FMEA-based DEMATEL Apportionment Approach

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ABSTRACT

Reliability allocation is one of the most important tools to improve system reliability, which totally influences product life cycle costs and system operational effectiveness. However, most reliability allocations methods often neglect many important features, such as maintainability and risk and do not consider indirect relations between subsystems or components. In this paper, an effective reliability allocation methodology has been developed using a system failure mode and effects analysis (FMEA) and decision-making trial and evaluation laboratory (DEMATEL) technique, which considers severity of failure, occurrence of a failure, and detection of a cause of failure in reliability design. It is an easy and effective approach, which uses system FMEA to determine subsystem allocation weighting factors and then uses the DEMATEL technique to consider the inter-relationships between subsystems and apportion reasonable reliability ratios into subsystems or components. This study evaluates reliability allocation in the context of a fighter aircraft engine data acquisition unit (EDAU). The results from comparison with traditional reliability methods show that the proposed method is both accurate and realistic.

Keywords: reliability allocation, risk priority number, failure mode and effects analysis, decision making trial and evaluation laboratory

運用失效模式與效應分析為基礎的可靠度配當方法

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摘　　要

可靠度配當方法是產品開發過程中非常重要的一項可靠度設計工具,其結果將影響到產品的壽期成本與系統操作效益。然而,傳統上的可靠度配當方法未從系統安全性及合理的風險評估角度進行考量,同時亦未考慮配當時因子間的間接影響關係。因此,本研究提出以失效模式與效應分析資料為基礎,並結合決策實驗室分析法進行可靠度配當;此方法可同時考量系統安全性、風險因子及配當因子間的間接影響關係。本研究並以引擎資料獲得單元實例與傳統可靠度配當方法進行比較;研究結果證明,所提之方法可獲得正確的可靠度配當值,並更符合使用者實際需求。

關鍵詞:可靠度配當,風險優先數,失效模式與效應分析,決策實驗室分析法

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Ⅰ. INTRODUCTION

Reliability allocation is one of the most important tools to improve system reliability and is a top-down approach for apportioning accuracy goals in a system. In a large complex system, it is necessary to translate reliability requirements into subsystems or components. Traditionally, if the reliability allocation methods have limited data about the system and/or component characteristics, it is better to consider subsystems as an equivalent and to use a simple method. All of these methods use simple variables (or factors) in apportioning system reliability and assume that a series subsystem has constant failure rates and that subsystem mission time is equal to system mission time, such as the advisory group on the reliability of electronic equipment (AGREE) method [1], ARINC method [2], Bracha method [3], Base method [4], equalization allocation method [5], and Boyd method [6].

On the other hand, if we know the system value characteristics and for data that are certain, it is possible to use a more complex method—allocate reliability parameters according to the combinations of different factors, such as criticality of the system (*C*), system intricacy (*I*), state-of-the-art technology (*S*), performance time (*P*), and environment (*E*), mission time (*T*), complexity (*K*), functionality (*F*), effectiveness (*E*), and operational profile (*O*), etc. The related literatures, such as the Karmiol method [7], the feasibility-of-objectives (FOO) technique [5, 8, 9], the average weighting allocation method [10], the pair comparison allocation, the integrated factors method (IFM) [4], and the minimization of effort algorithm [5], are widely used for reliability allocation in different industrial fields. More recently, Omkarprasad and Sushil [11] proposed a flexible multicriteria reliability allocation technique, which can explore as many as 10 different criteria in order to allocate reliability. Omkarprasad and Sushil [12] used the analytic hierarchy process (AHP) to allocate component reliability. Their approach supports the hierarchical structure of the system. However, when considering an increased number of criteria for appointing subsystems reliability, the complex methods become more difficult and very time-consuming, and frequent and precise rating updates are required. Chern [13] presented a redundancy allocation problem (RAP) of a series-parallel system, referring to difficult NP-hard problems. Being a top-down approach, it is not always sufficient in reliability design, and many other important features, such as maintainability, risk, and the inter-relationships, are often neglected; such omission may cause safety problems in future system operations.

With the rapid technological progress and increasing complexity of system structures, reliability and failure mode and effects analysis (FMEA) have expanded their influence in various industries and fields in recent years. FMEA is an important analytical tool for risk assessment in product design and in the production planning process. The purpose of the FMEA is to assign limited resources to the serious risk items. It is utilized to find weaknesses in product design and in production at the earliest stages possible before going into mass production. FMEA is a bottom-up approach, which explores all possible failure modes and their impact upon the system. The aerospace industry was the first to develop FMEA as a formal design methodology in the 1960s. FMEA has since been widely and successfully applied in many domains, such as the military, automobile, electricity, mechanical, and semiconductor industries, to mention a few [14-20]. In 1980, the procedures of performing a well-designed FMEA were published in MIL-STD-1629A [21]. Most current FMEA methods use the risk priority number (RPN) value to evaluate the risk of failure. The RPN uses the three factors—severity of the failure (*S*), the probability of failure (*O*), and the probability of not detecting the failure (*D*)—to identify the most serious risks for a potential failure mode. A lot of research has been carried out to enhance the performance of FMEA [22-29]. However, the FMEA method does not consider reliability allocation into system design.

The Battelle Memorial Institute first developed the decision-making trial and evaluation laboratory (DEMATEL) method through its Geneva Research Centre [30]. Seyed-Hosseini *et al*. [31] used the DEMATEL method for reprioritization of failures in a system. They proposed to use the DEMATEL method to prioritize the alternatives based on the type of relationships and the severity of influences. The DEMATEL method is a potent method that gathers group knowledge for capturing the casual relationships between criteria. Using the DEMATEL method to analyze indirect relations has been successfully used in many industrial fields, such as marketing strategies, R&D projects, e-learning evaluation, managers' competencies, control systems, and airline safety problems [32-35].

Examination of the foregoing studies does not indicate the existence of a well-defined, risk-based apportioning method for reliability design. However, such as a weapon system is a precise and sophisticated system that comprises several subsystems and components, which typically focuses considerably upon safety and risks issues. To fill the void, this paper proposes two types of reliability allocation methodologies, incorporating system FMEA (RPN values) and the DEMATEL calculation, to determine subsystem allocation weighting factors, which consider severity of failure, occurrence of a failure, and detection of a cause of failure in reliability design. The DEMATEL technique can also be used to identify indirect relations. The higher RPN should have a higher reliability allocation overall rating and apportion a higher reliability ratio into subsystems or components. Such an approach could not be found in existing literature. This study evaluates reliability allocation in a fighter aircraft engine data acquisition unit (EDAU). The results from comparison with traditional reliability methods show that the proposed method is an effective methodology, whose results are both accurate and realistic.

