Research on Maintainability Evaluation Model Based on Fuzzy Theory

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Abstract

Maintainability influencing attributes are analyzed, their weight and value calculating methods are given, and the maintainability fuzzy evaluation method is proposed based on the relative closeness. According to the maintenance task simulation operated in virtual environment, the maintainability virtual evaluation model is built by analyzing the maintenance task for each replaceable unit of product. At last, a case study is given based upon the main landing gear system of a certain type civil aircraft, and the result indicates that the model is suitable for maintainability qualitative evaluation and can support maintainability concurrent design.

Keywords: maintainability evaluation; multiple criteria decision making; fuzzy theory; virtual maintenance; concurrent design

1 Introduction

Maintainability decided by design is a significant characteristic of product that can make maintenance convenient, fast and economical. With the finalization of product design, maintainability becomes the inherent product attribute. Maintainability evaluation is an important way to assess product maintainability. In recent years, many scholars have applied the multiple criteria decision making theory in the field based on studying maintainability influencing attributes, and acquired good results\(^1\)-\(^3\). However, these studies still have some shortages, which mainly include two aspects: firstly, the studying object of maintainability evaluation is the whole product, and the influence of replaceable units on maintainability is not considered; secondly, how to assess maintainability in product design phase is not considered either, thus the evaluation model can not support maintainability concurrent design. The paper takes product digital mock-up in virtual environment as studying object, establishes a maintainability evaluation model for design phase based on fuzzy theory by analyzing the maintenance task of each replaceable unit.

2 Maintainability Attributes

2.1 Maintainability evaluation attributes set

The maintainability influencing factors of product which finalized the design include many aspects, such as design, maintenance personnel, logistic support, and operation context, etc\(^4\). In design phase, the design factor is the most important aspect, and the maintenance personnel and logistic factors also should be considered in design process, while the operation context (such as maintenance manual, illustrated part catalog, etc.) established after finalizing design is usually not considered. Base on above analysis, \(X = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7\}\) is used to express the maintainability design evaluat-
ing attributes set, where $x_i (i = 1, \cdots, 7)$ separately represent: simplicity, accessibility, standardization, modularization, identification, testability and ergonomics. Fig. 1 shows the maintainability evaluation attributes hierarchy chart.

Fig. 1  Hierarchical chart of maintainability evaluation factors.

2.2 Weight calculation

Analytic hierarchy process (AHP)\[^5\] method is used to determine the weight of each maintainability attribute in the paper. AHP method is widely used in decision and evaluation of complex problem, and the weight of each attribute is acquired by a pair-wise comparison matrix in the method. The elements of pair-wise comparison matrix express the relative importance for each two attributes, which has 9 classifications denoted by number 1 to 9 (from “equally preferred” to “extremely preferred”). The weights vector for all attributes is the unitary eigenvector corresponding to the principal eigenvalue ($\lambda_{\text{max}}$) of the pair-wise comparison matrix, namely

$$W = [w_1 \ w_2 \cdots \ w_n] \quad (1)$$

where $w_i$ is the weight of the $i$th attribute, and $n$ is the number of all attributes.

To ensure the consistency of pair-wise comparison matrix, the consistency judgment must be checked by consistency ratio, that is,

$$C_R = C_I / R_I (n) \quad (2)$$

where $C_I = (\lambda_{\text{max}} - n)/(n - 1)$ is the consistency index, and $R_I(n)$ is the random consistency index. If $C_R$ does not exceed 0.1, the consistency is accepted.

3 Maintainability Evaluation Model Based on Fuzzy Theory

3.1 Maintainability attribute value determination

The influence of maintainability attributes on product maintainability is related to the detailed maintenance task of each replaceable unit. For product in existence, the value of each maintainability attribute is traditionally determined by maintenance demonstration on entitative product in terms of maintainability verification list. However, there is no entitative product for maintenance demonstration in design phase, what leads to the above-mentioned traditional method can not support maintainability concurrent design.

