A new fuzzy-dynamic risk and reliability assessment

Majid Vaziri Sarashk[a*], Sohrab Khanmohammadi[b] and Mahmood Alborzi[a]

[a]Department of Management and Economy, Islamic Azad University, Science and Research Branch, Tehran, Iran
[b]Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

C H R O N I C L E	A B S T R A C T
	The purpose of this article is to consider system safety and reliability analysts to evaluate the risk associated with item failure modes. The factors considered in traditional failure mode and effect analysis (FMEA) for risk assessment are frequency of occurrence (O), severity (S) and detectability (D) of an item failure mode. Because of the subjective, qualitative and dynamic nature of the information and to make the analysis more consistent and logical, an approach using fuzzy logic and system dynamics methodology is proposed. In the proposed approach, severity is replaced by dependency parameter then, these parameters are represented as members of a fuzzy set fuzzified by using appropriate membership functions and they are evaluated in fuzzy inference engine, which makes use of well-defined rule base and fuzzy logic operations to determine the value of parameters related to system's transfer functions. The fuzzy conclusion is then defuzzified to get transfer function for risk and failure rate. The applicability of the proposed approach is investigated with the help of an illustrative case study from the automotive industry.

1. Introduction

Failure mode and effect analysis (FMEA) is an important technique used to detect and to eliminate known or potential failures to enhance the reliability and safety of complex systems and it is intended to provide information for making appropriate risk management decisions. In order to analyze a specific product or system, a cross-functional team needs to be established for carrying out FMEA first. The first step in FMEA is to detect all potential failure modes of the products using systematic brainstorming. A critical analysis is then executed on these failure modes to detect the risk factors including occurrence (O), severity(S) and detection (D). The purpose of FMEA is to rank the failure modes of the product or system in order to assign the limited resources to the most important risk factors.

* Corresponding author.
E-mail addresses: m_sarashk@yahoo.com (M. Vaziri Sarashk)

Normally, the prioritization of failure modes for corrective actions is prepared through the risk priority number (RPN) obtained by detecting the multiplication of the O, S and D of a failure as follows,

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

where O represents the probability of the failure, S denotes the severity of the failure, and D is determines the probability of not detecting the failure. For obtaining the RPN of a potential failure mode, we evaluate the three risk factors based on the 10-point scale. The higher the RPN implies the bigger product/system reliability. With respect to the scores of RPNs, the failure modes can be ranked and then proper actions will be preferentially taken on the high-risk failure modes. RPNs should be recalculated after making some corrections to see whether the risks are lowered or not. We also make sure to check the efficiency of the corrective action for each failure mode. However, the conventional RPN method has been criticized extensively in the literature for a variety of reasons explained in next section. With respect to this review, the innovation of this study is more released.

2. Literature Review

FMEA, first was developed as a formal design methodology in the 1960s by the aerospace industry (Pelaez & Bowles, 1996) and it has proven to be a useful and powerful tool in assessing potential failures and preventing unwanted incidents (Sankar & prabhu, 2001). FMEA is an analysis technique to define, to identify and to eliminate known and/or potential failures, problems, errors and so on from system, design, process and/or service before they reach the customer (Stamatis, 2003). When it is used for a criticality analysis, it is also referred to as failure mode, effects and criticality analysis (FMECA). The primary objective of FMEA is to identify potential failure modes, to evaluate the causes and effects of various component failure modes, and to detect what could eliminate or reduce the chance of failure. The results of the analysis can help analysts identify and correct the failure modes, which have special impact on the system and to improve its performance during the stages of design and production. FMEA has been extensively used in a wide range of industries, including aerospace, automotive, nuclear, electronics, chemical, mechanical and medical technologies industries (Chang et al., 2011; Chin et al., 2008; Sharma & Sharma, 2010).

Traditionally, risk assessment in FMEA is performed by developing a risk priority number (RPN). Nevertheless, the crisp RPN method incorporates some important weaknesses when FMEA is applied for some real-world problems. The major shortcomings of FMEA are:

1-The relative importance of different components of O, S and D is not taken into account.

