Research on the Plan of Plane Line Replaceable Units Based on FSMC Model

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Abstract. The line replaceable unit (LRU) is a direct carrier of the fighter’s field replacement and maintenance strategy. It is reasonably and accurately divided into modules, which can quickly locate the fault location, reduce maintenance support time, and improve the efficiency of maintenance support. Improve combat effectiveness.

Aiming at the problem of the LRU division method in the aircraft design stage, this paper proposes an FSMC aircraft LRU division method based on function-structure-maintainability-coupling, comprehensively uses fuzzy clustering and other methods to evaluate and analyse the LRU division scheme, and compare different LRU schemes. Use availability of the aircraft to perform simulation analysis. The research results show that the established on-site replaceable unit evaluation model can solve the problem of fighter aircraft LRU division schemes in the context of actual combat, and provide model support and empirical reference for further research on aircraft LRU division design research.

1. Introduction

A line replaceable unit (LRU) refers to a unit that can be removed and replaced from a system or equipment at the work site [1]. In fighter field maintenance and repair work, the field replaceable unit is an independent unit that can be disassembled or replaced in field-level maintenance by structurally, functionally, or electrically dividing aircraft parts, systems, or equipment. At present, my country’s field maintenance support model is mainly based on three-level maintenance, Operation-level maintenance, Intermediate-level maintenance, Deport-level maintenance. However, with the increasing demand for equipment support capabilities in future wars, it is urgent to simplify the maintenance system and optimize the support strategy. The United States is the first country to explore the two-level maintenance support model and recognizes it as the future direction of development, which can quickly respond to the needs of troops in the modern battlefield of the 21st century. From the perspective of the implementation of the second-level maintenance system planned by the US military, LRU division technology occupies a central position in the key technology of ‘three-level maintenance to two-level maintenance’, which is directly related to who is the object of component design, maintenance operation system and maintenance strategy. How to formulate the problem.
In recent years, the research on the division of the design stage of LRU at home and abroad is still in its infancy. In the application of related projects, system division methods such as functional planning and design, multi-constraint division, and minimum and maximum division have been explored. Zhang Bao-hui et al. [2] studied the functional module division method based on functional planning and design, comprehensively considering the functional correlation, physical correlation, time correlation, assembly correlation and other related criteria, and divided the example system; Tian Bao-zhen et al. [3] proposed the module division method under multiple constraints. This method takes the structural domain, functional domain and customer demand domain as multiple constraints, constructs the correlation matrix and uses the analytic hierarchy process to determine the weight coefficients between the three constraints, and generates the corresponding module division according to the modular correlation and threshold the plan was analyzed and verified by examples; J.E. Parada et al. [4] discussed the definition of LRU in terms of maintenance task analysis, maintenance strategy optimization, and repair level analysis based on the construction of comprehensive supportability analysis framework. Influencing factors. Asok et al. [5] proposed a module division method based on graph theory and fuzzy logic, which defined module division as the process of selecting the best module division seam position.

Aiming at the division of LRU in the aircraft design stage, this paper summarizes the system division method of complex product systems, and proposes an FSMC model based on function-structure-maintainability-coupling. Based on the principle of FSMC division, it quantifies function, structure, maintainability, and coupling. Use correlation analysis, multi-criteria normalization analytic hierarchy process, and fuzzy clustering method to classify and evaluate aircraft LRU, and evaluate aircraft availability under different LRU division schemes to obtain the most optimize the LRU division scheme.

2. Research on the division of replaceable units in the field

2.1. LRU hierarchical architecture of aircraft system

Function-structure model and function-behavior-structure model are typical models for index design of system division. The main idea is to find out the corresponding structure form that can achieve the required function. Through function definition, function planning and design, function Several steps, such as structure mapping and mutual combination between structures, are used to achieve the purpose of system design. The systematic design model proposed by Pahl and Beitz, the distributed hierarchical network model proposed by domestic scholars Han Xiao-jian and Deng Jia [6], and the functional reasoning model proposed by Zhang Guo-quan [7] have all made critical explorations.