With the development of computer graphics and virtual reality technique, the visible design and the virtual design of maintainability become possible\[^6\]. In the paper, the software DELMIA (digital manufacturing platform developed by IBM/Dassault System) is used as virtual environment, the maintenance task simulation is conducted on product digital mock-up by virtual human model in DELMIA, then the maintainability attributes value can be acquired by designers referring to maintainability verification list with the help of maintenance virtual simulation. Except for ergonomics factor, the maintainability verification list of all other attributes are given in related standard\[^7\], and the assessment of ergonomics can be finished by the DELMIA Human Activity/Posture Analysis module.

Because all maintainability attributes have fuzziness, the fuzzy evaluating set $V$ is established to measure them, $V = \{\text{“very dissatisfied”, “dissatisfied”, “a little dissatisfied”, “medium”, “a little satisfied”, “satisfied”, “very satisfied”}\}$. Triangular fuzzy numbers are used to quantify the elements in
fuzzy set \( V \). Table 1 shows the linguistic variables of fuzzy set \( V \) and their corresponding triangular fuzzy numbers. Fig. 2 shows the membership functions of triangular fuzzy numbers.

![Triangular membership functions](image)

**Fig. 2** Triangular membership functions.

### Table 1 Linguistic variables and corresponding triangular fuzzy numbers

<table>
<thead>
<tr>
<th>Linguistic variable</th>
<th>Triangular fuzzy number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very dissatisfied</td>
<td>(0, 0, 0.1)</td>
</tr>
<tr>
<td>Dissatisfied</td>
<td>(0, 0.1, 0.3)</td>
</tr>
<tr>
<td>A little dissatisfied</td>
<td>(0.1, 0.3, 0.5)</td>
</tr>
<tr>
<td>Medium</td>
<td>(0.3, 0.5, 0.7)</td>
</tr>
<tr>
<td>A little satisfied</td>
<td>(0.5, 0.7, 0.9)</td>
</tr>
<tr>
<td>Satisfied</td>
<td>(0.7, 0.9, 1.0)</td>
</tr>
<tr>
<td>Very satisfied</td>
<td>(0.9, 1.0, 1.0)</td>
</tr>
</tbody>
</table>

### 3.2 Fuzzy evaluation for maintenance task of each replaceable unit

Based on the maintenance task virtual simulation, technique for order preference by similarity to ideal solution (TOPSIS)[8] method is used here to assess the maintenance task of each replaceable unit.

1. **Maintainability evaluating vector**

   The method mentioned in Section 3.1 is used to determine each attribute value according to virtual maintenance task simulation, and the evaluating vector is expressed as

   \[
   V = \{v_{ij,1}, v_{ij,2}, \ldots, v_{ij,n}\} \tag{3}
   \]

   where \( (v_{ij,1}, v_{ij,2}, \ldots, v_{ij,n}) \) represents the triangular fuzzy number of the \( i \)-th attribute value.

2. **Weighted evaluating vector**

   As each attribute value is expressed as triangular fuzzy number that already has a normalized format, the weighted evaluating vector can be directly calculated from Eq.(1) and Eq.(3), namely,

   \[
   Z = \{w_{1}v_{1,i}, w_{2}v_{2,i}, \ldots, w_{n}v_{n,i}\} \tag{4}
   \]

3. **Weighted evaluating vector of ideal design solution**

   For the positive ideal design solution, the evaluating linguistic variable of all attributes should be “very satisfied”; whereas, for the negative ideal design solution, all should be “very dissatisfied”. So the weighted evaluating vectors of positive and negative ideal design solution are separately represented as

   \[
   Z^+ = \{(0.9w_{1}, w_{1,i}), \ldots, (0.9w_{n}, w_{n,i})\} \tag{5}
   \]
   and
   \[
   Z^- = \{(0,0,0.1w_{1}), \ldots, (0,0,0.1w_{n})\}
   \]

