International Journal of Industrial Engineering & Production Research (2018)

International Journal of Industrial Engineering & Production Research

September 2018, Volume 29, Number 3
pp. 359- 376

DOI: 10.22068/ijiepr.29. 3.359 http://IJIEPR.iust.ac.ir/

Using Fuzzy FMEA Approach to Improve Decision-Making Process in CNC Machine Electrical and Control Equipment Failure Prediction

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KEYWORDS

Fuzzy FMEA;
Risk priority number;
CNC Lathe Machine;
Sensitivity analysis;
Risk clustering.

ABSTRACT

Reliability and safety in the process industry, such as computer numerical control (CNC) machining industry, are the most important key success factors in upgrading availability and preventing catastrophic failures. Failure Mode and Effects Analysis (FMEA) method is one of the most useful approaches to the maintenance scheduling and, consequently, improvement of the reliability. This paper presents an approach to prioritize and assess the failures of electrical and control components of CNC lathe machine. In this method, the electrical and control components were analyzed independently for every failure mode according to risk priority number (RPN). The results showed that the conventional method by means of a weighted average generated different RPN values for the subsystems subjected to the study. The best result for Fuzzy FMEA was obtained for the 10-scale and centroid defuzzification method. The Fuzzy FMEA sensitivity analysis showed that the subsystem risk level was dependent on occurrence (O), severity (S), and detection (D) indices, respectively. The result of the risk clustering showed that the failure modes could be clustered into three risk groups, and a similar maintenance policy could be adopted for all failure modes placed in a cluster. In addition, the prioritization of risks could also help the maintenance team to choose corrective actions consciously. In conclusion, the Fuzzy FMEA method was found to be suitably adopted in the CNC machining industry. Finally, this method helped increase the level of confidence on CNC lathe machine.

1. Introduction

Nowadays, reliability and safety of processes and equipment are one of the major concerns in industry, especially automotive industry. Product defect in the field of function causes fixture damages, high maintenance cost, applying for warranty, consumer complaints, product call, lost sales, and, in the worst case, product wastes [1]. In the meantime, reliability is very important in machinery process in industry by using computer numerical control (CNC) machines due to effect of product defects on normal production. In addition, a failure in CNC machines causes very high production stops owing to different designs compared with usual machines tools and using electronic, hydraulic, pneumatic, and computer equipment. Therefore, maintaining these machines at a high reliability level is essential. Hence, compatible and regular programs for stable and optimal management of systems, costs, risks, and performance of CNC machines are developed by organizations. In addition, to understand, predict, and identify risks and avoid failure in CNC machines, producers use many different scientific methods [2].
In the manufacturing part, manufacturers use different scientific methods to identify risks and prevent failure occurrence in projects. One of the best methods in analyzing systems, especially when systems are complicated and have many parts, is Failure Mode and Effects Analysis (FMEA). Failure mode and effect analysis helps direct the maintenance on the desired failure modes and prevent the critical failure causes. Failure mode effects and criticality analysis is a very comprehensive tool to facilitate structuring maintenance management by considering each failure mode within the system [3]. On the other hand, this method is a systematic method to analyze a system and to identify potential failure modes, reasons, and effect of them on performance of system [4]. In addition, FMEA is one of the important risk analysis tools that is able to decrease failure modes in systems, processes, designs or services [5]. FMEA method was published for the first time in U.S. Armed Forces Military Procedures document as FMECA; then, by the early 1960s, it was used in the design of Apollo by U.S. National Aeronautics and Space Administration (NASA). In 1993, the Automotive Industry Action Group (AIAG) first published an FMEA standard for the automotive industry. [6] introduced FMEA as an engineering method to determine, identify, and eliminate potential, problems, and faults. In addition, over the last years, with developing International standards for quality management in industry such as IATF 16949:2016, FMEA is used even more.

[7] used FMEA method to analyze electrical safety in motor vehicles and calculated risk priority numbers (RPNs) on the basis of occurrence (O), severity (S), and detection (D) of each failure mode. [8] studied risk evaluation in failure mode and effects analysis of aircraft turbine rotor blades by using of FMEA method. [9] revealed that FMEA was capable of decreasing potential failures in systems with minimum effort and resource expenditure, thereby reducing development time and costs. [10] considered FMEA in Amhara Pipe Factory P.L.C., Bahir Dar, and Ethiopia. Three key indices (severity, occurrence, and detection) were assessed and the analysis was carried out with the help of FMEA Worksheet. Finally, the necessary corrective actions were recommended. [11] used FMEA to calculate improved criticalities and prioritize failures of feed systems based on the failure data of the feed system.

