Prediction model of aeronautics equipment spare parts considering spare part sharing

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Abstract: A prediction method of aeronautics equipment spare parts requirement considering spare part sharing was proposed aimed at reducing high spare parts sharing proportion of similar types of aeronautics equipment. Firstly, according to the structural similarity, the spare parts were divided into special spare parts and shared spare parts. Then, the spare parts requirement under the condition of daily support and wartime support was further considered. With the constraint of spare parts support probability, the requirement prediction model of special spare parts and shared spare parts were constructed respectively on the basic assumption that the daily failure obeyed the exponential distribution and the battle damage-oriented obeyed the binomial distribution. Finally, based on a certain kind of avionics system, the validity and effectiveness of the proposed model were verified.

Key Words: spare part, spare part sharing, spare part prediction, battle damage-oriented, aeronautic equipment

1. Introduction
One of the main tasks of aeronautics equipment support is to predict the requirement of support resources accurately and reduce the situation in equipment support - "preparing for no use, using without preparation", which is supposed to make the limited support cost play the maximum benefit. Spare parts, as one of the most important aeronautics equipment support resources, the prediction of requirement quantity has always been the focus of users and research institutions from home and abroad, and the results are relatively rich too. The existing conclusions can be classified into two categories: one is analytical algorithms, such as the Modified Pareto Ant Colony Optimization Approach (MPACO) algorithm, the requirement prediction method based on the failure time prediction, the prediction method based on the grey theory, the prediction method facing the lowest shortage of spare parts, the spare parts requirement prediction based on the genetic algorithm, etc. The main idea of this kind of method is to establish optimization and prediction model considering
different characteristics, and to determine the spare parts requirement based on the constraints concerned by the predictor and the known information, such as similar product information and prior information. With the increasing number of access to information, dynamic characteristics are gradually taken into account and corresponding dynamic models are derived, such as the Spare Aeroengine Requirement Prediction Model Based on Deep Croston Method⁹, the prediction of repairable spare parts requirement based on general renewal processes⁸, battle damage-oriented spare parts forecasting method based on support vector⁰, etc. The other is simulation method. With the development of computer technology, researchers start to simulate the use and maintenance of equipment by simulation gradually, and then predict the requirement of spare parts. For example, assuming that the support cost is limited, the simulation method is used to coordinate the number of aircraft, maintenance support personnel, maintenance support facilities and spare parts in an aircraft squadron to ensure that the aircraft can complete multiple tasks to the maximum extent.

The methods above pay more attention to the improvement and optimization of the model itself, but pay less attention to the characteristics of spare parts in the process of equipment use. In the use stage, it is common for the same type of spare parts to serve a variety of different types of aeronautics equipment, especially for the modified type of aircraft. Due to similarity between its structure and the basic type of aircraft, the proportion of the modified type inheriting its basic type structure is usually to 70%, which also leads to the high spare parts sharing proportion between similar types of equipments. Accordingly, a new requirement prediction method considering spare parts sharing is proposed in this paper.

2. Basic assumptions
Firstly, the spare parts can be divided into special spare parts and shared spare parts. "Special spare parts" means that spare parts are only equipped for a certain type of equipment; "Shared spare parts" means that spare parts can be shared by various types of equipment. They can be classified by the structural similarity of the equipment.

Under operational circumstance, the requirement for spare parts consists of two parts: one is the daily failure; the other is equipment battle damage-oriented. Then, we will predict the total requirement of spare parts from these two aspects.

(1) Assuming that the type of spare parts a certain army needs to predict is \( i (i=1,2,\ldots,n) \) , and there are \( n_1 \) types for special spare parts, which is denoted by \( i (i=1,2,\ldots,n_1) \) ; And there are \( n_2 \) types for shared spare parts, which is denoted by \( j=n_1+1, n_1+2,\ldots,n \) . So, the following formula can be easily obtained.

\[
 n_1 + n_2 = n
\]

(2) Assuming that the life of spare parts \( l (l=1,2,\ldots,L) \) of equipment \( i (i=1,2,\ldots,n) \) obeys the exponential distribution, the failure rate is denoted by \( \lambda_i (l=1,2,\ldots,L;i=1,2,\ldots,n) \); assuming the battle damage-oriented rate of equipment \( l (l=1,2,\ldots,L) \) is \( \lambda_{1l} (l=1,2,\ldots,L) \).

