Forecasting methods of repairable spare parts consumption based on maintenance cost

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Abstract. Exploring the consumption rule of partially repairable spare parts could improve the scientificity of support for partially repairable spare parts. Choosing the maintenance cost of partially repairable spare part as the constraint condition, forecasting models of partially repairable spares parts consumption are established based on calculating the limited value of the number of maintenance times, applying stochastic process theory and probability theory. At last, an example is taken to illustrate the applicability of these models. These models provide sufficient scientific basis for choosing repairable spare parts application, storage and supply amount reasonably, and have the vital important guiding significance.

Key words. Maintenance cost, partially repairable, spare parts consumption, forecasting models..

1. Introduction

With the high-precision weapons and equipment continuing to pack troops, the consumption law of equipment spare parts is more difficult to grasp, the current formed unit can collect spare parts consumption data that are often very limited, which is more limited to the forecast method. According to the design characteristics of the equipment, the characteristics of the use and the characteristics of the maintenance, the existing forecast methods are sometimes difficult to meet the actual needs of the equipment management work, and the consumption forecast problem of equipment spare parts also need to be studied in many complex cases.

Many methods of spare parts consumption forecast are of some reference value to our military research. Based on the maintenance rate to calculate the amount of

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equipment spare parts consumption, the United States first proposed the concept of maintenance rate [1]-[2], taking full account of the use of spare parts strength, the use of time, the use of the environment, the use of occasions, the inherent failure rate, the sensitivity of the damage to spare parts and other information which has an impact on the consumption of spare parts. The United States initially thought that there is approximately a proportional relationship between aircraft engine consumption of spare parts and flight hours, and established a forecast regression model of spare parts consumption [3], and later argued that the number of spare parts consumed by aircraft engines was not only related to flight time but also to the number of flights. The United States used the moving average method, the exponential smoothing method and other methods [4]-[5] to forecast the consumption of spare parts, and later achieved certain military economic benefits through the improvement of spare parts consumption forecasting method, with the logistics technology introduced into the management of spare parts. Other authors have also done research on spare parts consumption forecasting [6]-[8]. Through the analysis of the literature on the consumption law of equipment spare parts at home and abroad, it can be found that scholars in this field mainly study the consumption of spare parts, and the research on the consumption forecast method of repairable spare parts is rare.

In this paper, the repairable spare parts can be used as the research object to study the consumption forecast method of limited repairable spare parts..

2. Formulation of the problem

Equipment unit is collectively the components, parts, sub-systems, systems, etc. Now in the Troop-level maintenance, some units after the failure or damage are directly replaced by new parts. But some units after failure or damage can be repaired by the economically viable technical means to restore their original function. At present, the number of units that can be repaired of many equipment is large, which is directly related to the use of equipment availability and occupies a part of the spare parts protection funds. Through repairable maintenance of spare parts, on the one hand the availability of equipment can be improved; on the other hand maintenance resources and costs also can be saved. However, in practice, the repairable spare parts of the equipment can't be unlimited cycle maintenance, and the vast majority, which is partly scrapped based on maintenance costs and other factors, is limited to repair.

Equipment unit after failure is repaired. If the state of the unit is the basic same as the state before fault, we call it "maintenance as old"; if the state of the unit reaches the state of the new product, we call it "maintenance as new"; if the state of the unit can't reach the state of new products, but can be some improvement compared with the state before the maintenance, the unit reaches between a new state and the old, we call it "incomplete maintenance", which is the most common of a maintenance state.

After the first failure of unit occurred during the period of use, the unit's service age can be backward for a while through the repair of the maintenance period of time; after the second failure of unit occurred, the unit's service age can be backward

for a while again through the repair of the maintenance period of time; and so on, until the unit maintenance costs incurred by the maintenance is close to or reached the specified value, when the next failure is no longer used and repaired, repairable parts must be carried out, which results in a spare parts consumption.

The application, storage and supply of repairable spare parts must be based on repairable spare parts consumption. So it is necessary to do research on the forecasting models of repairable spare parts consumption based on maintenance cost. In the following, the consumption forecasting model of finite repairable spare parts is established based on the maintenance cost of the unit.

