J Intell Manuf (2014) 25:1413–1427
DOI 10.1007/s10845-013-0747-9

Applying the concept of exponential approach to enhance the assessment capability of FMEA

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Received: 3 October 2012 / Accepted: 16 February 2013 / Published online: 27 March 2013

Abstract Failure modes and effects analysis (FMEA) has been used to identify the critical risk events and predict a system failure to avoid or reduce the potential failure modes and their effect on operations. The risk priority number (RPN) is the classical method to evaluate the risk of failure in conventional FMEA. RPN, which ranges from 1 to 1000, is a mathematical product of three parameters—severity (S), occurrence (O), and detection (D)—to rank and assess the risk of potential failure modes. However, there are some shortcomings of the conventional RPN method, such as: the RPN elements have many duplicate numbers; violate the assumption of measurement scales; and have not considered the weight of S, O, and D. In order to improve the aforementioned shortcomings of the conventional RPN calculation problem, this paper presents an easy yet effective method to enhance the risk evaluation capability of FMEA. The new method is named exponential risk priority number (ERPN), which uses a simple addition function to the exponential form of S, O, and D to substitute the conventional RPN method, which is a mathematical product of three parameters. Two practical cases are used to demonstrate that the ERPN method can not only resolve some problems of the conventional RPN method but also is able to provide a more accurate and reasonable risk assessment in FMEA.

Keywords Risk assessment · Failure modes and effects analysis · Risk priority number · Exponential risk priority number · Data envelopment analysis

Introduction

Risk management is an important part of strategic management in any organization. In order to perform risk management well, organizations require appropriate analysis tools with the capabilities of identification and treatment of these risks (Zhang et al. 2012). Many methods have been developed for risk assessment (Hsiao and Lu 2008; Chang 2009; Chang and Cheng 2009; Karlsson et al. 2000; Chien and Zheng 2012; Hussain et al. 2012; Kubat and Yuce 2012). Failure modes and effects analysis (FMEA) is an important risk assessment tool to eliminate or reduce the probability of failure occurring by a potential failure process or product. For the purpose of ranking the risks of potential failure modes, the traditional FMEA uses the risk priority number (RPN) methodology. The RPN, which is the product of the severity (S), occurrence (O), and detection (D) of a failure mode, is ranging from 1 to 1000. The three parameters S, O, and D are used to describe each failure mode of a product or process, and each parameter can be assigned a rating from 1 to 10. However, there are some shortcomings of the conventional RPN method, such as: the RPN elements have many duplicate numbers; violate the assumption of measurement scales; and have not considered the weight of S, O, and D.

Gilchrist (1993) discussed the shortage of any cost evaluation of the failures in FMEA and thus developed an expected cost model; i.e., $EC = C_n P_f P_d$, where C is the failure cost, n denotes the annual production quantity, P_f is the probability of failure, and P_d is the probability of the failure not to be detected. However, Ben-Daya and Raouf (1996) found some

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problems of the expected cost model; it is difficult to estimate these probabilities at the design stage of a product, and the economic model completely ignores the important aspect of severity. Wang et al. (1995) proposed a methodology combining FMEA and the Boolean representation method to identify and estimate risks of failures. However, it might be difficult to construct Boolean representation tables for some components of a system, especially during early phases of product design, since the relationships between components may be difficult to precisely represent. Sankar and Prabhu (2001) presented a modified approach to prioritize failure modes for corrective actions in FMEA. This technique extends the risk prioritization beyond the conventional RPN method. The ranks 1 through 1000 are used to represent the increasing risk of the 1000 possible severity-occurrence-detection combinations, called risk priority ranks (RPRs). The RPRs method has the advantage in solving the duplication problem of the conventional RPN method, but it requires a lot of time to deal with the risk-ranking process than what traditional RPN method does.

Moreover, the management of FMEA is usually confronted with several problems, such as the imprecise and vague linguistic information. To overcome this problem in the conventional RPN method, a lot of more reasonable and systematic methods were proposed. Bowles and Pelaez (1995) were the first ones to propose a technique using membership function in FMEA. Their approach uses fuzzy logic to work with the linguistic terms directly in making the criticality assessment. Chang et al. (1999) used fuzzy linguistic terms that described the decision factors as Very Low, Low, Moderate, High, and Very High to evaluate S, O, and D and utilized the grey relational analysis to determine the risk priorities of failure modes. Pillay and Wang (2003) utilized fuzzy rules base and grey relation theory in FMEA. However, these methods have the same problem of high duplication rate. There are also some studies that have applied fuzzy theory to incorporate with FMEA to improve the traditional FMEA (such as Braglia et al. 2003; Sharma et al. 2005; Tay and Lim 2006; Wang et al. 2009; Xu et al. 2002; Yeh and Hsieh 2007; Chang et al. 2010).

Seyed-Hosseini et al. (2006) used the decision-making trial and evaluation laboratory (DEMATEL) to prioritize failures in a system. DEMATEL was developed by the Battelle Memorial Institute (Gabus and Fontela 1973) through its Geneva Research Centre. DEMATEL is an effective method to analyze the relationships between components of a system regarding is type (direct/indirect) and severity. However, Seyed-Hosseini et al.'s approach still could not solve the shortcomings of the conventional RPN method. When each cause of failure is assigned to only one potential failure mode, the risk ranking orders obtained by DEMATEL corresponds with the ones obtained by the conventional RPN method (Chang and Cheng 2011). Recently, some researchers utilized data envelopment analysis (DEA), which is a well-known managerial tool, to evaluate the efficiency of a number of producers, to take the relative importance of risk factors S, O, and D into account. Chang and Sun (2009) applied the DEA technique to enhance assessment capabilities of FMEA. Chin et al. (2009) also used DEA to determine the risk priorities of failure modes. In the DEA approach used by Chang and Sun (2009) and Chin et al. (2009), existing complicated operations owing to multiplication and division are extensively applied to the values of S, O, and D. However, like Bowles (2003) indicated—that one of the problems with the RPN method is the use of the ordinal ranking numbers as numeric quantities—the same problem remains while applying DEA in FMEA from a statistical point of view. It is meaningless to directly perform mathematical operations to the values of S, O, and D, since they are actually on an ordinal scale.