2-Different combinations of O, S and D may produce precisely the same value of RPN, but their hidden risk implications may be totally different.

3- It is often a tedious task to evaluate all three risk factors.

4- The mathematical formula for calculating RPN is under question.

5- The conversion of scores is different for the three risk factors.

6- The RPN cannot be applied to measure the effectiveness of corrective actions.

7- RPNs are not continuous with many holes.

8- Interdependencies among various failure modes and effects are not taken into account.

9- The mathematical form adopted for calculating the RPN is strongly sensitive to variations in risk factor evaluations.

10- The RPN elements have several duplicated numbers.

11- The RPN considers only three risk factors mainly in terms of safety.

Therefore, many alternative approaches have been suggested in the literature to resolve some of the shortcomings of the traditional RPN method and to implement FMEA into real-world circumstance, more efficiently. This section provides a review of those academic works trying to tackle with problems in the traditional RPN method and to classify the existing literature by the approaches implemented. Furthermore, those articles that report on a method or technique that specifically aims at overcoming some of the drawbacks of the traditional FMEA. This implies that related articles merely explaining the FMEA process or applying the traditional FMEA have not been included.

The methods used in the literature are divided into five main categories presented in Table 1. This review not only provides evidence that some alternate approaches are better than the traditional RPN approach, but also aids the researchers and risk analysts in implementing the FMEA, more effectively. The results are derived from applying FMEA directly influence on reliability, while this only theoretically is pointed by researchers and in practical scope has been not surveyed. Doing these as the most important problems in field of system reliability is challenging issue in this study.

Table 1
Classification of risk evaluation methods in FMEA

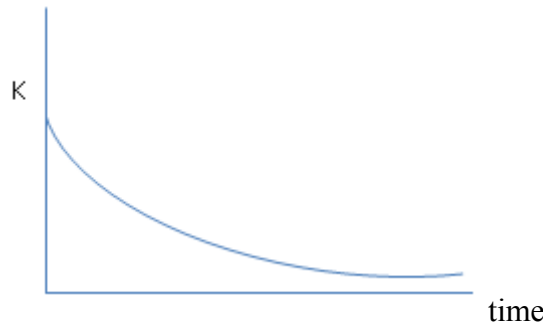| Categories	Approaches	Literature
MCDM	ME-MCDM; Evidence theory; AHP/ANP; Fuzzy TOPSIS; Grey theory; DEMATEL; Intuitionistic fuzzy set; Ranking technique VIKOR	Franceschini & Galetto, 2004, 2005; Chin et al., 2009b; Chin et al., 2011; Braglia et al., 2003b; Seyed-Hosseini et al., 2006; Chang et al., 2010; Liu et al., 2012
Mathematical programming	Linear programming; DEA/Fuzzy DEA	Wang et al., 2009b; Garcia et al., 2005
Artificial intelligence	Rule-base system; Fuzzy rule-base system; Fuzzy ART algorithm; Fuzzy cognitive map	Sankar & prabhu, 2001; Pelaez & Bowles, 1996; Guimaraes et al., 2004, 2006, 2007
Integrated approaches	Fuzzy AHP-Fuzzy rule-base system WLSM-MOI-partial ranking method OWGA operator-DEMATEL Fuzzy OWA operator-DEMATEL IFS-DEMATEL 2-tuple-OWA operator FER-Grey theory Fuzzy AHP-Fuzzy TOPSIS ISM-ANP-UPN	Chang et al., 1999, 2001; Pillay & Wang, 2003; Xu et al., 2002
Other approaches	Kano model Probability theory	Shahin, 2004; Shahin & Zairi, 2009; Sant'Anna & Sant'Anna, 2008; Ben-Daya & Raouf, 1996; Grosh, 1982

3. Suggested methodology

The methodology used in this study is composed of two separable sections. The first section is associated with system's transfer functions and the second section describes how to calculate the parameters.

