spare parts allocation model based on the criticality of spare parts is established.

The number of spare parts shortage is an important indicator to measure the efficiency of spare parts support. The meaning of the expression is the number of spare parts that cannot meet the actual demand for spare parts. Because the actual demand for spare parts is a random variable, the expected shortage number \( EBO \) is introduced in order to measure the effectiveness of spare parts \( (s) \), this indicator is calculated as:

\[
EBO(s) = \sum_{x=s+1}^{\infty} (x - s) pr(x).
\]

(7)

Among the formula above: \( s \) is the initial stock quantity of spare parts; \( pr(x) \) is the probability distribution function corresponding to the demand of spare parts. According to Palm’s theorem, it obeys Poisson distribution:
\[ p_r(x = k) = \frac{m^k}{k!} e^{-mT}, \quad k = 0, 1, \ldots \]  
(8)

Where \( mT \) is the average value of the Poisson distribution, which represents the average demand for spare parts during the task cycle, \( m \) is the average annual demand, and \( T \) is the duration of the task cycle.

According to the METRIC model, the availability of equipment can be calculated indirectly through the spare parts shortage number EBO \( s \), and the calculation formula is:

\[ A_j = 100 \prod_{i=1}^{m} \left\{1 - \frac{EBO_i(s_i)}{N_j Z_i}\right\}^{Z_i} = 100 \prod_{i=1}^{m} A_i. \]  
(9)

According to the formula, the availability of the equipment system can be approximated as the availability of each spare part \( A_i \), where \( N_j \) is the number of installations of the equipment on the ship; \( Z_i \) is the number of installations of \( i \) spares in this type of equipment.

\( N_j \) and \( Z_i \) are fixed values. According to the calculation formula of \( A_i \), we can know that the size of \( EBO_i(s_i) \) determines the availability of spare parts \( A_i \). The smaller the value of \( EBO_i(s_i) \) is, the higher the availability of spare parts is. So the problem of finding the minimum of the shortage of critical spare parts can be transformed into the problem of finding the maximum of the availability of critical spare parts.

Multiply the critical weight coefficient \( I_Si \) of the spare part with the spare part availability \( A_i \) to obtain the spare part availability based on the criticality of the spare part:

\[ A_i' = I_Si A_i. \]  
(10)

Because \( I_Si \) is constant, if the objective function is calculated by multiplication, we can get the result below:

\[ A_j' = \prod_{i=1}^{m} A_i' = \prod_{i=1}^{m} I_Si A_i. \]  
(11)

Observing the formula carefully, we can find that the traditional equipment availability \( A_j \) is multiplied by a new constant \( \prod_{i=1}^{m} I_Si \). If the objective function of the model is obviously back to the traditional calculation scope of equipment availability, it cannot reflect the key differences of spare parts. Because the goal of the model is to give priority to meeting the configuration of critical spare parts with limited funding and to reflect the critical differences of spare parts, so the above-mentioned problems can be avoided by adding the availability of critical spare parts. The calculation formula is:

\[ C = \sum_{i=1}^{m} A_i'. \]  
(12)

\( A_i' \) indicates the availability of spare parts based on the criticality of spare parts, and \( C \) indicates the sum of availability of spare parts.

Based on the above analysis, a critical spare parts optimization model is established as follows:

\[
\begin{align*}
\max & \quad \sum_{i=1}^{m} A_i' \\
\text{s. t.} & \quad \sum_{i=1}^{n} s_i a_i \leq M
\end{align*}
\]

Where \( a_i \) represents the cost of spare parts \( i \), \( s_i \) represents the number of spare parts \( i \), and \( M \) represents the total expenditure.

**Genetic Algorithm Solving**

Because the objective function of the model is a multivariate non-linear function, in order to solve the global optimization problem of this kind of function, this article uses Genetic Algorithm (GA) solving, and Matlab software is used to call the GA function to optimize the model. The core method of Genetic Algorithm is to evaluate the fitness of all individuals in each generation of the population,
and select some individuals for gene replication, crossover, and mutation to form the next generation population. According to the theory of evolution, highly adaptable individual genes have a greater probability of being passed on to the next generation. Therefore, through the evolution of multiple generations, the overall fitness of the population and the adaptability of the individuals within it will be improved, thereby achieving the purpose of optimal calculation. The process is shown in Figure.

