Engineering Failure Analysis 18 (2011) 1162–1170

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Multiple failure modes analysis and weighted risk priority number evaluation in FMEA

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ARTICLE INFO

Article history:
Received 30 July 2010
Received in revised form 5 January 2011
Accepted 2 February 2011
Available online 3 March 2011

Keywords:
Multiple failures mode
Risk priority number
Weight risk priority number
FMEA

ABSTRACT

Traditionally, failure mode and effects analysis (FMEA) only considers the impact of single failure on the system. For large and complex systems, since multiple failures of components exist, assessing multiple failure modes with all possible combinations is impractical. Pickard et al. [1] introduced a useful method to simultaneously analyze multiple failures for complex systems. However, they did not indicate which failures need to be considered and how to combine them appropriately. This paper extends Pickard's work by proposing a minimum cut set based method for assessing the impact of multiple failure modes. In addition, traditional FMEA is made by addressing problems in an order from the biggest risk priority number (*RPN*) to the smallest ones. However, one disadvantage of this approach is that it ignores the fact that three factors (Severity (S), Occurrence (O), Detection (D)) (S, O, D) have the different weights in system rather than equality. For examples, reasonable weights for factors S, O are higher than the weight of D for some non-repairable systems. In this paper, we extended the definition of *RPN* by multiplying it with a weight parameter, which characterize the importance of the failure causes within the system. Finally, the effectiveness of the method is demonstrated with numerical examples.

1. Introduction

Failure mode and effects analysis (FMEA) is a very powerful and effective analytical tool which is widely used in engineering projects to examine possible failure modes and eliminate potential failure during system designs. In particular, it provides design engineers with quantitative or qualitative measures necessary to guide the implementation of corrective actions by focusing on the main failure modes and its impact on the products [2]. FMEA has been widely adopted by reliability practitioners and has become standard practice in Japan, America, and European manufacturing companies [2,3]. Onodera [2,4] investigated about 100 FMEA applications in various industries in Japan and found that the FMEA is successfully in the many areas such as automobiles, electronics, consumer products, power plants, and telecommunications. Hsu et al. [5] proposed a method that utilizes the FMEA to analyze the risks of components in compliance with the EU RoHS directive in the incoming quality control (IQC) stage. Bluvband et al. [6] introduced an expanded FMEA or EFMEA for electronic designs. However, FMEA usually evaluates the failures impact on the system reliability based on a single failure. This significantly restricts the application of FMEA. Fortunately, Pickard et al. [1] proposed a method to combine multiple failure modes into a single one, which opens the possibility for us to analyze a system considering multiple failure modes at the same time. Unfortunately, although they proposed such method, the detailed procedure such as which multiple failures need to be com-

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doi:10.1016/j.engfailanal.2011.02.004

Nomenclature

FMEA	failure mode and effects analysis
FTA	fault tree analysis
RPN	risk priority number
DFTA	dynamic fault trees analysis
WRPN	weighted risk priority number
MCS	minimum cut set
PI	probability importance
PPM	parts per million
S	severity
O	occurrence
D	detection
&	AND Operator
$\geqslant 1$	OR Operator
OSF1	occurrence of single failure 1
OSF2	occurrence of single failure 2
DSF1	detection of single failure 1
DSF2	detection of single failure 2

bined was not given. In addition, the issue of overflow related to the factors is not addressed in Pickard's paper when three factors (S, O, D) are scored from 1 (best) to 10 (worst) on the basis of degree.

Based on the works done by Pickard et al. [1], this paper aims to develop a new FMEA method that enables us to combine multiple failure modes into single one, considering importance of failures and assessing their impact on system reliability. The new method is established upon the minimum cut sets theory (MCS). Hence, it can be easily applied to large systems with complex structures.