(3) For the convenience of calculation, the arrival of the fault parts are assumed to obey the Poisson Process. In a basic combat unit, there are \( K_l \) equipment \( l \). In the case of battle damage, it is assumed that the proportion of lightly damaged equipment is \( \beta_{l1} \), the proportion of moderately damaged equipment is \( \beta_{l2} \), the proportion of heavily damaged equipment is \( \beta_{l3} \). It is set that the lightly damaged equipment should be repaired at the basic level, the moderately damaged equipment should be sent to the rear for repair, and the heavily damaged equipment should be sent to the base to repair. However, due to the long repairing time, it is not considered that the repair will be completed. Instead, it should be supplemented directly by the reserve team to ensure sufficient combat effectiveness.
3. Requirement prediction model of spare parts considering spare part sharing

3.1. Requirement prediction model of special spare parts

According to the analysis above, it can be learned that in the operational state, the spare parts of equipment can be consumed by not only daily failures, but also damage in battles. For special spare parts, the daily failure number of corresponding equipment component $i$ is $\lambda_i = K_i \lambda_0$ ($i=1,2,\ldots,L; \; L=1,2,\ldots,n_i$). Assuming that the battle damage rate of equipment $l$ is $\lambda_{ij}$, then the light damage rate is $\beta_i \lambda_{ij}$, the light damage rate of its component $i$ is $N_i \beta_i \lambda_{ij}$ ($N_i$ denotes the number of single installation of component $i$). Therefore, for a basic combat unit, the light damage rate of component $i$ is $K_i N_i \beta_i \lambda_{ij}$. Under the condition that the daily support probability of spare part $i$ is $P_{si}$, the battle damage support probability spare part $i$ of equipment $l$ must reach $P_{si}$ to meet the support probability of spare part $P_{i}$. Obviously, the following formula can be obtained

$$P_i = P_{si} P_{i}$$

According to the difference between the two cases, the support probability $P_{i}$ of spare parts can be allocated as follows

$$P_{i} = P_{i}^{N_i \lambda_i K_i \beta_i} = P_{i}^{K_i \lambda_i} = P_{i}^{K_i \lambda_i}$$

Then the requirement caused by the daily failure of spare part $i$ can be expressed as the following formula

$$\sum_{k=0}^{S_i} \binom{N_i}{k} \lambda_{ij}^k e^{-\lambda_{ij}} \leq P_{si} \sum_{k=0}^{S_i} \binom{N_i}{k} \lambda_{ij}^k e^{-\lambda_{ij}}$$

Where $N_i$ denotes the number of single installation of spare parts $i$ in equipment $l$, $t_i$ denotes the accumulated working time of equipment $l$, and $S_i$ is the requirement for spare part $i$ of equipment $l$, as well as the daily requirement for spare part $i$.

Assuming that the battle damage of each moving component $X_i$ is mutually independent, then $X_i$ obeys the binomial distribution. The requirement caused by battle damage of spare parts $i$ can be expressed as the following formula

$$\sum_{k=0}^{S_i} \binom{K_i N_i \beta_i \lambda_{ij}}{k} (1-(K_i N_i \beta_i \lambda_{ij}))^{K_i - k} \leq P_{si} \sum_{k=0}^{S_i} \binom{K_i N_i \beta_i \lambda_{ij}}{k} (1-(K_i N_i \beta_i \lambda_{ij}))^{K_i - k}$$

Where $S_{ij}$ is the battle damage requirement of the requested spare part $i$.

Then, the total requirement $S_i$ of the special spare part $i$ is

$$S_i = S_{si} + S_{ij}$$

The algorithm of moderately damaged equipment is similar, which is limited to space and will not be described in detail.
3.2. Requirement prediction model of shared spare parts

For shared spare parts, the number of daily failures of a basic combat unit component \( j \) is denoted as \( \lambda_j = \sum_{i=1}^{K} N_i \lambda_{0j} \) \( (j = n_i + 1, n_i + 2, \ldots, n) \). Assuming the battle damage rate of equipment \( l \) is \( \lambda_{0l} \), then the light damage rate is \( \beta_{l} \lambda_{0l} \), the light damage rate of its component \( j \) is \( N_i \beta_{l} \lambda_{0j} \) \( (N_i \) denotes the number of single installation of component \( j \)). Therefore, for a basic combat unit, the light damage rate of component \( j \) is \( K_i N_i \beta_{l} \lambda_{0j} \). The battle damage rate of the spare part \( j \) is equal to the sum of the battle damage rate of the equipment which shared the spare part \( \lambda_{0j} = \sum_{i=1}^{K} K_i N_i \beta_{l} \lambda_{0j} \) \( (j = n_i + 1, n_i + 2, \ldots, n) \). Under the condition that the daily support probability of spare part \( j \) is \( P_{rj} \), the battle damage support probability spare part \( j \) must reach \( P_{zj} \) to meet the support probability of spare part \( P_{j} \). Obviously, the following formula can be obtained

\[
P_{j} = P_{rj} P_{zj}
\]

