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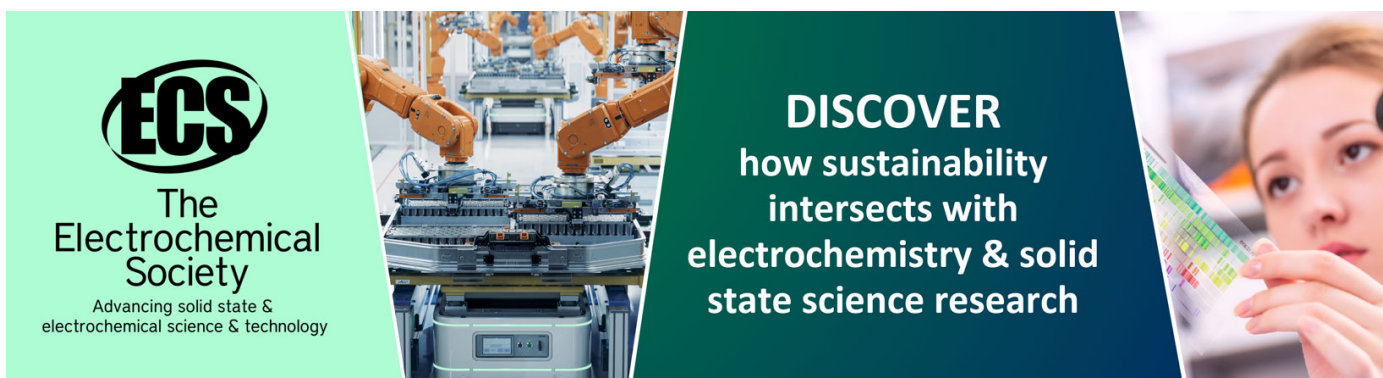
An improved method for risk evaluation in failure modes and effects analysis of CNC lathe

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An improved method for risk evaluation in failure modes and effects analysis of CNC lathe

N Rachieru¹, N Belu¹ and D C Anghel¹

¹University of Pitești, Faculty of Mechanics and Technology, Department of Manufacturing and Industrial Management, 110040 Pitesti, Targu din Vale Street, no. 1, Argeș, Romania

E-mail: nrachieru@yahoo.com

Abstract. Failure mode and effects analysis (FMEA) is one of the most popular reliability analysis tools for identifying, assessing and eliminating potential failure modes in a wide range of industries. In general, failure modes in FMEA are evaluated and ranked through the risk priority number (RPN), which is obtained by the multiplication of crisp values of the risk factors, such as the occurrence (O), severity (S), and detection (D) of each failure mode. However, the crisp RPN method has been criticized to have several deficiencies. In this paper, linguistic variables, expressed in Gaussian, trapezoidal or triangular fuzzy numbers, are used to assess the ratings and weights for the risk factors S, O and D. A new risk assessment system based on the fuzzy set theory and fuzzy rule base theory is to be applied to assess and rank risks associated to failure modes that could appear in the functioning of Turn 55 Lathe CNC. Two case studies have been shown to demonstrate the methodology thus developed. It is illustrated a parallel between the results obtained by the traditional method and fuzzy logic for determining the RPNs. The results show that the proposed approach can reduce duplicated RPN numbers and get a more accurate, reasonable risk assessment. As a result, the stability of product and process can be assured.

1. Introduction

Quality planning is a process that leads to the effectiveness and efficiency of production processes. Correctness of quality planning lies in the fact that the individual stages and operations process should be designed so as to eliminate the possibility of non-compliance. However, in case of their occurrence, a high probability of detection should be ensured [1]. Failure Mode and Effects Analysis (FMEA) is one of the first structured, systematic and proactive techniques used for failure analysis. It is a widely used engineering technique for defining, identifying and eliminating known and/or potential failures, problems, errors and so on from system, design, process, and/or service before they reach the customer [2]. For analysing a specific product or system, a cross-functional expert team should be set up to conduct FMEA first. The first step in FMEA is to identify all possible failure modes of the product or system. Next, critical analysis is performed on the identified failure modes taking into consideration the risk factors: occurrence (O), severity (S), and detection (D). Conventionally, the ranking of failure modes for corrective actions is determined in terms of the risk priority number (RPN), which is the mathematical product of the S, O and D corresponding to the failure modes [3]. That is $RPN = S \times O \times D$, where O is the probability of the failure, S is the severity of the failure, and D is the probability of not detecting the failure. In order to obtain the RPN of a potential failure mode, the traditional FMEA uses an integer scale from 1 to 10 for evaluating the three risk factors. Generally, failure modes with