Traditionally, decisions on how to improve an operation are based on risk priority number (*RPN*) in FMEA. This is a very powerful and useful method often adopted for risk assessment. Traditionally, the way for FMEA to improve the system reliability is made by addressing problems in an order from the largest *RPN* to the smallest ones [6]. However, this method ignores the fact that three factors (S, O, and D) may have different weights in system. Patrick et al. [7] emphasize that severity (S) and occurrence (O) are two key items which should be used in FMEA priority analysis rather than the item of detection (D). For example, in a non-repairable system, the *RPN* of two components failure are equal, that is, 100 ($RPN_1 = 10(S) \times 5(O) \times 2(D)$, $RPN_2 = 10 \times 2 \times 5$). There maybe have a conclusion that the priority for the corrective action applied to the two components is equal. However, the priority should be given to the first component instead of the second one. The reason is that, the failure rate of the first component is much higher than the second one and the factor (O) is a key factor in *RPN* analysis, especially for the non-repairable system. In this paper, we mainly deal with non-repairable systems, so the factor (D) is not a key item needed to be considered. The severity of every minimum cut sets (MCS) is equal because our key concern is focus on the top event. Every MCS can lead to a top event occurrence while have the same effects on the system. So in this paper, the severity (S) for every MCS is equality, that is, 10. Because the severity of each MCS is the same, the only factor that needs to be considered in system is O (occurrence).

After the introduction, the rest of the paper is organized as follows. The evaluation of *RPN* and multiple failure mode combination are presented in Section 2. The method to calculate *WRPN* is described in Section 3. The case study is presented in Section 4. The conclusion is given in Section 5.

2. Evaluation of *RPN* and multiple failure modes combination

2.1. Evaluation of RPN

In the traditional FMEA, the *RPN* is used to conduct the risk assessment. The Potential Failure shows the risk factors as [2,8]

Severity (S): Result generated from failure.
Occurrence (O): Opportunity or probability of a failure.
Detection (D): Opportunity for an unidentified failure because of the difficulty in detection.

The three factors are all scored from 1 (best) to 10 (worst) on the basis of degree. *RPN* is the product of occurrence, detection, and severity, which is expressed as:

$$RPN = S \times O \times D \tag{1}$$

RPN is used widely in engineering analysis, once all items have been analyzed and assigned with a *RPN* value, corrective actions will be implemented from the highest *RPN* value down to the lowest one [2]. The intention of the corrective action is to remove or mitigate critical failure modes that show a high severity, occurrence and detection ranking. *RPN* should be recalculated after the corrections to determine whether the risks have decreased or how efficient the corrective action is [6].

2.2. Review of multiple failure modes combination

As described previously, traditional FMEA only considers a single failure and the results only indicates the system-level effect or top events stemming from that single failure. Pickard et al. [1] proposed a method which can evaluate the system reliability by considering multiple failure modes simultaneously. However, they only described how to combine multiple failure modes into a single mode without detailed discussion on which multiple failures should be combined. In addition, the problem associated with the overflow during the combination is not addressed clearly as well. In the following, we will briefly introduce their method with a little amelioration. We propose a method called the linear interval mapping to resolve the overflow problem. We further generalize their method by introducing minimum cut sets and *WRPN* when the system structure is very large and complicated. The method by Pickard et al. [1] will be explained through the example system in Fig. 1.

In the single failure analysis, a feasible method is that one can develop the potential system effects by evaluating and/or defining root causes from the bottom level. Different effect levels are networked through the OR operation [1]. Form Fig. 1, causes a, b and c each can lead to failure A and further to the top event X. The same principle can be applies for d and e. Combining the bottom up approach with the OR operation, it is impossible to detect the top event Y, as it is not reachable by the FMEA logic. If one begins, however, with the top event Y using the FMEA logistic, no single potential failure cause can be found either [1].

The FTA is another effective engineering analysis method that starts with the top events [9]. If one begins with the defined event in the system level, then all possible causes can be evaluated. Those that stand alone or those that are in combination with each other imply that the causes can be networked with the AND operation [1]. However, the AND gate can not be applied if sequences and orders of the causes do not satisfy the AND condition. Fortunately, dynamic fault trees offer an alternative to solve this type of problems by capturing component failure sequences. More details about dynamic fault trees are available in [10–14]. However, the method to solve dynamic fault trees relies on the Markov process which exists an assumption of exponential distribution. Obviously, this assumption limits the applications of dynamic fault trees. In this paper, we do not consider the sequences of the causes which are the goals in our future research works. Pickard et al. [1] introduced the assessment catalog which is shown in Table 1.