(8)

According to the difference between the two cases, the support probability \( P_{j} \) of spare parts can be allocated as follows

\[
P_{rj} = P_{zj}^{\frac{\lambda_{0j}}{\lambda_{0l}}} \quad \quad P_{zj} = P_{j}^{\frac{\lambda_{0j}}{\lambda_{0l}}}
\]

(9)

Then the requirement caused by the daily failure of spare part \( j \) can be expressed as the following formula

\[
\sum_{k=0}^{S_{j}-1} \left( \frac{M}{k!} \left( \sum_{j=1}^{L} \left( N_j \lambda_{0j} t_j \right) \right) \right)^{k} e^{- \frac{M}{k!} \left( \sum_{j=1}^{L} \left( N_j \lambda_{0j} t_j \right) \right)} \leq P_{rj} \leq \sum_{k=0}^{S_{j}} \left( \frac{M}{k!} \left( \sum_{j=1}^{L} \left( N_j \lambda_{0j} t_j \right) \right) \right)^{k} e^{- \frac{M}{k!} \left( \sum_{j=1}^{L} \left( N_j \lambda_{0j} t_j \right) \right)}
\]

(11)

Where \( N_j \) denotes the number of single installation of spare parts \( j \) in equipment \( l \); \( t_j \) denotes the accumulated working time of equipment \( l \), and \( S_{0j} \) is the requirement for spare part \( j \) of equipment \( l \), as well as the daily requirement for spare part \( j \).

Assuming that the battle damage of each moving component \( X_j \) are mutually independent, then \( X_j \) obeys the binomial distribution. If the dispatch number of equipment \( l \) of shared spare part \( j \) for one mission is \( K_j \), then the total number is \( M = \sum_{j=1}^{S_{j}} N_j K_j \). Then the requirement caused by battle damage of spare parts \( j \) can be expressed as the following formula

\[
\sum_{k=0}^{S_{j}-1} C_{M-k}^{k} \left( 1-\lambda_{0j} \right)^{M-k} \leq P_{zj} \leq \sum_{k=0}^{S_{j}} C_{M-k}^{k} \left( 1-\lambda_{0j} \right)^{M-k}
\]

(12)

where \( S_{0j} \) is the battle damage requirement of the requested spare part \( j \).

Then the total requirement \( S_{j} \) of the shared spare part \( j \) is

\[
S_{j} = S_{rj} + S_{zj}
\]

(13)

4. Case study
An avionics system is taken as an example to illustrate the validity of the requirement prediction and allocation model of the special spare parts and the shared spare parts.

(1) Requirement prediction of special spare parts in avionics system

Assuming that the reliability data of the main equipment of the avionics system is shown in Table 1.

**Table 1.** Reliability data of main equipment of an avionics system.

| Equipment                          | Amount | MTBF(h) |
|-----------------------------------|--------|---------|
| Ultra-shortwave radio             | 1      | 5000    |
| Shortwave radio                   | 1      | 5000    |
| Bootstrap receiver                | 1      | 8000    |
| Inertial navigation equipment     | 1      | 2000    |
| TACAN                             | 1      | 1500    |
| Director                          | 1      | 1000    |
| Pointing beacon machine           | 1      | 11828   |
| IFF system                        | 1      | 400     |
| Optical rangefinder               | 1      | 70      |
| Radar                             | 1      | 200     |
| Infrared and laser detection devices | 1  | 1400    |
| Computer                          | 1      | 5000    |
| Head-up display                   | 1      | 2000    |
| Multi-function display            | 1      | 5000    |
| Helmet Mounted Sight              | 1      | 240     |

Other parameter values to be input in the prediction model are shown in Table 2.

