Fault correlation analysis-based framework for reliability deployment of electromechanical system

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Abstract. Reliability allocation is a very critical step of product development process for setting achievable reliability goals. However, most research on reliability allocation have ignored the correlation between faults in a complex electromechanical system. In view of this problem, this work proposed an optimization method of reliability allocation by combining Quality Function Deployment (QFD) and Failure Tree Analysis (FTA). First, a fault tree of the system is built, and failure mode of the system is discovered in the bottom events of the fault tree. Second, the failure mode in previous step is input into House of Reliability (HoR), and the correlation of faults and fault severity could be calculated in the HoR. Finally, according to the results of HoR, the fault severity of each component is transformed into the importance degree, and the system reliability target is allocated to each component on the basis of the importance degree. A case study of a transmission agent was conducted to illustrate the analysis and application processes of the proposed method. The result showed that this method made the distribution more reasonable by considering the correlation between failures.

1. Introduction
An electromechanical system is composed of numerous complex components, the state of good working guaranteed directly by each of its constituent components[1]. The reliability deployment is to allocate the reliability requirements of users to each part of the system, and the purpose is to make sure the overall structure of the equipment can meet the functional requirements, cost requirements and user reliability requirements[2, 3]. The traditional methods of reliability development include score allocation[4], AGREE allocation[5], proportional allocation and so on. Besides, a large number of studies have focused on the reliability allocation design using optimization method, for example, redundant system allocation[6], minimization of cost optimization restricted by reliability, maximum reliability optimization under certain system cost and system reliability optimization[7, 8], and the multi objective optimization[9]. The scientificity and rationality of the allocation results are affected because these methods do not consider the allocation factors fully.

Most of the modern equipment can be viewed as a complex electromechanical system, the relationship between the function and failure of each component is complex, the failure of a device may lead to failure of other parts of the system, causing the Domino effect [10, 11]. The purpose of this work is to consider the effect of fault correlation in the reliability allocation by using a structured approach. In recent years, the study of fault correlation has been focused on the study of unidirectional
correlated faults. Product reliability is closely related to fault mode. In 1990s, the reliability researchers in the USA put forward the multi factor matrix decision method in QFD could be applied to the reliability analysis, and named it RFD (Reliability Function Deployment). Braglia, M build the HoR (House of Reliability) combined by FMEA and QFD, HoR provides a framework and structure to transform reliability concepts or requirements into reliability parameter characteristics and design measures. But the fault correlation did not be considered in the methods above.

On the basis of summarizing the previous studies, the RFD method which reckoning in fault correlation is used to improve the accuracy of reliability allocation, the basic idea is to consider the influence of fault correlation on the reliability allocation, and configuring a high reliability to the critical path and the vulnerability of the system. Firstly, it is required to describe fault propagation’s paths and trends qualitatively and quantitatively by integrating FTA, FMEA and QFD. Then, establishing fault severity evaluation index system, and calculating the criticality of each failure mode reckon in the effect of Fault propagation. Finally, the criticality of failure mode is transformed into the importance of each unit, to measure the vulnerability of a unit with an important degree. The important degree would be one of the factors of reliability allocation, because it has considered the vulnerability and correlation of the unit in the system, so, the failure avalanche could be prevented and its impact would be reduced. At the same time, the traditional reliability analysis method is changed from the way of filling in a form to the way based on the matrix structure correlation analysis, which makes it easier to identify the failure mode, and the results are more reasonable.

2. Reliability deployment framework based on fault correlation analysis

2.1. House of reliability
HoR is the core step of RFD which consists of an autocorrelation matrix of failure modes and a relation matrix between evaluating indicator of severity and failure modes. The source of HoR, the structure and function of each component of HoR is introduced in this section.

2.1.1. Fusion of FTA, FMEA and QFD
QFD converts user requirements into product technical requirements information, which through matrix structure of HoQ (House of Quality). The autocorrelation matrix of HoQ describes the effects on the other technical characteristics of a product when improving the performance of one technical characteristic.

The autocorrelation matrix describes how the parts failure can propagate in the system and lead to failure or deterioration of other parts, which describes the fault tree of a system in the form of a matrix, and measures the direct impact of the consequences of each fault. In order to obtain the fault propagation path and correlation between failures accurately, FTA qualitative analysis might be implemented supported by fault database, so, the location of the corresponding elements of fault mode in the autocorrelation matrix can be identified.