As it was defined in literature review, FMEA has been widely applied in the reliability research of machining centers in recent years. However, conventional FMEA that prioritized failure modes based on RPN calculated by multiplying occurrence (O), severity (S), and detection (D) does not take the relationship between the modes and causes of failure into account when considering the assignment of criticality [11]. In addition, conventional FMEA method did not consider the severity of relations between one failure and the others. Therefore, FMEA could not calculate the exact value of RPN, and it needs another parameter such as high, low, and medium. To overcome the limitation of conventional FMEA, many methods are used with FMEA such as fuzzy sets. Fuzzy sets were introduced independently by Lotfi A. Zadeh and Dieter Klaua in 1965 as an extension of the classical notion of set [12].
[13] presented a fuzzy geometric mean method to evaluate a risk in PFMEA. [14] used a PFMEA using fuzzy theory for CNC (Computer numerical control) machine tools. Reliability prediction and failure mode effects and criticality analysis

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Received 12 June 2018; revised 22 September 2018; accepted 6 October 2018

(FMECA) of electronic devices using fuzzy logic were studied by [15].
[16] calculated occurrence in PFMEA using expert opinion based on Trapezoid set; then, this method was developed for two other parameters of RPN: severity and detection.
[17] investigated modeling uncertainty in risk assessment with an integrated approach with fuzzy set theory and Monte Carlo simulation. [18] proposed a risk priority framework to overcome the shortcomings of the traditional FMEA through fuzzy TOPSIS and applied it to yacht system design. A study on reliability centered maintenance (RCM) was conducted to reduce the total number of failures and respective effects on the conventional lathe machine [19]. The severity, occurrence, and detection rating integrated with failure mode and effect analysis (FMEA) is taken from several experts; then, RPN is calculated for each of those experts. Then, the criticality of the failure mode of the functionally significant items of conventional lathe machine is judged on the basis of mean RPN value as well as using the range. [20] studied the comparison of results between the conventional FMEA and Fuzzy Developed FMEA (FDFMEA) to aircraft landing system as one of the important potential failure modes of the aerospace industry. They suggest that the risky failure modes accompanied with FDFMEA yield a more reliable result.

Literature review showed that to eliminate the aforementioned limitations, the Fuzzy set theory as a computational intelligence has been proposed. Therefore, in this paper, we mainly perform risk analysis between classical FMEA and developed FMEA under the fuzzy environment in electrical systems of CNC lathe machine. Thus, to rank the recognized failure modes of electrical subsystems, four experts with experience and technical knowledge in this field contributed to the development of this study. The rest of this paper is organized in five sections as follows. In Section 2, the proposed model is described in detail. Then, in Section 3, the results of the application of Fuzzy FMEA in electrical systems of CNC lathe machine are presented. Finally, Sections 4 and 5 will give the conclusion and recommendations of research.

2. Material & Methods

2-1. Application of FMEA to a lathe CNC machine

Nowadays, many industries have successfully developed their systems and facilities using the FMEA. In recent years, the CNC machining industry has used FMEA to improve performance, reduce component failure, and reduce downtime of the machines. If the causes, type and extent of each component failure, and their impact on machine performance could be identified, then appropriate corrective and control actions could be taken; accordingly, the failure conditions can be prioritized to improve machine reliability [21].
This study aims to analyze the failure modes of electrical and control components of CNC lathe machine and their effects, using conventional FMEA and Fuzzy FMEA methods. Required data and information for CNC machines were collected through FMEA form by respective experts and maintenance team (electrical and mechanical engineers). The case study concerns the CNC machine tools used by the machining department of Kayhan Sanat Ghaem Co., one of the manufacturers of cylinder bush in Iran.
CNC machines are categorized into different types based on its application in different industries, such as Lathe, milling, Laser cutter, Plasma cutters, Air cutters, water jet cutters machine, and so on. In this research, the analysis results of the failure modes of electrical and control components of lathe CNC machine used in the machining line of cylinder bush were used for investigation. The lathe machines used for this study include the Talent (Harding) machine, which has two horizontal and vertical axes for lathe operations. The electrical and control components of lathe CNC machine that provide electrical power and controlling for its components include the machine control unit (MCU), the drives system, the peripheral sensors, the peripheral electrical actuators, the electrical components on switchboard, the measuring system, the spindle and the conveyer motor (Fig.1). In order to implement the analysis of the modes and effects of failure, the type of subsystem and their functional tasks must be determined first.
In Fig. 2, a schematic diagram of electrical and control components of CNC lathe machine is shown. In accordance with Fig. 2, electrical and control components of CNC lathe machine include 8 general subsystems;
1. The control unit of the machine as the heart of the CNC machine controls all parts to be in accordance with the purpose of the machine, and it consists of three units: input, processors, and output.

2- The CNC drive system, which ensures the accuracy and repeatability of machine, includes a spindle drive and a power supply unit drives. The task of the drive system is to receive the command signal from the controlling system of the machine. The drive system then amplifies and sends this signal as an electric current to the servomotor, inverter, spindle or other components relative to the control unit.

3. The peripheral sensors undertake tasks such as detecting the allowable axial displacement limit, determining the reference direction of the machine, increasing the accuracy in detecting the position of the piece, and also, in some cases, checking the oil pressure, oil level, temperature inside the system, etc.

4. Electrical peripheral actuator ensures tasks such as providing rotary force for clamping and unclamping in hydraulic electric valves, controlling air pressure direction in pneumatic valves, and keeping the axis in the vertical direction.

