An integrated method of system maintainability, testability and supportability design and evaluation

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Abstract. General quality characteristics of equipment system have a guiding role for the design, production and use of equipment and are vital for the evaluation of these characteristics. They are important indicators to measure whether the equipment meets the established standard. Aiming at the problem that the design and evaluation process of equipment general quality characteristics are independent and unrelated, this paper proposes an integrated and continuous maintainability, testability and supportability design and evaluation process based on FMECA and MSFG, and designs corresponding evaluation parameters. An impact-based fault mode rating method is also proposed to better evaluate the general quality characteristics of equipment.

1. Introduction

The quality of equipment is described by a group of its intrinsic characteristics, which are divided in special and general quality characteristics\cite{1}. General quality characteristics include not only functions, properties, and various physical properties considered by traditional engineering technology, but also focus on the design, control, operation, and application\cite{2}. Through a long period of practice and exploration, the content of general quality characteristics has tended to be consistent, mainly refers to the "six properties" (reliability, maintainability, supportability, testability, safety and environmental adaptability)\cite{3}. However, "six properties" are designed separately and have scattered focus, which causes repetition and inefficiency of work\cite{4}. Based on the maintainability, testability and supportability (MTS), this paper proposes an integrated verification and evaluation method. The related parameters are also designed.

2. Construction of integrated MTS verification and evaluation model

The integrated MTS verification and evaluation model is based on Fault Mode, Effects and Criticality Analysis (FMECA) and Multi-Signal Flow Graph (MSFG), aims to analyse the system in detail and strengthen the relationship between the MTS of the product.

2.1. Analysis of the system based-on MSFG

The MSFG model, proposed by Somnath Deb et al. in 1994, is a commonly used modelling method in system testability analysis and PHM system design, which tracks the signals affected by components and the signal flow detected by test points, and establishes the dependency relationship between them\cite{5}. The MSFG, composed of nodes and directed edges, can construct a fault diagnosis model corresponding...
to the system's hierarchical structure[6], and will show the truest connection between the modules and components in the system. Formally, the multi-signal model consists of the following elements[7], and an example of MSFG is as figure 1:

- L-dimensional finite set of system components \( C = \{ c_1, c_2, ..., c_L \} \)
- K-dimensional set of system-related independent signals \( S = \{ s_1, s_2, ..., s_K \} \)
- n-dimensional finite set of test \( T = \{ t_1, t_2, ..., t_n \} \)
- P-dimensional finite set of test points \( TP = \{ TP_1, TP_2, ..., TP_P \} \)

Directed graph \( DG = \{ C, TP, E \} \), where edge \( E \) is physical connections of system

![Figure 1. An example of MSFG, \( C_i \) is component of system, \( T_i \) is test.](image)

### 2.2. Fault analysis based-on FMECA

FMECA includes two parts: Fault Mode and Effects Analysis (FMEA) and Criticality Analysis (CA). FMEA refers to an analysis technique that analyses each possible fault mode, determines its impact on this equipment and other upper-layer equipment, and classifies each fault mode according to the severity of its impact[8]. FMECA form is the base of the model, and is related with the determination of MTS parameters. The FMECA form is designed as shown in table 1

| Category                               | Line | Category                          | Line |
|----------------------------------------|------|-----------------------------------|------|
| No.                                    | 1    | Severity category                | 13   |
| Product or function mark               | 2    | Fault mode probability level      | 14   |
| Function                               | 3    | Fault rate \( \lambda \)          | 15   |
| Fault mode                             | 4    | Frequency ratio of fault modes    | 16   |
| Cause of fault                         | 5    | Probability of fault impact       | 17   |
| Task phase and working methods         | 6    | Detection method                  | 18   |
| Local fault effects                    | 7    | Isolation ability                 | 19   |
| Fault effects on upper layers          | 8    | System BIT                        | 20   |
| Final fault effects                    | 9    | Basic maintenance measures        | 21   |
| Fault detection method                 | 10   | In minimum equipment list or not  | 22   |
| Design improvement measures            | 11   | Remark                            | 23   |
| Usage compensation measures            | 12   |                                   |      |

The FMECA form should be filled in strictly according to the product level. Line 1 to 17 are standardized requirements[9]; line 18 is filled with various testing methods, including built-in test (BIT), automatic test equipment (ATE), manual testing; line 21 is used to fill in the required maintenance measures; line 22 is to fill in whether it belongs to the minimum equipment list.

