Importance Measure Analysis Method for Maintenance based on Multi-Function Testability States

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Abstract. Maintenance order plays an important role in industrial field, which influences multiple factors such as costs. Current method is based on importance measure using the fault tree analysis. Simply based on the fault tree of the failure condition, such method ignore some vital information hidden in other testability states, and may results in unsuitable maintenance order. This paper puts forward a novel method to evaluate importance measure based on multi-function testability states, which can be used to optimize the maintenance order. To illustrate the utility of this method, the article uses a vehicle model, and compares the different results to validate the effect of the proposed importance measure. This method can be utilized to evaluate the maintenance order containing multiple functions.

1. Introduction

Maintenance for a complicated system is important in industrial field. Usually, when a testability state is in its failure condition, maintenance engineer replaces the possibly broken units in a particular order based on their experience. Although the traditional method is aimed at maintaining the system with the least replacements of units, in practice it is inefficient and may ignore some other vital factors, resulting in high cost and an unnecessary waste of energy. 5.5% of the companies’ turnover in Finland is spent on maintenance on average, and this ratio may rise to 25%. Hence some companies try to improve the equipment reliability by increasing their Mean Time Between Failure (MTBF), etc. [1]. Besides, in fields of vehicle, some maintenance activities are cost much time and money, which make it necessary to carefully determine the order of maintenance [2].

To solve the above problem, researchers have tried a variety of modifications to optimize the process and take into consideration more factors to make the process of maintenance more efficient. Kang used Fault Tree Analysis (FTA) to qualitatively and quantitatively evaluate the failure characteristics of semi-submersible floating offshore wind turbine and gave some suggestions to improve the system performance [3]. Zhang analysed the heave compensation systems using Importance Measure (IM) and assessed the importance of each component to the whole system [4]. Cui used probability density evolution method to optimize the evaluation of importance measure [5]. Gao considered the cost factor during the process of the importance measure evaluation [6]. And
Almugrin emphasized the vital status of testability in the field of maintenance [7]. However, for a system with multi-function testability, the working states of other functions are often ignored, which in fact may be an advantage in guiding the process of maintenance.

In this paper, a novel analysis method based on multi-function testability state is put forward, which provides a different choice of maintenance order to better meet the requirements in industrial practice. The structure of the paper is listed as follows: Section 2 introduces the method to analyse importance measure based on multi-function testability. Section 3 gives a model which deeply illustrates the method as well as its applicability to explain its practical usage. Section 4 concludes the work done in this paper, and proposes some suggestions of future improvements.

2. Importance Measure Analysis Based on Multi-Function Testability States

Importance measure analysis contains qualitative assessment of the components in a defined system or function. By choosing the failure condition which can be analyzed as the top event, the corresponding intermediate or basic events, connected with logic gates “and” or “or”, can be written below. By analysing the event thoroughly, all the events could be divided into basic ones and a fault tree is completed. By comparing the values of importance measure in the fault tree, a preliminary and a final maintenance order can be determined accordingly. However, when considering multi-function testability, the method should be modified as the figure followed.

![Figure 1](image)

**Figure 1. Importance measure analysis process based on multi-function testability.**

As shown in figure 1, first, the fault tree for each possible failure condition should be modeled and their minimal cut set and structural function could be generated. Then, according to what happens in practice, determine whether a testability state is in its normal or failed state. For those in normal state, invert their structural function by using De Mogan’s Law, i.e. \( \prod_{i=1}^{n} x_i = \sum_{i=1}^{n} \bar{x}_i \), and \( \sum_{i=1}^{n} x_i = \prod_{i=1}^{n} \bar{x}_i \). After that, multiply the structural functions of all top events together and use Boolean algebra to simplify them. Specifically, when a basic event intersects with its inverse form, the whole term is canceled. For example, \( x_1 x_2 \times \bar{x}_1 \) should be canceled. Furthermore, if one term is the subset of another term, the subset ought to be canceled. For instance, given a structural function \( x_1 x_2 x_3 + x_2 x_3 \) the former term should be canceled, and the structural function will turn into \( x_2 x_3 \). As a result, the minimal cut set are generated, and equation (1) can be used to evaluate their importance measure \( IM_{mf} \) (multiple factor optimization):

\[
IM_{mf} = \frac{1}{k} \sum_{j=1}^{k} \left( -1 \right)^j \prod_{p=1}^{\beta} \left( 1 - \frac{1}{k_p} \sum_{j=1}^{m_p} \frac{1}{m_j} \right) \prod_{q=1}^{\alpha} \left( 1 + \frac{1}{k_q} \sum_{j=1}^{n_q} \frac{1}{m_j} \right)
\]  

