Spare Parts Optimization Models of Weapon System Based on Cost Effectiveness Analysis

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Abstract. Insufficient stocks affect overall performance of weapon system, as lack of spares may result in gross penalties, lower availability or increased operational risks. The spare parts optimization model of constant reliability and spare parts optimization mode of constant cost were established. The search function was improved and simplified, and solving optimization model .algorithms are given. On this basis of the criterion of cost analysis the optimization model of spare parts is give, and the effective algorithm is give also. Finally, the proposed method is proved to be effective and practicable by numerical example.

Introduction

With the development of military equipment, the determinants of the war are turn human to weapons. So weapons are not only an important factor in the war, but also influent the war more and more. The performance and readiness of weapon is the determinants of the war. Military operations are significantly affected by logistics operations. The system availability, also known as mission capable rate, of weapon systems and the ability to effect the repair of damaged equipment are significant contributors to the success of military operations. Systems that are in a mission-incapable status due lack of spare parts are said to be "awaiting parts", also known as not mission capable due to supply. Insufficient stocks affect overall performance of physical assets, as lack of spares may result in gross penalties, lower availability or increased operational risks[1-3]. In recent years, many domestic and foreign scholars have done a lot of research in the determination of spare parts [4-7]. the joint maintenance and spare parts ordering problem for more than one identical operating items is studied[8]. Mattia Armenzoni[9] develop and test a simulation approach, to forecast the demand of spare parts components during the lifetime of a complex product, such as an industrial plant. . According to the non-stationary demand for spare parts, the method of inventory optimization based on non-stationary Poisson process is proposed[10]. Taking into account the life of the old and new spare parts and the impact of scheduling for spare parts support, the spare parts scheduling support model has been established[11]. This paper presents various approaches for the determination of the optimal stock size, when the stock is composed of non-repairable or repairable parts. The paper is focused on spares for relatively expensive, highly reliable components, rather than on fast-moving spare parts. Optimization criteria considered are minimization of costs, maximization of equipment availability, and the achievement of a desired stock reliability (probability that a spare part request will not be rejected due to lack of spares in stock). For stock reliability, instantaneous and interval reliability calculations are considered. In addition, models directed to the estimation of the remaining life of a given stock of spare parts (at a certain stock reliability level) are introduced.

Spare Parts Optimization Models

Notion

A spare part is an interchangeable part that is kept in an inventory and used for the repair or replacement of failed parts. Spare parts are an important feature of logistics management and supply chain management, often comprising dedicated spare parts management systems. In logistics, spare parts can be broadly classified into two groups, repairables and consumables.

Repairable parts are parts that are deemed worthy of repair, usually by virtue of economic consideration of their repair cost. Rather than bear the cost of completely replacing a finished product, repairables typically are designed to enable more affordable maintenance by being more modular. This allows components to be more easily removed, repaired, and replaced, enabling cheaper replacement. Spare parts that are needed to support condemnation of repairable parts are known as replenishment spares. A rotatable pool is a pool of repairable spare parts inventory set aside to allow for multiple repairs to be accomplished simultaneously. This can be used to minimize stockout conditions for repairable items.

Parts that are not repairable, are considered consumable parts. Consumable parts are usually scrapped, or "condemned", when they are found to have failed. Since no attempt at repair is made, for a fixed MTBF, replacement rates for consumption of consumables are higher than an equivalent item treated as a repairable part. Because of this, consumables tend to be lower cost items. Because consumables are lower cost and higher volume, economies of scale can be found by ordering in large lot sizes, a so-called Economic order quantity.

We use the following abstract algebra nations and definitions throughout this paper.

R_s the system operational reliability

R_0 the system of predetermined readiness reliability

c_i cost of component i

n the number of components

C_s the total cost of spare parts, $C_s = \sum_{i=1}^n c_i x_i$,

R_i reliability of component i

x_i number of spares of component i , $x_i \geq 1$

T the average time for equipment to perform a task

a_i the number of components i

b_i failure rate of components i , the life is exponential distribution

λ_i failure coefficient if components i , $\lambda_i = a_i b_i$

C_0 the total predetermined cost of spare parts

C_s =cost of system

R_s =reliability of system

$R_i(x_i)$ =reliability of stage i , $R_i(x_i) = 1 - (1 - p_i)^{x_i}$

R_0 =lower bound on R_s

Spare Parts Optimization Models of Consumable Parts

From theory of reliability, the reliability of component i is

$$R_i = \sum_{j=0}^{x_i} e^{-\lambda_i T} \frac{(\lambda_i T)^j}{j!} = e^{-\lambda_i T} \left[1 + \lambda_i T + \frac{(\lambda_i T)^2}{2!} + \dots + \frac{(\lambda_i T)^{x_i}}{x_i!} \right] \quad (1)$$