higher RPN values are considered to be more important and are given higher priorities than those with lower RPN values [4]. However, it suffers from several shortcomings. It has been pointed out that the same RPN can be obtained from different combinations of different sets of S, O and D. Although the same RPN is obtained, the risk can be different and the relative importance of three risk factors is not taken into account. In other words, the risk factors are given to have the equal importance, which may not be the case in many practical applications of FMEA. The three risk factors are mostly difficult to be precisely determined. Much information in FMEA is often uncertain or vague and can be expressed by using linguistic terms such as *likely*, *important* or *very high* and so on [5,6,7,8]. In order to overcome the above shortcomings, a number of approaches have been suggested in the literature to enhance the FMEA methodology, such as grey theory [9], data envelopment analysis (DEA) [10], decision making trial and evaluation laboratory (DEMATEL) [11], Taguchi method, fuzzy logic and Genetic algorithms (GA) [12]. GA can be used to search for solutions difficult to obtain by other conventional methods, in different areas. They can be run on computer or can be accelerated on parallel hardware structures [13].

The aim of proposed paper is to present a new risk assessment system based on fuzzy theory to deal with the risk evaluation problems in FMEA. The paper presents a parallel between the typical and the fuzzy computation of RPNs of failure modes that could appear in the functioning of "Turn 55 Lathe CNC". Fuzzy set theory was initiated by Zadeh in the early 1960s. Fuzzy sets (FS) and fuzzy logic (FL) are powerful mathematical tools for modelling uncertain systems in industry, nature and humanity; and facilitators for common-sense reasoning in decision making in the absence of complete and precise information [8]. The three inputs (S) severity, (O) occurrence and (D) detecting are fuzzyfied and evaluated in a fuzzy inference engine built on a consistent base of IF-THEN rules. The fuzzy output is defuzzyfied to get the crisp value of the RPN that will be used for a more accurate ranking of the potential risks.

2. Application

2.1. Classical FMEA application

In the first part of the study a classical application of Design FMEA has been realized for Turn 55 Lathe CNC. The Concept Turn 55 is a desktop lathe driven by interchangeable CNC control Software running on a commercially available PC. This dual purpose turning center is the ideal solution for training students in further education when large industrial machines are not suitable. Its role in education is defined by its interchangeable control systems.

The evaluation of the failure modes is carried out by scoring the respective risk factors of occurrence, severity, and detection. For this purpose, usually 10-level scales are being used. The failure modes with higher RPNs are assumed to be more important and will be given higher priorities for correction. It is presented the failure with highest RPN values (54 and 72). Some of the data can be seen in table 1.

Table 1. Conventional FMEA for Lathe CNC.

Failure mode	Failure effect (s)	Cause (s)	S	O	D	RPN
F1. Wear of the mechanical components of tool machine	Poor quality of the surface of piece	C1. Overcoming life of the mechanic component	6	4	3	72
F2. Difficult processing (high energy consumption)	Deposition of material on the surface of the face of cutting tool	C2. Improper cutting regime	4	2	5	40
		C3. Electrical component can be damaged	4	2	3	24
F3. Incomplete	Nonconforming parts	C4. Writing error on NC	7	3	2	42

execution of the CNC program		program				
F4. CNC stopping	Cutting tool collision	C5. Errors on NC program	8	2	1	16
		C6. Incorrect installation of the blank on CNC	8	1	2	16
F5. Erosion of date cable	Data from computer are not transmitted to the tool machine	C7. Life cycle overflow	6	3	3	54
F6. Power LED no indication	Cannot determine whether the machine is on or off	C8. Faulty supply	2	2	1	4

2.2. Fuzzy FMEA Application

The fuzzy logic toolbox of Matlab software program has been used in calculating the values of RPN. A model was established for the FMEA technique having 3 inputs and 1 output variable, and given in figure 1. Four categories were associated to each fuzzy set: VL (Very Low), L (Low), M (Moderate) and H (High). The output of the fuzzy system, FRPN, was scaled in the range 0...1000 in order to be compatible with the previous results. The occurrence, severity and not detection values of the failures were identified with the help of expert opinions and by using decision rules determined specifically. The rules were designed to take into account all possible situations. For Fuzzy FMEA application we present two case studies.

