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FUZZY LOGIC IN RISK ASSESSMENT OF PRODUCTION MACHINES FAILURE IN FORMING AND ASSEMBLY PROCESSES

The article presents the application of fuzzy logic to risk assessment in assembly and forming production processes. The fuzzy FMEA method was used, enabling the assessment of risk parameters based on expert opinions. This resulted in the development of a system that allows for greater flexibility and increased resistance to errors associated with human factors, enabling risk assessment through the use of linguistic variables. This allows organisations to analyse and manage risk, improving the efficiency and safety of their operations. This article presents an analysis of the benefits of using fuzzy logic in risk assessment in production in conjunction with the FMEA method, which is one of the most widely used risk assessment methods in industry. It discusses how fuzzy logic can help capture uncertainties in production processes and provide a more flexible framework for their evaluation. A case study is also presented, in which fuzzy logic was applied to risk assessment, highlighting the benefits it brings to production efficiency and safety.

1. INTRODUCTION

The manufacturing industry, like other processes, is inherently tied to constantly occurring situations involving uncertainty and risk, impacting both external conditions and the actions taken within the industry. In production and distribution, these issues encompass everything from disruptions in the supply chain, through uncertainties in the market, both global and local, to machine and equipment failures. Engineers face challenges that require quick and effective decision-making in these risky conditions. Traditional risk assessment methods often rely on mathematics and statistics, which might not be sufficient to handle uncertainties of a difficult-to-quantify nature. This is especially true for expert systems where risk assessment is subjective and often defined through linguistic variables. This is where the

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potential for using fuzzy logic comes in. Thanks to its ability to handle ambiguity and imprecision, fuzzy logic is becoming an effective and increasingly preferred tool for risk assessment in manufacturing environments.

Fuzzy logic is a concept introduced by Lotfi Zadeh in the 1960s [1], which allows for graded assessment through the use of linguistic variables, rather than numerical parameter definitions. By applying fuzzy logic to risk assessment, experts can intuitively determine levels of the assessed risk, leading to a reduced susceptibility to errors caused by human factors. They can classify the risk i.e. as low, medium, or high, and, after selecting the appropriate membership function and defining suitable ranges for the specified linguistic variables, along with a rule base that allows the system's inference process to be defined, examine its final output based on fuzzy logic solutions.

2. FUZZY LOGIC IN RISK ASSESSMENT METHODS

The use of fuzzy logic in risk assessment in production systems is becoming increasingly popular among researchers worldwide. This can be confirmed by conducting a basic search in popular databases like ScienceDirect and Scopus (Fig. 1).

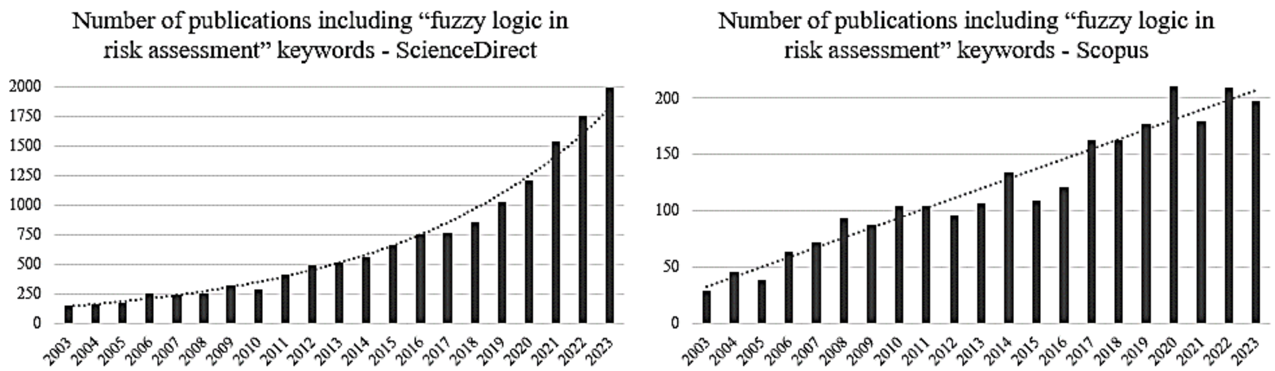


Fig. 1. Number of publications in last 20 years by searching for “fuzzy logic in risk assessment” in ScienceDirect and Scopus databases

In the process of risk assessment, Failure Mode and Effects Analysis (FMEA) is widely used in organisations. It is also recommended by the standards of the International Organization for Standardization, specifically in ISO 31010:2019 Risk Management – Risk assessment techniques [2]. FMEA is a method for identifying and assessing potential failures in the analysed systems and understanding their causes. FMEA is used in many industries as a tool to improve reliability, safety, and efficiency.