In the risk assessment and analysis, each altered failure modes combination, including double, triple or multiple failures, all of them can be represented by using the AND operation. This means that in observing the occurrence and detection probability, a feasible method be developed by using the AND operation which can maintain a correct relationship between single and multiple failures. In doing that, according to Boole operations, Pickard et al. [1] introduced a new combination method as follows.

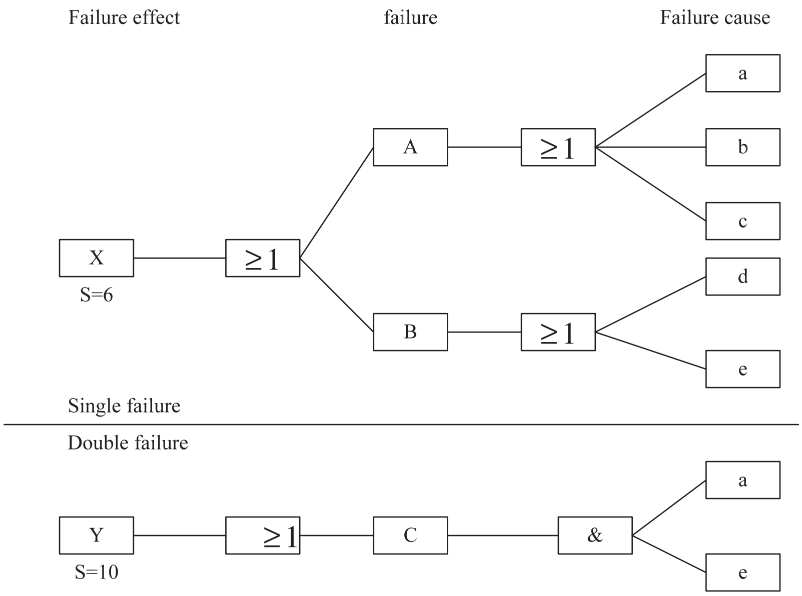

Fig. 1. Single and multiple failure networks in a failure tree.

Table 1
Catalog of requirements.

	Criteria		
Ranking	Severity S	Occurrence O (ppm)	Detection D (%)
10	Very high	500,000	90.00
9	Very high	100000	90.00
8	High	50000	98.00
7	High	10000	98.00
6	Moderate	5000	99.70
5	Moderate	1000	99.70
4	Moderate	500	99.70
3	Low	100	99.90
2	Low	50	99.90
1	Very low	1	99.99

I. The calculation rules according to Boole are, respectively listed in Eqs. (2) and (3) for AND and OR combinations.

$$\text{AND}: \quad O_{m\ failure} = \prod_{i=1}^{i=m} O_i D_{mfailure} = \prod_{i=1}^{i=m} D_i \tag{2}$$

$$\text{OR}: \quad O_{m\ failure} = \sum_{i=1}^{i=m} O_i D_{m\ failure} = \sum_{i=1}^{i=m} D_i \tag{3}$$

II. The traditional FMEA assessment is only applicable for single failures. For the explain how to combine multiple failures into a single one, AND operations are used, which leads to, according to Boole, that the individual probabilities are multiplied with one another.

$O_{failure1} = 3(\equiv 100\ ppm);\ O_{failure2} = 4(\equiv 500\ ppm)$

1	$O_{double\ failure} = O_{failure1} \times O_{failure2} = 3 \times 4 = 12$
2	$O_{double\ failure} = 0.0001 \times 0.0005 = 0.00000005$
3	$O_{double\ failure} = 0.0001 \times 0.0005 = 0.00000005 = 1$

