Spare parts allocation of amphibious aircraft based on hybrid two-level repair

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Abstract. In this paper, a hybrid two-level inventory allocation method based on multi-echelon technique for recoverable item control (METRIC) was applied to the spare parts allocation of amphibious aircraft. Firstly, the principle of the spare parts inventory configuration model for amphibious aircraft based on hybrid two-level repair was expounded. The mathematical model was established with maintenance cost as objective function and availability and volume of spare parts as constraints. Secondly, marginal analysis was used to help allocate spare parts, the process of solving the mathematical model was discussed, and the calculation formulas of the quantities involved were briefly stated. Finally, with the line replaceable units of landing gear as the research object, the spare parts inventory allocation of an amphibious aircraft was solved according to the method proposed in this paper. This paper provides an approach to allocate spare parts of amphibious aircraft.

1. Introduction

Amphibious aircraft can take off and land both on land and on the surface of the water, widely used in forest firefighting and sea rescue. The origin of amphibious aircraft can be traced back to the seaplane invented in the 1920s. Seaplane can take off and land on the water with a pontoon or a hull. With landing gear installed on the pontoon or hull, seaplane can also be operated on the land, which is known as amphibious aircraft. Huang et al. [1] summarized the development and technical characteristics of amphibious aircraft, and discussed the key technologies and application prospects of amphibious aircraft. Yan et al. [2] proposed a design for the strength and stiffness test of the structure connecting the main landing gear and fuselage of amphibious aircraft. Zheng et al. [3] studied the maintenance engineering method of seaplane wading structure based on the characteristics of seaplane wading structure. Since AG600 went through its trail flight successfully, it has become an urgent issue to work out the specifications of amphibious aircraft repairing, such as the level of repair, the spare parts allocation and so on, to ensure continuous and safe plane operation.

Since Sherbrooke [4] proposed multi-echelon technique for recoverable item control (METRIC) and applied it to the inventory allocation of multi-level maintenance support organization structure, many scholars have conducted a lot of researches on the maintenance resource allocation of aircraft or ship. Loo et al. [5] proposed a solution model that combined the multi-objective evolutionary algorithm with the multi-objective budget allocation method and applied it to the allocation of aviation materials. Ni [6] established a model of spare parts allocation for civil aircraft with utilization level as target and cost, order quantity, and waiting time for the shortage of spare parts as constraints, and the model was solved by the analysis of marginal utility. Frank Karsten [7] discussed the
inventory allocation of spare parts that were with high price and low demand. Regarding the minimum shortage of spare parts as the objective function, Sun et al. [8] solved the configuration model of civil aircraft by marginal analyzing. Taking the probability of no shortage as the goal, cost and space taken up by spare parts as constraints, Wei [9] solved the problem of the spare part allocation of ship. Cai et al. [10] also studied the optimization of shipboard spare parts under multi-constraint conditions and used the penalty function to dynamically adjust the constraint factors. Zhang [11] used the marginal analysis method to discuss the spare parts configuration of carrier aircraft. Feng [12] introduced the engineering factor, repair ratio into the METRIC model and established an optimization model of maintenance resources configuration of civil aircraft considering maintenance ratio. Guo et al. [13] constructed an optimization model of spare parts allocation for isolated system with the total spare parts cost as constraint. Li [14] et al. improved the efficiency of genetic algorithm used to allocate spare parts and proved it by numerical example. Wang et al. [15] proposed a method of spare parts allocation satisfying the fleet’s system reliability requirement for warships. Zio et al. [16] proposed an approach to combined optimization of system design and spare parts allocation with the respect to availability and cost, by genetic algorithm and Monte Carlo simulation. The above works make an in-depth study on the maintenance resource allocation of aircraft or ship under different support modes, but there is hardly any research on how to allocate spare parts for amphibious aircraft.

In order to solve the above problems, this paper proposed a method of spare parts allocation for amphibious aircraft based on hybrid two-level repair. Compared with the general civil aircraft repair, the airline repair of amphibious aircraft can be divided into two parts, repaired in airports for land operation and repaired by aviators for water operation. Based on the objective function of spare parts maintenance cost and the constraint condition of availability and volume of spare parts, the model is established, and the marginal analysis method is used to solve the model. The feasibility of the method is verified with the line replaceable units of amphibious aircraft landing gear system as the research object at last.