5. The switchboard is, in fact, an enclosure in which industrial electrical equipment is placed. This equipment includes power supply, inverter, contactor, fuse, I / O board, transformer, electrical relay, servo drive, brake resistance, etc.

6. The measurement system captures and delivers various information to the control unit, such as axis position feedback and, also, determines the displacement extent, positioning of the tools replacement jacks, shifting of the clamp position.

7. The spindle motor is an AC motor that can operate at a high speed and provides the required power for spindle to rotate and carry out its operation.

8. The conveyor motor is usually DC or AC, which provides the required power to rotate the conveyor chains to transport undesired materials from the inside of the cabin to the outside.

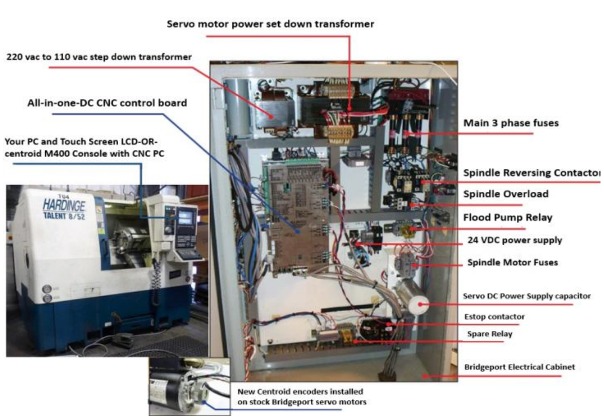

Fig. 1. Electrical and control systems of lathe CNC machine.

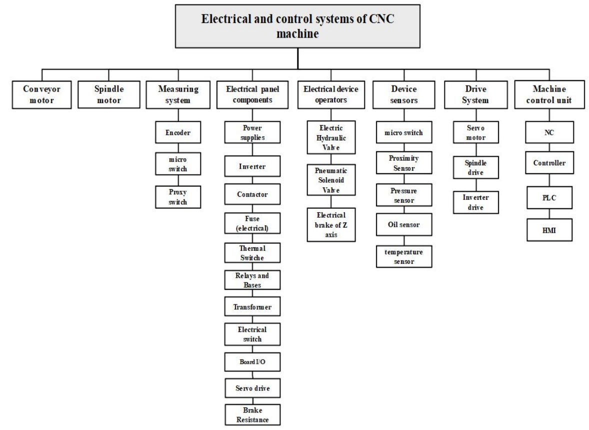

Fig. 2. A structural diagram of CNC machine's electrical and control systems

2-2. Determining all potential failure modes and defining scale of (S, O, D)

The result of the FMEA assessment including all modes and effects of functional failures and electronic components' failures are shown in Table A (as shown in in Appendix). The structure of the proposed model consists of two parts: the conventional method and fuzzy method (Fig. 3).

The FMEA's multi-specialist team was formed to collect information and analyze the failure modes. First, all subsystem failure modes and their potential effects were identified. Then, a risk number was assigned to each failure mode, and the sub-system with the highest risk rating was determined. To determine the severity of the failure and probability of misidentifying the failure or lack of ability for its detecting, related information is gathered from the experts of the FMEA team. In conventional FMEA method, the risk number is used to prioritize the risk modes or failures. The number of risk indexes or risk priority number (RPN) is obtained by product of three numbers: severity (S), occurrence probability (O), and number of detection (D). For each of S, O, and D indicators, the used number is placed between 1 and 10. These numbers will help the FMEA team to prioritize the failure mods and their effects [22].

Details and guide for language ratings for parameters S, O, and D are given in Table 1. The FMEA team specialists have different views on each of S, O, and D indices for each of the subsystems depending on their information, experience, and intellectual attributes. Therefore, a combination of expert opinions should be used for this purpose [23].

Furthermore, the values of risk assessment indicators will be influenced by several factors including the knowledge, perspectives, and individual goals of the experts; therefore, a completely neutral assessment is very difficult. On the other hand, the FMEA team in terms of age, expertise, skill, experience, knowledge level, etc. are almost heterogeneous [18].

The characteristics of specialist are given in Table 2 and are presented based on their weighted values in Table 3. To calculate the RPN, as a general approach, two methods are used. In the first method, the weighted averages of S, O, and D indices are obtained. Then, the RPN is calculated using Eq. (1). In the second method, weighed averages of the specialists are calculated (Eq. (2)).

$$S_m=\sum_{i=1}^{4} w_i S_i,\; O_m=\sum_{i=1}^{4} w_i O_i,\; D_m=\sum_{i=1}^{4} w_i D_i,\; RPN_m=S_m O_m D_m \tag{1}$$

$$RPN_w=\sum_{i=1}^{4} w_i RPN_i \tag{2}$$

Tab. 1. Linguistic scale for risk parameters. (Rank)