4. **Calculation of relative closeness**

   The distance between two triangular fuzzy numbers is expressed as

   \[
   d(v_{i}, v_{j}) = \left| v_{i,j} - v_{j,i} \right| + \left| v_{i,n} - v_{j,n} \right| + \left| v_{i,m} - v_{j,m} \right| \tag{6}
   \]

   And the distances between alternative design solution and positive and negative ideal design solution are separately given by

   \[
   D^+ = \sqrt{\sum_{i=1}^{n} d(z_{i}^+, z)^2} \tag{7}
   \]
   \[
   D^- = \sqrt{\sum_{i=1}^{n} d(z_{i}^-, z)^2}
   \]

   Then the relative closeness expressed as
can be gotten.

3.3 System maintainability evaluation

The occurrence probability of maintenance task is related to the failure/replaceable rate of each replaceable unit, so the failure/replaceable rate must be considered in the system maintainability evaluation. According to the relationship between mean time to repair \( \overline{M_{ct}} \) system and each repairable item,

\[
\overline{M_{ct}} = \frac{\sum_{j=1}^{m} \lambda_i M_{ct_j}}{\sum_{j=1}^{m} \lambda_i}
\]

then the relationship between maintainability of system and each replaceable unit is gotten,

\[
C_S = \frac{\sum_{j=1}^{m} \lambda_i C_j}{\sum_{j=1}^{m} \lambda_i}
\]

Where \( \lambda_i \) is the failure/replaceable rate of each replaceable unit, \( m \) is the number of replaceable units, \( C_j \) represents relative closeness of the \( j \)th replaceable unit, \( C_S \) represents the system relative closeness.

If there are several alternative design solutions, they can be compared directly by the system relative closeness. When there is only one alternative design solution, it can be evaluated by fuzzy membership for each element of evaluating set \( V \), which is converted from system relative closeness.

4 The Case Study

The main landing gear (MLG) system of a certain type civil aircraft in design is used as the studying object, and its line maintainability is evaluated here. In order to keep departure of civil aircraft in time, the line maintenance must be convenient, fast and economical, and the extent of fault isolation is only to line replaceable unit (LRU), so only the effects of LRUs on system maintainability need to be considered. Design solution of the MLG system lists its all LRUs, whose replaceable rates can be acquired by reliability prediction according to service data of similar civil aircraft. Table 2 shows LRUs of the MLG system and their replaceable rates.

<table>
<thead>
<tr>
<th>Code</th>
<th>LRUs</th>
<th>Number on one side</th>
<th>Replaceable rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shock strut</td>
<td>1</td>
<td>( 2.1 \times 10^{-6} )</td>
</tr>
<tr>
<td>2</td>
<td>Drag strut</td>
<td>1</td>
<td>( 5.3 \times 10^{-5} )</td>
</tr>
<tr>
<td>3</td>
<td>Torsion links</td>
<td>2</td>
<td>( 2.3 \times 10^{-4} )</td>
</tr>
<tr>
<td>4</td>
<td>Lock link</td>
<td>1</td>
<td>( 7.5 \times 10^{-3} )</td>
</tr>
<tr>
<td>5</td>
<td>MLG wheels</td>
<td>2</td>
<td>( 1.9 \times 10^{-3} )</td>
</tr>
</tbody>
</table>

4.1 Maintainability attribute weights calculation of MLG system

By some experts, the pair-wise comparison matrix of maintainability attributes shown in Fig.1 is given as

\[
A = \begin{bmatrix}
1 & 1/3 & 3 & 4 & 3 & 4 & 2 \\
3 & 1 & 6 & 8 & 6 & 7 & 3 \\
1/3 & 1/6 & 1 & 2 & 1 & 1 & 1/3 \\
1/4 & 1/8 & 1/2 & 1 & 1/3 & 1 & 1/4 \\
1/3 & 1/6 & 1 & 3 & 1 & 2 & 1/2 \\
1/4 & 1/7 & 1 & 1/2 & 1 & 3 & 1 \\
1/2 & 1/3 & 3 & 4 & 2 & 1/3 & 1 \\
\end{bmatrix}
\]