As mentioned above, there are abundant studies to enhance the assessment capability of traditional FMEA, such us fuzzy theory, grey relation theory, ordered weighted averaging (OWA), DEA, and others. However, these approaches are obviously a lot more complicated than the conventional RPN method. That might be the main reason that hinders most engineers and analysts from applying them in practice nowadays. Despite its simplicity, the shortcomings of the conventional RPN method still need to be improved. Therefore, this study developed a new method, named exponential risk priority number (ERPN), which uses a simple addition function to the exponential form of S, O, and D to enhance the risk evaluation capability of FMEA. The ERPN method is able to reduce the number of duplicate values in the conventional RPN method used in FMEA. Using the ERPN method, decision-makers can associate different weights with respect to different risk factors for more practical applications. Two case studies are presented in this study to demonstrate the effectiveness of the proposed approach.

The rest of this article is organized as follows. “Failure modes and effects analysis” section discusses the traditional FMEA method and its shortcomings. “Methodology” section proposes a new approach, which uses a simple addition function to the exponential form of S, O, and D to substitute the conventional RPN method. In “Simulations and comparison” section, a simulation example (safety assessments of fishing vessels) is adapted to demonstrate the effectiveness of the proposed new approach. Other than the new ERPN approach, results by using the conventional RPN method and DEA approach to the same case are compared and analyzed. In “Numerical verification” section, a practical case is used to demonstrate an application of the ERPN method on a situation that considers the relative importance among the parameters S, O, and D. The final section makes conclusions.

Failure modes and effects analysis

The development of FMEA

FMEA was first proposed by the aerospace industry in the 1960s, with their obvious reliability and safety requirements. Since then, it has been gradually used as a powerful technique for system safety and reliability analysis of products and processes. Meanwhile, the military of the United States of America (USA) also started to apply the FMEA technique and published the standard operational procedure MIL-STD-1629 of failure modes and effects criticality analysis (FMECA) in 1974 (US Department of Defense Washington, DC 1974), which then was revised as MIL-STD-1629A in 1980 (US Department of Defense Washington, DC 1980). Nowadays, the standard is still the one of the important FMEA references in the world.

In 1977, Ford Motor established the standard operational procedure of FMEA and popularized the FMEA technique. Afterwards, the automotive industry in the USA gradually adopted FMEA as a tool and divided it into two types: the design FMEA (DFMEA) and the process FMEA (PFMEA). In 1985, the International Electrotechnical Commission (IEC) published an international standard operational procedure of FMEA called IEC 812, partly based on MIL-STD-1629A (International Electrotechnical Commission 1985). In 1993, under the auspices of the American Society for Quality Control (ASQC) and the Automotive Industry Action Group (AIAG), Ford, Chrysler, and General Motors integrated the regulations of automotive companies to establish the FMEA reference manual to meet QS-9000 requirements. AIAG revised the FMEA reference manual several times since then (Automotive Industry Action Group 2008). Furthermore, FMEA is considered an important item for examining an analytic method by the international quality certification system, such as ISO-9000, ISO/TS 16949, CE, and QS-9000 in recent years. Today, it is widely used in risk assessment and quality improvement in many industries, such as aerospace, nuclear, military, medicine, automobile, mechanical, and semiconductor. In the future, FMEA may not only be the techniques and mechanisms of product competitiveness in enterprise but also become the basic procedures for product development. The development of FMEA is shown in Table 1.

Risk priority number (RPN) used in conventional FMEA

The introduction of RPN

RPN is a mathematical product of three parameters, which ranges from 1 to 1000, for ranking and assessing the risk of potential failure modes. It is an index score calculated as the severity (S), occurrence (O), and detection (D) of a failure mode, which can be represented in a mathematical way; i.e., RPN = $S \times O \times D$. A failure mode that has a higher RPN is assumed to be more important and thus demands higher priority for corrective action than those with lower RPN values. The detailed rating scales of the severity, occurrence, and detection used in FMEA are given in Tables 2, 3, and 4, respectively.

The drawbacks of conventional RPN

From a management perspective, the conventional RPN calculation is easy to use and understand. However, the conventional approach to obtain RPN has been considerably

Table 1 The development of FMEA

Year	Description
1963	FMEA was first proposed by aerospace industry
1965	The military of the US started to apply the FMEA technique
1974	The military of the US published the SOP of FMEA: MIL-STD-1629
1977	Ford Motor started to use FMEA
1980	The revised SOP of FMEA: MIL-STD-1629A
1985	The International Electrotechnical Commission (IEC) published SOP of FMEA: IEC 812
1993	Ford, Chrysler, and General Motor established the 1st edition FMEA reference manual
1995	The 2nd edition of FMEA reference manual was revised by AIAG
2001	The 3rd edition FMEA reference manual was revised by AIAG
2008	The 4th edition FMEA reference manual was revised by AIAG
2008-now	FMEA is considered as an important examining item and analytic method by ISO-9000, ISO/TS 16949, CE, and QS-9000, and it has been widely used in risk assessment and quality improvement in many industries

Table 2 The rating scales of severity (Ford Motor Company 1988)

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 3 The rating scales of occurrence (Ford Motor Company 1988)

Probability of failure	Possible failure 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 2000	4
Low	1 in 15000	3
Remote	1 in 150000	2
Nearly impossible	≦1 in 1500000	1

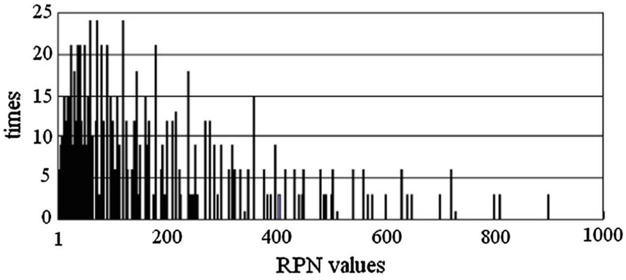

Fig. 1 Histogram of RPN values generated from all possible combinations

criticized for a variety of reasons. Significant criticisms include but are not limited to the following:

(1) The RPN elements have many duplicate numbers.
Many scholars questioned that the RPN elements have many duplicate numbers (Bowles 2003; Wang et al. 2009; Chang and Cheng 2010). There are 1000 possible combinations of S, O, and D, but in fact, only 120 unique RPN values may result due to the duplicate numbers. For example, the RPN value of 120 appears 24 times from different combinations of S, O, and D; it is difficult to accept that these 24 different combinations of S, O, and D have the same priority. Figure 1 shows the thorough listing of frequency distribution for the 1000 RPN numbers (Bowles 2003; Chang and Cheng 2010).