Linguistic term	Severity of effect (S)	Probability of occurrence (O)	Detectibility (D)
Remote (R)	A failure has little or no impact on the system, and the operator probably will not notice. (1)	A failure will be detected almost certainly by the inspection automatically of the whole process. (1)	A failure will be detected almost certainly by the inspection automatically of the whole process. (9, 10)
Low (L)	A failure causes slight annoyance to operator, and no deterioration on system.(2, 3)	A failure will be detected until the review inspected or test but not automatically. (2,3)	A failure will be detected until manual inspection or test carried out. (7, 8)
Moderate (M)	A failure causes slight deterioration in system performance and a high level of operator dissatisfaction. (4, 5, 6)	A failure will be detected until manual inspection or test carried out. (4, 5, 6)	A failure will be detected until the review inspected or test but not automatically. (4, 5, 6)
High (H)	A failure causes significant deterioration or inoperation on the system. (7, 8)	A failure will be detected only with thorough inspection or test, and it is not feasible to be done. (7, 8)	A failure will be detected only with thorough inspection or test, and it is not feasible to be done. (2, 3)
Very high (VH)	A failure causes extremely impact on system, production loss and/or serious injury to operators. (9, 10)	A failure will be detected hardly because of no known measure to solve. (9, 10)	A failure will be detected hardly because of no known measure to solve. (1)

Tab. 2. Score rating according to expert's traits.

Item	Categorize	Score	Item	Categorize	Score
Education	PhD	5	Profession position	Higher-ranking academic	5
	Master	4		Low-ranking academic	4
	Bachelor	3		Engineer	3
	Associate	2		Technician	2
	Diploma	1		Worker	1
Age	More than 40	4	Job Tenure	More than 20 years	5
	36–39	3		16–20	4
	30–35	2		10–15	3
	Less than 30	1		6–9	2
				≤5	1

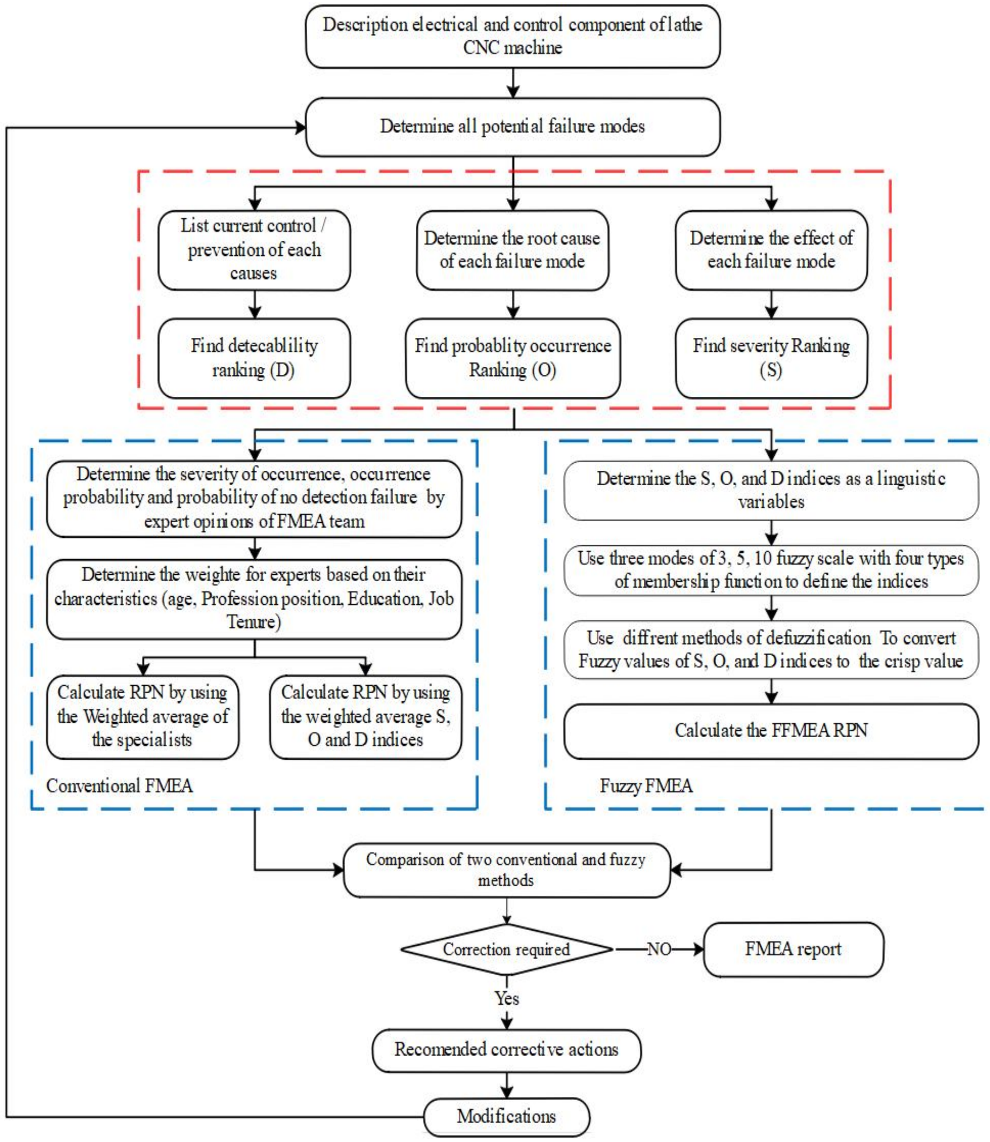

Fig. 3. A Framework of Fuzzy-FMEA model

Tab. 3. Expert weighting of group decision-making.