The weapon system operational reliability is

$$R_s = \prod_{i=1}^n R_i = \prod_{i=1}^n \sum_{j=0}^{x_i} e^{-\lambda_i T} \frac{(\lambda_i T)^j}{j!} \quad (2)$$

The spare parts optimization model of constant reliability is

$$\begin{aligned} \min C_s &= \sum_{i=1}^n c_i x_i \\ \text{s.t. } R_s &\geq R_0 \end{aligned} \quad (3)$$

The spare parts optimization mode of constant cost is

$$\begin{aligned} \max R_s \\ \text{s.t. } \sum_{i=1}^n c_i x_i &\leq C_0 \end{aligned} \quad (4)$$

The problems are NP-hard, only some special cases can be solved efficiently. Thus, many approaches have been proposed to find optimal design in reasonable time.

The ideas of the spare parts optimization model of constant reliability is as follows: From $(x_1, x_2, \dots, x_n) = (1, 1, \dots, 1)$, and then in each step, add a same part according to the heuristic factor, until the system reliability is greater than or equal to the predetermined reliability R_0 . The heuristic factor $D(j)$ ($j=1, 2, \dots, n$) is

$$D(i) = \frac{1}{c_i} [R_s(x_1, x_2, \dots, x_{i-1}, x_i + 1, x_{i+1}, \dots, x_n) - R_s(x_1, x_2, \dots, x_{i-1}, x_i, x_{i+1}, \dots, x_n)] \quad (5)$$

Because the search direction function (5) is complexity, the following formula can be used

$$D(i) = \frac{1}{c_i} [\ln R_s(x_1, x_2, \dots, x_{i-1}, x_i + 1, x_{i+1}, \dots, x_n) - \ln R_s(x_1, x_2, \dots, x_{i-1}, x_i, x_{i+1}, \dots, x_n)] \quad (6)$$

We can simplify the direction of search function (6) as follows:

$$\begin{aligned} D(i) &= \frac{1}{c_i} [\ln R_s(x_1, x_2, \dots, x_{i-1}, x_i + 1, x_{i+1}, \dots, x_n) - \ln R_s(x_1, x_2, \dots, x_{i-1}, x_i, x_{i+1}, \dots, x_n)] \\ &= \frac{1}{c_i} [\ln R_i(x_{i+1}) - \ln R_i(x_i)] \\ &= \frac{1}{c_i} \cdot \ln \left[1 + \frac{\frac{(\lambda_i T)^{(x_i+1)}}{(x_i+1)!}}{1 + \lambda_i T + \frac{(\lambda_i T)^2}{2!} + \dots + \frac{(\lambda_i T)^{x_i}}{x_i!}} \right] \end{aligned} \quad (7)$$

We use a heuristic method to solve the spare parts optimization model of constant reliability, the algorithm is as follows:

Step 1 Let $(x_1, x_2, \dots, x_n) = (1, 1, \dots, 1)$ and calculate C_s .

Step 2 Calculate the direction of search function (7)

Step 3 Find integer i^* satisfying $D(i^*) = \max_i [D(i)]$, and replace x_{i^*} by $x_{i^*} + 1$.

Step 4 If $R_s \geq R_0$, return. Otherwise go back step 2.

The method to solve spare parts optimization mode of constant cost is similar to above algorithm.

Step 1 Let $(x_1, x_2, \dots, x_n) = (1, 1, \dots, 1)$ and calculate R_s .

Step 2 Calculate the direction of search function (7)

Step 3 Find integer i^* satisfying $D(i^*) = \max_i [D(i)]$, and replace x_{i^*} by $x_{i^*} + 1$.

Step 4 If $C_s \geq C_0$, $x_{i^*} = x_{i^*} - 1$ and return. Otherwise go back step 2.