The remainder of this paper is organized as follows. Section 2 introduces conventional reliability allocation methods. Section 3 introduces DEMATEL methodology. Section 4 proposes the combined FMEA and DEMATEL apportionment method. In Section 5, an example is drawn from a fighter aircraft EDAU using the proposed approach for reliability allocation assessment. Section 6 is the conclusions.

Ⅱ. CONVENTIONAL RELIABILITY ALLOCATION METHODS

2.1 ARINC apportionment technique

Aeronautical Radio Inc. published the ARINC apportionment technique in 1964 [2]. This method assumes a series of subsystems with constant failure rates and uses predicted failure rates of system components to determine weight factors rather than requiring the user to determine weight factors. The fundamental assumptions are: (1) series subsystems; (2) constant failure rates; (3) same mission duration time T for each subsystems; and (4) a given and predefined allowable system failure rate, λ^*.

Suppose a system is composed of N subsystems. Let λ_i^* be the failure rate allocated to subsystem i. The objective is to choose λ_i^* such that [5]:

$$\sum_{i=1}^{n} \lambda_i^* \le \lambda^* \tag{1}$$

The failure rate of subsystem i (λ_i) is determined from past observation or estimation. Assign a weighting factor (w_i) to subsystem i by Eq. (2).

$$w_i = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i} \tag{2}$$

Allocate subsystem failure rate requirements as follows.

$$\lambda_i^* = w_i \lambda^* \tag{3}$$

2.2 The FOO technique

The FOO technique was first introduced in 1976 and is included in the Mil-hdbk-338B Electronic Reliability Design Handbook [5]. With the FOO method, subsystem allocation factors are computed as a function of a numerical rating of system intricacy (I), state-of-the-art technology (S), performance time (P), and environment (E). Each rating is based on a scale from 1 to 10 and is estimated using design engineering and expert judgments. The four respective rating values are then multiplied to derive the $ISPE$—i.e. $ISPE = I \times S \times P \times E$—so that the final product results in a value ranging from 1 to 10,000.

Suppose that a system is composed of N subsystems. Let λ_s be the system failure rate and let T be the mission duration. Also, let $\bar{\lambda}_k$ be the failure rate allocated to the k-th subsystem, $C_k^{'}$ be the complexity of the k-th subsystem, and $w_k^{'}$ be the rating for the k-th subsystem, $\forall k$. W' denotes the sum of the rated products, and $r_{ik}^{'}$ is used to represent the rating for each of the four factors for the k-th subsystem, $\forall k$ and $\forall i \in \{I, S, P, E\}$.

The reliability allocation-weighing factor is determined by equations (4) to (8).

$$\lambda_s T = \bar{\lambda}_k T \tag{4}$$

$$\bar{\lambda}_k = C_k^{'} \lambda_s, \forall k \tag{5}$$

$$C_k^{'} = \frac{w_k^{'}}{W^{'}}, \forall k \tag{6}$$

$$w_k^{'} = r_{Ik}^{'} \times r_{Sk}^{'} \times r_{Pk}^{'} \times r_{Ek}^{'}, \forall k \tag{7}$$

$$W^{'} = \sum_{k=1}^{N} w_k^{'} \tag{8}$$

Ⅲ. DEMATEL METHODOLOGY

3.1 Outline of the DEMATEL method

The Battelle Memorial Institute first developed the DEMATEL method through its Geneva Research Centre [30]. The DEMATEL method is a potent method that gathers group knowledge for capturing the casual relationship between criteria; it can precisely ascertain the cause-effect relationship of criteria when measuring a problem. In recent years, the DEMATEL method has been successfully applied in different industries and in many fields. The original DEMATEL method was aimed at the fragmented and antagonistic phenomena of world societies and the search for integrated solutions. It is especially practical and useful for visualizing the structure of complicated causal relationships with matrices or digraphs. The matrices or digraphs portray a contextual relation between the elements of the system in which a numeral represents the strength of influence. Hence, the DEMATEL method can convert the relationship between the causes and effects of criteria into an intelligible structural model of the system, which are not only the direct influences taken into account but also the indirect influences among multiple factors.

The essence of the DEMATEL method is reviewed below [31]:

DEFINITION 1. The pair-wise comparison scale may be designated into four levels, where the scores of 0, 1, 2, and 3 represent ‘‘No influence,’’ ‘‘Low influence,’’ ‘‘High influence,’’ and ‘‘Very high influence,’’ respectively.

DEFINITION 2. The initial direct-relation matrix Z is an $n \times n$ matrix that is obtained by pair-wise comparisons in terms of influences and directions between criteria, in which Z_{ij} is denoted as the degree to which the criterion D_i affects criterion D_j. Accordingly, all principal diagonal elements Z_{ii} of matrix Z are set to zero.

$$Z = \begin{matrix} & D_1 & D_2 & \cdots & D_n \\ D_1 & 0 & z_{12} & \cdots & z_{1n} \\ D_2 & z_{21} & 0 & 0 & z_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ D_n & z_{n1} & z_{n2} & \cdots & 0 \end{matrix} \tag{9}$$

DEFINITION 3. Let

$$s = \max_{1 \le i \le n} \left(\sum_{j=1}^{n} z_{ij} \right) \tag{10}$$

Then, the normalized direct-relation matrix X can be obtained through the following formula:

$$X = \frac{Z}{s} \tag{11}$$

DEFINITION 4. The total relation matrix T can be acquired by using formula (12), in which I is denoted as the identity matrix.

$$T = \lim_{k \to \infty} (X + X^2 + \cdots + X^k) = X(I - X)^{-1} \tag{12}$$

DEFINITION 5. Let t_{ij} (i, j = 1,2,. . .,n) be the elements of the total-relation matrix T; then, the sum of the rows and the sum of the columns, denoted as R_i and C_j, respectively, can be obtained through the following two formulas:

$$R_i = \sum_{j=1}^{n} t_{ij} \quad (i = 1,2,...,n), \tag{13}$$

$$C_j = \sum_{i=1}^{n} t_{ij} \quad (j = 1,2,...,n). \tag{14}$$

DEFINITION 6. A causal diagram can be acquired by mapping the ordered pairs of ($R + C$, $R - C$), where the horizontal axis ($R + C$) is named ''Prominence'' and the vertical axis ($R - C$) is named ''Relation''.