In the first row of the table above, there is a problem that the value of $O_{double\ failures}$ is 12 after multiplication which is bigger than the scale limit 10. This means that the occurrence probability of a double failure is higher than that of a single failure, which according to probability theory is not possible. However, Pickard et al. [1] did not provide a detail discussion for this problem. In order to solve this problem, we propose a very simple method called "Linear Interval Mapping (LIP)". Mathematically, we know that the interval [0,10] have one by one linear mapping between the interval [0,100]. For example, 0 maps to 0, 10 maps to 100. Assume that $x \in 0, 100]$, $y \in [0, 10]$, The mapping between interval [0, 100] and [0, 10] is $y = 0.1x$. By the linear mapping method, 12 belongs to the interval [0, 100] and the mapped value for the interval [0, 10] is 1.2. However, 1.2 is a decimal and the values in the assessment catalog are always integers. Obviously fetching the value 1 instead of 1.2 is one way to solve this problem. However, two additional methods are available to calculate $O_{double\ failures}$. These are linear mapping and multiplication according to the criteria value in Table 1. Pickard et al. [1] have given the assessment matrix of occurrence probability for double failures by multiplication in Table 2.

Table 2
Assessment matrix of occurrence probability for double failures.

	OSF2									
OSF1	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	2
2	1	1	1	1	1	1	1	2	2	2
3	1	1	1	1	1	1	1	2	2	2
4	1	1	1	1	1	2	2	2	2	4
5	1	1	1	1	1	2	2	2	3	4
6	1	1	1	2	2	2	2	4	4	6
7	1	1	1	2	2	2	3	4	5	6
8	1	2	2	2	2	4	4	6	6	8
9	1	2	2	2	3	4	5	6	7	8
10	2	2	2	4	4	6	6	8	8	9

Table 3
Representation of the new procedure.

Potential effects	S	⩾1 &	Potential failure modes	⩾1 &	Potential failure causes	O	D	*RPN*
Effect x	6	⩾1	Failure a	⩾1	Cause a	3	3	54
					Cause b	2	4	48
					Cause c	4	3	72
			Failure b	⩾1	Cause d	3	2	36
					Cause e	2	2	24
Effect y	10	⩾1	Failure c	&	Cause a	1	5	50
					Cause e			

With the same approach, the assessment matrix for detection probability with double failures can be acquired easily. Finally, Pickard et al. [1] showed their new method of Fig. 1 and the result is given in Table 3.

3. The method to calculate *WRPN*

Although Pickard et al. [1] introduced the method to combine multiple failures into single one, they did not specify which failures need to be combined to execute the FMEA procedure. For example, for a very large and complicated system with 1000 components, there may have 1000 failure causes. Generally speaking, it is very time-consuming, maybe impossible, to consider all possible combinations of failures because there are C_{1000}^{2}=499,000 pairs of failures. Nowadays, even simulation is used widely to automate the work of producing an FMEA report, it is still not feasible and very time-consuming in engineering design considering all possible combinations of failures, especially for some very large and complicated systems. Therefore, the MCS of a fault tree turns out to be one of the most convenient methods to resolve this problem.

3.1. Minimum cut sets (MCS)

Assume that there is a cut set and this cut set is not a cut set if a component belonging to the cut set was moved arbitrarily, then we call this cut set is a minimum cut set [15]. Suppose there is a system and its fault tree is *T*. The minimum cut sets of the system is B_1, $B_2 \ldots B_n$. Then *T* can be described as $T = \left\{\bigcup_{i=1}^{n} B_i\right\}$. To a great extent, system or fault tree can be described equally by an OR gate as shows in Fig. 2.

In fact, Fig. 2 is also a fault tree with only one OR gate and its bottom events are minimum cut sets $B_1, B_2, \cdots, B_n n \geqslant 1$. Furthermore, assume that a minimum cut set B_i includes the events $k_1, k_2, \cdots, k_m m \geqslant 1$, that is, $B_i = \{k_1, k_2, \cdots, k_m m \geqslant 1\}$, then B_i can be described by an AND gate as shows in Fig. 3 along with other minimum cut sets. The above discussion is very important and it inspires us to further the development of the research work.

3.2. Weighted risk priority number (WRPN)

As we described in Section 2, $RPN = S \times O \times D$. Once all items have been analyzed and assigned with a *RPN* value, it is common to implement corrective actions starting from the highest *RPN* value to the smallest ones. In Section 2, we described how to combine multiple failures into a single one using AND gate. When the priority is focused on top events, the next step is to calculate the minimum cut sets for the system. Many methods are available to obtain the minimum cut sets. The most popular one used in FTA is Fussell–Vesely [16].