3. Mathematical model

The function $f(t)$ is the failure probability density function of the unit after starting from the new product.; $R(t)$ is the reliability function of the unit after starting from the new product; $f_j(t_j)$ $(1 \leq j \leq N)$ is the probability density function of the unit between the $j-1$th time point of maintenance and the jth time point of maintenance; $f_{N+1}(t_{N+1})$ is the probability density function of the unit after the Nth maintenance; μ is the retreat factor of service age , that is, the repairable maintenance of the unit makes the repairable maintenance interval go back μ times averagely $(0 \leq \mu \leq 1)$; Q is the maintenance cost , and q is the cost of repairing the unit on average.

Then, based on the limited value of the maintenance cost of the unit and the average cost of a repair, the limited value of the average maintenance number of the unit is

$$N = \left\lfloor \frac{Q}{q} \right\rfloor \tag{1}$$

In formula (??)1), $\lfloor \rfloor$ represents a round-down.

The average usage time of the unit before the first maintenance is

$$\theta_1 = \int_0^{+\infty} t_1 f_1(t_1)\, dt_1 = \int_0^{+\infty} t f(t)\, dt \tag{2}$$

When the average usage time between the $j-1$th maintenance and the jth maintenance is calculated, its failure probability density function which has the characteristics of uncertainty is taken into account. And the average usage time depends on working time of the $j-1$th working time point of the unit and the retreat factor of service age μ, so it is necessary to integrate the failure probability density function in the j-dimensional space to obtain the average usable time

$$\theta_j = \int_0^{+\infty} \cdots \int_0^{+\infty} t_j \prod_{i=1}^{j} f_i(t_i)\, dt_i \, 2 \leq j \leq N \tag{3}$$

In formula (??)3):

$$r = 1 \tag{4}$$

The integral of the fault probability density function in $N + 1$ dimension space is obtained, and the average use time after the N th maintenance can be gotten:

$$\theta_{N+1} = \int_0^{+\infty} \cdots \int_0^{+\infty} t_{N+1} \prod_{i=1}^{N+1} f_i(t_i)\, dt_i \tag{5}$$

In formula (??)5):

$$f_{N+1}(t_{N+1}) = \frac{f\left[t_{N+1} + (1-u)\sum_{i=1}^{N} t_i\right]}{R\left[(1-u)\sum_{i=1}^{N} t_i\right]} 0 \le t_{N+1} < +\infty \tag{6}$$

According to the formulas (??)2), (??)3) and (??)5), the total average use time of the unit from the beginning of the use to scrap is

$$\theta = \sum_{j=1}^{N+1} \theta_j = \sum_{j=1}^{N+1} \int_0^{+\infty} \cdots \int_0^{+\infty} t_j \prod_{i=1}^{j} f_i(t_i)\, dt_i \tag{7}$$

Therefore, when the number of equipment is W and the unit's single number is L, the expected amount of the unit consumed spare parts in the next T period is

$$y = \frac{WLT}{\theta} = \frac{WLT}{\sum_{j=1}^{N+1} \int_0^{+\infty} \cdots \int_0^{+\infty} t_j \prod_{i=1}^{j} f_i(t_i)\, dt_i} \tag{8}$$

Here are three possible scenarios for the value of μ:

When $u = 1$ which represents that the spare parts is repaired as new, then in the next T period, the expression, which forecasts the amount of spare parts consumption of the unit, can be converted into:

$$y = \frac{WLT}{(N+1)\int_0^{+\infty} tf(t)\, dt} \tag{9}$$

When $u = 0$ which represents that the spare parts is repaired as old, then in the next T period, the expression, which forecasts the amount of spare parts consumption of the unit, can be converted into:

$$y = \frac{WLT}{\int_0^{+\infty} tf(t)\, dt + \sum_{k=2}^{N+1} \int_0^{+\infty} \cdots \int_0^{+\infty} [f(t_1)\, dt_1]\, t_k \prod_{j=2}^{k} \frac{f\left(\sum_{i=1}^{j} t_i\right)}{R\left(\sum_{i=1}^{j-1} t_i\right)}\, dt_j} \tag{10}$$

When $0 < \mu < 1$ which represents that the spare parts is repaired as incomplete, then in the next T period, the expression, which forecasts the amount of spare parts

consumption of the unit, is the formula (??)8).