![Figure 2. The process of the Genetic Algorithm.](image)

**Case Study**

Because there are too many types of spare parts for a certain equipment system, considering that the main purpose of this article is to introduce methods and models, five kinds of the most representative electronic spare parts are selected as research objects. Assuming the mission period $T$ is 0.25 years, the number of equipment systems installed on the ship is 1, and table 6 is the relevant data of 5 types of spare parts.

| Spare part type | Single quantity [Each] | Annual average demand | unit price [ten thousand] |
|-----------------|------------------------|-----------------------|---------------------------|
| $S_1$           | 2                      | 20                    | 5                         |
| $S_2$           | 2                      | 28                    | 3.7                       |
| $S_3$           | 2                      | 48                    | 2.6                       |
| $S_4$           | 2                      | 64                    | 1.4                       |
| $S_5$           | 3                      | 96                    | 0.8                       |

Eight experts are invited to score the various indexes of spare parts, and the critical weight coefficients of 5 types of spare parts are calculated through calculation. Among them, the critical weight coefficient of $S_1$ is 0.42, the critical weight coefficient of $S_2$ is 0.19, and the critical weight of $S_3$. The coefficient is 0.1, the critical weight coefficient of $S_4$ is 0.24, and the critical weight coefficient of $S_5$ is 0.07.

Under the constraint of only 1 million yuan in spare parts support funds, Matlab software is used to select a population size of 500 to generate a population based on the model and method built. After 50 generations of optimized calculation results, a spare parts configuration plan considering the key differences in spare parts is obtained. The specific results are shown in Table 7:
Table 7. Configuration scheme based on different criticality of spare parts.

| Spare part type | $s_1$ | $s_2$ | $s_3$ | $s_4$ | $s_5$ |
|-----------------|-------|-------|-------|-------|-------|
| Scheme of allocation | 6     | 5     | 6     | 17    | 15    |
| EBO             | 0.4868| 2.2646| 6.004 | 1.5853| 9.0208|

The results of the spare parts configuration plan based on the same criticality of the spare parts according to the genetic algorithm are shown in Table 8:

Table 8. Configuration scheme based on the same criticality of spare parts.

| Spare part type | $s_1$ | $s_2$ | $s_3$ | $s_4$ | $s_5$ |
|-----------------|-------|-------|-------|-------|-------|
| Scheme of allocation | 3     | 6     | 9     | 14    | 24    |
| EBO             | 2.1629| 1.5677| 3.2972| 2.7509| 1.9339|

Comparing the two configuration schemes, the arrangement order of the criticality coefficients of the spare parts based on the different criticality of the spare parts can be found to be the same as the order of the expected number of spare parts. The higher the critical weight coefficient of the spare parts is, the lower the expected shortage of the spare parts is, that is, the configuration of the model can give priority to the configuration of key spare parts with limited funding, reducing the possibility of shortages and increasing the availability of spare parts. Based on the same critical configuration scheme of spare parts, the expected shortage of all spare parts is relatively balanced, and it is impossible to highlight the highly critical spare parts. On the contrary, the $s_5$ spare parts, which are the most critical and at the lowest price, have the least expected shortage, and it is possible that the shortage of critical spare parts will have serious consequences for equipment systems.

Summary

By establishing a critical evaluation index system for spare parts, combining the analytic hierarchy process and TOPSIS method, the critical weight of the spare parts can be calculated to quantitatively describe the criticality of the spare parts, but the selection of the critical evaluation index will be different according to different equipment types. It is necessary to make reasonable choices for specific types of equipment, and the criticality of spare parts to the equipment is not fixed, it will change according to different tasks.

The critical spare parts configuration model constructed in this article can consider the critical differences of spare parts under the condition of limited funds, and can reduce the possibility of shortage of critical spare parts as far as possible. Therefore, this method can help the decision-making department when formulating the spare parts allocation plan.

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