FMEA is a method based on expert systems, thus the application of fuzzy set principles in FMEA has gathered significant interest among both the industry and researchers. This approach allows experts to intuitively define risk using linguistic variables, making the risk assessment system more resilient to errors caused by human factors. In the literature, there can be found many examples of applying fuzzy logic in the FMEA method. These are i.e.

using fuzzy logic in FMECA to analyse the reliability of cyber-power grid systems [3], a comparison of traditional and fuzzy FMEA in identifying risks in tests and calibration laboratories [4], in pharmaceutical production process [5], logistic systems failures during COVID-19 pandemic [6], problems with drought and other risk factors affecting the functioning of the agricultural industry [7], hazards that are connected with the underground coal mines [8], the IFF system used in military helicopters [9], collecting data from people by smartphones [10] and many more. Thus, fuzzy FMEA has many applications, due to the universal character of the FMEA method itself. It is the same with assessing the risk associated with the use of production resources, including machinery and equipment. The application of fuzzy set principles in FMEA in various forms when analysing machines can be found, among the others, in reducing the setup time [11], in cost optimization [12] and breakdowns [13].

Despite the fact that fuzzy logic is increasingly used for risk assessment (including fuzzy FMEA), the research gap primarily includes a lack of standardization in applying these methodologies, with only recommendations based on empirical research, the number of which is still limited despite the growing interest in the topic. Another significant aspect is the lack of understanding of fuzzy logic among industry practitioners, which often leads to the abandonment of these solutions despite their benefits. Practitioners are often accustomed to traditional methods, which also generates resistance to implementing innovations.

Fuzzy sets approach is connected with a general approach based on a fuzzy inference system (FIS), which is usually similar regardless of the problem (Fig. 2).

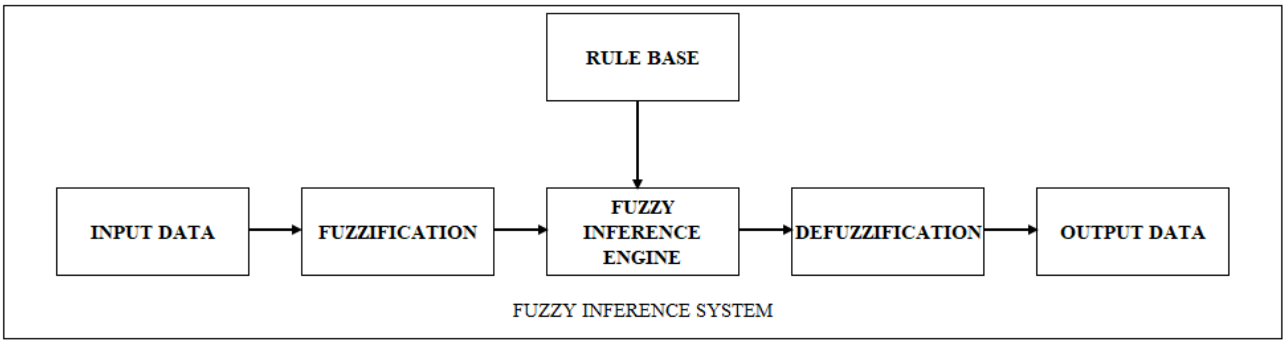


Fig. 2. Fuzzy Inference System (FIS)

The most popular FIS types are Mamdani and Sugeno. Mamdani FIS is known for being a very intuitive and suited to human inputs system [14], making it a frequently used system in studies that rely on expert-based data [15]. One of the expert-based methods is precisely FMEA. This method involves analysing individual elements or stages of a process to determine three parameters for evaluation: severity (S), detectability (D), and occurrence (O). Each potential defect is evaluated by experts on a scale from 1 to 10. Based on this evaluation, a Risk Priority Number (RPN) is calculated, which helps identify areas requiring intervention. However, assessing on a given scale by different experts is often prone to human error, linked to the subjective determination of risk levels. In the fuzzy FMEA the risks are evaluated by experts in linguistic variables, which are not numbers, but words or sentences in a natural language.