2.2.1. Case 1. In this case, for risk factors like severity, occurrence and priority number (RPN), the Gaussian membership function is selected because of its two important properties [14], viz., (i) it can lead to smooth, continuously differentiable hyper surfaces of a fuzzy model; (ii) it facilitates theoretical analysis of a fuzzy system because it is continuously and infinitely differentiable, i.e., it has derivatives of any grade (equation (1)). For Detection risk factor was used Cauchy membership function (generalized bell) (equation (2)).

$$\mu_A(x) = e^{-[x-c]^2/2\sigma^2} \quad (1)$$

$$\mu_A(x) = 1 / \left(1 + \left| \frac{x-c}{a} \right|^{2b} \right) \quad (2)$$

where c and σ parameterize the center and width of the Gaussian membership function, respectively; c represents the membership function center and a determines the membership function width, b a positive real parameter. The membership function for severity and detection are depicted in figure 2 - 3.

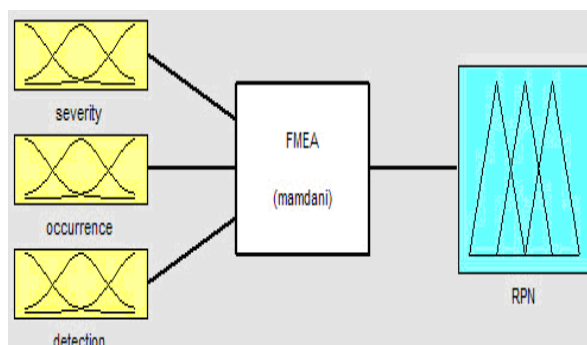


Figure 1. The Fuzzy FMEA model.

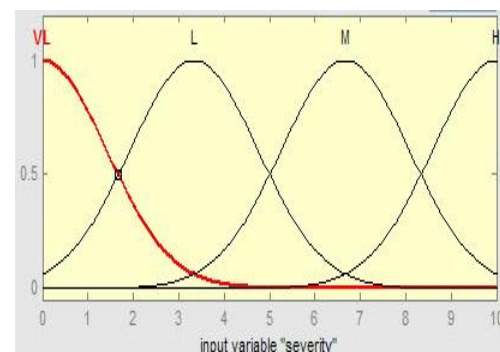


Figure 2. Membership functions for severity.

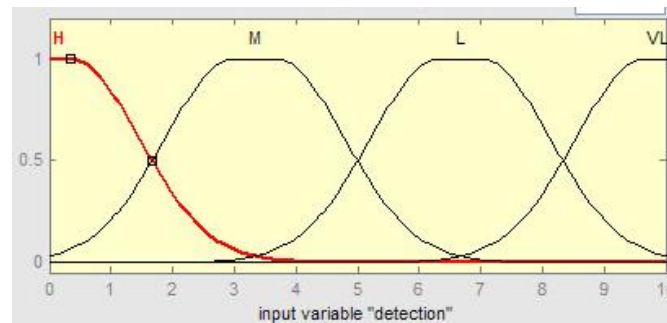


Figure 3. Membership functions for detection.

2.2.1. Case 2. In this case, for risk factors like severity, occurrence and priority number (RPN), the triangular membership function is selected (equation (3)) and for detection risk factor was used trapezoidal membership function (equation (4)). Triangular and trapezoidal fuzzy numbers are the most common used fuzzy numbers both in theory and practice. In fact, triangular fuzzy numbers are special cases of trapezoidal fuzzy numbers. When the two most promising values are the same number, the trapezoidal fuzzy number becomes a triangular fuzzy number. The membership functions are defined respectively as follows [15]:

$$\mu_A(x) = \begin{cases} (x-a)/(b-a), & \text{for } a \leq x \leq b \\ (c-x)/(c-b), & \text{for } b \leq x \leq c \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

$$\mu_A(x) = \begin{cases} (x-a)/(b-a), & \text{for } a \leq x \leq b \\ 1 & \text{for } b \leq x \leq c \\ (d-x)/(d-c) & \text{for } c \leq x \leq d \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

where $a \leq b \leq c \leq d$. The membership function for occurrence, detection and RPN are depicted in figure 4, figure 5 respectively figure 6.

