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FUZZY SETS APPROACH FOR DETERMINING FAILURE RISK INDICATORS

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Abstract: Carrying out of the manufacturing processes requires the proper functioning of the machines, equipment, and devices that participate in the process. In these conditions, the assessment of the risks of failure of the various components of the machines becomes a problem that requires a solution as appropriate as possible to the conditions of the real systems. The paper proposes three procedures based on fuzzy sets to determine the failure risk. For each group of CNC machine tools and for each type of failure, two parameters were quantified: failure times (failure duration) and the number of failures. By means of the fuzzy sets, the following were determined: the risk indicator due to failure times, the risk indicator due to the number of failures and the global (cumulative) risk indicator.
Key words: Fuzzy set, CNC machine tools, risk indicator

1. INTRODUCTION

The occurrence of machine-tool, equipment, device malfunctions can lead to significant disruptions in the production processes. In these conditions, the assessment of the risks of failure of the various components of the machines becomes a problem that requires a solution as appropriate as possible to the conditions of the real systems.

The paper [1] presents a model for quantifying the risks associated with maintenance activities by coupling the risk analysis method with fuzzy logic. The level of risk is described by the Risk Priority Number (RPN). The determination of the Risk Priority Number is based on three parameters: frequency, detectability and severity.

The research presented in [2] aims to determine the appropriate period for checking the condition of machines using predictive maintenance through vibration analysis. The proposed method, based on fuzzy logic, makes it possible to determine the life expectancy of the equipment under maintenance.

The work [3] presents a fuzzy system for determining the maintenance plans under conditions where the operating hours and failure periods are known in the case of 54 crude oil pumps.

The paper [4] focuses on the application of fuzzy logic in decision making for equipment maintenance planning using inputs such as mean time between failures, mean time to repair, availability of spare parts and age of equipment.

In [5] the authors introduce the concept of Maintenance Support Potentials (MSP) and develop a method for evaluating the potential level of maintenance support (MSP) of an organization based on fuzzy.

The FMEA (Failure Mode and Effects Analysis) method is one of the most useful approaches for planning maintenance and consequently improving reliability. In [6], this method has been integrated with a procedure based on fuzzy sets, achieving the prioritization and evaluation of electrical and control component failures in the case of CNC lathes.

In the paper [7], the Failure modes, effects, and criticality analysis (FMECA) method is applied to a CNC lathe. Composite mechanical subsystems are ranked in terms of the risk factor. It was found that the main shaft (spindle unit) is the subsystem with the highest risk factor.

The aim of the study [8] was to reduce the planned preventive maintenance time (PPM time) for a CNC machine by simulating the planned preventive maintenance time.

In [9] a decision-making application was developed to provide a visual analysis of the Remaining Useful Life (RUL) of a machining tool. The obtained results show that preventive maintenance (PM), performed in a real machining process, could be changed to a predictive approach (PdM).

The paper proposes three methods based on fuzzy sets to determine the failure risk. Fuzzy decision systems are multi-criteria systems that allow the assessment of failure risk by simulated consideration of several indicators. The following are determined: the risk indicator due to failure times, the risk indicator due to the number of failures and the global (cumulative) risk indicator.

2.DEVELOPMENT OF THE PROCEDURE FOR DETERMINING RISK INDICATORS

2.1. Problem description

The paper is based on the activity of monitoring the CNC machining centers of a company in the city of Oradea. The monitoring period was 12 months from January 1, 2020 to December 31, 2020. The defects that occurred on 79 CNC machining centers, grouped in 8 groups, were recorded.

The registered faults are of the following types:

1. APC (Automatic Pallet Changer) failure;
2. ATC (Automatic Tool Changer) failure;
3. BTS (Broken Tool System) failure;
4. Electrical failure;
5. Hydraulic failure;
6. Tool magazine failure;
7. Mechanical failure;
8. Pneumatic failure;
9. Hydraulic pump failure (fixture);
10. Emulsion system failure;
11. Spindle fault (main shaft).