![Figure 1. Aircraft LRU layering model](image_url)

The various units of the aircraft system are widely and closely connected. It is a complex network structure with multiple levels and multi-functions. It is difficult to analyse and evaluate it with strict mathematical analysis, so it can only be adopted by the combination modelling method, that is, the
description first Modelling establishes a hierarchical model of the division of the aircraft system into the LRU, and then establishes its mathematical model according to the specific hierarchical characteristic parameters described, and designs the LRU of the aircraft system. That is, the entire aircraft is first divided into the system layer, and then the system layer is divided into partial systems or equipment according to the structure and function realization. Finally, for the equipment layer, its components are clustered into LRU modules according to a certain module division method. As shown in Figure 1.

2.2. Hierarchical modeling of aircraft LRU division based on FSMC
The overall function in the aircraft system design specification is planned and designed into sub-functions, sub-functions and functional units through the FSMC model, and its functional structure is established, and then its carrier structure is obtained by mapping each sub-function, sub-functions and functional units. 3. Maintenance issues.

It can be seen from this that function, coupling, maintainability, and structure are closely related, and the relationship mapping between them can be mapped into a whole, denoted as $RM\left(FSMC\right)$. The meaning is: ‘ $F_1 \rightarrow S_1 \rightarrow M_1 \rightarrow C_1 \rightarrow F_2 \rightarrow S_2 \rightarrow M_2 \rightarrow C_2 \rightarrow F_3 \rightarrow S_3 \rightarrow M_3 \rightarrow C_3 \ldots$ ’ circular reciprocating mapping process [8]. In this way, a hierarchical model of aircraft LRU division is constructed. The ellipse represents an LRU. When each layer of the LRU meets the features of function, structure, maintainability, and coupling at the same time, the LRU is a component; if there are only some features, the LRU is a functional module or a structural module.

3. Analysis of aircraft LRU division based on FSMC model

3.1. Aircraft LRU division master plan
According to the requirements, the overall functions of the aircraft system design specification are planned and designed into sub-functions, sub-functions, and function elements through the FSMC mapping model. The functional structure of the aircraft system is established, and the structure and maintenance of each sub-function, sub-function, and function element are analyzed. Sex, coupling, obtain the FSMC-based division principle, and quantify the feature indexes or related characteristics of function, structure, maintainability, and coupling, and then comprehensively consider the elements of each life cycle with DFX design requirements to complete the LRU division of the aircraft. And through optimization screening to obtain the best division plan, as shown in Figure 2.

3.2. Principles for dividing LRU of aircraft based on FSMC
The LRU division principle based on FSMC is based on the analysis of the essential characteristics of the aircraft system, and the division and evaluation work is carried out from the functional characteristics, structural characteristics, maintainability characteristics, and coupling characteristics. By analysing the correlation between the functions, structure, maintainability, coupling and other characteristics of each element, an intuitive expression based on the FSMC aircraft LRU division principle is given. Ordinary relationship can only describe that two elements are related or not related. The two must be one of them. And only one. However, in addition to the absolute relationship or no relationship between objective things, there may also be fuzzy concepts such as "some relationships" and "close relationships". To express such relationships, fuzzy relationships must be introduced. This paper uses 0 to 1 average distribution to fuzzily define the relevant values, which is fuzzy the relevant values are shown in Table 1.