In the causal diagram, the horizontal axis "Prominence" shows how important the criterion is, whereas the vertical axis "Relation" may divide the criteria into the cause and effect groups. When the value ($R - C$) is positive, the criterion belongs to the cause group. If the value ($R - C$) is negative, the criterion belongs to the effect group. Hence, causal diagrams can visualize the complicated causal relationships between criteria into a visible structural model and provide valuable insight for problem solving. Furthermore, with the help of a causal diagram, this study will allow proper decisions to be made by recognizing the difference between cause and effect criteria.

3.2 The procedure of the DEMATEL method

The DEMATEL method can separate the relevant criteria of a system into the cause and effect groups to facilitate accurate decision-making. A DEMATEL procedure is explained as follows [31]:

(1) A system designer or decision-maker evaluates the relationship between sets of paired alternatives. As a result of this evaluation, a matrix M is obtained as the initial data of the DEMATEL analysis.
(2) The elements of the direct relative severity matrix (DRSM) are obtained by Eq. (11). It is the normalized version of matrix M.
(3) The elements of the direct and indirect relative severity matrix (DIRSM) are obtained by Eq. (12). The DIRSM consists of all of the relations, including direct and indirect relations between alternatives.

Using the values of R+C and R-C, where C is the sum of the columns and R is the sum of the rows of the DIRSM, a level of influence and a level of relationship are defined. The value R-C indicates the severity of influence for each alternative. Similarly, the value of R+C indicates the degree of relation between each alternative with one another.

Ⅳ. PROPOSED COMBINED FMEA AND DEMATEL APPORTIONMENT METHOD

4.1 Advantages of the combined FMEA and DEMATEL apportionment method

This paper proposes an approach to combine the FMEA and DEMATEL methods to consider maintainability and risk issues in reliability allocation and to overcome the traditional reliability allocation technique problems. The FMEA system is used to determine subsystem allocation weighting factors; then, we use the DEMATEL method for capturing the casual relationship between criteria and failure mode. After calculating each subsystem's total failure mode rating, we apportion reasonable reliability ratings into subsystems or components.

With the proposed method, subsystem allocation factors are computed as a function of a numerical rating for the severity of the failure (S), the probability of failure (O), and the probability of not detecting the failure (D). Each rating is based on a scale from 1 to 10 and is estimated using design engineering and expert judgments. The three respective rating values are then multiplied to derive the RPN—i.e., $RPN = S \times O \times D$—so that the final product results in a value ranging from 1 to 1000. A failure mode that has a higher RPN is assumed to be more important and is given a higher allocation ratio than those with lower RPN values. The three factors O, S, and D are all evaluated using the ratings from 1 to 10, as described in Tables 1–3 [16].

Table 1. Suggested evaluation criteria and ranking system for the severity of a failure

Effect	Criteria: severity of effect	Rank
Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable	8
Major	Product performance is severely affected but functions. The system may not operate	7
Significant	Product performance is degraded. Comfort or convince functions may not operate	6
Moderate	Moderate effect on product performance. The product requires repair	5
Low	Small effect on product performance. The product does not require repair	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance	2
None	No effect	1

Table 2. Suggested evaluation criteria and ranking system for the occurrence of a failure

Probability of occurrence	Rates	Rank
Extremely high: Failure almost inevitable	≧1 in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2,000	4
Low	1 in 15,000	3
Remote	1 in 150,000	2
Nearly impossible	≦1 in 1,500,000	1

Table 3. Suggested evaluation criteria and ranking system for the detection of a cause of failure

Detection	Criteria: likelihood of detection by design control	Rank
Absolute uncertainty	Design control does not detect a potential cause of failure or subsequent failure mode; or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of failure or subsequent failure mode	8
Very low	Very low chance the design control will detect a potential cause of failure or subsequent failure mode	7
Low	Low chance the design control will detect a potential cause of failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of failure or subsequent failure mode	2
Almost certain	Design control will almost certainty detect a potential cause of failure or subsequent failure mode	1

4.2. Procedures of the proposed method

The procedure of the proposed method is organized into 11 steps and is described as follows:

Step 1. List the structure of systems and subsystems.

Step 2. Define the system reliability and mission time.

Step 3. Compute the system failure rate from system specifications.

Let R be the system reliability and T be the mission duration; the system failure rate λ_s is computed as

$$\lambda_s = -\ln(R)/T \qquad (15)$$

Step 4. List potential failure modes

Based on historical data and past experience, list the potential failure modes of each risk assessment member of the entire system.

Step 5. List all of the possibilities that could cause each potential failure mode

Discover how systems fail and what caused each type of failure. Arrange failure mode contents to the FMEA table and list the reasons for failure mode occurrence.

Step 6. Determine the scales for *S*, *O,* and *D*, respectively.

Subsystem allocation factors are computed as a function of numerical ratings of; *S*, *O,* and *D*.

Step 7. Perform the DEMATEL procedure

The procedure of the DEMATEL process is described as follows [31]:

(1) A system designer or decision-maker evaluates the relationship between subsystems of paired alternatives.
(2) Obtained the elements of DRSM by Eq. (11).
(3) Obtained the elements of DIRSM by Eq. (12).
(4) Calculate the values of *R*+*C* and *R*-*C*.

Step 8. Compute the allocation rating r_k for each subsystem and derive the overall rating w_k for the *k*-th subsystem.

The apportioning weighing ratio is in accordance with the information and data, either certain or not. When data is uncertain, we proposed to use the basic model; on the other hand, for data that are certain, we proposed to use the prediction failure rate model to derive a more precise allocation rating. According to the results of DEMATEL's calculation, using *R*-*C* values and Eq. (16) or (17) for reliability rating, calculate the aggregated value by FMEA weights. There are two different models that can be used to allocate weighting factors w_i, $\forall i$:

(1) Basic model:

$$w_k = \sum_{i=1}^{n} CF_i / \sum_{i=1}^{n} \sum_{k=1}^{m} CF_i \qquad (16)$$

where CF_i is the cause of failure, n is the number of causes of failure, and m is the number of subsystems.