QFD cannot be directly used for reliability design due to the reliability design is different from quality design and the fault analysis is an indispensable part in reliability design. In order to solve this problem, HoQ is used as reference to HoR, in virtue of HoR, RFD can transform the reliability requirements of system into the reliability of product components by multilayer matrix. The core of RFD is integrating the reliability analysis tool with the matrix structure of the HoQ. In this paper, the fault analysis tool FMECA is introduced into the RFD, the relation matrix of fault severity evaluation index and fault mode and other matrix is established as the room of HoR, so HoR composed of the room and the roof (fault mode autocorrelation matrix) achieves the integration of FTA, FMECA and QFD.

In summary, HoR is a large matrix structure (Figure 1), which consist of autocorrelation matrix of fault propagation path and intensity, severity evaluation index weight vector, the relationship matrix between severity evaluation index and failure mode, fault probability vector, and fault detection rate...
vector. HoR achieves the integration of FTA, FMECA and QFD, furthermore, it outputs failure mode criticality which considering cascading failure.

![Figure 1. The Structure of HoR.](image)

2.1.2. Content and function of each component of HoR

(1) Severity evaluation index system and its weight

In order to evaluate the harm of the failure objectively, it is necessary to make a comprehensive consideration of the fault impact. For the general products, considering the correlation between indicators and the complexity of the analysis, the severity evaluation index should cover safety, function, economy, maintenance. The severity evaluation index would be added or deleted on the basis of the specific characteristics of the product. The weights of the severity evaluation index can be determined according to the relevant laws and regulations.

(2) Severity evaluation index and fault mode relation matrix

The relationship between the failure mode and the severity evaluation index reflects the contribution of the potential failure mode of each component to the corresponding evaluation index. The higher the index value is, the greater the influence degree of fault on the severity evaluation index is.

(3) Failure mode autocorrelation matrix

The autocorrelation matrix, also known as the Domino matrix, reflects the mutual influence between faults in the forward and reverse. In the autocorrelation matrix (Figure 1), element $\alpha_{ik}$ represents the influence of the failure $i$ modes on the failure $k$ modes, meanwhile, while element $\alpha_{ki}$ represents the influence of the failure $k$ modes on the failure $i$ modes. Generally, $\alpha_{ik}$ and $\alpha_{ki}$ are not equal. In this paper, values in 5 levels are used to express the degree of fault correlation (table 1).

![Table 1. Grade standard of autocorrelation matrix.](image)

### Table 1. Grade standard of autocorrelation matrix.

| Probability of "Domino effects" | Describe                                                                 | Grade |
|---------------------------------|---------------------------------------------------------------------------|-------|
| Very high                       | A cause of failure is the direct cause of another one                      | 9     |
| High                            | A cause is strongly linked with another one                                | 7     |
| Moderate                        | A cause is moderately related with another one                             | 5     |
| Low                             | A low link can be seen between a cause and another one                    | 3     |
| Remote                          | A cause infrequently leads to another one                                  | 1     |

2.2. Reliability deployment process based on fault correlation analysis

The reliability allocation process is divided into three stages:
(1) Building the fault tree of the product, and carrying on the qualitative analysis to determine the transmission link, determining the degree of correlation between failures;
(2) Calculating matrix of HoR, and calculating the degree of fault damage after the influence of Domino effect is obtained;
(3) The fault damage degree of each unit is converted to the importance degree of the unit to the system, reliability original score would be modified using the importance degree. Finally, the results of reliability allocation are obtained.

3. Mathematical model for allocating technical characteristics based on multi-failure modes correlation

3.1. Fault damage degree calculation based on fault correlation analysis
Fault hazard analysis is a method to evaluate the possible impact of various failure modes of the product. In this paper, Risk Priority Number (RPN) is used to evaluate the possible impact of various failure modes of the product. RPN is the product of severity level of a failure mode (S), probability grade of failure happens (P) and Difficulty level of fault detection (ND).

Assuming that the fault i directly causes k faults (k=1,2,3,...,m), and considering the effects of cascading failures, then the calculation formula of the Risk Priority Number (RPN) is the following:

$$RPN_i = P_i \cdot ND_i \cdot \sum_{j=1}^n w_j c_{ij} + \sum_{k=1}^m \alpha_{ik} \cdot P_k \cdot ND_k \cdot \sum_{j=1}^n w_j c_{kj}$$  \hspace{1cm} (1)

Where $P_i$ is the occurrence probability of failure, $w_j$ represents index weight of severity evaluation, $ND_i$ is Detection difficulty, $\alpha_{ik}$ is correlation between fault i and fault k, $c_{ij}$ is the contribution of fault i to the severity evaluation index j, $c_{kj}$ is the contribution of fault k to the severity evaluation index j, $\alpha_{ik} = 0, \forall i = k$.