Table 1. Fuzzy correlation value correspondence table

| Level | Degree of correlation | Description of correlation              | Correlation value |
|-------|-----------------------|----------------------------------------|-------------------|
| 1     | Extremely close       | Components cannot be divided            | 1.0               |
| 2     | Close                 | There are intimate relationships between components | 0.8               |
| 3     | Moderate              | There is a certain correlation between components | 0.6               |
| 4     | Not close             | Weak relationship between components    | 0.4               |
| 5     | Poor                  | Components are basically independent    | 0.2               |
| 6     | Unrelated             | No relationship between components      | 0                 |

Assuming that the correlation value between components $i$ and $j$ is $r_{ij}$, the correlation value has the following properties:

- Reflexivity: $r_{ii} = 1$, that is, the correlation between the component and himself is extremely strong.
- Symmetry: $r_{ij} = r_{ji}$, that is, the correlation between components $i$ and $j$ is equal to the correlation between components $j$ and $i$.
- Non-transitivity: $r_{ij} > 0$ and $r_{jk} > 0$ do not necessarily satisfy $r_{ik} > 0$, that is, component $i$ is related to $j$, and component $j$ is related to $k$, but component $i$ and $k$ are not necessarily related.

The correlation values between all components form a correlation matrix. The relevant principles and quantified values of FSMC based aircraft LRU division will be given in detail below.

1. Function-related principles
   This principle refers to starting from the system functional requirements that need to be met, and grouping together those components that jointly realize one or some functional requirements of the system to form an LRU. There is a certain correlation between the devices in terms of functions.

2. Structure-related principles
   This principle means that the structure inside the LRU has a certain degree of coupling, while the overall structure of the LRU is relatively independent. As the most basic principle of LRU division, it guarantees the structural integrity and independence of each module. This principle is mainly considered from the aspects of connection method and shape-position relationship of aircraft system components.

3. Maintainability related principles
   This principle refers to the degree of impact on other parts inside the LRU when a component inside the LRU is damaged. When the internal parts of the LRU fail, the difficulty of repairing the LRU.

4. Coupling related principles
   The principle refers to the degree of correlation between various components within LRU.
3.3. Aircraft LRU division comprehensive correlation matrix

According to the correlation principle of LRU division given above, the designer evaluates the function sub-correlation matrix $RM_F$, the structure sub-correlation matrix $RM_S$, the maintainability sub-correlation matrix $RM_M$, and the coupling sub-correlation matrix $RM_C$ between the constructed components. For example, the functional sub-correlation matrix $RM_F$ between $n$ components is constructed as follows:

$$RM_F = \begin{bmatrix}
    r_{f_1} & r_{f_2} & \ldots & r_{f_n} \\
    r_{s_1} & r_{s_2} & \ldots & r_{s_n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{m_1} & r_{m_2} & \ldots & r_{m_n}
\end{bmatrix}$$

(1)

In the formula, It means that the functional sub-correlation matrix $RM_F$, defined between the components $i$ and $j$ according to the functional correlation description $r_{f_{ij}}$ is the functional correlation value between the components $i$ and $j$.

The improved analytic hierarchy process is used to establish an analytic hierarchy structure and a comprehensive judgment matrix to determine each relevant weight. The structural hierarchy is shown in Figure 3.

According to the special hierarchical analysis structure established above, the multi-criteria normalization method is used to establish the judgment matrix, thereby simplifying the calculation process of the hierarchical analysis method under the multi-criteria conditions.

First, establish a single criterion upper triangular judgment matrix $[9]$ for $i, j = 1, 2, \ldots, m$, and use $a_{ij}$ to represent the ratio of the influence of $x_i$ and $x_j$ with respect to a certain criterion $k$ among the $z$ criteria.

$$A = \begin{bmatrix}
    a_{11} & a_{12} & \ldots & a_{1m} \\
    a_{21} & a_{22} & \ldots & a_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{m1} & a_{m2} & \ldots & a_{mm}
\end{bmatrix}$$

(2)

In the formula, $A$ is the upper triangular judgment matrix of the criterion $k$ pairwise comparison. The value of $a_{ij}$ generally takes 1-9 as the scale, which is called "9" scale method [10].