(1)
In equation (1), let $x_i$ denote the element being evaluated, then $k$ refers to the number of minimal cut set, $n_j$ refers to the number of homogenous elements (non-inverse basic event and inverse basic event) in a cut set containing $x_i$, $\lambda$ refers to sign-judging coefficient, $k_p$ and $k_q$ refer to the number of cut set in other normal function or failure condition respectively, and $m_j$ refers to $n_j$ in the specific failure condition. Here $\lambda$ equals to 1 when the basic event is non-inverse (i.e., $x_i$), and -1 when inverse (i.e., $\overline{x_i}$). In this equation, the basic events and their inverse forms are considered separately, and the final result is the difference between the importance measure of the basic events and their inverse forms. Since during the process of subset cancel, some terms disappear which actually contribute to the importance measure, the terms $\prod_{p=1}^{P} (1 - \frac{1}{k_p} \sum_{j=1}^{n_p} \frac{1}{m_j})$ and $\prod_{q=1}^{Q} (1 + \frac{1}{k_q} \sum_{j=1}^{n_q} \frac{1}{m_j})$ are added. To be more specific, although some events in other failure conditions do not influence the final minimal cut set, the failure possibility of a basic event is decreased/increased due to its appearance in another normal/failure condition.

To better determine the importance measure to obtain an optimal maintenance order, other vital factors, such as cost or risks, should be added, and the importance measure $IM_{mo}$ (with multiple factor optimization) can be evaluated as shown in equation (2):

$$IM_{mo} = IM_{wo} \prod_{i=1}^{P} \alpha_i \prod_{j=1}^{Q} \beta_j$$

In equation (2), $\alpha_i$ refers to the value of factors which has positive correlations (i.e. higher value of $\alpha_i$ is expected), and $\beta_i$ refers to the value of factors with negative correlations (i.e. lower value of $\beta_i$ is expected).

Eventually, the importance measure is generated, and the maintenance order can be determined accordingly based on the value of importance measure $IM_{mo}$.

3. Case Study

3.1. Vehicle failure Model

A vehicle is comprised of a variety of units possessing different functions. Common malfunctions of vehicles include failure in steering, transmission, electric control, or braking systems, etc. Ovidiu verified that during the entire running process, maintenance is vital for vehicles of all types [8]. And Atkinson mentioned that adequate attention on vehicle maintenance will result in economic benefits[9]. Often the function units are made in terms of Field Replace Unit (FRU) which enables quick and easy maintenance replacements. Due to its complexity, a simple FRU may serve as the basic event of different failure conditions. Hence even a normally working state provides information about the failure conditions, and has influence on the maintenance order. To better and clearly illustrate our model, examples in this paper have been simplified. There are three failure conditions in the model, including engine failure, lighting system failure and black exhaust failure, which are shown in figure 2 (a), (b), (c) respectively. Among them there exist 13 different basic events corresponding to 13 FRUs. When maintaining, an optimized order is generated with lower costs and less time, of replacing the possibly broken FRUs with new ones to successfully fix the vehicle with malfunctions.

3.2. Assumptions

In order that the system model is more accurate and easier to analyze, in this paper several common assumptions are taken [10].

- Failure will only occur on the devices and external systems will not have effect on the system;
- The state of a failure mode can only be classified into two categories, one is Normal and the other is Failure;
- The devices do not interact with each other.

3.3. Safety Model Construction
Based on the assumptions above, the fault tree analysis can be done as the follow figure.

![Fault Tree Diagram]

**Figure 2.** Fault Tree of System Function Failure.

As shown in figure 2(a), if the engine cannot be started, it may be caused by lack of fuel supply, insufficient cylinder compression or spark plug malfunction. Among them, lack of fuel supply happens when the oil tank is broken and the tube is blocked. Insufficient cylinder compression takes place when there is a gas leakage or piston immobility, which is caused by the joint effect of connecting rod fracture and starter malfunction. In figure 2(b), similarly, if the lighting system is in its failed state, it may be caused by fuse blowout, no power supply or bulb damage. And malfunctions of
tank and battery are responsible for power supply shortage. In figure 2(c), exhaust system may emit black tail gas, which is a common failure condition. Three factors may result in this failure: exhaust pipe leakage, tail gas cleanup unit malfunction, or spark plug malfunction. Among them, the failure of cleanup system is caused by electricity generation system malfunction and carbon deposit in exhaust pipe together. And either three-way catalytic converter or oxygen sensor failure will lead to the malfunction in electricity generation system. Since each event have been divided into basic event, three fault trees are constructed. It can be observed that the three fault trees share some basic events, and thus multi-function testability is applicable.