Three factors (S, O, and D) have different weights in system designs, especially in non-repairable systems. Generally the factor O is key factor. Now, we introduce an index called *WRPN* which is different from the common index *RPN*. Furthermore,

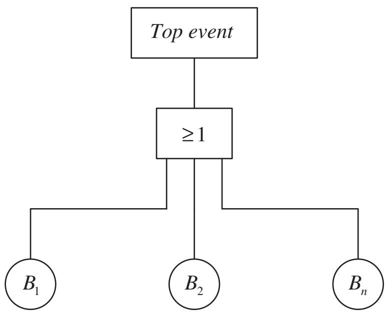

Fig. 2. Described system equally by an OR gate.

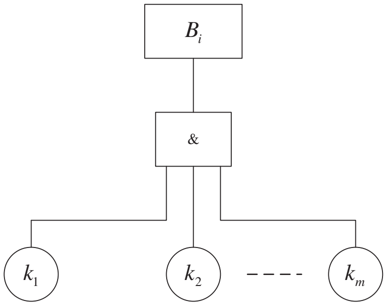

Fig. 3. A minimum cut set can be described equally by a AND gate.

the corrective actions can be used to make decisions on the improvement priority based on *WRPN* instead of *RPN*. The new index is defined as

$$WRPN_i = RPN_i \times f(W_i) = S_i \times O_i \times D_i \times f(W_i) \quad i \neq 0 \tag{4}$$

where W_i is the importance of *i*th minimum cut set in the system, and $f(W_i)$ is a function with independent variable W_i.

A system or fault tree can be described by an OR gate whose inputs are a bunch of minimum cut sets. A random minimum cut set can be described again by a AND gate with inputs representing different failures causes. The probability importance of a component is used widely in FTA. Some components are more important than others because they contribute more to the probability of occurrence for the top events. So the index W_i which is defined in Eq. (5) can reflect the importance of O in the system, especially for non-repairable systems. Based on the principle that a system can be described by an OR gate and the definition of the probability importance [16], the importance of the *i*th minimum cut set is obtained by taking the derivative as

$$W_i = \frac{\partial h(p)}{\partial p_i}, \quad i = 1, 2, \cdots, n \tag{5}$$

where $h(p)$ is the system structure function and p_i is occurs probability of the *i*th minimum cut set, respectively.

In this paper, we assume that all the failure causes are mutually independent. Thus it can be concluded that all minimum cut sets are independent with each other. Now $h(p)$ can be approximated as

$$h(p) = 1 - \prod_{i=1}^{n} (1 - p_i) \tag{6}$$

Because the minimum cut set is equivalent to an AND gate whose inputs are the probability of mutually independent failure causes, p_i can be calculated by:

$$p_i = p_{k_1} \times p_{k_2} \times \cdots \times p_{k_m}, m \neq 0 \tag{7}$$

where $p_{k_i}, i = 1, \cdots, m$ are the probability of the failure cause in the *i*th minimum cut set. From Eqs. (5)–(7), we have

$$W_i = \frac{\partial h(p)}{\partial p_i} = \frac{\partial [1 - \prod_{i=1}^{n} (1 - p_i)]}{\partial p_i} = \prod_{j=1}^{n} (1 - p_i)(i \neq j, \& i, j \neq 0) \tag{8}$$

where $p_i = p_{k_1} \times p_{k_2} \times \cdots \times p_{k_m}, m \neq 0$.

Eq. (8) states that W_i is a importance index which, in general, approaches to one because p_i is often less than 0.01 by noticing that $p_{k_i} < 0.1$ in Eq. (7). Since W_i is close to 1, RPN_i will not change even it is multiplied by W_i. Here are two reasons.

I. The value of W_i almost has no effect on the ranking of the priority order. For example, W_1 = 0.99, W_2 = 0.80. RPN_1 = 60, RPN_2 = 80. After multiplication, $W_1 \times RPN_1$ = 59.4, $W_2 \times RPN_2$ = 64. The propriety order did not change. However, the value of W_1 is much larger than W_2 and it plays a more important role in non-repairable systems.

Table 4
Ranking criteria for W_i.