The number of machining centers in each group is presented in table 1**:**

Table 1

The number of CNC machining centers corresponding to each group.

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
No. CNC machining centers	29	18	10	8	3	6	4	1

For each processing center, out of the 79 monitored, the following were recorded:

- The number of each type of failure;
- The duration of failure time associated with each type of failure.

2.2. Data set organization

In order to be processed, the recorded data, it was organized in matrix form.

Thus, for each type of failure, the Matrix corresponding to the number of failures was defined. The general form is shown in relation (1):

$$MN^k = \begin{bmatrix} mn_{11}^k & mn_{11}^k \\ mn_{21}^k & mn_{22}^k \\ \dots & \dots \\ mn_{i1}^k & mn_{i2}^k \\ \dots & \dots \\ mn_{n1}^k & mn_{n2}^k \end{bmatrix} \quad (1)$$

Where:

- MN^k- The matrix corresponding to the number of type *k* failures , k=$\overline{1,11}$;
- mn_{i1}^k- The number of machining centers in group *i* that were monitored for type failure *k*, i=$\overline{1,8}$ and k=$\overline{1,11}$;
- mn_{i2}^k- The number of type *k* failures associated with machines in the group *i*, i=$\overline{1,8}$ and k=$\overline{1,11}$;

The duration of the failure time corresponding to each type of failure was related with the number of machines in each group in matrices of the form (2).

$$MT^k = \begin{bmatrix} mt_{11}^k & mt_{11}^k \\ mt_{21}^k & mt_{22}^k \\ \dots & \dots \\ mt_{i1}^k & mt_{i2}^k \\ \dots & \dots \\ mt_{n1}^k & mt_{n2}^k \end{bmatrix} \quad (2)$$

Where:

- MT^k- The matrix corresponding to the duration of the failure time associated with the failure k

- type, k=$\overline{1,11}$;
- mt_{i1}^k- The number of machine tools in group i that were monitored for k failure type, i=$\overline{1,8}$ and k=$\overline{1,11}$;
- mt_{i2}^k- The duration of failure time associated with k failure type corresponding to machines in group i, i=$\overline{1,8}$ and k=$\overline{1,11}$.

2.3 Defining the procedure

To determine the risk indicators due to the number of failures, the following steps will be taken (figure 1):

I- The Matrices corresponding to the Number of defects are constructed (MN^k- The matrix corresponding to the number of type k failures, k=$\overline{1,11}$);

II- Each matrix MN^k(k=$\overline{1,11}$) is processed through the Fuzzy System for the Assessment of Risk Indicators due to the Number of Type k Defects (FSARIND);

III- For each type of failure k (k=$\overline{1,11}$), the Matrix of Risk Indicators due to the Number of Defects is obtained $MRIND^k$;

IV- *The matrices of the Risk Indicators due to the Number of Defects* are concatenated;

V- The result is *The Matrix of Risk Indicators due to the Number of Defects* (MRIND).

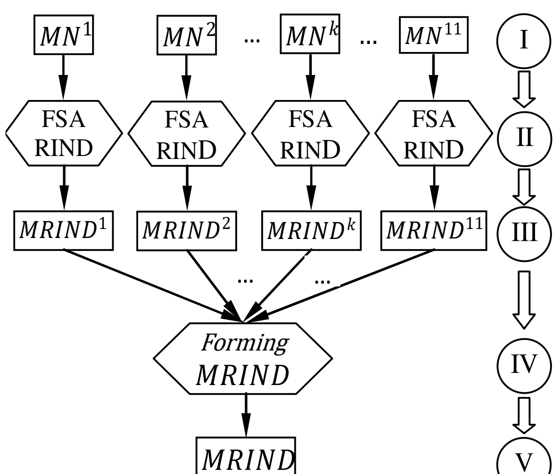

Fig. 1. The procedure for determining the risk indicator due to the number of failures

Matrix of Risk Indicators due to the Number of Defects (MRIND) has the following structure (3).

$$MRIND = \begin{bmatrix} rind_{1\,1} & \dots & rind_{1\,11} \\ rind_{2\,1} & \dots & rind_{2\,11} \\ \dots & \dots & \dots \\ rind_{8\,1} & \dots & rind_{8\,11} \end{bmatrix} \quad (3)$$

Where: $rind_{ik}$ is the risk indicator corresponding to the group of machines and due to the number of type k failure, i=$\overline{1,8}$ and k=$\overline{1,11}$.