(2) With the predicted failure rate model:

$$w_k = \sum_{i=1}^{n} CF_i * \lambda_k / \sum_{i=1}^{n} \sum_{k=1}^{m} CF_i * \lambda_k \qquad (17)$$

Step 9. Compute the complexity $C_k^{'}$ for the *k*-th subsystem, $\forall k$.

Use Eq. (6) to calculate the complexity $C_k^{'}$, $\forall k$.

Step 10. Compute the allocated subsystem failure rate.

Use Eq. (5) to calculate the allocated subsystem failure rate $\bar{\lambda}_k$, $\forall k$.

Step 11. Analyze the results and select the optimal reliability allocation decision.

V. CASE STUDY

A case study of an engine data acquisition unit (EDAU) that uses an electronic engine display system (EEDS) for a fighter aircraft manufactured by an aircraft company in Taiwan was used to illustrate the implementation of the proposed FMEA-based DEMATEL apportionment method. The EDAU is a modern, digital, computer-controlled system which provides a variety of flight information and data from the engine, and helps pilot to control flight attitude. To support the requirements of the engine and hydraulic pressure system, the EEDS requires the following capability to interface with other aircraft units: (1). Capability to transmit hydraulic pressure data, oil pressure data, fuel flow data and engine control unit (ECU) data; and (2). Host operational flight software and support software updates. The EDAU block diagram is shown in Fig. 1.

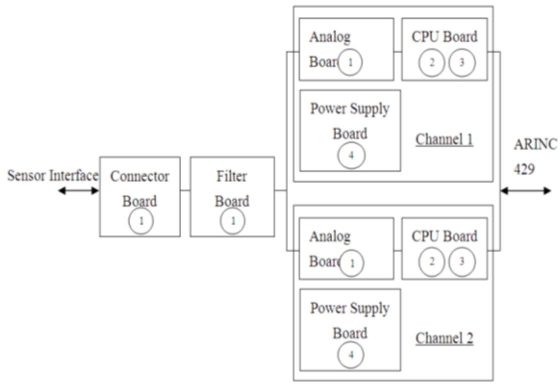

Fig. 1. EDAU reliability block diagram.

The EDAU is a microprocessor-based signal conditioning system. Each functional area in Fig. 2 is labeled with a circled identification number. The system accepts aircraft and engine sensor signals (identification number 1), performs signal conditioning and validation (identification number 1 and 2), and then presents this information to the display system via ARINC 429 serial buses (identification number 3). The EDAU configuration is based upon dual channel architecture. Two independent processing channels (Channel #1 and Channel # 2) interface with engine sensors providing for signal input processing and an output of sensor data for which the channel interfaces. The EDAU supports four ARINC 429 output ports and two RS-232 serial data buses. The RS-232 bus is used for maintenance only and is not operated during a flight mission or sortie. Each bus is managed as an asynchronous data port. Each EDAU channel is powered by an independent power supply (identification number 4). Information transmitted includes the following engine parameters: nozzle position, exhaust gas temperature, oil pressure, hydraulic pressure, and fuel flow. In addition, the EDAU includes a built-in test and performance and health-monitoring functions. The EDAU/EEDS consists of five major line replaceable units (LRUs). The LRUs are the connector board, filter board, analog board, CPU board, and power supply board. The EDAU/electronic engine display system architecture is depicted in Fig. 2.

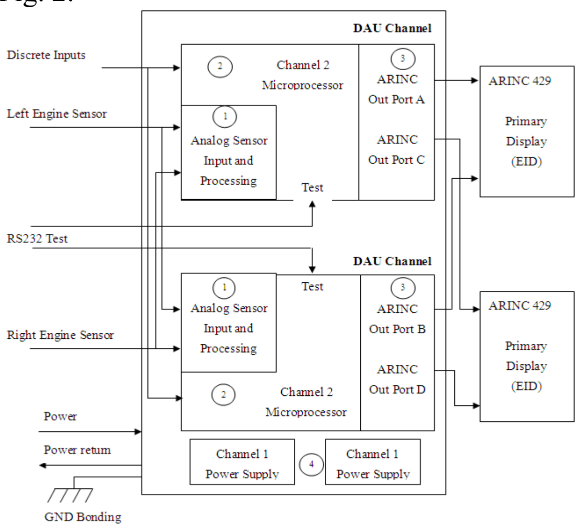

Fig. 2. EDAU/electronic engine display system architecture.

Based on system engineering and expert judgments, the FMEA of this EDAU is shown in Table 4.

This EDAU has 14 potential failure modes (FM) and 17 causes of failure (CF). The functions of numerical ratings of *S*, *O,* and *D* conditions were estimated by experts in design engineering. For ease of comparison of the three methods described in this paper, we use the same three system factors as allocation reliability weightings: *S*, *O,* and *D*. Each rating is based on a scale from 1 to 10 and is estimated using design engineering and expert judgments. The three respective rating values are then multiplied to derive the RPN. The corresponding diagraph consists of 31 nodes and 21 connections as shown in Fig. 3. According to the results of Fig. 3, the FMEA of this EDAU is shown in Table 5.

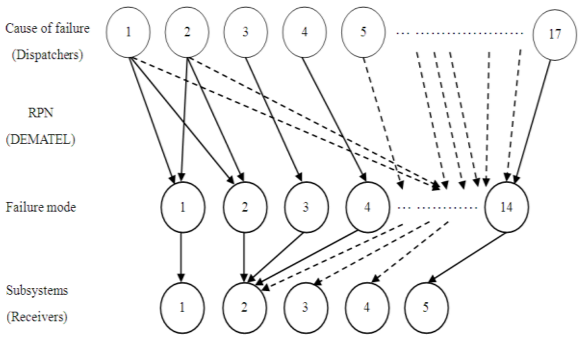

Fig. 3. Corresponding FMEA diagraph of the EDAU process.