4. Analysis of an example

A formed unit is equipped with a certain type of 10 pieces of equipment. Three types of the equipment after the unit failure under the permitted conditions are repaired. The basic information, such as the number of the units used for the three types of equipment, the limited cost of maintenance, the average cost of a repairable maintenance, the retreat factor of service age, and the failure probability density function since the beginning, is shown in Table 1. Please predict the average number of spare parts consumed by the three types of units when the average working time of the equipment is 2000 hours per unit.

Table 1 The information of three types of basic

Serial number	Number of units	The limited cost of maintenance	The average cost of a repairable maintenance	The retreat factor of service age	The failure probability density function since the beginning
1	2	26000	12500	0	$f(t) = \frac{1}{100\sqrt{2\pi}}e^{-\frac{(t-1500)^2}{20000}}$
2	4	15000	4800	0.4	$f(t) = \frac{2t}{1500^2}e^{-\left(\frac{t}{1500}\right)^2}$
3	3	45000	11000	1	$f(t) = \frac{0.005^4}{\Gamma(4)}t^3 e^{-0.005t}$

First, according to the formula (??)1), on average, the limited number of repairable maintenance for the three types of units respectively is

$$N_1 = \left\lfloor \frac{Q_1}{q_1} \right\rfloor = \left\lfloor \frac{26000}{12500} \right\rfloor = 2$$

$$N_2 = \left\lfloor \frac{Q_2}{q_2} \right\rfloor = \left\lfloor \frac{15000}{4800} \right\rfloor = 3$$

$$N_3 = \left\lfloor \frac{Q_3}{q_3} \right\rfloor = \left\lfloor \frac{45000}{11000} \right\rfloor = 4$$

According to the formulas (??)2) to (??)7), the average working time of the three different units is programmed and calculated in turn, and finally the calculation results of the average working hours of the three types of units are obtained, as shown in Table 2.

Table 2 The average working time and the total average working time

Serial number	θ_1	θ_2	θ_3	θ_4	θ_5	θ
1	1500	522	73			2095
2	1061	789	642	550		3042
3	800	800	800	800	800	4000

The number of equipment is 10; the number of the single unit used for the three types of equipment respectively is $L_1 = 2$ $L_2 = 4$ $L_3 = 3$ the retreat factor of service age for the three types of equipment respectively is $\mu_1 = 0$ $\mu_2 = 0.4$ $\mu_3 = 1$; the failure law of the unit 1 obeys the normal distribution, and the each unit is repaired as old after maintenance; the failure law of the unit 2 obeys the Weibull distribution, and the each unit is repaired as incomplete after maintenance; the failure law of the unit 3 obeys the gamma distribution, and the each unit is repaired as new after maintenance; therefore, the formula (??)10), the formula (??)8) and the formula (??)9) can be substituted into the relevant parameters of the three kinds of units respectively. When the average working time of the equipment is 2000 hours per unit, the average number of spare parts consumed by the three types of units respectively is

$$y_1 = \frac{10 \times 2 \times 2000}{2095} = 19.1$$

$$y_2 = \frac{10 \times 4 \times 2000}{3042} = 26.3$$

$$y_3 = \frac{10 \times 3 \times 2000}{4000} = 15$$

Therefore, in order to meet the needs of equipment maintenance of the three types of spare parts in the future 2000 hours, the formed units should reserve at least 20 first class spare parts, 27 second category spare parts and 15 third category spare parts.

5. Conclusion

In this paper, in order to forecast the consumption of limited repairable spare parts, the restorative maintenance cost is used as the constraint condition, and the stochastic process theory is used to deduce the calculation method of the average working time of the different stages of the unit. On this basis, this paper establishes a forecasting model of finite repairable spare parts consumption. The forecasting methods of repairable spare parts consumption based on maintenance cost are the highlight of innovation in this paper. They are the important basis for spare parts support. With reference to the forecasting model, when the maintenance costs, repair methods and other comprehensive factors can be as a constraint, consumption forecast method for limited repairable spares can be given to provide a theoretical basis for the equipment support department to develop scientific and reasonable repairable spare parts support program.

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