The RPN in first item of equation (1) is a number without considering the interaction between faults, the second item of equation (1) expresses the RPN’s added value of the first fault that caused by the second fault which directly leaded by the first fault. After simplify equation (1), equation (2) is following:

$$RPN_i = \sum_{k=1}^m \alpha_{ik} \cdot P_k \cdot ND_k \cdot \sum_{j=1}^n w_j c_{kj}$$  \hspace{1cm} (2)

where $\alpha_{ik} = 1, \forall i = k$.

Considering the matrix form of HoR, equation (2) can be expressed as matrix:

$$R = \begin{bmatrix} W^T S \end{bmatrix} \begin{bmatrix} P \end{bmatrix} \begin{bmatrix} ND \end{bmatrix} \begin{bmatrix} 1 \end{bmatrix} \begin{bmatrix} A \end{bmatrix}$$  \hspace{1cm} (3)

where $R$ is row (1x$m$) vector of fault damage degree, $A$ is $m$x$m$ autocorrelation matrix; $W$ is column (n x 1) vector of weights, $S$ is $n$x$m$ correlation matrix, $P$ is row (1x$m$) vector of failure probability, $ND$ is column (1x$m$) vector of fault detection difficulty, $1_m$ is $m$x$m$ identity matrix.

3.2. Reliability allocation based on fault correlation analysis
The reliability allocation score matrix is the relationship matrix between the distribution factor sets and the system unit, reflecting the various parts of the product reliability of the correlation degree of corresponding evaluation factors. The scores of evaluation factors were between 1~10.

Most of the equipment or its subsystems belong to the series system, that is to say, the fault of any unit in the series line can lead to a fault of all the system. Suppose that the series system consists of t units, and reliability index of the system is $\lambda'$. When considering the influence of fault propagation, failure rate $\lambda'$, assigned to each unit is following:
\[ \lambda_i' = C'_i \lambda', \]  
\[ C'_i = \omega'_i / \sum_{i=1}^{m} \omega'_i \]  

where \( C'_i \) is scoring coefficients of unit \( i \) when considering fault propagation effect, \( \omega'_i \) is score of unit \( i \).

\[ \omega'_i = Q_i \prod_{j=1}^{i} g_{ij} \]  

where \( Q_i \) is importance degree of unit \( i \) when considering fault propagation effect, \( g_{ij} \) is the score value of unit \( i \) in score factor \( j \).

\[ Q_i = 10 - 10 R A_i / \sum_{i=1}^{i} R A_i \]  

Where \( R A_i \) is the sum of the hazard degree of the fault related to unit \( i \).

\( Q_i \) is importance degree of unit \( i \) when considering fault propagation effect. According to the structure of the system, series model or others model will be used and \( Q_i \) will be the allocation coefficient.

4. Empirical research and analysis

There is a transmission agent of machine tool headstock, and the target value of its MTBF (Mean Time Between Failure) is \( \lambda = 4516h \). According to the reliability deployment process presented in this paper, the fault correlation analysis HoR was build, and then the target value was allocated to each part of the transmission agent. This paper attempts to illustrate the effectiveness of the proposed method by this example. The structure of headstock transmission agent is shown in Figure 2 and the function structure tree is established as Figure 3.

In order to obtain cascading failure propagation data of autocorrelation matrix in HoR, the Fault Tree was established and fault correlation could be found. There were several fault propagation chains in the fault tree: D8→B02, B05→D5, B09→D5, D8→D5, B01→B12→D3, B14→D7→D3, B07→D3, and the codes representing failure modes as shown in the Table 2. Based on the statistical data of fault and other factors, the correlation coefficient of fault propagation chain was determined by the designer, and inputting the correlation coefficient to autocorrelation matrix in HoR, as shown in the figure 2.

As shown in Figure 4, Hazard degree 1 (CR1) and Hazard degree 2 (CR2) had been calculated in the HoR, CR1 indicates the degree of hazard without considering the effect of fault correlation, while CR2 indicates the degree of hazard with considering the effect of fault correlation. When the effect of fault correlation was ignored, the most harmful faults were B11, B08, D8 and B09 according to the Order 1, but after cumulative effect of fault propagation was considered, hazard ranking has changed, for example, B09 increased from third to first, D8 increased from eighth to third. It was because these
failure modes were located at the starting point of the fault propagation chain, and they had been given a greater value of damage in the effect calculation of multiple factors.