Table 4. The FMEA of EDAU

No.	Potential failure mode	Cause of failure
1	Aircraft/Engine Sensor Interface, Connector Board failure (FM1)	Failure indication caused by corrupt parameter (CF1)
2	Aircraft/Engine Sensor Interface, Connector Board failure (FM1)	Inaccurate data followed by Miscompare indication (CF2)
3	Aircraft/Engine Sensor Interface, Filter Board failure (FM2)	Failure indication caused by corrupt parameter (CF1)
4	Aircraft/Engine Sensor Interface, Filter Board failure (FM2)	Inaccurate data followed by Miscompare indication (CF2)
5	Aircraft/Engine Sensor Interface, Filter Board for Nozzle Position failure (FM3)	Maintenance indication caused by EID data retrieval from alternate EDAU channel for Nozzle Position (CF3)
6	Aircraft/Engine Sensor Interface, Filter Board for EGT Failure (FM4)	Maintenance indication caused by EID data retrieval from alternate EDAU channel for Exhausted Gas Temperature (EGT) (CF4)
7	Aircraft/Engine Sensor Interface, Filter Board for Hydraulic Pressure failure (FM5)	Maintenance indication caused by EID data retrieval from alternate EDAU channel for Hydraulic Pressure (CF5)
8	Aircraft/Engine Sensor Interface failed, Filter Board for Oil Pressure failure (FM6)	Maintenance indication caused by EID data retrieval from alternate EDAU channel for Oil Pressure (CF6)
9	Aircraft/Engine Sensor Interface, Filter Board for Fuel Flow failure (FM7)	Maintenance indication caused by EID data retrieval from alternate EDAU channel for Fuel Flow (CF7)
10	Aircraft/Engine Sensor Interface, Filter Board for N2 Tachometer failure (FM8)	Maintenance indication caused by EID data retrieval from alternate EDAU channel for N2 Tachometer (CF8)
11	Aircraft/Engine Sensor Interface, Analog Board failure (FM9)	Failure indication caused by corrupt parameter (CF1)
12	Aircraft/Engine Sensor Interface, Analog Board failure (FM9)	Inaccurate data followed by Miscompare indication (CF2)
13	Aircraft/Engine Sensor Interface, Analog Board for EGT failure (FM10)	Maintenance indication caused by EID data retieval from alternate EDAU channel for EGT (CF9)
14	Aircraft/Engine Sensor Interface, Analog Board for Hydraulic Pressure failure (FM11)	Maintenance indication caused by EID data retrieval from alternate EDAU channel for Hydraulic Pressure (CF10)
15	Microprocessor failure (FM12)	Maintenance indication caused by Microprocessor failure (CF11)
16	Microprocessor failure(FM12)	Maintenance indication caused by Microprocessor corrupt data (CF12)
17	Microprocessor failure (FM12)	Cannot test the EDAU channel (CF13)
18	Microprocessor failure (FM12)	EDAU channel malfunction (CF14)
19	ARINC 429 Communications Interface failure (FM13)	Maintenance indication caused by ARINC 429 Communications Interface failure (CF15)
20	Power Supply failure (FM14)	Maintenance indication caused by Power Supply failure (CF16)
21	Power Supply failure (FM14)	Maintenance indication caused by Power Supply inaccurate data (CF17)

Table 5. The *S*, *O*, and *D* of the failure for EDAU

No.	Subsystem	Potential failure mode	Cause of failure	*S*	*O*	*D*	RPN
1	Connector board	FM1	CF1	2	2	1	4
2	Connector board	FM1	CF2	2	2	1	4
3	Filter board	FM2	CF1	5	2	2	20
4	Filter board	FM2	CF2	5	2	2	20
5	Filter board	FM3	CF3	3	2	2	12
6	Filter board	FM4	CF4	3	2	2	12
7	Filter board	FM5	CF5	3	2	2	12
8	Filter board	FM6	CF6	3	2	2	12
9	Filter board	FM7	CF7	3	2	2	12
10	Filter board	FM8	CF8	3	2	2	12
11	Analog board	FM9	CF1	2	2	2	8
12	Analog board	FM9	CF2	2	2	2	8
13	Analog board	FM10	CF9	2	2	2	8
14	Analog board	FM11	CF10	2	2	2	8
15	CPU board	FM12	CF11	3	3	3	27
16	CPU board	FM12	CF12	3	3	3	27
17	CPU board	FM12	CF13	3	1	1	3
18	CPU board	FM12	CF14	3	1	1	3
19	CPU board	FM13	CF15	3	1	1	3
20	Power supply board	FM14	CF16	7	3	3	63
21	Power supply board	FM14	CF17	5	5	5	125

5.1. ARINC apportionment technique analysis

To illustrate this method, consider an EDAU in an EEDS, which consists of five major line replaceable units (LRUs). The LRUs are the connector board, filter board, analog board, CPU board, and power supply board. The predicted failure rates of the five subsystems are $\lambda_1 = 0.483988$ (connector board), $\lambda_2 = 19.56778$ (filter board), $\lambda_3 = 10.94831$ (analog board), $\lambda_4 = 12.62981$ (CPU board), and $\lambda_5 = 19.41701$ (power supply board) failures per 10^7 hours, respectively. The system has a mission time of 2.4 hours, and a 0.99993333 reliability is required to ascertain the subsystem requirements.

The apportioned system reliability goal is found by Eq. (15) as:

$\lambda s = -\ln(R)/T = -\ln(0.99993333)/2.4 = 277.8$ failures per 10^7 hours

Based on this goal, the predicted failure rates for the five subsystems are:

$\lambda_1 = 0.483988$, $\lambda_2 = 19.56778$, $\lambda_3 = 10.94831$, $\lambda_4 = 12.62981$, $\lambda_5 = 19.41701$

Using Eq. (2), the weighting factors (w_i) for the five subsystems are:

$$w_1 = \frac{0.483988}{0.483988 + 19.56778 + 10.94831 + 12.62981 + 19.41701} = 0.00768$$

$$w_2 = \frac{19.56778}{0.483988 + 19.56778 + 10.94831 + 12.62981 + 19.41701} = 0.31037$$

$$w_3 = \frac{10.94831}{0.483988 + 19.56778 + 10.94831 + 12.62981 + 19.41701} = 0.17365$$

$$w_4 = \frac{12.629806}{0.483988 + 19.56778 + 10.94831 + 12.62981 + 19.41701} = 0.20032$$

$$w_5 = \frac{19.41701}{0.483988 + 19.56778 + 10.94831 + 12.62981 + 19.41701} = 0.30798$$

The corresponding allocated reliability requirements for the five subsystems are calculated by Eq. (3) as:

$$\lambda_1^* = w_1 \lambda s = 2.13257$$

$$\lambda_2^* = w_2 \lambda s = 86.22041$$

$$\lambda_3^* = w_3 \lambda s = 48.24093$$

$$\lambda_4^* = w_4 \lambda s = 55.65001$$

$$\lambda_5^* = w_5 \lambda s = 85.55608$$

5.2. FOO technique analysis

The FOO technique is a detailed reliability allocation procedure for mechanical-electrical systems. For ease of comparing the three methods described in this paper, we use the same three system factors (*S*, *O,* and *D*) as used in RPN method when allocating reliability weighting instead of the *I, S*, *P,* and *E* factors used by the classical FOO technique. The three respective rating values are then multiplied to derive the corresponding RPN value, which is used in apportioning subsystem reliability ratings.