Its principal eigenvalue \( \lambda_{max} = 7.7491 \), \( R_1 = 1.32 \) when \( n \) is 7, then it is gotten that \( C_I = 0.1249 \) and \( C_R = 0.098 < 0.1 \) from Eq.(2). So consistency of the matrix is accepted. Weights vector of all maintainability attributes is acquired eventually, namely,

\[
W = [0.1969, 0.4104, 0.0633, 0.0412, 0.0826, 0.0893, 0.1163]
\]

4.2 Maintenance task simulation

The maintenance task of torsion links fault is taken as an example to operate the simulation in virtual environment of DELMIA, as shown in Fig.3 and Fig.4.
It can be seen from both Fig.3 and Fig.4 that the maintenance portion of torsion links can be seen clearly and no clash happens during maintenance process, so it can be concluded that the accessibility of torsion links is satisfied.

Fig. 5 is the result of DELMIA Human Activity Analysis module, which uses the scoring method of rapid upper limb assessment (RULA) [9], and the smaller the scores are, the better the result is. So, it can be seen that the ergonomic requirement of this maintenance task is a little satisfied.

In the same way, the maintenance task simulations of other LRUs are done to help design personnel to assess maintainability attributes of other LRUs.

### 4.3 Evaluation of each maintenance task

The maintainability attributes of each LRUs are measured by fuzzy evaluating set mentioned in Section 3.1, as shown in Table 3.

Then, the maintainability evaluating vector of each LRU in the form of Eq. (3) can be acquired according to the relationship between linguistic variable and triangular fuzzy number in Table 1. In terms of Eq(4) to Eq. (8), the relative closeness of all LRUs can be gotten,

\[ C_1 = 0.9283, \quad C_2 = 0.9487, \quad C_3 = 0.9527, \quad C_4 = 0.9755, \quad C_5 = 0.9889 \]

\[ C_5 = 0.9841 \]

Then, the fuzzy membership vector for evaluating set \( V \) according to triangular membership function is gotten,

\[ U = \{0, 0, 0, 0, 0.159, 0.841\} \]

It shows that the membership of “very satisfied” is the largest one, so the line maintainability of MLG system is regarded as very satisfied.

### 4.4 Maintainability evaluation of MLG system

From \( C_i (i = 1, \ldots, 5) \), the replaceable rate of each LRU in Table 2 and Eq.(9), it is gotten that the system relative closeness of MLG \( C_5 = 0.9841 \). Then, the fuzzy membership vector for evaluating set \( V \) according to triangular membership function is gotten,

\[ U = \{0, 0, 0, 0, 0.159, 0.841\} \]

It shows that the membership of “very satisfied” is the largest one, so the line maintainability of MLG system is regarded as very satisfied.

### 5 Conclusions

(1) In design phase, the design solution is not finalized, the maintenance task simulation in virtual environment can help designer to assess the maintainability of design solution, and then it can support maintainability concurrent design.
(2) By fuzzifying maintainability evaluating attribute value, and using the relative closeness to ideal design solution as evaluating standard, the maintainability of each alternative design solution can be sorted; furthermore, by fuzzifying the system relative closeness according to triangular membership function, the maintainability of design solution can be evaluated qualitatively.

(3) Based on maintenance task of each LRU, considering the replaceable rate, the system maintainability can be evaluated more comprehensively. As shown in case study of Section 4, the maintainability of “shock strut” is satisfied which is worse than these of other LURs, but this has little influence on system maintainability since its lower replaceable rate, so the system maintainability is still very satisfied.

References


Biography:

Lu Zhong  Born in 1980, he is a Ph.D. student of Nanjing University of Aeronautics and Astronautics, his researching fields are reliability and maintainability engineering, maintainability virtual design, etc.

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