2. Configuration model

The maintenance and supply system of civil land-based aircraft is generally divided into two levels, the airline level and the depot level. The airline maintenance carries out maintenance work that can be completed in a short time while the depot is responsible for the overhaul and complete renovation of parts, components and final products. The depot maintenance can do the jobs unfinished on airline level. The naval aircrafts usually are maintained and supported by three organizations, the sailor level, the relay level and the depot level. The sailor and the relay level can repair the aircraft in some way, while the depot level has comprehensive maintenance and support capabilities. In this context, the research on hybrid two-level single-layer spare parts allocation for amphibious aircraft was proposed. The hybrid two-level repair includes the depot level and the airline level. And the airline level includes the airport level for the land operation repair work of amphibious aircraft and the aviator level for the water operation repair work. Single layer refers to that only the line replaceable units (LRU) but the shop replaceable units(SRU) are under consideration.

The hybrid two-level maintenance and supply system of amphibious aircraft consists of aircraft, structures in need of maintenance and spare parts storehouse and so on. As is shown in figure 1, there is $m$ Central Repair Depots (CRD) in the repair level of depot, and $n$ airports and one aviator repair station in the repair level of airline, and $k$ line replaceable units in the system. The supply process of repair is shown in figure 2.
Figure 1. The system of maintenance supply based on hybrid two-level single-layer repair for amphibious aircraft

Figure 2. The supply process of hybrid two-level single-layer repair for amphibious aircraft

Figure 2 shows that if a LRU failure found in the airline level, it could be in an airport or on the surface of water. On the one hand, when it’s on the surface of water, the defective part will be dismantled in accident site on the water and replaced with a spare part from the spare storehouse of aircraft. If there is no such a spare part in the storehouse, there will be a shortage, and application for the spare part will be transmitted to CRD. The defective part will be repaired by aviators, and be preserved in the storehouse of aircraft when it’s repaired. Otherwise the defective part will be sent to CRD after aircraft turning around and get repaired there and be preserved in storehouse of CRD finally. On the other hand, when the LRU failure occurred in an airport, the spare part will be supplied by the storehouse of airport or CRD and defective part will be repaired in the airport or CRD, which is exactly the same with the transfer of LRU part of land-base planes. Supply of spare parts among airports is ignored in this situation. The LRU parts satisfied the classical inventory formula in the process of hybrid two-level single-layer repair.

\[ S = S_{OH} + S_{DI} - S_{BO} \]  

where, \( S \) is the number of initial inventory of the storehouse and is constant, \( S_{OH} \) the number of current inventory, \( S_{DI} \) the number of spare parts under repair or in the supply, and \( S_{BO} \) the number of shortage. When the turnover parts and repairable parts are under repair for failure, \( S_{DI} \), the number of spare parts obtained from repair will increase by 1. If there is a spare part to substitute the defective part in the storehouse, \( S_{OH} \) will decrease by 1, otherwise \( S_{BO} \) will increase by 1. When the repair work is completed, \( S_{DI} \) will be reduced by 1, either \( S_{OH} \) will increase by 1 or \( S_{BO} \) will be reduced by 1 in this situation. In order to simplify modeling and improve engineering practicability, the following assumptions are made,

1. The type of aircrafts in a fleet is the same, and all LRU are equally important. Once there is a shortage of spare part, the aircraft will go be grounded.
2. Supply of spare parts among airports and multiple failure is not under consideration. Defective part doesn’t need to queue up for repair.
3. Suppose that defective LRU parts must be repaired in CRD.
(4) Suppose that when a shortage occurs on the level of airline, the round-trip time of LRU parts from CRD to repair station in airport is the same as the time from CRD to the accident site on the water, and so does the transportation cost.

3. Mathematical model
Mathematical model based on METRIC, with maintenance cost as objective function and availability and volume of spare parts as constraints was built to optimize inventory allocation. The model is shown as the follow.

\[
\begin{align*}
\min C \\
\sum_{j=1}^{k} V_i S_j & \leq V \\
A & \geq A_{\text{min}}
\end{align*}
\]

where \( C \) is total maintenance cost, \( A \) is the practical availability, \( A_{\text{min}} \) is the minimum availability of fleet, \( V_i \) and \( S_i \) are the volume and number of each LRU parts allocated in storehouse in aircraft respectively, and \( V \) is the volume of spare parts storehouse in aircraft.

4. Spare parts allocation solution

4.1. The process of spare parts allocation
The solution based on marginal analysis can be divided into two steps, firstly optimize the inventory allocation of each spare parts among the storehouses of airports, aircraft and CRD. Secondly optimize the inventory allocation of all kinds of spare parts by using marginal analysis. The process of inventory configuration model solution is shown in figure 3.

![Figure 3](image_url)

Figure 3. The process of spare parts allocation for amphibious aircraft
4.2. **Formulas**

The calculation formula of nouns involved in the above process is shown as the following.