Using Eqs. (4)–(8), we compute the overall rating $w_k^{'}$ and complexity factors $C_k^{'}$ and then ascertained the allocated failure rate. Based on the design requirements and the system operational environment, the system reliability of the fighter aircraft EDAU is set as 0.99993333 and the mission time as 2.4 hours, and then the failure rate for the system can be calculated by:

$\lambda s = -\ln(R)/T = -\ln(0.99993333)/2.4 = 277.8$ per 10^7 hr.

Based on Fig. 3 and Table 5, the filter board (subsystem 2) has 7 potential failure mode: FM2, FM3, FM4, FM5, FM6, FM7, and FM8, which include 8 cause of failures (CF1, CF2, CF3, CF4, CF5, CF6, CF7, CF8). Accumulate the CF1, CF2, CF3, CF4, CF5, CF6, CF7, and CF8 values to derive the overall rating, then use Eq. (6) to derive complexity factors, and then ascertain the allocation failure rate for the filter board as follows.

$$w_k^{'} = 20 + 20 + 12 + 12 + 12 + 12 + 12 + 12 = 112$$

$$C_k^{'} = \frac{w_k^{'}}{W^{'}} = \frac{112}{403} = 0.27792$$

The allocated failure rate is $277.8 \times 0.27792 = 77.20496$ per 10^7 hr.

The allocated failure rates for the connector board, filter board, analog board, CPU board, and power supply board can therefore be calculated as 5.51464, 77.20496, 22.05856, 43.42779, and 129.59404, respectively. The results are summarized in Table 6, column (17).

Table 6. The reliability allocation results for the EDAU (FOO technique)

Subsystem	FMEA														(15)	(16)	(17)
	(1) FM 1	(2) FM 2	(3) FM 3	(4) FM 4	(5) FM 5	(6) FM 6	(7) FM 7	(8) FM 8	(9) FM 9	(10) FM 10	(11) FM 11	(12) FM 12	(13) FM 13	(14) FM 14	Total RPN	Complexity C'k	Allocated Failure Rate (per 10^7 hours)
Connector board	8	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0.01985	5.51464
Filter board	0	40	12	12	12	12	12	12	0	0	0	0	0	0	112	0.27792	77.20496
Analog board	0	0	0	0	0	0	0	0	16	8	8	0	0	0	32	0.07940	22.05856
CPU board	0	0	0	0	0	0	0	0	0	0	0	60	3	0	63	0.15633	43.42779
Power supply board	0	0	0	0	0	0	0	0	0	0	0	0	0	188	188	0.46650	129.59404
Total	8	40	12	12	12	12	12	12	16	8	8	60	3	188	403	1.00000	277.80000

5.3. Proposed combined FMEA and DEMATEL apportionment method

The proposed combined FMEA and DEMATEL method is a well-defined, risk-based apportioning structure for reliability design, which uses system FMEA to determined subsystem allocation weighting factors, and then, using the DEMATEL method, considers indirect relations in analysis. The higher RPN value, the higher reliability is allocated. In this way, reasonable reliability is apportioned into each subsystem or component. The matrix *M* of the EDAU process is obtained, shown in Fig. 4. As Fig. 4 depicts, there exist only unilateral flows from CF to FM, and other entries are equal to zero (three zero blocks). In other words, FM has no influence on CF.

According to Eq. (9), the elements of the direct relative severity matrix (DRSM) are obtained, and then, using Eq. (12), the elements of the direct and indirect relative severity matrix (DIRSM) are obtained,–which are shown in Fig. 5.

According to Eq. (9) to (14), the outcome of DEMATEL implementation for the EDAU with respect to direct and indirect relationships is shown in Table 7.

matrix *M*	CF1	CF2	…	CF17	FM1	FM2	FM3	….	FM14
CF1					4	20			
CF2					4	20			
⋮			0		⋮	⋮	⋮	⋮	⋮
CF16									63
CF17									125
FM1									
FM2									
FM3			0				0		
⋮									
FM14									

Fig. 4. Corresponding matrix *M* of the EDAU.

DIRSM	CF1	CF2	…	CF17	FM1	FM2	FM3	….	FM14
CF1					0.0320	0.1600			
CF2			0		0.0320	0.1600			
⋮					⋮	⋮	⋮	⋮	⋮
CF16									0.5040
CF17									1.0000
FM1									
FM2									
FM3			0				0		
⋮									
FM14									

Fig. 5. Corresponding DIRSM of the EDAU.

Table 7. Failure modes for the EDAU by the DEMATEL technique

No.	*R*	*C*	*R+C*	*R-C*
CF1	0.2560	0	0.2560	0.2560
CF2	0.2560	0	0.2560	0.2560
CF3	0.0960	0	0.0960	0.0960
CF4	0.0960	0	0.0960	0.0960
CF5	0.0960	0	0.0960	0.0960
CF6	0.0960	0	0.0960	0.0960
CF7	0.0960	0	0.0960	0.0960
CF8	0.0960	0	0.0960	0.0960
CF9	0.0640	0	0.0640	0.0640
CF10	0.0640	0	0.0640	0.0640
CF11	0.2160	0	0.2160	0.2160
CF12	0.2160	0	0.2160	0.2160
CF13	0.0240	0	0.0240	0.0240
CF14	0.0240	0	0.0240	0.0240
CF15	0.0240	0	0.0240	0.0240
CF16	0.5040	0	0.5040	0.5040
CF17	1.0000	0	1.0000	1.0000
FM1	0	0.0640	0.0640	-0.0640
FM2	0	0.3200	0.3200	-0.3200
FM3	0	0.0960	0.0960	-0.0960
FM4	0	0.0960	0.0960	-0.0960
FM5	0	0.0960	0.0960	-0.0960
FM6	0	0.0960	0.0960	-0.0960
FM7	0	0.0960	0.0960	-0.0960
FM8	0	0.0960	0.0960	-0.0960
FM9	0	0.1280	0.1280	-0.1280
FM10	0	0.0640	0.0640	-0.0640
FM11	0	0.0640	0.0640	-0.0640
FM12	0	0.4800	0.4800	-0.4800
FM13	0	0.0240	0.0240	-0.0240
FM14	0	1.5040	1.5040	-1.5040