Table 4 The rating scales of detection (Ford Motor Company 1988)

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 certainly detect a potential cause of failure or subsequent failure mode	1

(2) Violate the assumption of measurement scales (Bowles 2003; Chang and Cheng 2011).
The first step of any statistical analysis is to identify the scale of measurements. Data can be classified into four different types of measurement scales: nominal scale, ordinal scale, interval scale, and ratio scale. It is not allowed for all measurements to have the same level of quantification. By definition, the values of S, O, and D of FMEA are classified as ordinal scale. Bowles (2003) mentioned that the calculation of multiplication and division are meaningless on ordinal scales, and addition and subtraction while sometimes meaningful, must be carefully done, since they assume an equal interval between the category labels.

(3) Have not considered the weight of S, O, and D.
Sankar and Prabhu (2001) mentioned that the three parameters S, O, and D are assumed to be equally weighted with respect to one another in terms of risk. It neglects the relative importance among the three parameters and may not be able to correctly quantify the risk when considering a practical application of FMEA.

(4) The RPN scale itself has some non-intuitive statistical properties.
Bowles (1998) pointed out that the FMEA scales for severity and detection are only qualitative. The statement in FMEA is often subjective, and the information in FMEA is described qualitatively in linguistic way, such as “likely”, “important”, or “very high” and so on. Therefore, it is difficult to precisely evaluate reliability of a product or process for the traditional FMEA. One of the shortcomings of the RPN method is that the RPN scale itself has some non-intuitive statistical properties. The initial and correct assumption observation is that the scale starts at 1 and ends at 1000, often leading to incorrect assumptions in the middle of the scale. Table 5 contains some common faulty assumptions (Sankar and Prabhu 2001).

Methodology

In order to improve the shortcomings of conventional RPN method and provide an easier yet effective approach than those approaches found in literature, this research proposes a new method to substitute the use of RPN method used in conventional FMEA. The new method is named exponential RPN (ERPN), which uses a simple addition function to the exponential form of S, O, and D.

The exponential risk priority number (ERPN)

The conventional FMEA uses the mathematical product of the severity (S), occurrence (O), and detection (D) of a failure mode to form the RPN values. However, multiplying the values of S, O, and Dmay cause some problems, since they are actually on an ordinal scale. It is actually meaningless to perform multiplication directly to values in an ordinal scale. A general form of the exponential risk priority number (ERPN) proposed in this study is defined in Eq. (1).

$$\mathrm{ERPN}(X) = X^{W_s\times S} + X^{W_o\times O} + X^{W_d\times D},\\ X\in Z \text{ and } X\geq 2 \tag{1}$$

In Eq. (1), S, O, and D are the ratings of a failure as defined in the conventional RPN method. That is, S, O, and D are integers ranging between 1 and 10. X is defined as any positive integer that is no less than 2. X serves as a parameter in the ERPN method. Moreover, it is possible to assign different weights to S, O, and D to consider the relative importance among the three parameters. Let W_S, W_O, and W_d be the weights assigned to S, O, and D, respectively. Since X is unknown, the first step is to obtain an appropriate value X on the assumption that W_S, W_O, and W_d are set as 1. The process of determining an appropriate value of X is presented and discussed in “Parameter determination in ERPN” section.

Parameter determination in ERPN

One of the problems of the conventional RPN method is it has too many duplicate numbers. For the purpose of searching an appropriate value of X, the number of unique values and the frequency associated with each unique value that ERPN(X) could possibly generate for various X are calculated for comparison. The number of unique values is the count of all possible values resulting from ERPN(X) for a given X. The frequency of each unique value represents the number of possible combinations to generate that value.

Table 5 RPN scale statistical data

Incorrect assumption	Actual statistical data
The average of all RPN values is roughly 500	The average RPN value is 166
Roughly 50 % of RPN values are above 500 (The median is near 500)	6 % of all RPN values are above 500 (The median is 105)
There are 1000 possible RPN values	There are 120 unique RPN values

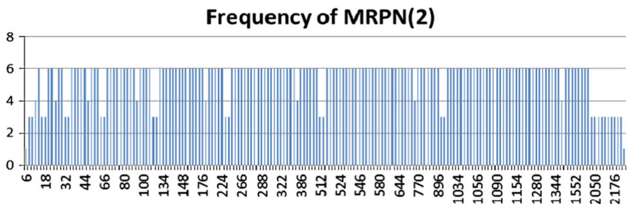

Fig. 2 Histogram of ERPN(2) values generated from all possible combinations

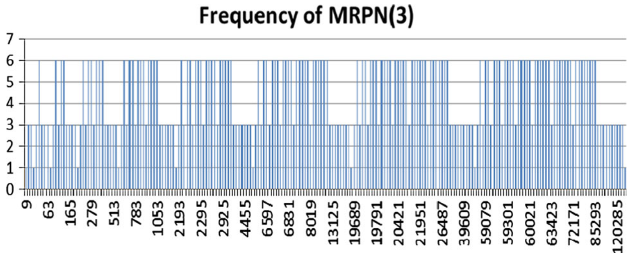

Fig. 3 Histogram of ERPN(3) values generated from all possible combinations

The smallest value of X is 2 per Eq. (1). All the possible values of ERPN(2) ($= 2^S + 2^O + 2^D$) and the frequency of each value are computed. The histogram of ERPN(2) values generated from all possible combinations is given in Fig. 2. Figure 2 clearly shows that there are 184 unique values generated by ERPN(2). Recall that there are only 120 unique values in the conventional RPN method. Furthermore, the highest frequency of ERPN(2) is 6. In contrast, the highest frequency of the conventional RPN method is 24. Therefore, ERPN(2) has fewer duplicate numbers than the conventional RPN method.