4.2.1 **Annual average demand.**

Annual average demand means the total spare parts needed in a year,

\[
m_i = \frac{FH \times OPA_i \times N}{MTBUR_i}
\]  \hspace{1cm} (3)

where \( m_i \) is the annual average demand of each LRU parts, \( FH \) is the annual average flying hours of aircraft, \( N \) is the number of aircrafts in a fleet, \( OPA_i \) is the number of LRU parts installed on a plane, \( MTBUR_i \) is the unscheduled maintenance interval.

And the annual average demand in spare parts storehouse of airports or aircraft is as the following,

\[
m^j_i = \frac{D_j}{\sum_{j=1}^{n} D_j} m_i \lambda^j_i
\]  \hspace{1cm} (4)

where \( j=1,\ldots,n+1 \) is the number of storehouses of airports and aircraft, \( D_j \) \((j=1,\ldots,n)\) is the voyage between \( airport_i \) and \( airport_{i+1} \), \( D_{n+1} \) is the average voyage between \( airport_n \) and the point where plane lands on the surface of water, \( \lambda^j_i \) is the repair ratio of defective parts in the airports or aircraft.

And the annual average demand in CRD,

\[
m^0_i = \sum_{j=1}^{n} m^j_i (1 - \lambda^j_i)
\]  \hspace{1cm} (5)

4.2.2 **Expected demand.**

The expected demand of the spare parts preserved in storehouse in CRD is as the following,

\[
\mu^0_i = m^0_i \cdot RTAT_i
\]  \hspace{1cm} (6)

where \( RTAT_i \) is the sum of time used by repair in CRD and spent on transportation of spare parts from CRD to airports. And the expected demand of the spare parts preserved in storehouse in airports or aircraft is as the following,

\[
\mu^j_i = m^j_i \cdot TRT_i + \frac{m^j_i}{m_i} \cdot (EBO^j_i(s))
\]  \hspace{1cm} (7)

where \( TRT_i \) is the time of spare parts transportation from CRD to airports.

4.2.3 **Expected shortage.**

\[
EBO^0_i(s) = \sum_{x=1}^{\infty} (x-s) \left(\frac{\mu^0_i}{x!}\right)^x \exp\left(-\frac{\mu^0_i}{x!}\right)
\]  \hspace{1cm} (8)

where \( EBO^0_i(s) \) is the expected shortage in CRD when the number of spare parts inventory in CRD is \( s \).

\[
EBO^j_i(s) = \sum_{x=1}^{\infty} (x-s) \left(\frac{\mu^j_i}{x!}\right)^x \exp\left(-\frac{\mu^j_i}{x!}\right)
\]  \hspace{1cm} (9)

where \( EBO^j_i(s) \) is the expected shortage in airports when the number of spare parts inventory in airports is \( s \).

4.2.4 **Availability.**
\[ A^0_i = \left(1 - \frac{EBO_i(s)}{N \times QPA} \right)^{QPA} \]  
(10)

\[ A^j_i = \left(1 - \frac{EBO^j_i(s)}{N \times QPA} \right)^{QPA} \]  
(11)

where \( A^0_i \) and \( A^j_i \) are the availability of spare parts in CRD and airports respectively.

5. Case study
An aircraft fleet consists of 10 amphibious aircrafts, with an average annual flying hour of 1920h, a minimum fleet availability of 0.98, and the volume of the storehouse in the plane of 10m\(^3\). As is shown in figure 4, the maintenance support system includes 1 CRD repair, 3 airport repair and 1 aviator repair. And there are 15 LRU parts of amphibious aircraft landing gear system. The parameters of these LRU parts are shown in table 1.

![Figure 4. The system of maintenance supply.](image)