The proposed approach uses failure modes to determine weight factors for each of the subsystems and the subsystem apportioning ratio obtained from DEMATEL in terms of the *R-C* criterion. This study proposed two different models to calculate the reliability allocation weighting ratio, which can be used to allocate weighting factors w_k, $\forall k$. The choice of model depends on the certainty of information and the data used in the prediction failure rate model. The basic model is suitable for uncertain data, and the model with the predicted failure rate is recommended for data with better certainty. In this case study, we can use the model with the predicted failure rate, because the data is certain. However, in order to demonstrate the two different proposed models, we also provide the calculation for the basic model. The calculation results for these two different models are as follows:

(1) Basic model:

Based on Fig. 3 and Table 5, the filter board (subsystem 2) has 7 potential failure modes: FM2, FM3, FM4, FM5, FM6, FM7, and FM8, which include 8 cause of failures (CF1, CF2, CF3, CF4, CF5, CF6, CF7, CF8). Using Eq. (16), accumulate the CF1, CF2, CF3, CF4, CF5, CF6, CF7, and CF8 values to derive the overall rating $w_2^{'}$.

$$w'_2 = 0.2560 + 0.2560 + 0.0960 + 0.0960 + 0.0960 + 0.0960 + 0.0960 + 0.0960 = 1.0880$$

Using Eq. (6), ascertain the complexity factors as follows.

$$C_2^{'} = \frac{w_2^{'}}{W^{'}} = \frac{1.0880}{4.2480} = 0.2561$$

The allocated failure rate is $277.8 \times 0.25612 = 71.1501$ per 10^7 hr.

The allocated failure rates for the connector board, filter board, analog board, CPU board, and power supply board can therefore be calculated as 33.4832, 71.1501, 41.8534, 32.9582, and 98.3551, respectively. The results are summarized in columns (6) and (7) of Table 8.

(2) With the prediction failure rate model:

The subsystem failure rates (λ_k, $\forall k$) are estimated from past observations or estimations. The LRUs are the connector board, filter board, analog board, CPU board, and power supply board. The predicted failure rates of the five subsystems are $\lambda_1 = 0.483988$ (connector board), $\lambda_2 = 19.56778$ (filter board), $\lambda_3 = 10.94831$ (analog board), $\lambda_4 = 12.62981$ (CPU board), and $\lambda_5 = 19.41701$ (power supply board) failures per 10^7 hours, respectively. If the causes of failure for the subsystem filter board are CF1, CF2, CF3, CF4, CF5, CF6, CF7, and CF8, respectively, then based on Fig. 3 and Table 7 and using Eq. (17), we compute the overall rating and complexity factors and then ascertain the allocation failure rate for the connector board as follows.

$$w'_2 = (0.2560 + 0.2560 + 0.0960 + 0.0960 + 0.0960 + 0.0960 + 0.0960 + 0.0960) \times 19.5678 = 21.2897$$

Using Eq. (17) and Eq. (6), ascertain the complexity factors as follows.

$$C_2^{'} = \frac{w_2^{'}}{W^{'}} = \frac{21.2897}{64.1131} = 0.3321$$

The allocated failure rate is $277.8 \times 0.3321 = 92.2479$ per 10^7 hr.

The allocated failure rates for the connector board, filter board, analog board, CPU board, and power supply board can therefore be calculated as 1.0737, 92.2479, 30.3608, 27.5811, and 126.5365, respectively. The results are summarized in columns (8) and (9) of Table 8.

Table 8. Comparison of failure rate with three different methods

Subsystem	(1) Subsystem Predict Failure Rate	ARINC technique		FOO technique		DEMATEL technique (Basic)		DEMATEL technique (With Failure Rate)	
		(2) Overall Rating w'_k	(3) Allocated Failure Rate (per 10^7 hours)	(4) Complexity C'_k	(5) Allocated Failure Rate (per 10^7 hours)	(6) Complexity C'_k	(7) Allocated Failure Rate (per 10^7 hours)	(8) Complexity C'_k	(9) Allocated Failure Rate (per 10^7 hours)
Connector board	0.4840	0.0077	2.1326	0.0199	5.5143	0.1205	33.4832	0.0039	1.0737
Filter board	19.5678	0.3104	86.2204	0.2779	77.2062	0.2561	71.1501	0.3321	92.2479
Analog board	10.9483	0.1737	48.2409	0.0794	22.0573	0.1507	41.8534	0.1093	30.3608
CPU board	12.6298	0.2003	55.6500	0.1563	43.4285	0.1186	32.9582	0.0993	27.5811
Power supply board	19.4170	0.3080	85.5561	0.4665	129.5937	0.3541	98.3551	0.4555	126.5365
Total	63.0469	1	277.8	1	277.8	1	277.8	1	277.8

5.4. Method comparison

As shown in Table 8, the failure rates using the ARINC apportionment technique for the connector board, filter board, analog board, CPU board, and power supply board are summarized in columns (2) and (3) of Table 8. The failure rates obtained by using the FOO technique are also calculated, and the results are shown in columns (4) and (5) of Table 8. Using the proposed FMEA-based DEMATEL (Basic) method, the results are summarized in columns (6) and (7) of Table 8.

Using the ARINC apportionment technique, the appointing failure rates of the subsystems have the following relationship:

filter board (86.2204) > power supply board (85.5561) > CPU board (55.6500) > analog board (48.2409) > connector board (2.1326).

Compared with the FOO technique, the appointing failure rates of the subsystems have the following relationship:

power supply board (129.5940) > filter board (77.2050) > CPU board (43.4278) > analog board (22.0586) > connector board (5.5146).

Because the power supply board has higher RPN values (188) than the filter board (112), CPU board (63), analog board (32), and connector board (8), from the risk prevention viewpoint, it is more reasonable to appoint a higher reliability ratio in the power supply board and CPU board.