Using the same procedure, the possible values of ERPN(3) and the frequency of each value are also computed. The histogram of ERPN(3) values generated from all possible combinations is given in Fig. 3. Comparing Figs. 2 and 3, although the highest frequency in both cases is 6, the number of values associated with the highest frequency of ERPN(3) is less than ERPN(2). Furthermore, there are 220 unique values generated by ERPN(3), which is 36 more what ERPN(2) generates. Therefore, it would result in a better performance to assign X as 3 than as 2.

The trend of the number of unique values resulting from ERPN(X) is shown in Fig. 4. Therefore, it is appropriate to assign X as 3 while keeping the resulting ERPN numbers easy to interpret and effective to use. Some statistics of the values generated by different functions are summarized in Table 6.

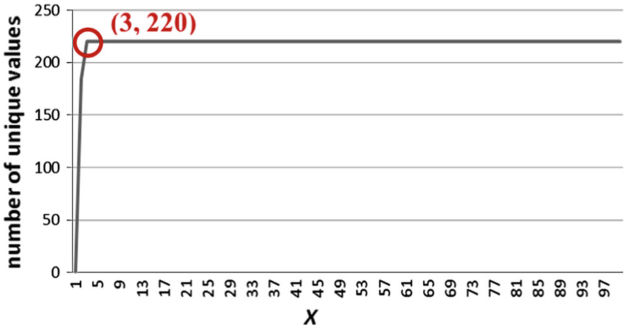

Fig. 4 The number of unique values resulted from $\mathrm{ERPN}(X) = X^S + X^O + X^D$

Actually, the number of unique values resulting from ERPN(X), for $X \in Z$ and $X \geq 2$, can be calculated analytically as follows. When X is a given number other than 2, there are three possible situations under which the resulting $\mathrm{ERPN}(X) = X^S + X^O + X^D$ is a unique value: (1) when the values of the three factors S, O, and D are totally different; (2) any two values of the three factors S, O, and D are same and the other one is different; and (3) the values of the three factors S, O, and D are all the same. Since S, O, and D could be any integer ranging from 1 to 10, situation (1) is able to generate $C_3^{10} = 120$ unique numbers. Situation (2) is able to generate $C_2^{10} = 90$ unique numbers. Ten unique numbers are generated by situation (3). Therefore, there are total of 220(=120 + 90 + 10) unique values resulting from ERPN(X) as long as X is equal to or greater than 3. When X=2, the number of unique values resulting from ERPN(X) only is 184, less than 220. The reduction in the number of unique values is resulting from the property that $2^a + 2^a = 2^{a+1}$ for $a \in Z$. For instance, (S, O, D) values of (3, 3, 2) and (4, 1, 1) would generate the same value of 20 in ERPN(2).

Since it makes no difference to adopt any value that is larger than or equal to 3 as the value of X, we recommend assigning X to be 3, because it could produce the most unique values and the easiest calculation. As a result, the new method to substitute the conventional RPN method is described in Eq. (2).

$$\mathrm{ERPN} = 3^{W_s \times S} + 3^{W_o \times O} + 3^{W_d \times D} \tag{2}$$

The properties of the new ERPN method

In brief, there are the following four properties of the new ERPN method proposed in this study.

(1) ERPN method uses a simple addition function to the exponential form of S, O, and D to substitute the multiplication used in the conventional RPN method. Consequently, the problem of measurement scales found in the conventional RPN method is improved.
(2) ERPN method has fewer duplicate values than what the conventional RPN method has. That means that few failure modes would be assigned to the same priority; thus, the risk evaluation capability of FMEA is enhanced.

Table 6 Comparison of statistics resulting different functions

Function	Average	Median	Number of unique values	Minimum	Maximum
RPN = $S \times O \times D$	166	105	120	1	1000
$\text{ERPN}(2) = 2^S + 2^O + 2^D$	613.8	518	184	6	3072
$\text{ERPN}(3) = 3^S + 3^O + 3^D$	26571.6	13203	220	9	177147
$\text{ERPN}(4) = 4^S + 4^O + 4^D$	419430	131328	220	12	3145728
$\text{ERPN}(5) = 5^S + 5^O + 5^D$	3662109	781875	220	15	29296875

(3) The ERPN method could take the relative importance among the three parameters S, O, and D into consideration (the relative importance weights of S, O and D are obtained by FMEA team members based on their judgment).

(4) If it does not violate the premise of measurement scales, the ERPN method offers an easier way for identifying ranking-order for all failure modes in a system than the other proposed approaches.

Simulations and comparison

As aforementioned, a new approach named ERPN is proposed to overcome some shortcomings of the conventional RPN method in FMEA. The main shortcomings are: (1) the three parameters S, O, and D are assumed to be equally weighted with respect to one another in terms of risk; (2) different combinations of S, O, and D may produce the same value of RPN, but their degree of hidden risk may be different; (3) the problem of the measurement scale; and (4) the RPN elements have many duplicate numbers. In order to verify that the ERPN method proposed in this paper can improve some problems of conventional RPN method, a practical case of FMEA is used to demonstrate the new ERPN method. Besides, the traditional RPN method and the approach using data envelopment analysis (DEA) (Chang and Sun 2009) are also applied to the same case for comparison. The results of the three methodologies are analyzed and compared in "Comparison" section.