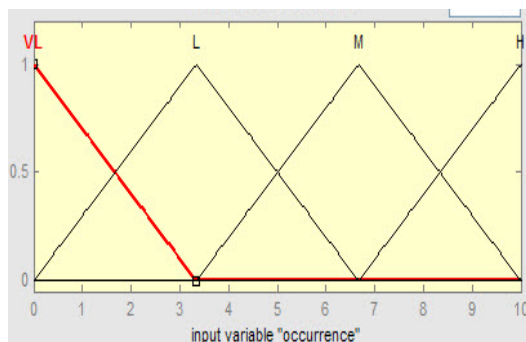


Figure 4. Membership functions for occurrence.

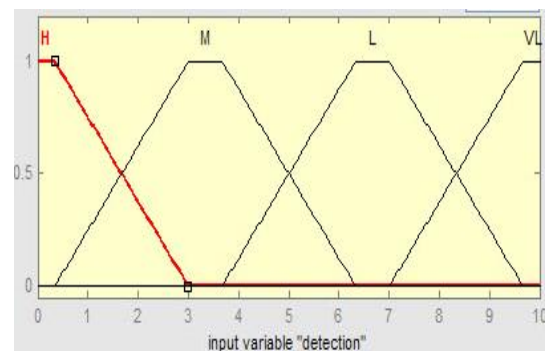


Figure 5. Membership functions for detection.

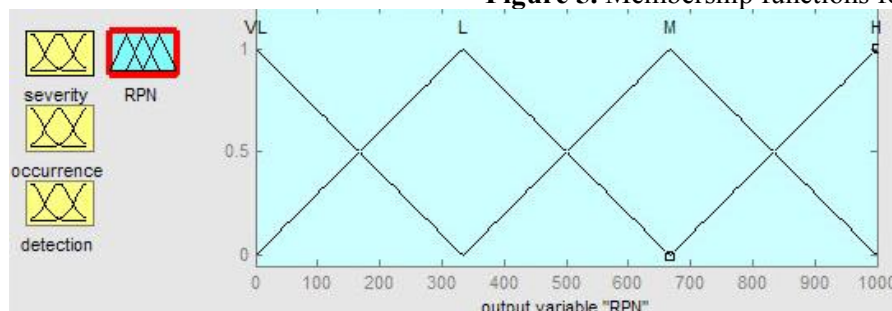


Figure 6. Membership functions for RPN.

The membership function derived from the expert is used to generate the fuzzy rule base. Table 2 presents the inference rules adopted for these applications.

Table 2. Inference rules.

<i>Severity: VL</i>					
FUZZY RPN		<i>Occurrence</i>			
		<i>VL</i>	<i>L</i>	<i>M</i>	<i>H</i>
<i>Detection</i>	<i>VL</i>	VL	VL	VL	L
	<i>L</i>	VL	VL	L	L
	<i>M</i>	VL	L	L	M
	<i>H</i>	L	L	M	M
<i>Severity: M</i>					
FUZZY RPN		<i>Occurrence</i>			
		<i>VL</i>	<i>L</i>	<i>M</i>	<i>H</i>
<i>Detection</i>	<i>VL</i>	VL	L	L	M
	<i>L</i>	L	L	M	M
	<i>M</i>	L	M	M	H
	<i>H</i>	M	M	H	H
<i>Severity: L</i>					
FUZZY RPN		<i>Occurrence</i>			
		<i>VL</i>	<i>L</i>	<i>M</i>	<i>H</i>
<i>Detection</i>	<i>VL</i>	VL	VL	L	L
	<i>L</i>	VL	L	L	M
	<i>M</i>	L	L	M	M
	<i>H</i>	L	M	M	H
<i>Severity: H</i>					
FUZZY RPN		<i>Occurrence</i>			
		<i>VL</i>	<i>L</i>	<i>M</i>	<i>H</i>
<i>Detection</i>	<i>VL</i>	L	L	M	M
	<i>L</i>	L	M	M	H
	<i>M</i>	M	M	H	H
	<i>H</i>	M	H	H	H

A total of 64 fuzzy rules ($4 \times 4 \times 4$) are gathered from domain experts. These fuzzy rules are presented in an If-Then format and an example of two fuzzy rules is shown in figure 7.