Then use the normalization method to establish a multi-criteria comprehensive judgment matrix $CA$. The method used is the weighting method [11], the formula is as follows:

$$CA = \left( ca_{ij} \right)_{nm} = \left[ \sum_{k=1}^{z} \omega_k (a_{ij})_k \right]_{m \times n}$$

(3)
In the formula: \( Z \) represents the number of criteria; \( ca_{ij} \) represents the comprehensive comparison value of \( x_i \) and \( x_j \) with respect to \( Z \) criteria; \( \omega_k \) represents the weight of the \( k \) th criterion, which can be directly passed through the standard AHP method to make sure.

Find the maximum feature root \( \lambda_{\text{max}} \) of the positive and negative consistency comprehensive judgment matrix \( CA \), and then use the solution to solve the corresponding feature vector \( \omega \), and finally normalize the feature vector \( \omega \), which is the weight value corresponding to each index.

\[
\lambda_{\text{max}} = \frac{1}{m} \sum_{i=1}^{m} \frac{\omega_j}{\omega_j} \quad (4)
\]

\[
\omega_j = \left( \prod_{i=1}^{n} ca_{ij} \right)^{1/m} \quad (5)
\]

In the formula, \( \omega_j \) is the weight of the \( j \)-th index (that is, the weight of the \( i \)-th correlation)

After the calculated weight value passes the consistency test, it can be considered reasonable. The smaller \( CR \) is, the better the consistency of the comprehensive judgment matrix, and when \( CR < 1 \), it can be considered that the comprehensive judgment matrix has satisfactory consistency. Otherwise, it is necessary to perform a pairwise comparison again to adjust the elements in the upper triangular judgment matrix until the comprehensive judgment matrix has proper consistency.

According to each sub-correlation matrix, the comprehensive correlation matrix of \( n \) components is constructed in the form of square roots. The construction method is as follows:

\[
RM = \sqrt{\sum_{k=1}^{n} (\omega_j RM_k)^2} = (r_{ij})_{n,n} \quad (8)
\]

In the formula: \( RM \) is the comprehensive correlation matrix, and its order is \( n \); \( RM_k \) is the \( k \)-th sub-correlation matrix, which in turn represents the functional sub-correlation matrix \( RM_F \), the structural sub-correlation matrix \( RM_S \), the maintainability sub-correlation matrix \( RM_M \), and the coupling sub-correlation matrix \( RM_C \); \( \omega_k \) is the weight of the \( k \)-th correlation and satisfies \( \sum_{k=1}^{n} \omega_k = 1 \); \( r_{ij} \) is the comprehensive correlation coefficient between the \( i \)-th and \( j \)-th components.

Compared with the traditional direct summation method, the square root form is used to construct the comprehensive correlation matrix, which can reflect the tightness of the correlation between components. For the aircraft system, due to its very high complexity, it is difficult to directly obtain a reasonable LRU division. A fuzzy cluster analysis method is used to screen the LRU division scheme of the aircraft system. After the previous calculations, we have obtained the comprehensive correlation matrix divided by the aircraft LRU. Next, we will use the angle cosine method to obtain the fuzzy equivalent matrix, and then through the fuzzy equivalent transformation to obtain the comprehensive equivalent matrix; Using the matrix method, the threshold \( \lambda \) under different division schemes is obtained, and the \( F \) statistic is introduced to measure the suitability of the LRU division scheme, and the division scheme is initially selected.
Let $m$ be the number of LRUs corresponding to the threshold $\lambda$, $n_i$ be the number of components in the $i$th LRU, $\bar{x}_{ik} = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ijk}$ be the average of the $k$th feature of the $i$th LRU, and $\bar{x}_k = \frac{1}{n} \sum_{j=1}^{n} x_{ijk}$ be the average of the $k$th feature of the entire LRU.