The combined FMEA and DEMATEL apportionment method (basic) uses RPN values as a base. Because the DEMATEL (with the predicted failure rate) method considered direct and indirect relationships in the causes of failure CF1 and CF2, after DEMATEL calculation, the connector board was shown to have higher *R-C* values (0.5120) than the CPU board (0.5040) to derive the results: connector board (33.48323) > CPU board (32.95819). The failure rates appointed by using the combined FMEA and DEMATEL method have the following relationship:

power supply board (98.3551) > filter board (71.1501) > analog board (41.8534) > connector board (33.4832) > CPU board (32.9582).

The combined FMEA and DEMATEL apportionment method (with the predicted failure rate) uses RPN values as a base and considers the predicted failure rate between each subsystem at same time. The failure rates appointing by using combined the FMEA and DEMATEL apportionment method (with predicted failure rate have the following relationship:

power supply board (126.5365) > filter board (92.2479) > analog board (30.368) > CPU board (27.5811) > connector board (1.0737).

Because the DEMATEL (with predicted failure rate) method considered direct and indirect relationships and predicted failure rate between each subsystems, that the higher cause of failure for each failure mode and the higher predicted failure rate subsystems are appointing a higher allocation ratio. The subsystem-apportioning ratio obtained from DEMATEL in terms of the *R-C* criterion (relation) is suitable for real-world applications. As shown in Fig. 6, the results of the combined FMEA and DEMATEL apportionment method obtained a correct and discriminating allocation ratio. The result is a more reasonable allocation rating than the conventional ARINC apportionment technique and the FOO technique. The results of the proposed method are compared with the ARINC apportionment technique and the FOO technique that are shown in Fig. 6 below.

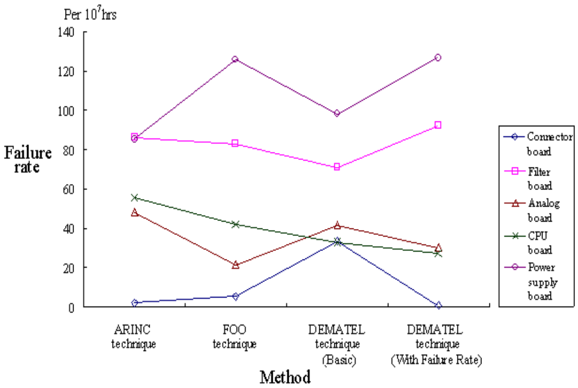

Fig. 6. Comparison of the three methods for reliability allocation.

In comparing the conventional ARINC apportionment technique, the FOO technique, and the proposed combined FMEA and DEMATEL apportionment method, the proposed method has concluded a number of advantages and its potentialities, including:

(1) Consider risk assessment issues in reliability allocation: Using a system FMEA-based method, which efficiently considers three important factors: severity of the failure (*S*), the probability of failure (*O*), and the probability of not detecting the failure (*D*) in apportioning system reliability, it can overcome fundamental shortcoming of the reliability allocation methods. The proposed method considers risk and safety issues and maintenance problems, which may avoid safety problems in future system operation.

(2) Consider indirect relationships between subsystems and components: The DEMATEL technique can consider indirect relationships between subsystems and

components. DEMATEL calculation holds that the higher cause of failure for each failure mode is appointing a higher allocation ratio, which is based on the most important RPN values to efficiently allocate limited resources in subsystems or components. The study obtained a correct and discriminating allocation ratio in reliability design; the results showed that it is easier and close to military products and a customer's needs.

(3) Provide an organized approach and a more flexible structure in reliability allocation. The combined FMEA and DEMATEL method is applicable to the different design phases. According to the information and data that are certain or not, the proposed method is suitable for either simple (basic model) or complex (with the predicted failure rate model) apportionment methodologies. Depending upon the selection of applicable variables, such as system intricacy, state-of-the-art (technology), cost, and maintenance, etc., the allocating ratio is more suitable for different alternatives. There is no limitation for implementation of DEMATEL in very large and complex systems.

(4) Combined the FMEA and DEMATEL approach can also be used in a wide variety of different fields and industries.

Reliability designers must make sure to obtain the appropriate and correct failure mode and numerical ratings of *S*, *O*, *D* before conducting failure mode analysis, because such errors or inappropriate data will contribute to inaccuracy failure mode analysis results. In order to verify the performance of the proposed approach, we consulted with an experienced reliability engineer and manager to verify the results of the reliability allocation rating. These experts indicated that the FMEA-based DEMATEL method yielded results that were not only correct but the method proved flexible for real-world applications, and could thereby provide an improved structured arrangement for reliability allocation.

Ⅵ. CONCLUSIONS

This paper has successfully demonstrated the application of the combined FMEA and DEMATEL apportionment method for reliability allocation using a fighter aircraft EDAU as an illustrative example. It is an easy and proven effective approach that uses severity of failure, occurrence of a failure, and detection of a cause of failure to determine subsystem allocation weighting factors and uses the DEMATEL technique to ascertain indirect relations. The higher RPN translates to a higher reliability allocation overall rating in apportioning a precise reliability ratio into subsystems or components.

The main advantages of the proposed approach are: (1) the combined FMEA and DEMATEL method is a well-defined, risk-based apportioning structure in apportioning system reliability, which is measured from a risk viewpoint to prevent potential problems. The results show that it is easier and close to military products and customer's needs. Such a framework has never been documented. (2) Most reliability allocation methods are using a top-down approach, while the proposed combined FMEA and DEMATEL apportionment method, on the other hand, uses a bottom-up approach, which explores all possible failure modes and their impact upon the system, while emphasizing and considering risk assessment issues in reliability allocation. (3) Using the severity of the failure (*S*), the probability of failure (*O*), and the probability of detecting the failure (*D*) in reliability allocation design can more accurately assess maintainability and risk issues in reliability allocation processes at the same time. (4) The DEMATEL method also considers indirect relationships between subsystems and components for the efficient allocation of limited resources in higher RPN subsystems or components, which may avoid safety problems in system operation. The result shows that the combined FMEA and DEMATEL apportionment method obtains a correct and discriminating allocation ratio. (5) The proposed method also provides an organized approach and a more flexible structure, suitable for either simple or complex apportionment methods, depending upon the selection of applicable variables, such as system intricacy, state-of-the-art (technology), cost, and maintenance, and the like. The DEMATEL technique can also be applied to a large and complex system. The combined FMEA and DEMATEL apportionment method can also be used in a wide variety of different industries and fields. The results from comparison with traditional reliability methods show that the proposed method is both correct and realistic. Also, DEMATEL can be considered in Fuzzy environments that are suggested for further research.

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