To determine the risk indicators due to the duration of the failure time associated with each type of failure, the following steps will be taken (figure 2):

I- *The Matrices corresponding to the duration of the Failure Time* are constructed (MT^k- The matrix related to the duration of the failure time associated with the type k failure, k=$\overline{1,11}$);

II- Each matrix MT^k(k=$\overline{1,11}$) is processed through *The Fuzzy System for the Assessment of Risk Indicators due to the duration of the Failure Time* related with the type k failure (FSARIFT);

III- For each type of failure k (k=$\overline{1,11}$) the *Matrix of Risk Indicators due to the duration of the Failure Time* is obtained $MRIFT^k$;

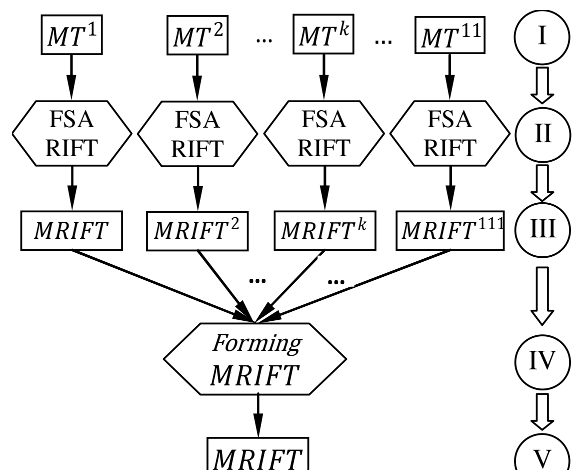

Fig. 2. The procedure for determining the risk indicator due to the duration of the failure time

IV- *The matrices of the Risk Indicators due to the Failure Time* are concatenated;

V- The result is *the Matrix of Risk Indicators due to the duration of the Failure Time* ($MRIFT$).

Matrix of Risk Indicators due to the duration of the Failure Time (MRIFT) has the following structure (4):

$$\text{MRIFT} = \begin{bmatrix} rift_{1\,1} & \dots & rift_{1\,11} \\ rift_{2\,1} & \dots & rift_{2\,11} \\ \dots & \dots & \dots \\ rift_{8\,1} & \dots & rift_{8\,11} \end{bmatrix} \quad (4)$$

Where $rift_{ik}$ is the risk indicator corresponding to the group of machines *i* and due to the duration of the failure time associated with the type k failure, i=$\overline{1,8}$ and k=$\overline{1,11}$.

In order to take into account, the number of defects and the duration of the failure time, for each group of machining centers and for each type of failure, a *Cumulative Risk Indicator* is determined.

Matrix of Risk Indicators due to the Number of Defects (MRIND) and *Matrix of Risk Indicators due to the duration of the Failure Time* (MRIFT) are the entries in the *Fuzzy System for the Assessment of Cumulative Risk Indicators* (SFACRI) (figure 3). The result is the Matrix of Cumulative Risk Indicators (MCRI).

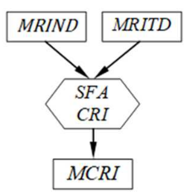

Fig. 3. Determination of the *Matrix of Cumulative Risk Indicators*

Matrix of Cumulative Risk Indicators (MCRI) has the following structure (5).

$$MCRI = \begin{bmatrix} cri_{1\,1} & \dots & cri_{1\,11} \\ cri_{2\,1} & \dots & cri_{2\,11} \\ \dots & \dots & \dots \\ cri_{8\,1} & \dots & cri_{8\,11} \end{bmatrix} \quad (5)$$

Where cri_k is the cumulative risk indicator corresponding to the group of machines *i* and due to the k failure type, i=$\overline{1,8}$ and k=$\overline{1,11}$.