A practical case of FMEA

The practical case is obtained from Pillay and Wang (2003), which is an application of FMEA to a fishing vessel. The FMEA for the fishing vessel investigates four different systems, which are structure, propulsion, electrical, and auxiliary systems. Each system is considered for different failure modes that could lead to an accident with undesired consequences. The effects of each failure mode on the system and vessel are studied, along with the provisions that are in place or available to mitigate or reduce risk. For each of the failure modes, the system is investigated for any alarms or condition monitoring arrangements that are in place. The failure modes of this case and their ratings on the three parameters S, O, and D are shown in Table 7.

Application of the conventional RPN method

According to the conventional RPN method, the risk of each failure mode is assessed based on its severity, occurrence, and detection on a numerical scale from 1 to 10. RPN values are calculated by multiplying the three parameters of S, O, and D. A failure mode that has a higher RPN value is assumed to be more important and demands higher priority for corrective action than those with lower RPN values. The result of the conventional RPN method for this fishing vessel is carried out in Table 8 (Pillay and Wang 2003).

Application of the DEA approach

The DEA approach (CCR AR model) used by Chang and Sun (2009) was implemented step by step to determine the risk priorities of failure modes in this case. The DEA approach calculates the relative performance or efficiency of a specific group. The efficiency score is evaluated mathematically by the ratio of weighted sum of outputs and weighted sum of inputs; a lower efficiency score implies a higher priority for corrective actions.

To apply the DEA approach in this case, the first step is to convert the FMEA data matrix to DEA data format. The output of each failure mode is set as 1. The input-oriented CCR assurance region (AR) model with S, O, and D as inputs is employed to generate comprehensive risk scores for evaluating failure modes. The case data were computed by DEA EXCEL SOLVER, developed by Zhu (2003). The result of applying DEA to this case is shown in Table 9.

Application of the ERPN method

This case did not consider the relative importance among the three risk factors; i.e., $W_s = W_o = W_d = 1$ in Eq. (2). The results of this case by using the ERPN method are summarized in Table 10.

Table 7 FMEA for a fishing vessel (Pillay and Wang 2003)

No.	Description	Component	Failure mode	Failure effect (system)	Failure effect (vessel)	Alarm	Provision	*S*	*O*	*D*
1	Structure	Rudder bearing	Seizure	Rudder jam	No steering ctrl	No	Stop vessel	8	1	3
2	Structure	Rudder bearing	Breakage	Rudder loose	Reduced steering ctrl	No	Stop vessel	8	1	3
3	Structure	Rudder bearing	Structural failure	Function loss	Reduced steering	No	Use beams	8	2	4
4	Propulsion	Main engine	Loss of output	Function loss	Loss of speed	Yes	None	8	8	5
5	Propulsion	Main engine	Auto shutdown	M/E stops	Loss of speed	Yes	Anchor	8	6	6
6	Propulsion	Shaft and propeller	Shaft breakage	Loss of thrust	Loss of speed	No	Anchor	8	2	1
7	Propulsion	Shaft and propeller	Shaft seizure	Loss of thrust	Loss of speed	Yes	Anchor	9	2	2
8	Propulsion	Shaft and propeller	Gearbox seizure	Loss of thrust	Loss of speed	Yes	Anchor	4	1	3
9	Propulsion	Shaft and propeller	Hydraulic failure	Cannot reduce thrust	Cannot reduce speed	No	Anchor	2	3	3
10	Propulsion	Shaft and propeller	Prop. blade failure	Loss of thrust	Loss of speed	No	Slow steaming	2	1	4
11	Air services	Air services	No start air press.	Cannot start M/E	No propulsion	Yes	Recharge receiver	2	4	3
12	Electrical system	Power generation	Generator fail	No elec. power	Some system failures	Yes	Use st-by generators	3	9	7
13	Electrical system	Main switch	Complete loss	Loss of main supply	No battery charging	Yes	Use emergency 24 V	3	8	6
14	Electrical system	Emergency S/B	Complete loss	Loss of emer. supp.	No emergency supp.	No	Use normal supply	7	3	4
15	Electrical system	Main batteries	Loss of output	Loss of main 24 V	Loss of main low volt	Yes	Use emergency 24 V	3	3	4
16	Electrical system	Emer. Batteries	Loss of output	Loss of emer. supp.	No emer. supp.	No	Use normal supply	8	1	3
17	Auxiliary system	Fuel system	Contamination	M/E and gen. stop	Vessels stops	Yes	Anchor	8	4	5
18	Auxiliary system	Fuel system	No fuel to M/E	M/E stops	Vessel stops	No	Anchor	7	2	7
19	Auxiliary system	Water system	No cooling water	Engine overheat	M/E auto cut-out	Yes	Use st-by pump	2	7	4
20	Auxiliary system	Hydraulic	System loss	No hydraulics	No steering	Yes	Stop vessel	8	9	9
21	Auxiliary system	Lube oil system	Loss of pressure	Low pressure cut-off	M/E stops	Yes	Use st-by pump	3	9	6

Table 8 FMEA for a fishing vessel by RPN

No.	Description	Component	Failure mode	*S*	*O*	*D*	RPN
1	Structure	Rudder bearing	Seizure	8	1	3	24
2	Structure	Rudder bearing	Breakage	8	1	3	24
3	Structure	Rudderbearing	Structural failure	8	2	4	64
4	Propulsion	Main engine	Loss of output	8	8	5	320
5	Propulsion	Main engine	Auto shutdown	8	6	6	288
6	Propulsion	Shaft and propeller	Shaft breakage	8	2	1	16
7	Propulsion	Shaft and propeller	Shaft seizure	9	2	2	36
8	Propulsion	Shaft and propeller	Gearbox seizure	4	1	3	12
9	Propulsion	Shaft and propeller	Hydraulic failure	2	3	3	18
10	Propulsion	Shaft and propeller	Prop. blade failure	2	1	4	8
11	Air services	Air services	No start air press.	2	4	3	24
12	Electrical system	Power generation	Generator fail	3	9	7	189
13	Electrical system	Main switch	Complete loss	3	8	6	144
14	Electrical system	Emergency S/B	Complete loss	7	3	4	84
15	Electrical system	Main batteries	Loss of output	3	3	4	36
16	Electrical system	Emer. Batteries	Loss of output	8	1	3	24
17	Auxiliary system	Fuel system	Contamination	8	4	5	160
18	Auxiliary system	Fuel system	No fuel to M/E	7	2	7	98
19	Auxiliary system	Water system	No cooling water	2	7	4	56
20	Auxiliary system	Hydraulic	System loss	8	9	9	648
21	Auxiliary system	Lube oil system	Loss of pressure	3	9	6	162