To illustrate the usage of proposed method, further assume that such condition is satisfied: The engine mode is in its failure condition, while the lighting system and the exhaust system are in their normal state. According to the process explained in section 2, the structural functions of these fault trees can be written as follows:

\[ \Phi_1 = x_1 + x_2 + x_3 + x_4x_5 + x_6 \]
\[ \Phi_2 = x_2x_6 + x_1 + x_9 \]
\[ \Phi_3 = x_6 + x_{10} + x_{11}x_{13} + x_{12}x_{13} \]

### 3.4. Importance measure

To find out the importance measure, since \( F_2 \) and \( F_1 \) are in normal state, they ought to be inverted. The results \( \overline{\Phi_2} \) and \( \overline{\Phi_3} \) are:

\[ \overline{\Phi_2} = x_2 \cdot x_6 \cdot \overline{x_9} + \overline{x_2} \cdot x_6 \cdot x_9 \]
\[ \overline{\Phi_3} = x_6 \cdot \overline{x_{10}} \cdot \overline{x_{11}} \cdot \overline{x_{12}} + x_6 \cdot \overline{x_{10}} \cdot x_{13} \]

Hence, by intersecting \( \Phi_1, \overline{\Phi_2} \) and \( \overline{\Phi_1} \), the multi-function testability based structural function \( \Phi_{mft} \) is calculated as followed equation.

\[ \Phi_{mft} = \Phi_1 \cdot \overline{\Phi_2} \cdot \overline{\Phi_3} \]

Then, \( x_7 \sim x_{13} \) are omitted because they are irrelevant to the failure condition \( F_1 \).

\[ \Phi_{mft} = x_1 \cdot x_2 \cdot \overline{x_6} \cdot x_6 + x_1 \cdot \overline{x_2} \cdot x_6 + x_1 \cdot \overline{x_2} \cdot \overline{x_6} + x_1 \cdot x_6 + x_2 \cdot \overline{x_6} + \overline{x_2} \cdot x_6 + \overline{x_2} \cdot \overline{x_6} + \overline{x_1} \cdot x_6 + \overline{x_1} \cdot \overline{x_2} \cdot x_6 + \overline{x_1} \cdot \overline{x_2} \cdot \overline{x_6} + \overline{x_1} \cdot \overline{x_6} + \overline{x_2} \cdot \overline{x_6} + \overline{x_2} \cdot \overline{x_6} + \overline{x_1} \cdot \overline{x_6} \]

Therefore the four minimal cut sets \( x_1 \cdot \overline{x_6}, x_2 \cdot \overline{x_6}, x_3 \cdot \overline{x_6}, x_2 \cdot \overline{x_6} \) are generated. According to equation (1), the importance measure \( IM_{mft} \) (without multiple factor optimization) for \( x_1 \sim x_6 \) can be evaluated. Due to the fact that the bigger the value of \( IM_{mft} \), the more possible the unit is broken, the preliminary maintenance order is determined.

However, since the importance measure of \( x_1 \) equal to \( x_3 \), and \( x_4 \) equal to \( x_5 \), maintenance order of their corresponding FRU \( U_{x_1} \) and \( U_{x_3} \) cannot be decided. Thus multiple factors regarding maintenance are introduced, which help optimize the result further.

The information about the costs and MTBF are listed in Table 1. According to equation (2), since
both MTBF and costs have negative correlations, \( IM_{\text{mf}} \) can be calculated from multiplying \( IM_{\text{nr}} \) by the influence factor of MTBF and costs. Based on the optimized importance measure, final results can be determined, which are shown in Table 1.

| Basic Event | Information | Traditional Method | Optimized Method |
|-------------|-------------|---------------------|------------------|
|             | MTBF (h)    | Average Cost ($)    | \( IM_{\text{nr}} \) | Maintenance Order | \( IM_{\text{mf}} \) | Preliminary Maintenance Order | \( IM_{\text{mo}} \) | Final Maintenance Order |
| \( x_1 \)   | 1200        | 180                 | 0.2              | 1               | 0.250            | 1                            | 1.157E-6            | 2                       |
| \( x_2 \)   | 1000        | 370                 | 0.2              | 1               | 0.208            | 3                            | 5.622E-7            | 5                       |
| \( x_3 \)   | 800         | 120                 | 0.2              | 1               | 0.250            | 1                            | 2.604E-6            | 1                       |
| \( x_4 \)   | 900         | 220                 | 0.1              | 5               | 0.125            | 4                            | 6.313E-7            | 4                       |
| \( x_5 \)   | 1000        | 100                 | 0.1              | 5               | 0.125            | 4                            | 1.150E-6            | 3                       |
| \( x_6 \)   | 800         | 30                  | 0.2              | 1               | -0.750           | +\( \infty \)               | -3.142E-5           | +\( \infty \)            |

3.5. Results Analysis

As shown in Table 1, by using the traditional method which simply based on importance measure of the failure condition, it may cost more money and time to carry out maintenance. However, by considering the influence of other normal states, maintenance will cost less money and time as \( x_6 \) is confirmed to be well. Finally, if the influence of other factors such as costs and MTBF are included, maintenance order can be further optimized, resulting in a better maintenance order.

4. Conclusions

This paper introduces a novel importance measure analysis method for maintenance based on multifunction testability state. Different from traditional methods, the proposed method considers the influence of testability of other function state on the studied one, which ensures a more reasonable maintenance order. Taking the vehicle model as an example, there exists 3 function corresponding to 3 failure conditions. Besides the failed function, the importance measure considers the influence of the normal ones, and presents an optimized maintenance order, which is more reasonable comprehensively.

However, when dealing with systems with high complexity, the method may be too complicated to evaluate the value of importance measure quickly.

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