Ranking	1	2	3	4	5
Criteria	500000 ppm (0.5)	900,000 ppm (0.9)	950,000 ppm (0.95)	990,000 ppm (0.99)	995,000 ppm (0.995)
Ranking	6	7	8	9	10
Criteria	999,000 ppm (0.999)	999,500 ppm (0.9995)	999,900 ppm (0.9999)	999,950 ppm (0.99995)	999,999 ppm (0.999999)

II. Factors S, O, D are to be scored from 1 (best) to 10 (worst) on the basis of degree. In order to make the probability importance factor W_1 uniform across three factors, we need to define a new set of criteria in a range between 1 and 10 on the basis of degree. However, it is very difficult for us to define a reasonable criterion for W_i. There is a reasonable way for us to solve this problem in term of the assessment catalog in Table 1. The ranking criteria for W_i defined by us are shown in Table 4.

From Eqs. (4) and (8), the *WRPN* can be calculated by

$$WRPN_i = RPN_i \times f(W_i) = S_i \times O_i \times D_i \times f\left[\prod_{j=1}^{n}(1-p_i)\right], (i \neq j) \quad (9)$$

The operation of $f(W_i)$ is a mapping process between W_i and its ranking. The domain of the function is $W_i \in [0, 1]$, the range is $f(W_i) \in \{1, 2, 3, \ldots, 10\}$. For example, from the Table 4, we have when $W_i = 0.999999$, $f(W_i)=10$; when $W_i = 0.99$, $f(W_i)=4$, etc.

4. Case study

In this section, the complex system in Fig. 4 with a large number of failure causes will be used to demonstrate the effectiveness of the proposed WFMEA method.

The minimum cut sets of the fault tree are obtained using the method called Fussell–Vesely algorithm, and the result is shown in Table 5.

From the Table 5, there are seven cut sets

$$\{x_1\}, \{x_2\}, \{x_1, x_3\}, \{x_4, x_6, x_7\}, \{x_5, x_6, x_7\}, \{x_3\}, \{x_5, x_6\}$$

In order to acquire the whole minimum cut sets, the following principle needs to be noticed:

Assume that x_i, x_j are two random cut sets, if

$$x_i \subset x_j$$

There is a conclusion that x_j is not a minimum cut set. Then minimum cut sets of the system can be acquired by comparing each others. In the example above, because of

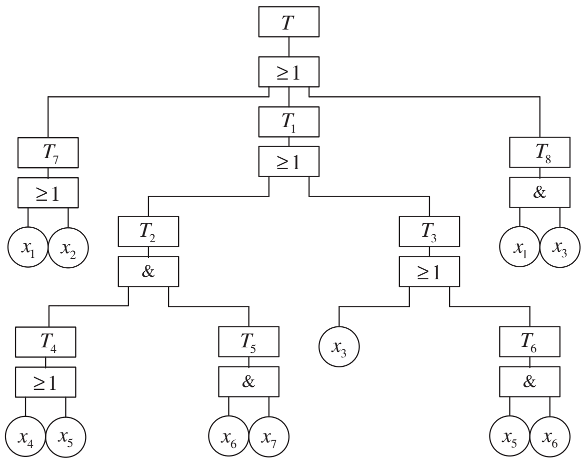

Fig. 4. Fault tree of a system.

Table 5
Step of Fussell–Vesely algorithm.

Step	1	2	3	4	5
	T_7	x_1	x_1	x_1	x_1
		x_2	x_2	x_2	x_2
	T_8	x_1, x_3	x_1, x_3	x_1, x_3	x_1, x_3
	T_1	T_2	T_4, T_5	x_4, T_5	x_4, x_6, x_7
		T_3	x_3	x_5, T_5	x_5, x_6, x_7
			T_6	x_3	x_3
				x_5, x_6	x_5, x_6

$$\{x_1, x_3\} \subset \{x_1\} \& \{x_5, x_6, x_7\} \subset \{x_5, x_6\}$$

So the minimum cut sets of the system are

$$\{x_1\}, \{x_2\}, \{x_3\}, \{x_5, x_6\}, \{x_4, x_6, x_7\}$$

The values of three factors are shown in Table 6.