3. FUZZY FMEA IN FORMING AND ASSEMBLY

In this article, the two subprocesses of product manufacturing were considered. These are forming and the assembly of the semi-finished product. At first, the identification of potential risks was performed (Table 1).

Table 1. Risks identification

Risk no	Risk type	Process
R1	Thermocouple failure	forming
R2	High compressor vibrations operation	
R3	Failure of optical sensors during inspection	
R4	Improper installation of the capillary	assembly
R5	Incorrect bending of the tube	
R6	Too loose a fit	
R7	Too tight a fit	

Each risk was evaluated by three experts separately (tab. 2). They assigned values to the severity, occurrence and detectability. In this case, the risk was evaluated by three experts (E1, E2, E3) not on a 1–10 scale, but as linguistic variables defined as low (L), moderate (M) or high (H). The experts were asked the same questions for all the risks:

- S: What is the risk of not being able to manage the consequences of a defect?
- O: What is the risk that the defect will occur based on the historical data?
- D: What is the risk of not being able to detect that the defect occurred?

Table 2. Risks assessment by experts – linguistic values

	R1			R2			R3			R4			R5			R6			R7		
	E1	E2	E3	E1	E2	E3	E1	E2	E3	E1	E2	E3	E1	E2	E3	E1	E2	E3	E1	E2	E3
S	M	H	M	M	M	M	M	M	M	H	H	H	M	H	H	L	M	L	L	M	M
O	L	L	L	H	H	H	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M
D	H	H	H	M	M	M	L	L	L	L	L	L	M	M	M	H	H	H	H	H	H

To perform the fuzzy FMEA, the membership functions (MF) were defined. These functions are very important in fuzzy representation since they affect a FIS in general. There are different types of MFs being used in fuzzy sets and the selection of MFs shape depends on the distribution and characteristics of the data under study, and in practice, it often turns out to be quite subjective [16]. However, a review of numerous studies indicates that the triangular and trapezoidal membership functions are commonly chosen due to their simple implementation and computational efficiency [17].

In this case, the MFs for all researched data were defined as triangular and trapezoidal (Fig. 3 and Fig. 4).

$$\mu_A(x) = \begin{cases} 0 & if\ x \le a \\ \dfrac{x-a}{b-a} & if\ a \le x \le b \\ \dfrac{c-x}{c-b} & if\ b \le x \le c \\ 0 & if\ x \ge c \end{cases}$$

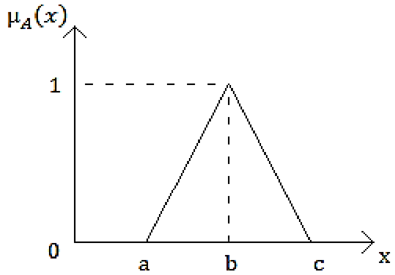


Fig. 3. Triangular MF

$$\mu_A(x) = \begin{cases} 0 & if\ x \le a \\ \dfrac{x-a}{b-a} & if\ a \le x \le b \\ 1 & if\ b \le x \le c \\ \dfrac{d-x}{d-c} & if\ c \le x \le d \\ 0 & if\ x \ge d \end{cases}$$

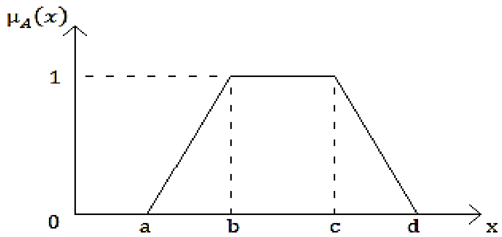


Fig. 4. Trapezoidal MF

The intervals of indicated values of membership functions are listed in Table 3.