Expert	Education	Age	Profession position	Job Tenure	Weighting score (w)
Expert 1:	Associate (2)	39 (3)	Technician (2)	16 (4)	0.23
Expert 2:	Master (4)	38 (3)	Engineer (3)	17 (4)	0.29
Expert 3:	Master (4)	32 (2)	Technician (2)	10 (3)	0.23
Expert 4:	Master (4)	34 (2)	Engineer (3)	13 (3)	0.25
Total	14	10	10	14	48/48=1

2-3. Application of fuzzy FMEA to a lathe CNC machine

The Fuzzy Developed Failure Mode and Effects Analysis (FDFMEA) method was used as an alternative for calculating the RPN of electrical and control components of CNC lathe machines [20].

The Fuzzy FMEA method procedure is shown in Fig. 3. The purpose of ranking the risk factors using the Fuzzy FMEA method is to identify and rank potential failure and defects. Three indices of S, O, and D were determined by the experts as linguistic variables. To define S, O, and D indices, three modes of 3-scale, 5-scale, and 10-scale scales were used along with four types of membership function including: Triangular-shaped (Trimf), Trapezoidal-shaped (Trapmf), Π-shaped (Pimf) and Gaussian combination (Gauss2mf) (Tables 4 , 5, and 6).

Tab. 4. Fuzzy 3-scale with 4 Membership functions

Rank	Linguistic expression	MF function	Fuzzy number
1, 2, 3	Low (L)	Trapmf	(0.0, 0.0, 0.2, 0.04)
		Gauss2mf	(0, 0, 0.07, 0.22)
		Pimf	(0.0, 0.0, 0.22, 0.38)
4, 5, 6, 7	Medium (M)	Trimf	(0.2, 0.5, 0.8)
		Trapmf	(0.23, 0.47, 0.53, 0.77)
		Gauss2mf	(0.10, 0.47, 0.10, 0.53)
		Pimf	(0.23, 0.47, 0.53, 0.77)
8, 9, 10	High (H)	Trapmf	(0.6, 0.8, 1.0, 1.0)
		Gauss2mf	(0.07, 0.08, 0.0, 1.0)
		Pimf	(0.62, 0.78, 1.0, 1.0)

Tab. 5. Fuzzy 5-scale with 4 Membership functions

Rank	Linguistic expression	MF function	Fuzzy number
1	Very low (VL)	Trapmf	(0.0, 0.0, 0.1, 0.2)
		Gauss2mf	(0.0, 0.0, 0.03, 0.11)
		Pimf	(0.00, 0.00, 0.11, 0.19)
2, 3	Low (L)	Trapmf	(0.1, 0.2, 0.3, 0.4)
		Trimf	(0.05, 0.25, 0.45)
		Gauss2mf	(0.03, 0.19, 0.03, 0.31)
		Pimf	(0.11, 0.19, 0.31, 0.39)
4, 5, 6	Medium (M)	Trapmf	(0.3, 0.4, 0.6, 0.7)
		Trimf	(0.20, 0.50, 0.80)
		Gauss2mf	(0.03, 0.39, 0.03, 0.61)
		Pimf	(0.31, 0.39, 0.61, 0.69)
7, 8	High (H)	Trapmf	(0.6, 0.7, 0.8, 0.9)
		Trimf	(0.55, 0.75, 0.95)
		Gauss2mf	(0.03, 0.69, 0.03, 0.81)
		Pimf	(0.61, 0.69, 0.81, 0.89)
9, 10	Very high (VH)	Trapmf	(0.8, 0.9, 1.0, 1.0)
		Gauss2mf	(0.03, 0.89, 0.00, 1.00)
		Pimf	(0.81, 0.89, 1.00, 1.00)