**Table 2.** Parameter value of spare parts requirement prediction case.

| Parameter                          | Value |
|-----------------------------------|-------|
| Mission time                      | 8h    |
| Equipment battle damage rate      | 0.03  |
| Lightly damaged                   | 0.3   |
| Equipment damage ratio            |       |
| Moderately damaged                | 0.3   |
| Heavily damaged                   | 0.4   |
| Equipment amount                  | 5     |

Under the constraint of the probability of spare parts support, substituting the parameter values of each equipment into the formula in section 2.2, and the total requirement corresponding to the different spare parts support probability can be calculated. Figure 1 shows the relationship between TACAN's spare parts support probability and its total requirement. It can be learned from the figure that when the probability of spare parts support is less than 0.66, TACAN's total spare parts requirement is 2, while when the probability of spare parts support is increased to 0.98, its total spare parts requirement reaches 4. When the number of spare parts increases from 3 to 4, the probability of spare parts support increases from 0.78 to 0.98 with an increase of 0.2. If we want to increase the number of spare parts, the support probability of spare parts can only increase by 0.02 at most, which is in low cost-benefit ratio. From the perspective of economy, the total requirement of TACAN should not exceed 4. The specific allocation quantity can be determined according to the spare parts support probability.
Figure 1. Relationship between TACAN spare parts support probability and total requirement.
Through similar calculation, the total requirement of various equipment in Table 1 is obtained, as shown in Table 3.

Table 3. Total spare parts requirement of various equipment under different support probability.

| Equipment                        | Different spare parts support probability P | Total requirement of spare parts corresponding to different P |
|----------------------------------|---------------------------------------------|-------------------------------------------------------------|
| Ultra-shortwave radio            | 0.68 0.78 0.98                              | 2 3 4                                                       |
| Shortwave radio                  | 0.68 0.78 0.98                              | 2 3 4                                                       |
| Bootstrap receiver               | 0.68 0.78 0.98                              | 2 3 4                                                       |
| Inertial navigation equipment    | 0.68 0.78 0.98                              | 2 3 4                                                       |
| TACAN                            | 0.66 0.78 0.98                              | 2 3 4                                                       |
| Director                         | 0.66 0.76 0.98                              | 2 3 4                                                       |
| Pointing beacon machine          | 0.66 0.76 0.98                              | 2 3 4                                                       |
| IFF system                       | 0.62 0.74 0.96                              | 2 3 4                                                       |
| Optical rangefinder              | 0.54 0.82 0.96                              | 3 4 5                                                       |
| Radar                            | 0.56 0.68 0.94                              | 2 3 4                                                       |
| Infrared and laser detection devices | 0.66 0.76 0.98                      | 2 3 4                                                       |
| Head-up display                  | 0.68 0.78 0.98                              | 2 3 4                                                       |
| Multi-function display           | 0.68 0.78 0.98                              | 2 3 4                                                       |
| Helmet Mounted Sight             | 0.58 0.7 0.96                               | 2 3 4                                                       |

(2) Requirement prediction of shared spare parts in avionics system
The input parameters are the same as above, assuming that three different types of equipment of a certain type are required to execute simultaneously for a certain mission, and their radar equipment models are the same. This section takes this as an example to verify the shared spare parts model. It is assumed that the reliability data of three different types of radar equipment of the same type are shown in Table 4.

Table 4. Same type of radar of different models data.

| Model | J1   | J2   | J3   |
|-------|------|------|------|
| Rader |      |      |      |
|       | 0.00067 | 0.000568 | 0.00067 |
Substitute the data in the above table into the formula in section 2.3 to calculate the total requirement of radar spare parts under different spare parts support probabilities, as shown in Figure 2. It can be seen that when the number of spare parts reaches 4, the support probability of spare parts can reach 0.98. If the radar is considered as a special product respectively, under the constraint of the spare parts support probability of 0.92 and calculated by the model in section 2.2, the spare parts requirement of each radar is 2, 3, 3, and the total requirement is 8, which is 1 times of the prediction result of the shared model. If the support probability of spare parts is required to reach 0.98, the total requirement for spare parts will be greater. Thus, the shared spare parts model is effective.

Figure 2. Relationship between radar shared spare parts support probability and total requirement.
5. Conclusion
A prediction method of aeronautics equipment spare parts requirement considering spare part sharing is proposed aimed at the common phenomenon of spare parts sharing in the use stage. Firstly, according to the structural similarity of equipment, the spare parts are divided into special spare parts and shared spare parts. Then, considering the difference of spare parts requirement between daily support case and wartime support case, the requirement prediction models of special spare parts and shared spare parts are given respectively, which are verified by an avionics system. The results of the case study show that, under the constraint of the same spare parts support probability, the prediction method of spare parts considering spare part sharing can reduce the requirement of spare parts greatly and reduce the inventory at the same time, which helps to reduce the annual average spare parts storage cost of combat forces and the use and maintenance support costs effectively.
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