Table 3. Risks MFs intervals definition

Risk level	MF interval values	MF type
S, O, D parameters		
Low	[0, 2, 4]	Triangular
Moderate	[2, 4, 6, 8]	Trapezoidal
High	[6, 8, 10]	Triangular
Risk Priority Number (RPN)		
Low	[0, 200, 400]	Triangular
Moderate	[200, 400, 600, 800]	Trapezoidal
High	[600, 800, 1000]	Triangular

Based on the collected data, an FIS was developed. The MathWorks software was used to conduct the analysis, specifically the MatLab R2024a version with the use of Fuzzy Toolbox. It is a widely used tool by researchers to perform fuzzy FMEA. The MFs diagrams of S, O and D parameters implemented in MatLab are shown in Fig. 5.

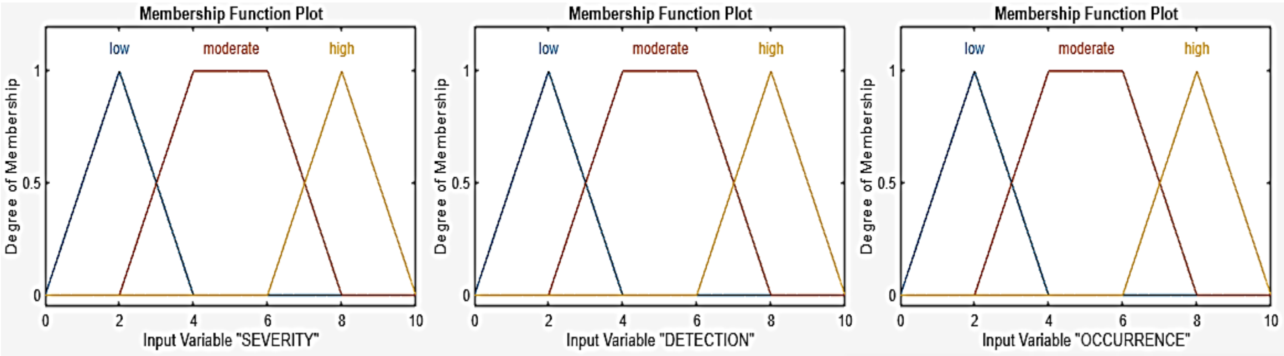


Fig. 5. Severity, detection and occurrence of risks MFs in MatLab

The risk priority numbers MF is similar to the S, O, D ones with the intervals listed in Table 3. In this case, the Mamdani type-1 system was performed as it was chosen as sufficient for the level of uncertainty in the data under study. Then, the rule base was defined. It is the part of fuzzy FMEA that needs to be done with the base of experts knowledge, historical data and other external information. In this case, the Mamdani implication model of if then formulation was used:

$$IF\ x\ is\ A\ AND\ y\ is\ B\ AND\ z\ is\ C\ THEN\ r\ is\ D \tag{1}$$

where:

x, *y*, *z* – input parameters (S, O, D),

r – output result (RPN).

The most important factor in building a rule base is to develop it to be complete, thus it needs to include all possible rules. The number of rules in a complete rule base directly depends on the number of input parameters under study and the number of levels at which they are evaluated. In this case, there are three parameters (S, O, D) evaluated at three risk levels (low, moderate and high) so the complete rule base should include 27 rules in total. In the case under the study, the rule base for considered organisation designed by the experts is presented in the Fig. 6.

The control surface plot of implemented FIS presented in MatLab is shown in Fig. 7.

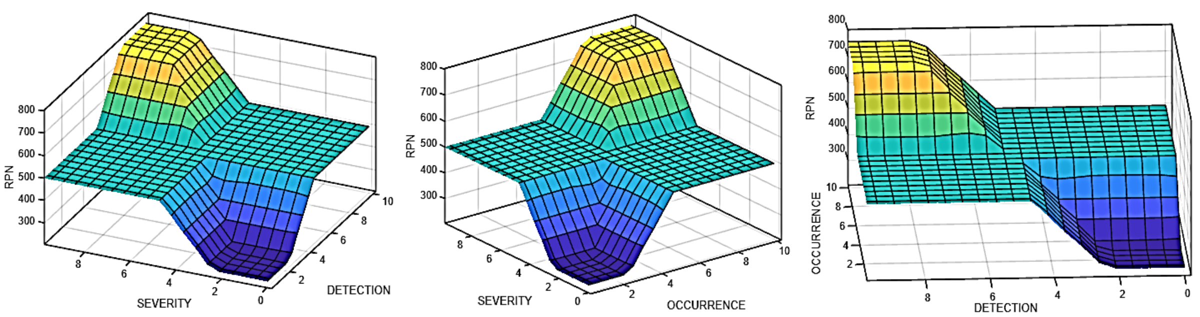
The risk parameters defined by experts in the form of linguistic variables, were then subjected to defuzzification according to the established membership functions using the arithmetic mean aggregation operator. Then, each risk was evaluated and calculated using implemented FIS and the centroid (CoA) method of defuzzification, which is determined by the equation (2) [16]:

$$CoA, z^* = \frac{\int \mu_A(z) \times dz}{\int \mu_A(z)\, dz} \tag{2}$$

where: *z* – defuzzied output, $\mu A(z)$ – the aggregated output MF, *z* – the universe of discourse.

	Rule	Weight	Name
1	If OCCURRENCE is low and DETECTION is low and SEVERITY is low then RPN is low	1	rule1
2	If OCCURRENCE is moderate and DETECTION is low and SEVERITY is low then RPN is low	1	rule2
3	If OCCURRENCE is high and DETECTION is low and SEVERITY is low then RPN is moderate	1	rule3
4	If OCCURRENCE is low and DETECTION is moderate and SEVERITY is low then RPN is low	1	rule4
5	If OCCURRENCE is moderate and DETECTION is moderate and SEVERITY is low then RPN is moderate	1	rule5
6	If OCCURRENCE is high and DETECTION is moderate and SEVERITY is low then RPN is moderate	1	rule6
7	If OCCURRENCE is low and DETECTION is high and SEVERITY is low then RPN is moderate	1	rule7
8	If OCCURRENCE is moderate and DETECTION is high and SEVERITY is low then RPN is moderate	1	rule8
9	If OCCURRENCE is high and DETECTION is high and SEVERITY is low then RPN is high	1	rule9
10	If OCCURRENCE is low and DETECTION is low and SEVERITY is moderate then RPN is low	1	rule10
11	If OCCURRENCE is moderate and DETECTION is low and SEVERITY is moderate then RPN is moderate	1	rule11
12	If OCCURRENCE is high and DETECTION is low and SEVERITY is moderate then RPN is moderate	1	rule12
13	If OCCURRENCE is low and DETECTION is moderate and SEVERITY is moderate then RPN is moderate	1	rule13
14	If OCCURRENCE is moderate and DETECTION is moderate and SEVERITY is moderate then RPN is moderate	1	rule14
15	If OCCURRENCE is high and DETECTION is moderate and SEVERITY is moderate then RPN is moderate	1	rule15
16	If OCCURRENCE is low and DETECTION is high and SEVERITY is moderate then RPN is moderate	1	rule16
17	If OCCURRENCE is moderate and DETECTION is high and SEVERITY is moderate then RPN is moderate	1	rule17
18	If OCCURRENCE is high and DETECTION is high and SEVERITY is moderate then RPN is high	1	rule18
19	If OCCURRENCE is low and DETECTION is low and SEVERITY is high then RPN is moderate	1	rule19
20	If OCCURRENCE is moderate and DETECTION is low and SEVERITY is high then RPN is moderate	1	rule20
21	If OCCURRENCE is high and DETECTION is low and SEVERITY is high then RPN is moderate	1	rule21
22	If OCCURRENCE is low and DETECTION is moderate and SEVERITY is high then RPN is moderate	1	rule22
23	If OCCURRENCE is moderate and DETECTION is moderate and SEVERITY is high then RPN is moderate	1	rule23
24	If OCCURRENCE is high and DETECTION is moderate and SEVERITY is high then RPN is high	1	rule24
25	If OCCURRENCE is low and DETECTION is high and SEVERITY is high then RPN is moderate	1	rule25
26	If OCCURRENCE is moderate and DETECTION is high and SEVERITY is high then RPN is high	1	rule26
27	If OCCURRENCE is high and DETECTION is high and SEVERITY is high then RPN is high	1	rule27

Fig. 6. Rule base for implemented FIS for presented organisation



(a) (b) (c)

Fig. 7. Surface control plot of implemented FIS: (a) severity vs detection plot; (b) severity vs occurrence plot; (c) occurrence vs detection plot

The results of these steps are presented in the Table 4.