The formula of $F$ statistic is shown in the formula:

$$F = \sum_{i=1}^{m} \sum_{k=1}^{n_i} \frac{(\bar{x}_{ik} - \bar{x}_k)^2}{(m-1)/\sum_{i=1}^{m} \sum_{k=1}^{n_i} (\bar{x}_{ik} - \bar{x}_k)^2} / (n-m) \sim F(m-1,n-m) \quad (9)$$

It follows the $F$ distribution with degrees of freedom $m-1$ and $n-m$. The numerator represents the degree of coupling between LRUs, and the denominator represents the degree of polymerization of components within the LRU. Therefore, the larger the value of $F$, the smaller the degree of coupling between LRUs, and the better the division effect. For a given credibility $\hat{\alpha}$, check the $F$ critical value table to get $F_{\hat{\alpha}}$. If $F > F_{\hat{\alpha}}(m-1,n-m)$ (usually $\hat{\alpha}=0.05$), according to the analysis of variance theory, the difference between LRUs is significant, and the division result is more reasonable. In general, if there is more than one $F$ value that satisfies the inequality $F > F_{\hat{\alpha}}(m-1,n-m)$, the size of $F - F_{\hat{\alpha}}$ can be further investigated. The larger value obtains a relatively satisfactory $F$ value, and the corresponding division value is the required division scheme.

### 4. Application Example Analysis of Aircraft LRU Division Based on FSMC Model

Taking the canopy of a certain type of aircraft canopy system as an example, the control system is used to divide the LRU. The structure [12] is shown in Figure 4. In order to reduce the space and matrix size, the main components of the higher level are used as an example to divide the LRU. Therefore, the components are simplified from the design perspective as shown in Table 2.

![Figure 4. Aircraft canopy use control system structure diagram](image)

| Number | Name                   | Number | Name                             |
|--------|------------------------|--------|----------------------------------|
| 1      | Case                   | 13     | Handle                           |
| 2      | Rocker                 | 14     | Cabin opening switch             |
| 3      | Axle 1                 | 15     | Sector Rocker 1                  |
| 4      | Axle 2                 | 16     | Ejection double unlock switch    |
| 5      | Rocker arm with cam    | 17     | Inner handle                     |
| 6      | Support                | 18     | Handle connecting rod            |

Table 2. Aircraft canopy use control system components list
Based on the FSMC's LRU division principle and correlation analysis method, the functional sub-correlation matrix, structural sub-correlation matrix and maintainability sub-correlation matrix between the components of the manual control system of the cockpit canopy are constructed by the designer as described above. Coupling sub-correlation matrix. The correlation matrices are not shown here due to space limitations. Using the multi-criteria normalized analytic hierarchy process above, the weight of each sub-correlation is determined to be 0.33 for design, 0.20 for manufacturing, 0.45 for maintenance, and 0.02 for retirement. Using analytic hierarchy process, the weights of each stage of the criterion layer are determined to be 0.29, 0.28, 0.31, 0.12. According to each sub-correlation matrix and its weight, determine the comprehensive correlation matrix between the system components, as shown in Figure 5. The fuzzy equivalent matrix \( CM^* \) is calculated by MATLAB, as shown in Figure 6.

### Table 3. Preferred LRU division scheme

| Number | Threshold | LRU dividing program | LRU Value | Non-LRU Value |
|--------|-----------|----------------------|-----------|--------------|
| 1      | 0.492     | \{1, 2, 5, 6\}, \{3, 4\}, \{7, 8\}, \{9, 10\}, \{11\}, \{12\}, \{13\}, \{14\}, \{15\}, \{16\}, \{17, 18, 19, 20\}, \{21\}, \{22\}, \{23, 24\} | 5         | 10           |
| 2      | 0.484     | \{1, 2, 5, 6\}, \{3, 4\}, \{7, 8\}, \{9, 10\}, \{11\}, \{12, 13\}, \{14, 16\}, \{15\}, \{17, 18, 19, 20\}, \{21\}, \{22, 23, 24\} | 7         | 5            |
| 3      | 0.48      | \{1, 2, 5, 6\}, \{3, 4\}, \{7, 8\}, \{9, 10\}, \{11\}, \{12, 13\}, \{14, 15, 16\}, \{17, 18, 19, 20\}, \{21\}, \{22, 23, 24\} | 7         | 4            |