Table 9 The efficiency scores of each failure mode in the fishing vessel case by using DEA

No.	DMU	Efficiency score
1	1	1.0000
2	2	1.0000
3	3	0.6250
4	4	0.4783
5	5	0.4310
6	6	1.0000
7	7	0.8333
8	8	1.0000
9	9	1.0000
10	10	1.0000
11	11	1.0000
12	12	0.6667
13	13	0.6667
14	14	0.6250
15	15	0.7857
16	16	1.0000
17	17	0.5102
18	18	0.5000
19	19	1.0000
20	20	0.3165
21	21	0.6667

Table 10 ERPN for the fishing vessel case

No.	Failure mode	S	O	D	ERPN
1	Seizure	8	1	3	6591
2	Breakage	8	1	3	6591
3	Structural failure	8	2	4	6651
4	Loss of output	8	8	5	13365
5	Auto shutdown	8	6	6	8019
6	Shaft breakage	8	2	1	6573
7	Shaft seizure	9	2	2	19701
8	Gearbox seizure	4	1	3	111
9	Hydraulic failure	2	3	3	63
10	Prop. blade failure	2	1	4	93
11	No start air press.	2	4	3	117
12	Generator fail	3	9	7	21897
13	Complete loss	3	8	6	7317
14	Complete loss	7	3	4	2295
15	Loss of output	3	3	4	135
16	Loss of output	8	1	3	6591
17	Contamination	8	4	5	6885
18	No fuel to M/E	7	2	7	4383
19	No cooling water	2	7	4	2277
20	System loss	8	9	9	45927
21	Loss of pressure	3	9	6	20439

Comparison

In order to evaluate the effectiveness of the new ERPN method, a case for a fishing vessel was performed by three approaches: the conventional RPN, DEA, and ERPN in sections “Application of the conventional RPN method”, “Application of the DEA approach”, “Application of the ERPN method”. The results of the three methods are presented in Table 11. Some findings in this paper are discovered and analyzed as follows.

(1) The ERPN method can reduce the high duplication rate problem.
Table 8 clearly shows the basis of the conventional RPN method, both items No. 2 (S, O, and D are 8, 1, and 3, respectively) and No. 11 (S, O, and D are 2, 4, and 3, respectively) have the same RPN values of 24. Per the DEA method, the efficiency scores of both items are the same, with the value of 1 from Table 9. Therefore, items No. 2 and No. 11 have the same priority for corrective actions based on the conventional RPN and DEA methods. However, these two items represent two failure modes that have different combinations of S, O, and D, which should lead to different risks. Using the proposed ERPN method, the resulting ERPN values (Table 11) for items No. 2 and No. 11 are 6591 and 117, respectively; this means that item No. 2 has a higher risk than item No. 11 due to the fact that No. 2 has a quite large rating on its severity than No. 11. This illustration implies that the ERPN method is more effective in distinguishing the risks of failure modes than the other two methods.
Furthermore, according to Table 11, the conventional RPN method generated 17 unique RPN values among a total of 21 items in this case; that is, the duplication rate is 19.05 %. The DEA approach yields 10 unique efficiency scores among these 21 items; that means that the duplication rate is 52.38 %. The number of unique ERPN values among these 21 items is 19; that means that the duplication rate is 9.52 %. Note that the two duplicate ERPN values are actually caused by the same combinations of S, O, and D. Nevertheless, the result shows that the ERPN method can reduce the problem of high duplication rate.

(2) The ERPN method can carry out more accurate risk ranking.
Based on Table 11, it shows that the RPN values of item No. 7 with an (S, O, D) combination of (9, 2, 2) and No. 15 with an (S, O, D) combination of (3, 3, 4) are both 36. Using the DEA approach, the efficiency scores of items No. 7 and No. 15 are 0.8333 and 0.7857, respectively. This implies that items No. 7 and 15 have the same priority according to the conventional RPN method, while

Table 11 Comparison of RPN, DEA, and ERPN approach

No.	Failure mode	RPN	DEA Score	ERPN	Ranking RPN	Ranking DEA	Ranking ERPN
1	Seizure	24	1.0000	6591	14	13	10
2	Breakage	24	1.0000	6591	14	13	10
3	Structural failure	64	0.6250	6651	10	6	9
4	Loss of output	320	0.4783	13365	2	3	5
5	Auto shutdown	288	0.4310	8019	3	2	6
6	Shaft breakage	16	1.0000	6573	19	13	13
7	Shaft seizure	36	0.8333	19701	12	12	4
8	Gearbox seizure	12	1.0000	111	20	13	19
9	Hydraulic failure	18	1.0000	63	18	13	21
10	Prop. blade failure	8	1.0000	93	21	13	20
11	No start air press.	24	1.0000	117	14	13	18
12	Generator fail	189	0.6667	21897	4	8	2
13	Complete loss	144	0.6667	7317	7	8	7
14	Complete loss	84	0.6250	2295	9	6	15
15	Loss of output	36	0.7857	135	12	11	17
16	Loss of output	24	1.0000	6591	14	13	10
17	Contamination	160	0.5102	6885	6	5	8
18	No fuel to M/E	98	0.5000	4383	8	4	14
19	No cooling water	56	1.0000	2277	11	13	16
20	System loss	648	0.3165	45927	1	1	1
21	Loss of pressure	162	0.6667	20439	5	8	3

using the DEA approach, item No. 15 has a higher priority than item No. 7. However, by the ERPN method, item No. 7 has a higher priority compared with No. 15. In fact, item No. 7 has a quite larger rate on severity than item No. 15; thus, it should be more reasonable to receive a higher priority than item No. 15 in taking corrective actions. This example indicates that the ERPN method we proposed can carry out a more accurate risk ranking for evaluating the orderings of failure modes.