3. DEFINITION OF DECISION-MAKING SYSTEMS BASED ON FUZZY SETS

3.1 General considerations

Any decision system based on fuzzy sets will be developed through the following steps:

1.Establishing the input sizes;
2.Defining the range of values for each input quantity;
3.Definition of the linguistic variable associated with each input size;
4.Establishing the linguistic grades associated with each linguistic input variable;
5.Establishing the membership functions associated with each linguistic term. Input sizes;
6. Defining the output size of the decision-making process;
7.Defining the range of values for the output sizes;
8.Definition of the linguistic variable associated with each output size;
9.Establishing the linguistic degrees associated with each linguistic output variable;
10.Establishing the membership functions associated with each linguistic grade. Output sizes;
11. Establishing the method of connecting the various values of the membership functions.

3.1 The Fuzzy System for the Assessment of Risk Indicators due to the Number of Defects

The input sizes in the system are:

- Number of CNC machining centers (N-CNC-MC) in group *i* that were monitored for type k failure, i=$\overline{1,8}$ and k=$\overline{1,11}$;
- The number of defects (ND) of type k associated with the machines in the group *i*, i=$\overline{1,8}$ and k=$\overline{1,11}$.

This information is organized in 11 form matrices (1). The fuzzy system was developed in the Matlab Fuzzy Toolbox.

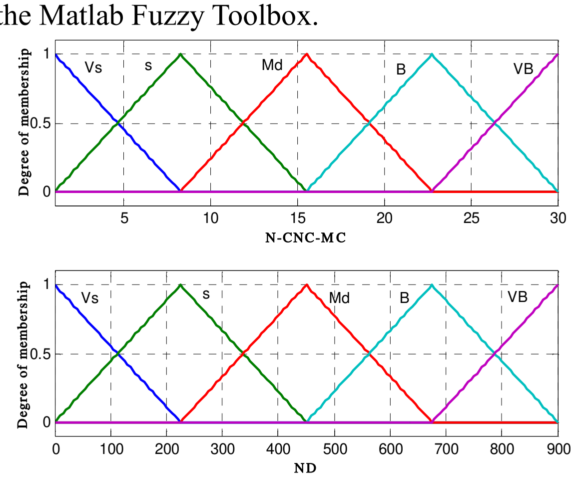

Fig. 4. The Fuzzy System for the Evaluation of Risk Indicators due to the Number of Defects. Inputs

Figure 4 shows the inputs in the N-CNC-MC and NC system. The following information was associated to inputs: the domains of values, the linguistic variable, the linguistic degrees associated with each linguistic variable, the membership functions associated with each linguistic term.

Figure 5 shows the output from the Fuzzy System for the Evaluation of Risk Indicators due to the Number of Defects (RIND).

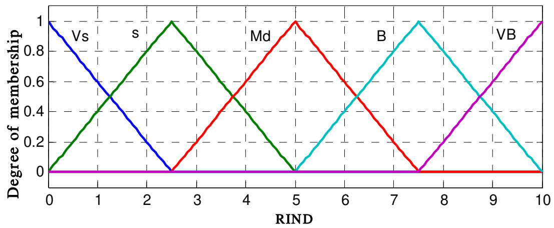

Fig. 5. The Fuzzy System for the Evaluation of Risk Indicators due to the Number of Defects. The output size

The dependence of the output base on the input is described by the inference rules (the method of connecting the various values of the membership functions).