3.1. Estimation of transfer function (TF)

The problem of system's identifying is concentrated on determining its transfer function (TF), which is the operation that a system does on its inputs to receive output. If TF is determined, then output (system's response) with respect to various inputs by using of convolution integral and properties of Laplace transform is obtained, i.e. $X(t) = \int_0^t U(\tau)G(t-\tau)\, d\tau = U(s)G(s)$. On the other words, if

input is unit step and TF is determined at frequency domain then Laplace transform of output will be: U(s) G(s) =X(s). Inverse Laplace transform of above equation is equivalent to X (t), where X (t) is system's step response and shows the state of system at every instant of time. As an example, there are many cases where increasing time results in failures. Therefore, risk change at start point (O) is maximum and when time increases it trends to zero. Fig. 1 shows details of such system.

Fig. 1. Time response of risk change, w.r.t time

Systems with such behavior shown in Fig. 1 have TF in form of $G(s) = \frac{k\tau s}{1+\tau s}$ where k is a parameter, which represents velocity of cause's unit impact, τ is a parameter represents effecting time (equivalent with system's time constant) and s is Laplace variable, i.e. s= j +σ ω. Because input is unit step and its Laplace is $\frac{1}{s}$ so Laplace transform of output is as follows,

$$X(s) = \frac{1}{s} \times \frac{k\tau s}{1+\tau s} = \frac{k\tau}{1+\tau s}. \tag{2}$$

Therefore, the inverse Laplace transform is as follows,

$$X(t) = ke^{-\frac{t}{\tau}}. \tag{3}$$

Normalized behavior is: $\frac{X(t)}{k} = e^{-\frac{t}{\tau}}$ and Table 2 presents states of the system.

Table 2
Calculating states of the system

$\frac{t}{\tau}$	0	1	2	3	4	4.6	5	…….	∞
$\frac{x(t)}{k}$	1	.368	.135	.05	.18	.01	.007	…..	0

According to Table 2, when $\frac{t}{\tau} \geq 4.6$, the system reaches 99% of its steady state. This time is named settling time to one percent of steady state. So, time to failure (T) is assumed as $T = 5\tau$. Using similar procedure, time response of failure rate is calculated. Transfer function for failure rate function is as follows,

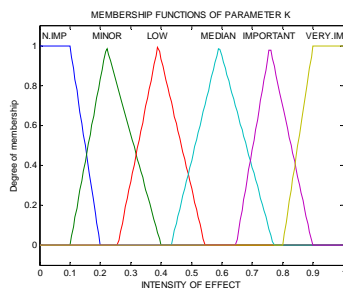$$G(s) = \frac{k\omega_n{}^2}{s^2 + 2\zeta\omega_n s + \omega_n{}^2} \tag{4}$$

where K is the average that system finally follows and is representing system's steady state response, i.e. $k = \frac{1}{T}$ such that $T = 5\,\tau$, ζ is damping ratio that is determined based on parameters of risk controlling signal obtained in previous stage (k & τ). In addition, ω_n is natural frequency of system that is equal with: $\omega_n = \frac{2\pi}{T}$. Parameters of the transfer functions are calculated by using fuzzy inference systems (FIS) explained, next.
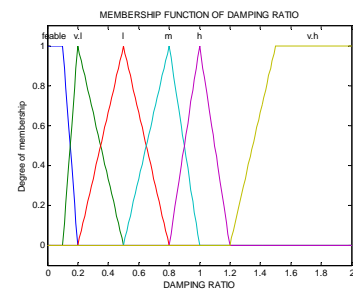
3.2. Fuzzy assessment methodology