From the above analysis, among the conventional RPN method, DEA approach, and the proposed ERPN method, the proposed ERPN method can not only achieve a more reasonable, accurate risk ranking for failure modes in FMEA but also reduce the high duplication rate problem found in the conventional RPN method.

Numerical verification

According to the conventional RPN method, the three parameters S, O, and D are assumed to be equally weighted with respect to one another. It neglects the relative importance among the three parameters and thus may not be flexible enough in practical application of FMEA. In this section, a real case of PFMEA drawn from a mechanical factory in Taiwan is used to illustrate the application of the proposed ERPN method. This example illustrates that the ERPN method can be applied to the case where different risk factors have different importance to decision-makers.

Case description

This case study is regarding the inlet plate manufactured via powder metallurgy by a mechanical factory located in Taiwan. This company has been in business for many years; it is not just a production facility and also has its own independent technology development team. All the products produced by the company are widely used in industries all over the world. The inlet plate of this case regulates the fluid displacement per revolution of a hydraulic pump used in automobiles engines, and it is shown in Fig. 5. A PFMEA was carried out to improve the manufacturing process. The resulting PFMEA table is summarized in Table 12. The decision-maker assigned the relative weights of S, O, and D as 0.4, 0.35, and 0.25, respectively.

The proposed ERPN method

The relative importance weights of S, O and D are obtained by FMEA team members based on their judgment.

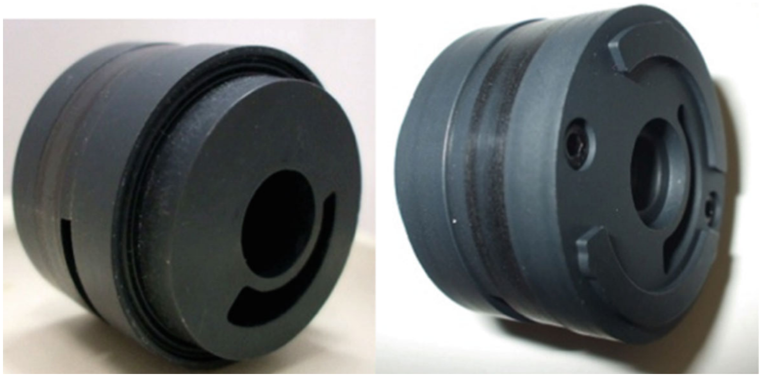

Fig. 5 Inlet plate

Table 12 The PFMEA for inlet plate

No.	Process function/requirements	Potential failure mode	Potential effects of failure	*S*	*O*	*D*
1	Premix powder	Unstable apparent density and flow rate	Unstable filling during compacting	5	2	6
2	Premix powder	Unstable flow rate	Unstable filling during compacting	5	2	6
3	Premix powder	Wrong powder used	Effect function	6	1	7
4	Compacting	Damage of the tool	Can not compact the parts	6	1	3
5	Compacting	Damage of the tool	Can not compact the parts	6	1	3
6	Compacting	Damage of the tool	Can not compact the parts	6	1	3
7	Compacting	Damage	Out of function	6	2	7
8	Compacting	Crack	Out of function	6	2	7
9	Compacting	Crack	Out of function	6	2	7
10	Compacting	Unstable weight	Out of function	5	3	3
11	Compacting	Unstable weight	Out of function	5	2	5
12	Compacting	Length out of spec.	Effect grinding process	5	2	5
13	Compacting	Length out of spec.	Effect grinding process	5	2	5
14	Compacting	Depth out of spec.	Effect assembly	5	2	5
15	Compacting	Sectioned density out of spec.	Out of function	4	3	5
16	Compacting	Sectioned density out of spec.	Out of function	4	3	5
17	Compacting	Position	Effect tapping	4	5	3
18	Compacting	Without label	Can not to retrace	4	2	6
19	Sintering	Color change	Poor appearance	6	1	7
20	Sintering	Damage	Poor function	6	2	7
21	Sintering	O.D. out of spec	Effect assembly	7	2	6
22	Sintering	I.D. out of spec.	Out of function	7	2	2
23	Sintering	Improper hardness	Out of function	5	2	2
24	Sintering	Automatic temperature test is failure	Can not get real temperature; affects the dimension and hardness	6	2	2
25	Sintering	Position	Effect tapping	4	5	2
26	Sintering	Without label	Can not retrace	4	2	5
27	Tapping	Damage	Poor function	6	2	2
28	Tapping	Screw diameter is too small	Effect assembly	5	2	2
29	Tapping	Depth out of spec.	Effect assembly	5	3	2
30	Tapping	Profile out of spec.	Effect assembly	5	3	3
31	Tapping	Without label	Can not retrace	4	2	3
32	Grinding	Damages	Out of function	6	2	2
33	Grinding	Length out of spec.	Effect assembly	5	2	2
34	Grinding	Length out of spec.	Effect assembly	5	2	2

Table 12 continued

No.	Process function/requirements	Potential failure mode	Potential effects of failure	S	O	D
35	Grinding	Parallelism out of spec.	Out of function	5	2	2
36	Grinding	Flatness out of spec.	Out of function	7	2	2
37	Grinding	Roughness out of spec.	Out of function	6	2	2
38	Grinding	Rust	Out of function	6	2	2
39	Grinding	Without label	Can not retrace	4	2	6
40	Brushing	Burrs and dents	Out of function	6	2	7
41	Brushing	Without label	Can not retrace	4	2	6
42	Steam treatment	Rust	Out of function	6	2	7
43	Steam treatment	O.D. out of spec.	Effect assembly	7	2	6
44	Steam treatment	I.D. out of spec.	Out of function	7	2	6
45	Steam treatment	Improper hardness	Out of function	5	2	6
46	Steam treatment	Thickness of steam oxide out of spec	Out of function	5	2	6
47	Steam treatment	Roughness out of spec.	Out of function	6	2	6
48	Steam treatment	Without label	Can not retrace	4	2	6
49	Q.C.	Failure material out going	Production shut down	6	2	6
50	Oil spray	Too much oil	Improper appearance	4	2	7
51	Oil spray	Mixing in different oil	Out of function	6	2	4
52	Oil spray	Cleanliness out of spec.	Out of function	7	2	5
53	Packaging/labeling	Rust	Out of function	6	2	7
54	Packaging/labeling	Dirty, slag	Out of function	6	2	7
55	Packaging/labeling	Without label or wrong data	Can not retrace	4	2	7

Using Eq. (2) while letting $W_s = 0.4$, $W_o = 0.35$, and $W_d = 0.25$, the ERPN values and the resulting ranking are organized in Table 13.