Rule 1: If *Severity* is **Very Low**, *Occurrence* is **High** and *Detection* is **Moderate** then RPN is **Moderate**
 Rule 2: If *Severity* is **Low**, *Occurrence* is **High** and *Detection* is **Moderate** then RPN is **High**
 Rule 3: If *Severity* is **Moderate**, *Occurrence* is **High** and *Detection* is **Moderate** then RPN is **High**
 Rule 4: If *Severity* is **High**, *Occurrence* is **Moderate** and *Detection* is **Moderate** then RPN is **High**

Figure 7. An example of four fuzzy rules.

Figure 8, presents the surface viewer a three-dimensional curve that represents the mapping from occurrence and severity.

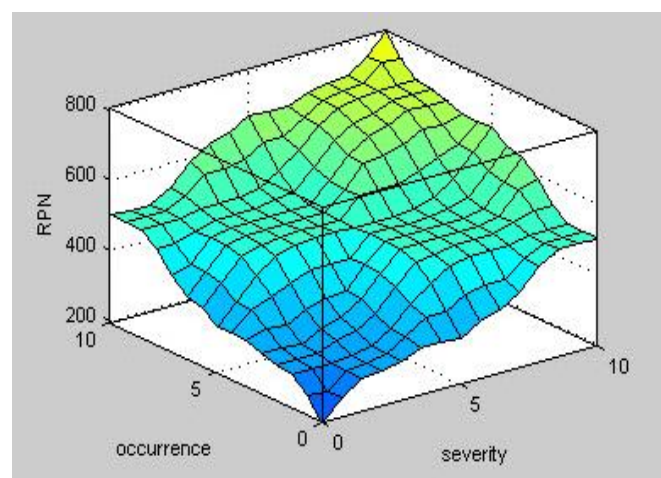


Figure 8. Surface viewer.

Minimum function was used in order to implement AND method and implication. Maximum function was used in order to implement OR method and aggregation. An important step in fuzzy modeling and fuzzy multi-criteria decision-making is the defuzzification task which transforms a fuzzy number into a crisp value.

Various techniques for this transformation are available, including the mean of maxima (MOM), center of area (COA), center of gravity (COG) or α - cut.

Different defuzzification methods extract different levels of information. Defuzzification is performed according to the membership function of the output variable. For our study the center of area was chosen for defuzzification. It finds the point where a vertical line would slice the aggregate set into two equal masses. The fuzzy logic system was simulated using MATLAB-SIMULINK.

As to the types of failure, the fuzzy RPN values provided in the model are given in table 3 in comparison with the RPN values of classical FMEA.

Table 3. Prioritization of failure modes.

Failure mode	Failure cause	RPN	Rank 1	Fuzzy RPN1	Rank 2	Fuzzy RPN2	Rank 3
F1	C1	72	1	598	3	586	3
F2	C2	40	5	393	8	399	8
	C3	24	6	412	7	423	7
F3	C4	42	4	615	1	619	1
F4	C5	16	7	601	2	591	2
	C6	16	8	478	6	492	6
F5	C7	54	2	527	4	513	4
F6	C8	4	3	527	5	513	5

3. Conclusions

Risk evaluation in FMEA, due to its intrinsic ambiguity and difficult formalization, is a particular complex task, usually accomplished by FMEA team members' experience and intuition. In this paper, a new risk evaluation methodology for FMEA based on fuzzy theory was proposed to deal with the risk factors and identify the most serious failure modes for corrective actions.

The results obtained by fuzzy inference in two case studies provide a hierarchy of potential risks that differs from the ranking established by classical FMEA. Also, two fuzzy proposed methodologies offer the same hierarchy of potential risks, although the RPNs value differs. The fuzzy inference does not allow identical values of RPNs to appear for different sets of risk factors. According to the analysis of the results produced by the traditional FMEA and the fuzzy FMEA methods, this research shows that a more accurate, reasonable ranking can be achieved by the application of FMEA based on fuzzy theory. More risk factors can be included if necessary. For further research, the results of our study can be compared with that of other results using Genetic Algorithm technique and Taguchi method.

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