Table 2. the relationship of codes and fault events in transmission agent.

| codes | Fault events                  | codes | Fault events                  |
|-------|-------------------------------|-------|-------------------------------|
| D0    | Main transmission agent failure | D1    | Large cutting vibration       |
| D2    | Big noise of spindle box       | D3    | Spindle rotation anomaly      |
| D4    | Spindle box overheating        | D5    | Gear meshing accuracy decreased |
| D6    | Electrical fault               | D7    | Hydraulic transmission failure |
| D8    | Poor spindle bearing coaxiality| D9    | Spline shaft surface damage   |
| B01   | Loosening of screw and nut     | B02   | Poor coaxiality of principal axis |
| B03   | Severe tooth surface damage    | B04   | Excessive deformation of spindle |
| B05   | Bearing preload is too large   | B06   | Poor bearing lubrication      |
| B07   | Shaft fracture                 | B08   | Spline shaft fatigue crack    |
| B09   | Bearing wear                   | B10   | Looseness of bearing inner and outer rings |
| B11   | Large meshing clearance        | B12   | Proximity switch is not closed |
| B13   | Spline shaft wear              | B14   | Hydraulic tubing leakage      |

Figure 4. Fault hazard analysis results of transmission agent.

According to the results of HoR, the fault hazard degree of each unit was summed up and transformed into the importance degree, as shown in Table 3. The bearing had the largest importance degree, it was pointed out that the bearing is the most vulnerable point of failure in the operation of the system, and the bearing should be focused in reliability allocation.
Table 3. Reliability allocation result of transmission system components.

| Rating matrix of reliability allocation | Shaft | Hydraulic speed change mechanism | Connecting piece | Rolling bearing | Gear |
|----------------------------------------|-------|---------------------------------|------------------|----------------|------|
| Complexity                             | 3     | 1                               | 1                | 8              | 4    |
| Technology development level           | 4     | 2                               | 2                | 7              | 6    |
| Working hours                          | 10    | 10                              | 10               | 10             | 10   |
| Working environment.                   | 4     | 3                               | 3                | 8              | 5    |
| Importance degree                      | 7.77  | 9.91                            | 9.52             | 5.64           | 7.21 |
| Reliability allocation coefficient $c_1$ | 0.076 | 0.0095                          | 0.0095           | 0.713          | 0.191|
| Allocation value of MTBF $\lambda_1$ (h) | 59094 | 472749                          | 472749           | 6331           | 23637|
| Reliability allocation coefficient $c_2$ | 0.096 | 0.015                           | 0.014            | 0.651          | 0.223|
| Allocation value of MTBF $\lambda_2$ (h) | 47006 | 294844                          | 306923           | 6938           | 20281|

As is known the transmission agent whose target value of MTBF (Mean Time Between Failure) is $\lambda = 4516$ h, according to the reliability model of the series system, the reliability distribution of the main components of the transmission system was carried out. Among them, $C_1$ and $\lambda_1$ were the allocation results without considering importance degree, while $C_2$ and $\lambda_2$ were the allocation results with considering importance degree.

According to the reliability allocation result of the transmission agent, bearing as a weak link in the system, when considering the cumulative effect of fault propagation, its MTBF had increased from 6331 hours to 6938 hours, also 9.58%. Meanwhile, Hydraulic transmission mechanism with a low importance degree, its MTBF had declined 37.6%.

5. Conclusions
Reliability deployment is the necessary means to improve the reliability of product, a fault correlation analysis-based reliability deployment process has been discussed here, as the influence that one fault leads to another is considered in reliability deployment, the result of reliability deployment has become more credible and accurate. Firstly, with the support of FTA and FMECA, failure mode of system has been analysed and vulnerable points of fault propagation chain has been found. Secondly, in the HoR, the severity of failures has been calculated by the fuse of failure autocorrelation matrix and correlation matrix of failure and severity index. Finally, according to the results of HoR, the fault severity of each component is transformed into the importance degree, and the system reliability target is allocated to each component on the basis of the importance degree. The allocation results of transmission agent show that the proposed method can effectively adjust and optimize the results of conventional reliability allocation, and provides a new way for equipment reliability deployment.

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