It can be seen from Figure 3, \( \lambda = 1 \), 0.608, 0.601, 0.588, 0.562, 0.54, 0.532, 0.502, 0.492, 0.484, 0.48, 0.477, 0.462, 0.461, 0.44, 0.43, 0.419, 0.374, 0. Choose different, corresponding to different
intercept arrays, get different division schemes, a total of 19 kinds. The smaller the $\lambda$ value, the lower the number of LRUs for each scheme. When $\lambda = 1$, the system is divided into 24 LRUs; when $\lambda = 0$, it is divided into one LRU, that is, the entire sub-system is divided into one LRU. After removing the maximum value and the minimum value, the primary selection of the division scheme is performed by using the statistical method. Calculate the $F$ statistic values corresponding to the 17 thresholds respectively. Since the calculation result hopes that the larger the value of $F - F_{0.05}$, the better. Therefore, the largest integer value is selected as the alternative, that is, the three alternatives when the corresponding threshold $\lambda = 0.492, 0.484, 0.48$ Alternative LRU division schemes are selected to determine the optimal number of LRUs and the clustering center of each LRU, as shown in Table 4.

**Table 4. Planning of the whole machine LRU division scheme**

| Number | Threshold | LRU Value | Non-LRU Value |
|--------|-----------|-----------|---------------|
| 1      | 0.492     | 25        | 42            |
| 2      | 0.484     | 32        | 25            |
| 3      | 0.48      | 34        | 20            |

According to the above example, the planning of the LRU division scheme of the whole machine under different $\lambda$ situations is given, as shown in Table 6, and it is substituted into the simulation software to analyze the availability of the aircraft. The simulation environment is set to a fixed four-crew system, the number of simulation days is 100 days, and the average usability of the 24 aircraft of the entire crew of 100 days is analyzed and a conclusion is drawn. The three division schemes are shown in Figure 7.

**Figure 7. Simulation comparison of average usability**
By comparing the average use availability of aircraft, we can see that when the threshold $\lambda = 0.492$, the average use availability of the entire crew aircraft is 82.65%; when the threshold $\lambda = 0.484$, the average use availability of the entire crew aircraft is 69.92%; When the threshold $\lambda = 0.48$, the average availability of the entire crew aircraft is 55.58%; the preliminary conclusion is: when the threshold $\lambda = 0.492$, the aircraft LRU division scheme is the most appropriate.

Assuming three different aircraft LRU division schemes for different thresholds, we can see that among the three thresholds that were initially selected through statistics, the availability of use also decreases as the threshold decreases. First, the number of LRUs and non-LRUs has a certain impact on the average availability of the crew. Second, the total number of LRUs and non-LRUs may also be a factor that affects the availability of aircraft. However, in the division results in this article, they're basically unchanged. Therefore, in the use guarantee stage, a reasonable LRU division has a great significance for improving the availability of aircraft use.

5. Conclusion
This paper studies aircraft LRU partitioning methods based on availability, summarizes and analyzes the current status of system design research at home and abroad, proposes FSMC-based aircraft LRU partitioning model, and comprehensively uses correlation analysis, multi-criteria normalized analytic hierarchy process and fuzzy clustering Methods: Design and analyze the aircraft LRU division scheme, and optimize the LRU scheme through case analysis and flight support simulation comparison. It can be seen from the conclusions that the pros and cons of the LRU scheme division will have a significant impact on the availability and mission success rate of wartime aircraft. This paper proposes that the aircraft LRU division method can effectively optimize the outfield LRU division scheme, and its model construction has engineering practical value, can provide experience reference for further research on aircraft LRU division.

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