$$\left.\begin{array}{c}
1.\ If\,(N-CNC-MC\ is\ Vs) and\ (ND\ is\ Vs)\\
then\ (RIND\ is\ s)\\
2.\ If\,(N-CNC-MC\ is\ Vs) and\ (ND\ is\ s)\\
then\ (RIND\ is\ s)\\
\ldots\\
14.\ If\,(N-CNC-MC\ is\ Md) and\ (ND\ is\ B)\\
then\ (RIND\ is\ B)\\
15.\ If\,(N-CNC-MC\ is\ Md) and\ (ND\ is\ VB)\\
then\ (RIND\ is\ B)\\
\ldots\\
24. If\ (N-CNC-MC\ is\ VB) and\ (ND\ is\ B)\\
then\ (RIND\ is\ Md)\\
24. If\ (N-CNC-MC\ is\ VB) and\ (ND\ is\ B)\\
then\ (RIND\ is\ Md)
\end{array}\right\}\quad (6)$$

The Fuzzy System for the Evaluation of Risk Indicators due to the Number of Defects, implemented in the MatLab Fuzzy Toolbox is the one in figure 6.

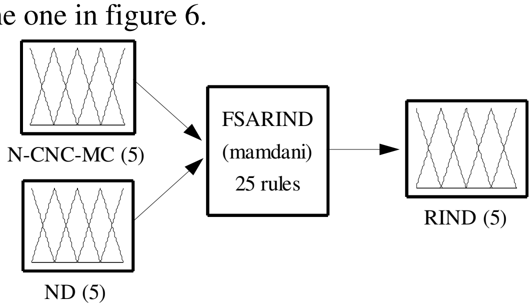

Fig. 6. The Fuzzy System for the Evaluation of Risk Indicators due to the Number of Defects

In the fuzzy system 25 inference rules were defined. These are presented in (6).

Figure 7 shows the variation surface of the output quantities of the Risk Indicators due to the Number of Defects (RIND) in relation to the input quantities: *Number of machining centers* (N-CNC-MC) and *Number of Defects* (ND).

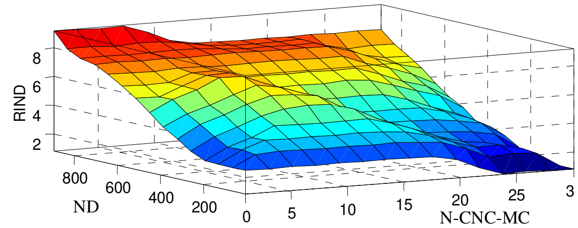

Fig. 7. Surface variation RIND= f(N-CNC-MC, ND)

After determining the risk indicators due to the number of failures for each type of failure, the 11 resulting matrices are concatenated (composed) into the Matrix of Risk Indicators due to the Number of Failures (MIRND).

3.2 The Fuzzy System for the Assessment of Risk Indicators due to the duration of the Failure Time (FSARIFT)

The inputs in the system are:

- Number of machining centers (N-CNC-MC) in group *i* that were monitored for type k failure, i=$\overline{1,8}$ and k=$\overline{1,11}$;
- Duration of Failure Time (DFT) corresponding to failure type *k*, associated with the machines in the group *i*, i=$\overline{1,8}$ and k=$\overline{1,11}$.

The output is the Risk Indicators Due to Duration of Failure Time (RIDFT).

The development of the Fuzzy System for the Evaluation of Risk Indicators due to the duration of the Failure Time was carried out following the sequences described in subchapter 3.1. The system implemented in the Matlab Fuzzy Toolbox is shown in figure 8.

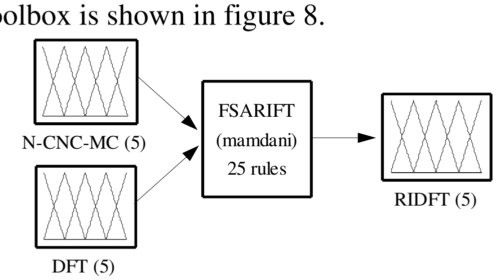

Fig. 8. The Fuzzy System for the Assessment of Risk Indicators due to the duration of the Failure Time

The 11 matrices resulting from the determination of the Risk Indicators due to the duration of the Failure Time for each type of failure, are concatenated (composed), resulting in the *Matrix of the Risk Indicators due to the duration of the Failure Time* (*MIRFT*).