With FMECA and MSFG, the design of MTS parameters can be further carried out.
3. Design of MTS parameters

3.1. Impact-based fault level assessment

The equipment is usually a complex system, the fault modes generated are diverse and have different impact and frequency of occurrence. Therefore, the establishment of a fault level assessment method based on the impact is necessary. The fault level assessment can be carried out by using severity and the occurrence rate defined in the FMECA form in 2.2. The fault rate $\lambda$ is the probability of each fault, ranging from 0% to 100%; the severity is usually classified into 4 categories as shown in table 2[9], and are quantified as 1 to 4, which indicate the class I to IV respectively.

| Classes | Impact level | Description |
|---------|--------------|-------------|
| Class I | Catastrophic | Death or damage to products, severe environmental damage. |
| Class II | Fatal | Serious injury to personnel and economic loss, serious product damage and environmental damage. |
| Class III | Moderate | Moderate injury to personnel and economic loss, moderate damage to products environmental damage. |
| Class IV | Mild | No personal injury, mild economic loss and environmental damage, but it will cause unplanned maintenance or repair. |

The more frequent and severe fault modes should be treated with higher priority, so the fault mode weight is calculated as follows:

$$ s_i = \exp(S_0 - S_l) \quad (1) $$

$$ \hat{s}_i = \frac{s_i - \min(s_i)}{\max(s_i) - \min(s_i)} \quad (2) $$

$$ w_i = \hat{s}_i \times \lambda_i \quad (3) $$

Where $S_l$ is the severity index of each fault mode before quantification and equals 1–4, $S_0$ represents the severity index of normal state which equals 5, $\hat{s}_i$ is the severity index after normalization, ranging in [0,1], $\lambda_i$ is the fault rate and $w_i$ is the impact-based weight.

After the quantification, the higher the severity and occurrence rate, the greater the weight of fault, and the high-severity fault modes are highlighted by the exponential function in (1).

3.2. Parameters of Maintainability

Maintainability refers to the ability to maintain or recover to a specified state by prescribed procedures and methods within a specified period and based-on a given condition[10].

Since the Maintainability depends on many factors, such as the organization of maintenance, the pre-plan of maintenance, the skill of maintenance personnel, etc., which are difficult to be quantified, the Mean Time to Repair (MTTR) is used in this paper to evaluate comprehensively the Maintainability. The shorter the MTTR, the better the Maintainability.

MTTR is a basic parameter of Maintainability, and is calculated as follows:

$$ MTTR = \frac{T_{CM}}{N_T} \quad (4) $$

Where $T_{CM}$ is the total corrective maintenance time and $N_T$ is the total number of corresponding faults.

The impact-based weight of fault mode can be integrated:

$$ w_{MTTR} = \frac{\sum_i(T_{CMi} \times w_i)}{\sum_i w_i} \quad (5) $$
Where \( w_i \) is the impact-based weight of fault mode \( F_i \) and \( T_{CMI} \) is the corrective maintenance time of \( F_i \).

### 3.3. Parameters of Testability

Testability refers to the ability of a product to determine its status (working, non-working, or performance degradation), and to isolate its internal faults[11].

The testability of the system mainly considers the detection and processing capabilities for system functional faults. The corresponding parameters are the fault detection rate (FDR), the fault isolation rate (FIR), and the false alarm rate (FAR), which are calculated as follows:

\[
FDR = \frac{N_D}{N_T} \times 100\%, \quad FIR = \frac{N_L}{N_D} \times 100\%, \quad FAR = \frac{N_{FA}}{N_D + N_{FA}} \times 100\%\tag{6}
\]

Where \( N_D \) is the number of faults correctly detected, \( N_L \) is the number of faults correctly isolated, \( N_T \) is the total number of faults and \( N_{FA} \) is the number of false alarms.