In this study, we use three FIS, where the first FIS and the second one have similar inputs, i.e. O, D and Dependency. The output of *FIS1* is *K* and for the *FIS2* is τ used to for risk's transfer function. In next stage, K & τ will be as inputs of FIS3 such that the output is ζ. In every stage, inputs are fuzzified using appropriate membership functions to determine degree of membership in each input class. The resulting fuzzy inputs are evaluated in fuzzy inference engine, which makes use of well-defined rule base consisting of if-then rules and fuzzy logic operations to determine output level of the every FIS. The fuzzy conclusion is then defuzzified to get crisp values for outputs at various FIS levels so that transfer functions related to quantities (risk and failure rate) can be evaluated, accordingly. Finally, the unit step responses of the systems are calculated by using of convolution integral and properties of Laplace transform explained in section 3.1. The fuzzy linguistic assessment model was developed using toolbox platform of MATLAB 6.5 R.13. To represent input and output variables in FIS, graphically, triangular and trapezoidal membership functions (Figs. 2-4) are used, which are consistent with the definitions of the variables used in the study as depicted in Tables 3-6.

Fig. 2. Fuzzy membership functions for inputs of FIS1 & FIS2

Fig. 3. Fuzzy membership functions for outputs of FIS1 & FIS2

Fig. 4. Fuzzy membership functions for output of FIS3

The descriptive terms explaining the dependency membership functions are Feeble, Low, Moderate, High and very high.

Table 3
Scales used to measure probability of failure occurrence

Descriptive assessment of probability of failure	Mean time between failures	Score	Occurrence rate(%)
Feeble	>5 years	1	<0.01
Low	2-5 years	2-3	0.01- 0.1
Moderate	1-2 years	4-6	0.1-0.5
High	3-6 months	7-8	0.5 – 1
Very high	<3 months	9-10	>1

Table 4
Scales used to determine probability of non-detection

Non-detection	Score	Likelihood of non-detection (%)
Feeble	1	0 - 5
Low	2	6 - 15
	3	16 - 25
Moderate	4	26 – 35
	5	36 – 45
	6	46 - 55
High	7	56 – 65
	8	66 – 75
	9	76 - 85
Very high	10	86 - 100

Table 5
Scales used for parameters k & τ assessment

Rank no.	Effect on risk change (time & magnitude effect)	Meaning
0-0.1	Not important (N.IMP)	Less MTTR>1hour
0.11-0.25	Minor (M)	MTTR >1day
0.26-0.50	L	MTTR 1-4 days
0.51-0.60	Median (ME)	MTTR4-8days
0.61-0.80	Important (IMP)	External intervention for repairs
0.81-1	Very important (V.IMP)	Line shut down or production loss

Table 6
Scales used for damping ratio assessment

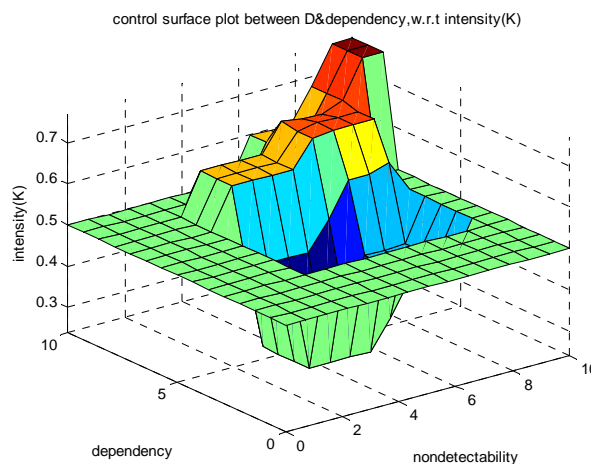| Descriptive assessment of damping ratio	Time to failure	Score
V.L	Very short	0 – 0.2
L	Short	0.21 – 0.8
M	Median	0.81 – 1.4
V .H	Long	1.2-2.0

4. Case study

To demonstrate the application of proposed approach for implementing the proposed method, a case study from an industrial firm is considered. There are many functional units in this case, while it is decided to conduct failure mode analysis of the main functioning unit i.e. piston's seat exfoliation operation. Two potential failure modes are released: 1- Increasing seat's diagonal and 2- Decreasing distance from piston's seat to piston's bottom. The cause of first mode is unregulated tool and for second is wobbling snip in system.