| Number | \( c_i \), /$ | MTBUR, /h | \( \lambda \) | TRT, /a | RT, /a | PL, (min) | \( c_{TRT} \), /$/ | \( c_{RT} \), /$/ | \( v_i \), /m\(^3\) | QM, |
|--------|---------------|-----------|-------------|---------|-------|-----------|----------------|----------------|--------------|-----|
| LRU\(_1\) | 6147 | 400 | 0.4 | 0.02 | 0.1 | 0.953 | 100 | 200 | 150 | 0.4 | 1 |
| LRU\(_2\) | 14189 | 1500 | 0.6 | 0.03 | 0.12 | 0.947 | 200 | 400 | 350 | 0.4 | 1 |
| LRU\(_3\) | 17057 | 400 | 0.4 | 0.02 | 0.1 | 0.961 | 100 | 200 | 150 | 0.7 | 1 |
| LRU\(_4\) | 21833 | 8500 | 0.5 | 0.05 | 0.15 | 0.985 | 300 | 400 | 350 | 0.4 | 1 |
| LRU\(_5\) | 32699 | 1500 | 0.6 | 0.03 | 0.12 | 0.958 | 300 | 300 | 250 | 0.6 | 2 |
| LRU\(_6\) | 19660 | 1000 | 0.4 | 0.04 | 0.12 | 0.938 | 300 | 500 | 450 | 0.5 | 1 |
| LRU\(_7\) | 6164 | 500 | 0.6 | 0.02 | 0.1 | 0.985 | 100 | 300 | 250 | 0.5 | 1 |
| LRU\(_8\) | 27603 | 12500 | 0.4 | 0.03 | 0.12 | 0.948 | 300 | 300 | 250 | 0.3 | 1 |
| LRU\(_9\) | 25428 | 400 | 0.4 | 0.03 | 0.12 | 0.967 | 400 | 400 | 350 | 0.3 | 2 |
| LRU\(_10\) | 9223 | 3000 | 0.5 | 0.06 | 0.15 | 0.931 | 200 | 500 | 450 | 0.6 | 1 |
| LRU\(_11\) | 28171 | 500 | 0.5 | 0.02 | 0.1 | 0.971 | 300 | 200 | 150 | 0.3 | 1 |
| LRU\(_12\) | 71029 | 1500 | 0.6 | 0.05 | 0.15 | 0.979 | 400 | 800 | 750 | 0.5 | 1 |
| LRU\(_13\) | 5761 | 500 | 0.4 | 0.03 | 0.12 | 0.968 | 100 | 200 | 150 | 0.4 | 2 |
| LRU\(_14\) | 54722 | 1500 | 0.5 | 0.07 | 0.18 | 0.921 | 400 | 600 | 550 | 0.6 | 1 |
| LRU\(_15\) | 33862 | 500 | 0.6 | 0.02 | 0.1 | 0.937 | 200 | 200 | 150 | 0.5 | 1 |

\(^a\) The repair time spending in CRD.

\(^b\) The availability of LRU.
The transport cost from airport to CRD.

The repair cost of LRU parts in CRD.

The repair cost of LRU parts in airports.

A mathematical model with maintenance cost as the objective function and availability and volume of spare parts as constraints is constructed, according to the above data. The annual average demand is calculated from the equations (3)–(5), the expected demand and the expected shortage of the CRD storehouse are calculated from the equations (6) and (8), and then the expected demand and the expected shortage of the airports storehouse and aircraft storehouse are calculated from equations (7) and (9).

The mathematical model was solved with marginal analysis. The allocation result is showing in table 2.

Table 2. The result of spare parts allocation.

| Security groups | LRU_1 | LRU_2 | LRU_3 | LRU_4 | LRU_5 | LRU_6 | LRU_7 | LRU_8 | LRU_9 | LRU_10 | LRU_11 | LRU_12 | LRU_13 | LRU_14 | LRU_15 | c/($) |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| CRD             | 6     | 3     | 5     | 2     | 4     | 4     | 5     | 1     | 9     | 3     | 4     | 3     | 9     | 3     | 4     | 1446914 |
| Airport 1       | 3     | 2     | 2     | 2     | 2     | 2     | 2     | 1     | 1     | 2     | 2     | 1     | 1     | 2     | 1     | 601830  |
| Airport 2       | 2     | 2     | 1     | 1     | 1     | 2     | 1     | 1     | 2     | 1     | 1     | 1     | 2     | 1     | 1     | 438339  |
| Airport 3       | 2     | 2     | 1     | 1     | 1     | 2     | 1     | 1     | 2     | 1     | 1     | 2     | 1     | 1     | 1     | 421132  |
| Aircraft        | 2     | 2     | 2     | 1     | 1     | 2     | 1     | 1     | 2     | 1     | 1     | 2     | 1     | 1     | 1     | 438339  |

As is shown in table 2, when the number of spare parts inventory in the storehouses of CDR, airports and aircraft is 156 totally, the practical availability of whole fleet will be 0.9818 and the total volume of spare parts carried in the aircraft will be 10 m³, which satisfies the constraint conditions. And the total maintenance cost is 3346554 dollars. The curve of fleet availability and cost is shown in figure 5.

![Figure 5](image_url)

**Figure 5.** Diagram of fleet availability and cost.

6. **Conclusions**

(1) This paper established a hybrid two-level aircraft repair model based on depot, airport and aviator repair and introduced the marginal analysis method to solve the model, allocating the spare parts of amphibious aircraft.

(2) Regarding the line replaceable units of landing gear of amphibious aircraft as the research object, the mathematical model was established with the maintenance cost as the objective function, the availability and the volume of the spare parts as the constraints. The results show that when the fleet availability is 0.9818 and the volume of spare parts carried in the aircraft is 10 m³, the cost of maintenance is $3346554.
(3) The research in this paper fills in the blanks of the spare parts allocation of amphibious aircraft and provides ideas for future research.

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