Table 4. Risks assessment by experts – aggregated crisp values and fuzzy RPN results

	R1	R2	R3	R4	R5	R6	R7
S	6	5	5	8	7	3	4
O	2	8	2	5	5	5	5
D	8	5	2	2	5	8	8
fRPN	M	M	L	M	M	M	M

4. CONCLUSION

In this case, the results of the risk assessment indicated that most of the analysed risks are moderate, according to the experts (Fig. 8). This applies to both the forming and assembly processes.

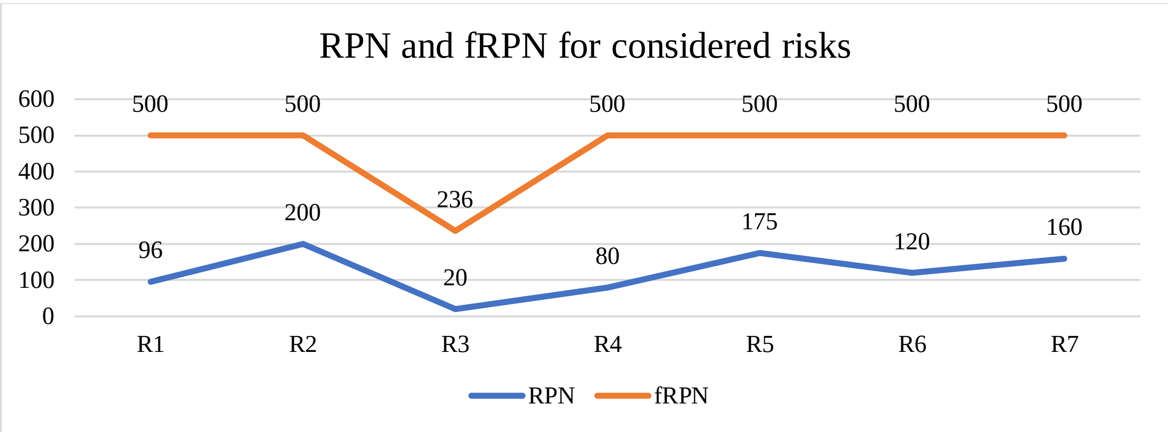


Fig. 8. RPN and fRPN values for considered risks

Only risk number 3, which is the failure of optical sensors during inspection, is assessed as a low risk. The limited variability in the assessment is likely due to several factors:

- in this case, the experts were generally in agreement in their risk evaluations,
- the rule base (which was also built based on expert knowledge) has broader boundaries for moderate risk (trapezoidal MS) than for low and high risks (triangular MF),
- the analysed risks, even if they scored high in one parameter, were typically low in another — for example, improper installation of a capillary (R4) has high consequences but is very easy to detect,
- the analysed risk assessment example was not a very complicated example (only a few risks with just three degrees of *low*, *moderate*, *high*).

The results of the discussed example demonstrates not only the feasibility but also the effectiveness of applying fuzzy set principles to risk analysis in production processes. The key benefits of using fuzzy sets in risk assessment, especially the fuzzy FMEA method, include:

- greater resilience to errors common in expert linguistic evaluations,
- validation and consistency with expert assessment systems (like Mamdani FIS),
- flexibility for the experts to consider various options for each risk without requiring excessive detail.

However, challenges in implementing the fuzzy FMEA method in everyday industrial settings revolve around:

- software limitations – to perform fuzzy FMEA there is a need to have proper software (i.e. MatLab) or the ability to implement the own application (i.e. in Python),
- expertise required to employ fuzzy sets in risk assessments.

These are the limitations for practical implementation of fuzzy logic in industry. However, companies should consider using fuzzy logic in risk assessment, especially when conducting processes with risks that are more complex to calculate than those presented in the example. Future studies on the use of fuzzy logic in risk assessment could focus on expanding the scope to include other resource types or processes. Additionally, exploring the applicability of fuzzy logic in other risk assessment frameworks besides FMEA — such as scenario analysis or different expert systems — might also enhance the reliability and error resilience of these analyses.

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