Tab. 6. Fuzzy 10-scale with 4 Membership functions

Rank	LE	MF function	Fuzzy number	Rank	LE	MF function	Fuzzy number
1	Very low (VL)	Trimf	(0.0, 0.1, 0.2)	6	Medium (M)	Trimf	(0.5, 0.6, 0.7)
		Trapmf	(0.01, 0.09, 0.11, 0.19)			Trapmf	(0.51, 0.59, 0.61, 0.69)
		Gauss2mf	(0.03, 0.09, 0.03, 0.11)			Gauss2mf	(0.03, 0.59, 0.03, 0.61)
		Pimf	(0.01, 0.09, 0.11, 0.19)			Pimf	(0.51, 0.59, 0.61, 0.69)
2	Very low (VL)	Trimf	(0.1, 0.2, 0.3)	7	High (H)	Trimf	(0.6, 0.7, 0.8)
		Trapmf	(0.11, 0.19, 0.21, 0.29)			Trapmf	(0.61, 0.69, 0.71, 0.79)
		Gauss2mf	(0.03, 0.19, 0.03, 0.21)			Gauss2mf	(0.03, 0.69, 0.03, 0.71)
		Pimf	(0.11, 0.19, 0.21, 0.29)			Pimf	(0.61, 0.69, 0.71, 0.79)
3	Low (L)	Trimf	(0.2, 0.3, 0.4)	8	High (H)	Trimf	(0.7, 0.8, 0.9)
		Trapmf	(0.21, 0.29, 0.31, 0.39)			Trapmf	(0.71, 0.79, 0.81, 0.89)
		Gauss2mf	(0.03, 0.29, 0.03, 0.31)			Gauss2mf	(0.03, 0.79, 0.03, 0.81)
		Pimf	(0.21, 0.29, 0.31, 0.39)			Pimf	(0.71, 0.79, 0.81, 0.89)
4	Low (L)	Trimf	(0.3, 0.4, 0.5)	9	Very high (VH)	Trimf	(0.8, 0.9, 1.0)
		Trapmf	(0.31, 0.39, 0.41, 0.49)			Trapmf	(0.81, 0.89, 0.91, 0.99)
		Gauss2mf	(0.03, 0.39, 0.03, 0.41)			Gauss2mf	(0.03, 0.89, 0.03, 0.91)
		Pimf	(0.31, 0.39, 0.41, 0.49)			Pimf	(0.81, 0.89, 0.91, 0.99)
5	Medium (M)	Trimf	(0.4, 0.5, 0.6)	10	Very high (VH)	Trimf	(0.9, 1.0, 1.0)
		Trapmf	(0.41, 0.49, 0.51, 0.59)			Trapmf	(0.91, 0.99, 1.00, 1.00)
		Gauss2mf	(0.03, 0.49, 0.03, 0.51)			Gauss2mf	(0.03, 0.99, 0.00, 1.00)
		Pimf	(0.41, 0.49, 0.51, 0.59)			Pimf	(0.91, 0.99, 1.00, 1.00)

LE: Linguistic expression, MF: Membership function

Aggregating the Fuzzy FMEA method is conducted by the following steps:

1- Calculating degree of similarity between opinion of every two experts S(A˜,B˜) Eq. (3):

$$S(\tilde{A},\tilde{B}) = 1 - \frac{1}{J}\sum_{i=1}^{J}\left|a_i - b_i\right| \qquad (3)$$

where J is the parameters of the membership function; (a) and (b) are also the parameters of the membership function for each of S, O, and D indices for every two experts. White closing $S(\tilde{A},\tilde{B})$ value to the unit, the similarity between the two fuzzy sets of $\tilde{A}$ and $\tilde{B}$ are obtained their maximum values.

2- Computing the Relative Agreement (RA) degree (AA(E_u)) of experts' opinions in Eq. (4):

$$AA(E_u) = \frac{1}{J-1}\sum_{v=1,u\neq v}^{J} S(\tilde{R}_u,\tilde{R}_v) \qquad (4)$$

3- Computing the Relative Agreement (RA(E_u)) degree of experts' opinions in Eq. (5):

$$RA(E_u) = \frac{AA(E_u)}{\sum_{u=1}^{J} AA(E_u)} \qquad (5)$$

4. Calculating the consensus coefficient degree of experts' opinions in (CC (E_u)) Eq. (6):

$$CC(E_u) = \beta W(E_u) + (1-\beta).RA(E_u) \qquad (6)$$

where W is the weight of each experts, and β is relaxation factor based on which $0 \le \beta \le 1$.

5. Computing the final result of experts' opinions ($\tilde{R}_{AG}$)
In Eq. (7):

$$\tilde{R}_{AG} = CC(E_1)\otimes\tilde{R}_2 \oplus CC(E_2)\otimes\tilde{R}_2 \oplus \ldots \oplus CC(E_m)\otimes\tilde{R}_M \qquad (7)$$

where ⊕ is a fuzzy sum operation, and ⊗ is a fuzzy scalar multiplication operation.
$\tilde{R}_{AG}$ is a fuzzy set in which the defuzzification method must be used to calculate explicit RPN values.
In this research, five defuzzification methods were used: contains centroid of the area under the

output fuzzy set (centroid), bisector of the area under the output fuzzy set (bisector), mean of the values for which the output fuzzy set is maximum (mom), largest value for which the output fuzzy set is maximum (lom), and smallest value for which the output fuzzy set is maximum (som).

3. Results and Discussion

In this section, the results obtained by implementing conventional FMEA method and Fuzzy FMEA method for electrical and control components in axis lathe machine are presented. In order to analyze the risk of electrical and control system, in the first step, the conventional method is used to rank the RPNs for each expert and determines the priority rank of each of 30 subsystems according to the experts' opinion. In the next section, result and discussion of implementing the novel fuzzy method of Fuzzy FMEA, for three scenarios of S, O, and D indices' definition, in the form of 3-scale, 5-scale, and 10-scale, are presented by using four membership functions and five defuzzifications. Then, the results of the sensitive analysis to rank subsystem risk level with respect to S, O, and D variations are presented.