3.3. Fuzzy System for Assessment of Cumulative Risk Indicators

The Fuzzy System for the Assessment of Cumulative Risk Indicators (FSACRI) (figure 9) was implemented in the Matlab Fuzzy Toolbox.

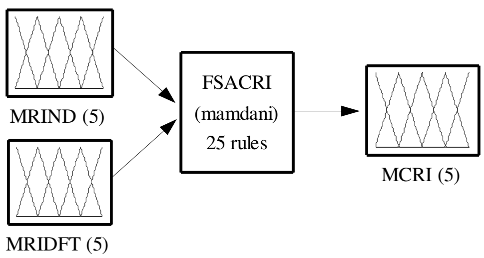

Fig. 9. Fuzzy System for Assessment of Cumulative Risk Indicators

The input sizes in the system are:

- Matrix of Risk Indicators due to the Number of Defects ($MRIND_{8x11}$);
- Matrix of Risk Indicators due to the duration of the Failure Time ($MRIFT_{8x11}$).

The output size is:

- Matrix of Cumulative Risk Indicators ($MCRI_{8x11}$);

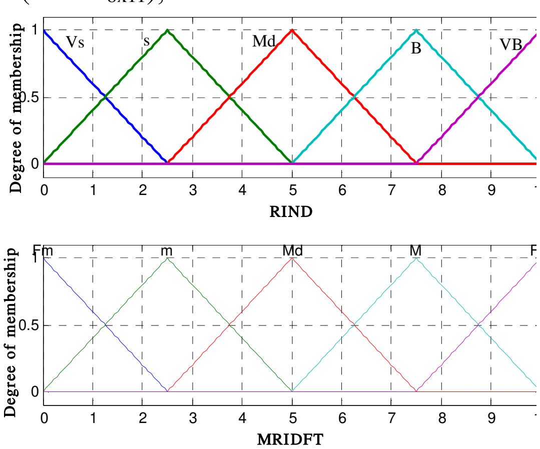

Fig. 10. Fuzzy System for Assessment of Cumulative Risk Indicators

Figure 10 shows the inputs in the RIND and RIDFT system. The following information was associated: the domains of values, the linguistic variable, the linguistic degrees associated with each linguistic variable, the membership functions associated with each linguistic term.

The characteristics of the output size (Cumulative Risk Indicators) from the fuzzy system are presented in figure 11.

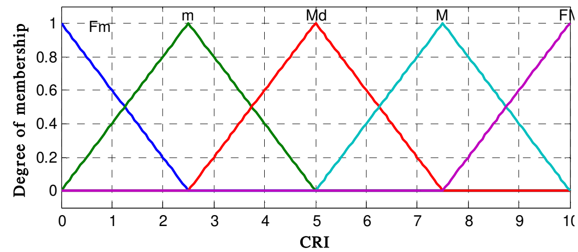

Fig. 11. Fuzzy System for Assessment of Cumulative Risk Indicators

4. RESULTS. DISCUSSIONS

For example, consider the Matrix corresponding to the number of type 5 failures (hydraulic failure) MN5 and the Matrix corresponding to the duration of the failure time associated with the type 5 failure (hydraulic failure) MT5 with the values shown in (6).

$$MN^5 = \begin{bmatrix} 29 & 246 \\ 18 & 125 \\ 10 & 227 \\ 8 & 55 \\ 3 & 6 \\ 6 & 62 \\ 4 & 119 \\ 1 & 22 \end{bmatrix} \quad MT^5 = \begin{bmatrix} 29 & 6341 \\ 18 & 6088 \\ 10 & 7468 \\ 8 & 2193 \\ 3 & 205 \\ 6 & 9616 \\ 4 & 8140 \\ 1 & 1042 \end{bmatrix} \quad (6)$$

After applying the Fuzzy System for the Evaluation of the Risk Indicators due to the Number of Defects and the Fuzzy System for the Evaluation of the Risk Indicators due to the duration of the Failure Time, it results $MRIND^5$- *Matrix of Risk Indicators due to the Number of defects* associated with type 5 failure and $MRIFT^5$- *Matrix of Risk Indicators corresponding to the Duration of Failure time* associated with type 5 failure. The two matrices are presented in (7).