Cost-effectiveness Analysis of Spare Parts

In the spare parts optimization model of constant reliability and spare parts optimization mode of constant cost, the reliability and cost are given by experience in general. There is no scientific reason. On the basis of cost-effectiveness analysis criteria [11], we can use the ratio of reliability and cost as objective function, establish the optimization model of spare parts.

$$\begin{aligned} \max \quad & R_s / C_s \\ \text{s.t.} \quad & C_s = \sum_{i=1}^n c_i x_i \\ & R_s = \prod_{i=1}^n \sum_{j=0}^{x_i} e^{-\lambda_i T} \frac{(\lambda_i T)^j}{j!} \end{aligned} \quad (8)$$

For Programming (8), (R_s^*, C_s^*) is the best solution. But the R_s^* may be relatively small, or the C_s^* may be too large, the results are not satisfactory. The factors such as reliability or cost should be considered in the models. For example, considering the reliability, the model is as follows:

$$\begin{aligned} \max \quad & R_s / C_s \\ \text{s.t.} \quad & C_s = \sum_{i=1}^n c_i x_i \\ & R_s = \prod_{i=1}^n \sum_{j=0}^{x_i} e^{-\lambda_i T} \frac{(\lambda_i T)^j}{j!} \\ & R_s \geq R_0 \end{aligned} \quad (9)$$

The algorithm is as follows:

Step 1 Let $(x_1, x_2, \dots, x_n) = (1, 1, \dots, 1)$ and calculate R_s .

Step 2 Calculate the direction of search function (7)

Step 3 Find integer i^* satisfying $D(i^*) = \max_i [D(i)]$, and replace x_{i^*} by $x_{i^*} + 1$. Calculate R_s

and R_s / C_s .

Step 4 If $R_s \geq R_0$ goto step 5, otherwise go step 2.

Step 5 If R_s / C_s is decreasing, stop, otherwise go step 2.

Comparison of the Example

Assume that a ship has 20 components. The reliability of the data are shown in table 1. The average time for equipment to perform a task is $T = 2$. Using programming (3), with $R_s \geq R_0 = 0.9999$, the results are shown in Table 1. The relationship between cost and reliability are shown in fig 1. Now $C_s = 657$ and $R_s = 0.999933$.

Figure 1 The relationship between cost and reliability Figure 2 The relationship between reliability cost ratio and the reliability

Table 1 The reliability of the data and spare parts of a ship

Number	a_i	b_i	c_i	x_i
component 1	1	0.02	1	2
component 2	2	0.08	2	3
component 3	3	0.18	10	4
component 4	2	0.16	1	4
component 5	1	0.10	1	4
component 6	3	0.36	3	5
component 7	2	0.28	1	5
component 8	3	0.48	1	6
component 9	2	0.20	4	4
component 10	1	0.16	5	4
component 11	1	0.16	12	4
component 12	2	0.08	23	3
component 13	3	0.18	24	4
component 14	2	0.32	24	4
component 15	1	0.10	1	4
component 16	3	0.36	4	5
component 17	2	0.28	6	5
component 18	3	0.48	7	6
component 19	2	0.20	8	4
component 20	1	0.16	34	3

From figure 1, with the increase in cost, reliability tends to saturation. In figure 2, when the reliability $R_s = 0.8023$, the ratio of reliability and cost is maximum. But the reliability 0.8023 is not high, so the ratio of reliability and cost is acted as objective function. When $R_0 = 0.99$, the model is

$$\begin{aligned}
 & \max R_s / C \\
 & s.t. \quad C_s = \sum_{i=1}^n c_i x_i \\
 & \quad R_s = \prod_{i=1}^n \sum_{j=0}^{x_i} e^{-\lambda_i T} \frac{(\lambda_i T)^j}{j!} \\
 & \quad R_s \geq 0.99
 \end{aligned} \tag{10}$$

The spare number are 2, 2, 2, 3, 2, 4, 4, 4, 3, 2, 2, 1, 2, 3, 2, 3, 3, 4, 2 and 2, $C_s = 384$ and $R_s = 0.990464$.

Conclusion

Spare parts optimization is an important means to ensure high mission reliability of the weapons and equipment systems. On the one hand, weapons and equipment systems can find themselves carrying an excessive number of spare parts. On the other hand, if they were not available when needed, weapons and equipment systems will face severe downtime consequences. As many parts are very expensive, critically important and their failure rates are so low that they are difficult to forecast, spare parts inventory management within these industries is one of the hardest problems to deal with. On this basis

of the criterion of cost analysis the optimization model of spare parts is give, and the effective algorithm is give also.

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