From the FMEA report in Tables 6 and 2 and the minimum cut sets of the system, we can acquire a new FMEA report with the consideration of multiple failure modes shown in Table 7.

In Table 7, this is a FMEA report considering the minimum cut sets and multiple failures in the system. The traditional FMEA report usually is a simple enumeration. The disadvantages/or problems of the traditional FMEA are:

I. The traditional FMEA only considers single failures and displays only those system effects or top events stemming from single failures.
II. The traditional FMEA cannot characterize a system failure due to multiple failures from component or subsystem levels. From the example above, $\{x_1\}$, $\{x_2\}$, $\{x_3\}$, $\{x_5, x_6\}$, $\{x_4, x_6, x_7\}$ all of them can lead to the occurrence of the top event.
III. The traditional FMEA do not indicate which failure deserves more attention. In our proposed method, we can know which failures or their combination are the important causes.
IV. The traditional FMEA does not consider the importance of the different failure causes. To resolve this issue, we introduced the index of *WRPN* to evaluate the relative importance among multiple failure causes.

From the Tables 4 and 6 and the definition of function $f(W_i)$ and W_i, we have

$$\begin{cases} W_1 = 0.9850 \\ W_2 = 0.9890 \\ W_3 = 0.9940 \\ W_4 = 0.9841 \\ W_5 = 0.9840 \end{cases} \Rightarrow \begin{cases} f(W_1) = 4 \\ f(W_2) = 4 \\ f(W_3) = 5 \\ f(W_4) = 4 \\ f(W_5) = 4 \end{cases}$$

The new priority order of potential failure modes after using *WRPN* is shown in Table 8.

Table 6
Values of three factors of the system.

Failure	S	Causes	O	Control method	D	*RPN*
Top event occurrence	10	x_1	5	......	3	150
		x_2	6	......	1	60
		x_3	7	......	2	140
		x_4	3	......	3	90
		x_5	4	......	4	160
		x_6	6	......	3	180
		x_7	4	......	4	160

Table 7
New FMEA report.

Failure	S	⩾1&	Potential failure modes	⩾1&	Potential failure causes	O	D	*RPN*
Top event occurrence	10	⩾1	$\{x_1\}$	&	x_1	5	3	150
			$\{x_2\}$		x_2	6	1	60
			$\{x_3\}$		x_3	7	2	140
			$\{x_5, x_6\}$		x_5	2	7	140
					x_6			
			$\{x_4, x_6, x_7\}$		x_4	1	8	80
					x_6			
					x_7			

Table 8
New priority order using *WRPN*.

Potential failure modes	*RPN*	Old priority	$f(W_i)$	*WRPN*	New priority
$\{x_1\}$	150	1	4	600	2
$\{x_2\}$	60	5	4	240	5
$\{x_3\}$	140	2	5	700	1
$\{x_5, x_6\}$	140	2	4	560	3
$\{x_4, x_6, x_7\}$	80	4	4	320	4

Form Table 8, we have a new priority of failure modes in the system. Potential failure mode $\{x_3\}$ is the first priority according to *WRPN* rather than $\{x_1\}$ which is the first priority according to *RPN*. Because this system is a non-repairable system, so the factor O is more importance than D. The reasonable corrective action plan on system should be based on the order from the largest *WRPN* to the smallest ones instead of the order of *RPN*.

5. Conclusions

Many systems failed due to the simultaneous onslaught of multiple failure modes. In this paper, the minimum cut set theory has been successfully incorporated into the traditional FMEA for assessing the system reliability in the presence of multiple failure modes. As shown by the illustrative example, the method is theoretically sound and computationally efficient in dealing with large and complex systems. In addition, we expanded the definition for *RPN* by multiplying a weight parameter to characterize the importance of the failure causes or components. Following the weighted *RPN* or *WRPN*, the utility of corrective actions is improved and the improvement effect brings the favorable result in the shortest time. Future research will focus on the investigation of dynamic FTA considering non-exponential failures.

Acknowledgements

This research was partially supported by the National Natural Science Foundation of China under the Contract No. 50775026 and Specialized Research Fund for the Doctoral Program of Higher Education of China under the Contract No. 20090185110019.

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