As the same with the RPN values, a failure mode with a higher ERPN value is assumed to be more important and demands higher priority for corrective action than those with lower ERPN values. As a result, the risk ranking is based on their ERPN values. According to Table 13, items No. 20 and No. 21 with different (S, O, D) combinations of (6, 2, 7) and (7, 2, 6), respectively, have the same PRN values of 84. However, using the ERPN method, item No. 21 has a higher priority compared with No. 20; the severity has a higher weight than the detection in this case. This example indicates that the ERPN method can be implemented in the case where different risk factors have different importance to decision-makers, while the conventional RPN method could not. Considering the relative importance among the three parameters S, O, and D, the ERPN method seems to be more practical in the application of FMEA.

Conclusion

A new method named ERPN is developed in this study to improve some of the problems found in the conventional RPN method in FMEA. Different from those approaches found in the literature that were also developed to improve the conventional RPN method, the ERPN proposed in this study is very easy to apply. This method used "Microsoft Office Excel" tool to make the calculation, which does not require other computer software to obtain the ranking result. An application of FMEA on a fishing vessel case (Pillay and Wang 2003) is presented to demonstrate the effectiveness of the new ERPN method. Other than the conventional RPN method, DEA (Chang and Sun 2009) is also applied to the fishing vessel case. The analysis of results shows that the proposed ERPN method can solve the shortcomings of the conventional RPN method, such as the high duplication rate problem. It can also provide an effective and easy way to identify the priority of failure modes. Another PFMEA case on an inlet plate drawn from a mechanical factory located in Taiwan is used to demonstrate that the ERPN method is capable of taking the relative importance among the parameters S, O, and Dinto consideration.

In summary, the advantages of the proposed ERPN method are as follows:

(1) The new method ERPN uses a simple addition function to the exponential form of S, O, and D to substitute the multiplication function used in the conventional RPN method. The problem of measurement scales found in the conventional RPN is resolved this way.

Table 13 PFMEA for the inlet plate case by ERPN and RPN

No.	*S*	*O*	*D*	RPN	RPN ranking	ERPN	ERPN ranking
1	5	2	6	60	22	16.3538	28
2	5	2	6	60	22	16.3538	28
3	6	1	7	42	51	22.2740	18
4	6	1	3	18	53	17.7150	25
5	6	1	3	18	53	17.7150	25
6	6	1	3	18	53	17.7150	25
7	6	2	7	84	1	22.9628	7
8	6	2	7	84	1	22.9628	7
9	6	2	7	84	1	22.9628	7
10	5	3	3	45	50	14.4489	47
11	5	2	5	50	35	15.1059	36
12	5	2	5	50	35	15.1059	36
13	5	2	5	50	35	15.1059	36
14	5	2	5	50	35	15.1059	36
15	4	3	5	60	22	12.9172	54
16	4	3	5	60	22	12.9172	54
17	4	5	3	60	22	14.9176	43
18	4	2	6	48	42	13.1534	48
19	6	1	7	42	51	22.2740	18
20	6	2	7	84	1	22.9628	7
21	7	2	6	84	1	29.0278	1
22	7	2	6	84	1	29.0278	1
23	5	2	6	60	22	16.3538	28
24	6	2	4	48	42	19.1243	23
25	4	5	3	60	22	14.9176	43
26	4	2	6	48	42	13.1534	48
27	6	2	7	84	1	22.9628	7
28	5	2	6	60	22	16.3538	28
29	5	3	5	75	16	16.1176	34
30	5	3	5	75	16	16.1176	34
31	4	2	6	48	42	13.1534	48
32	6	2	7	84	1	22.9628	7
33	5	2	5	50	35	15.1059	36
34	5	2	5	50	35	15.1059	36
35	5	2	5	50	35	15.1059	36
36	7	2	5	70	20	27.7799	5
37	6	2	5	60	22	20.0725	22
38	6	2	7	84	1	22.9628	7
39	4	2	6	48	42	13.1534	48
40	6	2	7	84	1	22.9628	7
41	4	2	6	48	42	13.1534	48
42	6	2	7	84	1	22.9628	7
43	7	2	6	84	1	29.0278	1
44	7	2	6	84	1	29.0278	1
45	5	2	6	60	22	16.3538	28
46	5	2	6	60	22	16.3538	28
47	6	2	6	72	18	21.3204	20

Table 13 continued

No.	*S*	*O*	*D*	RPN	RPN ranking	ERPN	ERPN ranking
48	4	2	6	48	42	13.1534	48
49	6	2	6	72	18	21.3204	20
50	4	2	7	56	33	14.7957	45
51	6	2	4	48	42	19.1243	23
52	7	2	5	70	20	27.7799	5
53	6	2	7	84	1	22.9628	7
54	6	2	7	84	1	22.9628	7
55	4	2	7	56	33	14.7957	45

(2) To enhance the risk evaluation capability of FMEA, the proposed ERPN method is able to generate fewer duplicate values than what the conventional RPN method does.

(3) The ERPN method offers an easier way to prioritize the failure modes in a system than any other approaches found in the literature.

Acknowledgments The author would like to express his sincerest gratitude to the anonymous referees for providing very helpful comments and suggestions which led to an improvement of the article. This work was supported in part by the National Science Council of the Republic of China under Contract No. NSC 99-2410-H-145-001 and NSC 101-2410-H-145-001.

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