3-1. Conventional FMEA

In Table 7, RPNs' values for each of 30 CNC electronic and control subsystems for four experts with their priority rank are given. Since the results showing priority rank of subsystems according with the experts' opinions vary. However, all the experts' high-level opinions are the same for the first and second subsystems. For example, the 5th and 27th subsystems have priority ranks of 1 and 2, respectively. Although the RPN values of the subsystem obtained by experts' opinions are different from each other. For example, the RPNs of the 27th subsystem with priority rank of 1 for the first to 4th experts are 350, 315, 360, and 360, respectively. Furthermore, priority risks of subsystems from the 3th priority to end priority are different from each other. It is noteworthy that any experts could not cluster 30 subsystems in 30 risk groups. Accordingly, the first to 4th experts have grouped 30 subsystems into 20, 21, 22, 23 clusters. Its means that several different subsystems have the same priority rank. For example, the 7th,8th,10th subsystems in the first expert' opinion have the same priority rank of 7. This result also is obtained for other experts. This problem is considered as withdrawn for conventional FMEA method. Therefore, it is necessary to consider all experts' opinions and achieve maximum cluster numbers (equal to subsystem numbers).

To verify the effects of experts' opinions and subsystems on RPN value, the randomized complete block design was used. The analysis of variance was conducted using subsystem factor and expert as experimental treatment and block, respectively. The results of the analysis of variance for the randomized complete block design are presented in Table 8. As shown by the P-Value, the effects of the subsystem and experts on RPN value are 1% and 5%, respectively, that can be considered as meaningful value. Moreover, the percentage of contribution (PC) is shown whose effects of the subsystem and experts on RPN value are 95% and 56%, respectively. The results of the comparison between the averages of RPN for experts using LSD method are shown in Fig. 4. These results confirm that there are four distinctive experts in two statistic groups. Therefore, to calculate the RPN, the expert results should be averaged.

F = Failure mode; S=Severity**;** O=Occurrence; D=Detection; P=Prioritization.

Tab. 7. RPN values of the subsystems of CNC machine and their priority rank (P) for four experts

	Expert 1		Expert 2		Expert 3		Expert 4	
F	RPN	P	RPN	P	RPN	P	RPN	P
1	135	8	160	5	144	8	135	11
2	150	5	180	3	160	6	150	8
3	48	19	64	19	72	18	63	21
4	75	13	64	19	100	15	80	18
5	**336**	**2**	**288**	**2**	**324**	**2**	**294**	**2**
6	120	9	128	8	135	10	120	14
7	140	7	144	6	140	9	144	9
8	140	7	126	9	192	4	175	5
9	96	11	120	10	140	9	128	12
10	140	7	140	7	168	5	144	9
11	48	19	64	19	64	20	63	21
12	180	4	168	4	210	3	210	3
13	180	4	168	4	150	7	168	6
14	64	15	72	17	112	13	72	19
15	60	16	84	15	60	21	90	16
16	105	10	120	10	120	12	84	17
17	56	17	80	16	120	12	105	15
18	70	14	108	11	70	19	80	18
19	56	17	63	20	72	18	56	22
20	105	10	105	12	96	16	140	10
21	70	14	90	14	60	21	126	13
22	105	10	96	13	105	14	105	15
23	120	9	168	4	120	12	160	7
24	84	12	126	9	126	11	84	17
25	42	20	70	18	40	22	70	20
26	60	16	72	17	60	21	72	19
27	**350**	**1**	**315**	**1**	**360**	**1**	**360**	**1**
28	196	3	168	4	210	3	196	4
29	144	6	160	5	126	11	144	9
30	50	18	40	21	75	17	50	23

Tab. 8. Analysis of variance of subsystems RPN by randomized complete block design

Source of variation	DF	SS	PC (%)	MS	F-Value	P-Value
Treatment (sub system)	29	546235	95.00	18835.7	64.19	0.000
Block (Expert)	3	3197	0.56	1065.6	3.63	0.016
Error	87	25528	4.44	293.4		
Total	119	574960	100.00			

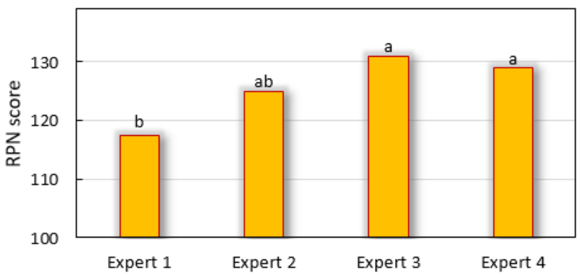

Fig. 4. The results of the comparison between the RPN averages for four experts by LSD method

The RPN values of each subsystem using product of weighted average of one of three S, O, and D indices (Eq. (1)) and, also, using the product of weighted average of the RPN for four experts (Eq. (2)) along with the priority rank are shown in Figures 5(a),(b), respectively. There is no meaningful difference between the RPN through two methods. Although their priority rank is slightly different from each other (for example, priority risk level of the first and 29th subsystems have displacement), every subsystem has a unique priority risk, meaning that there are no two subsystems with the same RPN; therefore, the result of assessing the FDFMEA fuzzy method is obtained.