For the first cause input data is obtained: O=8, D=9 and Dependency=6

For the second cause, data is obtained: O=5, D=3 and Dependency=4

By using of two fuzzy inference systems, parameters of TF for the first cause will be K=.768 and τ=.24. In addition, parameters of TF for the second cause will be K=.5 and τ=.5. The mapping of inputs to the outputs through the linguistic if-then rules adopted in the study is represented using a control surface plot (Fig. 5). Since in the study three inputs have been used, so the surface plot can be represented with a group of surfaces keeping one of the input variables stable. In this study, one figure is shown for example. The rest of figures also have similar behaviors.

Fig. 5. Control surface plot between (D) & (Dep), w.r.t K

These three-dimensional plots represent very well the systems used to in this study. Obtained values for K & τ are used as the inputs of the third FIS. For the first cause is calculated ζ = .268 and for the second cause ζ=.536. Then, by using of the procedure detailed in the section 3-1 failure rate function for the first failure will be:

$$\lambda(t) = .83\{1 - e^{-1.41t}cos5.04t + .28sin5.04t\},$$ (5)

and for the second failure is as follows,
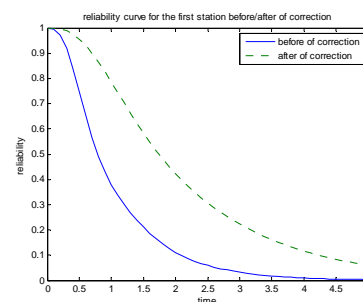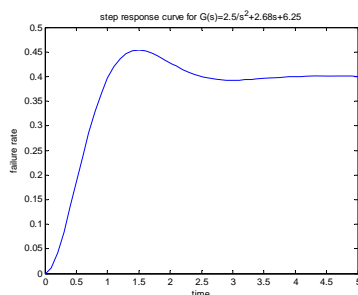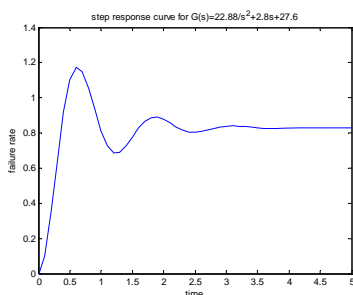
$$\lambda(t) = .4\{1 - e^{-1.34t}cos2.1t + .64sin2.1t\}$$ (6)

The corresponding figures for calculated λ(t) s is shown in Fig. 6 and Fig. 7, respectively. It is pointed out that, this special case is composed of two failure modes, so failure rate for the corresponding operation is summation of two functions calculated before, i.e.

$$\lambda_s(t) = \lambda_1(t) + \lambda_2(t)$$ (7)

On the other hand, relation between failure rate and reliability functions is:

$$R(t) = e^{-\int_0^T \lambda(t)dt}$$ (8)

Therefore, in this case reliability is as shown in Fig. 8.

Fig. 6. Failure rate function for the first failure

Fig. 7. Failure rate function for the second failure

Fig. 8. The impact of corrective action (feedback) on reliability

With respect to Fig. 6 and Fig. 7, because of lower settling time for the first cause, it was decided that first cause selected for corrective actions. Reliability after of correction is as shown in figure 8 by dashed line (--). It is concluded from Fig. 8 that in every instant of time reliability after correction is bigger than before correction. This is due to feedback factor in system.

5. Conclusions

We have presented a new method for risk assessment in FMEA method based on fuzzy technique. The proposed study of this paper has tried to use linguistic numbers to handle uncertainty associated with different components of FMEA methodology. The proposed study has been implemented for a case study and the results have been discussed. In addition, this study shows that integrating of fuzzy logic-based approach and system dynamics methodology resolve the limitations associated with traditional method for RPN evaluation of failure causes in reliability analysis of system.

Acknowledgement

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