With the MSFG model of system (introduced in 2.1), the relationship between faults and tests can be shown in a matrix, called the Fault-Test dependency matrix (D-matrix), shown in equation (7). Rows of the matrix are fault sources \( S \), and columns are tests \( T \), \( d_{ij} = 1 \) if the fault information \( s_i \) can be shown at the test point \( t_j \), and \( d_{ij} = 0 \) if not[12]. According to D-matrix, \( N_D \) is the number of non-zero rows, \( N_L \) is the number of rows which are unique and \( N_T \) is the total number of rows.

\[
D_{mn} = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{bmatrix}\tag{7}
\]

The impact-based weight of fault mode can be also integrated:

\[
\begin{align*}
\bar{w}_{FDR} &= \frac{\sum_{i \in D} w_i}{\sum_i w_i} \times 100\%, \quad \bar{w}_{FIR} = \frac{\sum_{i \in I} w_i}{\sum_i w_i} \times 100\% \\
\bar{w}_{FAR} &= \frac{N_{FA} \times \bar{w}}{\sum_{i \in D} w_i + N_{FA} \times \bar{w}} \times 100\%, \quad \bar{w} = \frac{\sum_i w_i}{N_T}\tag{8}
\end{align*}
\]

Where \( D \) is the set of detected faults, \( I \) is the set of isolated faults and \( \bar{w} \) is the average weight of faults.

### 3.4. Parameters of Supportability

Supportability refers to the ability of support resources to meet the requirements of peacetime combat readiness and wartime utilization requirements[11].

Table 3. Definition of Supportability parameters.

| Parameter | Numerator                      | Denominator                      |
|-----------|--------------------------------|---------------------------------|
| \( R_{SEF} \) | Available support equipment number | Needed support equipment number |
| \( R_{SEU} \) | Used support equipment number | Owned support equipment number |
| \( R_{SF} \) | Available spares number | Needed spares number |
| \( R_{SU} \) | Used spares number | Owned spares number |

According to the above definition of Supportability, this paper uses support equipment fulfill rate \( R_{SEF} \), support equipment utilization rate \( R_{SEU} \), spare fulfill rate \( R_{SF} \) and spare utilization rate \( R_{SU} \) to quantify the Supportability, which are defined as table 3[13].

In the actual use of equipment, in order to obtain the actual working status, this paper introduces a time record table to record various time parameters (active time, up time, maintenance time, etc.). The various time parameters[13] are shown in Figure 2.
With these time parameters, other useful Supportability parameters can be designed \[13\].

(1) Operational availability \( A_O \)

\[
A_O = \frac{T_U}{T_T} = \frac{T_U}{T_U + T_{DW}} = \frac{T_O + T_S + T_{CM} + T_{PM} + T_{OS} + T_D}{T_T}
\]

Where \( T_U \) is up time, \( T_T \) is total time, \( T_{DW} \) is down time, \( T_O \) is operating time, \( T_S \) is standby time, \( T_{CM} \) is corrective maintenance time, \( T_{PM} \) is preventive maintenance time, \( T_{OS} \) is operational support time and \( T_D \) is delay time.

The higher the \( A_O \), the better the Supportability.

(2) Mission capable rate \( R_{MC} \)

\[
R_{MC} = \frac{T_{MC}}{T_T} = \frac{T_{FMC} + T_{PMC}}{T_T}
\]

Where \( T_{MC} \) is mission capable time, \( T_T \) is total time, \( T_{FMC} \) is full mission capable time and \( T_{PMC} \) is partial mission capable time.

The higher the \( R_{MC} \), the better the performance of equipment, and so the better the Supportability.

(3) Utilization rate \( R_U \)

\[
R_U = \frac{T_O}{T_T}
\]

Where \( T_O \) is operating time and \( T_T \) is total time.

The higher the \( R_U \), the better the health state of equipment, and so the better the Supportability.

4. Conclusions

To solve the problem that the general quality characteristics are designed and evaluated separately, this paper presents an integrated method to evaluate MTS. In the design phase, the system is firstly modelled by FMECA and MSPG, then the parameters of MTS are built. Then in the testing phase, these parameters are calculated by the tests results. At last in the use phase, other MTS parameters are obtained by time records along the usage. Therefore, the MTS of equipment are designed and evaluated integrally and continuously. In the future, other characteristics would be integrated in, such as the Reliability, Safety and Environmental Adaptableness.

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