$$MRIND^5 = \begin{bmatrix} 2.0031 \\ 3.6787 \\ 5.0346 \\ 3.2106 \\ 2.6038 \\ 3.2958 \\ 3.6223 \\ 2.5000 \end{bmatrix} \quad MRIFT^5 = \begin{bmatrix} 1.4159 \\ 2.8843 \\ 3.1111 \\ 2.7034 \\ 2.5218 \\ 3.2578 \\ 3.2218 \\ 2.5000 \end{bmatrix} \quad (7)$$

Considering the matrices $MIRND^5$ and $MIRTD^5$, by applying the Fuzzy System for the

Evaluation of Cumulative Risk Indicators, the Matrix of Cumulative Risk Indicators corresponding to failure 5 (CRI5) results (Table 2). The matrix of Cumulative Risk Indicators for all groups of machines and for each type of failure is presented in table 2.

Table 2

Matrix of Cumulative Risk Indicators

CNC GROUP \ CRI	CRI^1	CRI^2	CRI^3	CRI^4	CRI^5	CRI^6	CRI^7	CRI^8	CRI^9	CRI^{10}	CRI^{11}
1	3.56	2.67	2.48	2.29	2.26	2.07	2.27	1.97	2.30	2.25	3.57
2	3.53	5.00	4.01	3.94	3.09	2.69	3.88	2.50	2.49	3.31	2.53
3	3.71	4.71	6.59	5.00	3.21	3.05	3.13	2.66	3.38	4.07	2.55
4	2.61	2.89	2.57	6.31	2.80	2.78	5.84	2.57	2.88	3.07	3.46
5	2.74	2.83	2.73	3.40	2.53	2.50	2.90	2.50	2.50	2.70	4.43
6	3.29	3.68	2.76	3.81	3.35	2.70	3.18	2.50	2.50	2.85	2.51
7	3.05	3.47	2.63	2.83	3.40	2.52	2.97	2.51	2.52	3.14	2.71
8	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50

5. CONCLUSION

Modern manufacturing systems are increasingly complex, both structurally and functionally. Under these conditions, it is necessary to implement the most effective maintenance policies.

The work proposed a complex procedure for determining the risks of failure, starting from a specific situation of a parts processing company. The three types of risk indicators determined by means of fuzzy systems constitute information that can be the basis of decisions regarding maintenance management. The prioritization of risk indicators allows the scheduling of maintenance activities within the company's specialized department.

Future research will aim to increase the accuracy of fuzzy systems by assigning more linguistic degrees to the defined linguistic variables. Also, the integration of fuzzy systems in the IOT associated with the manufacturing system will be pursued.

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PROCEDURA DE DETERMINARE A INDICATORILOR DE RISC DE DEFECTARE FOLOSIND MULȚIMI FUZZY

Rezumat: Desfășurarea în bune condiții a proceselor de fabricație presupune buna funcționare a mașinilor, echipamentelor, dispozitivelor care intervin în proces. Apariția defecțiunilor mașinilor- unelte, echipamentelor, dispozitivelor poate duce la perturbații semnificative in desfășurarea proceselor. In aceste condiții evaluarea riscurilor de defectare a diferitelor componente ale mașinilor- unelte devine o problema care necesita o soluție cât mai adecvată condițiilor sistemelor reale. Lucrarea propune trei proceduri bazate pe mulțimi fuzzy de determinare a riscului de defectare. Pentru fiecare grupa de mașini- unelte CNC și pentru fiecare tip de defecțiune au fost cuantificați doi parametri: timpii de defectare (durata de defectare) și numărul defecțiunilor. Prin intermediul mulțimilor fuzzy s-au determinat: indicatorul de risc datorat timpilor de defectare, indicatorul de risc datorat numărului defecțiunilor și indicatorul de risc cumulat.

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