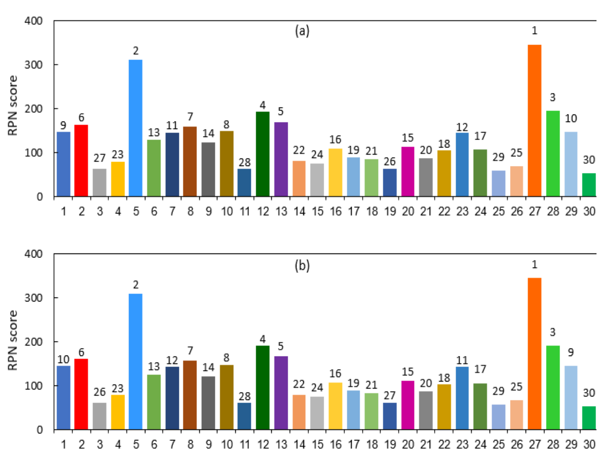

Fig. 5. The RPN scores of the subsystems were determined by product of weighted averages of S, O, and D (a) and weighted averages of the subsystems RPN (b).

3-2. Fuzzy FMEA

The Fuzzy FMEA method also used as an alternative for calculating RPN and risk priority level of subsystems. The assessment results of Fuzzy FMEA method for three modes of definition for RPN, in the form of 3-scale, 5-scale, and 10-scale, are presented by using four membership functions and five defuzzifications. The results of implementing four membership functions for 3-scale, 5-scale, and 10-scale and fuzzy value of RPN and priority results are given in **Fig**ures 6,7,8. The results obtained through a statistical comparison of the RPN averages of implementing four membership functions for 3-scale, 5-scale, and 10-scale suggested that there was not any meaningful difference between these results. In other words, the type of membership functions has not influenced RPN's value. However, the comparison of the RPN averages obtained from the three scales for each type of membership function showed that they had a significant difference. The averages of RPN obtained by 5-scale and 10-scale modes were not significantly different; however, their difference with 3-scale was significant. The averages of RPNs' values in 3-scale, 5-scale, and 10-sacle modes were 91.00, 128.20, and 124.70, respectively. Therefore, the number of scale in the definition of S, O, and D indices has a significant effect on RPN values. The results of 3-scale implementation show that, in this case, the Fuzzy FMEA method failed to cluster 30 subsystems into 30 risk groups; instead, it classified 30 failed modes in 22 clusters. In other words, the results of the conventional FMEA method are better than those of 3-scale for the fuzzy FMEA method. For example, in this case, the RPN values of subsystems 1 and 2 are equal to 141. Such results are also seen for other subsystems such as 10, 12, 3, 16, 17, 24, and 30. The results of the 5-scale implementation show that the performance of the Fuzzy FMEA method has improved. Nevertheless, 30 subsystems are grouped in 29 clusters. Only the RPN values of two subsystems of 16 and 17 are equal to 94. The results of the 10-scale implementation showed that the Fuzzy FMEA method successfully grouped 30 sub-systems in 30 clusters. Therefore, the number of scales is a very important parameter in the performance of the Fuzzy FMEA method.

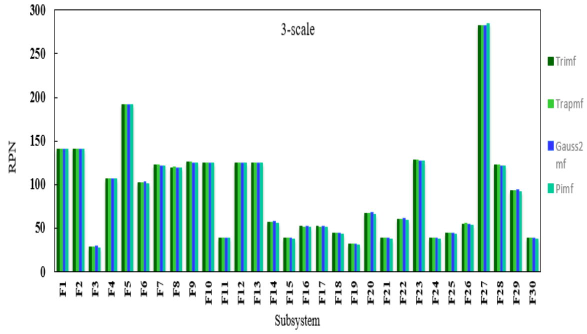

Fig. 6. The results of using a 3-scale fuzzy method for different membership functions

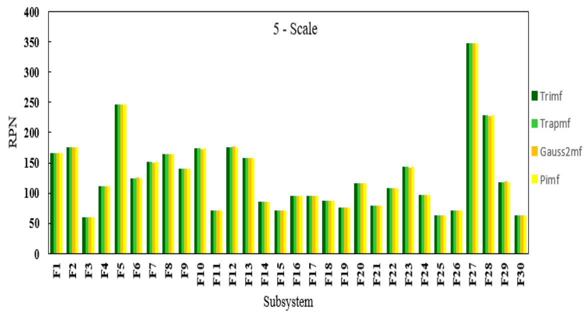

Fig. 7. The results of using 5-scale fuzzy method for different membership functions

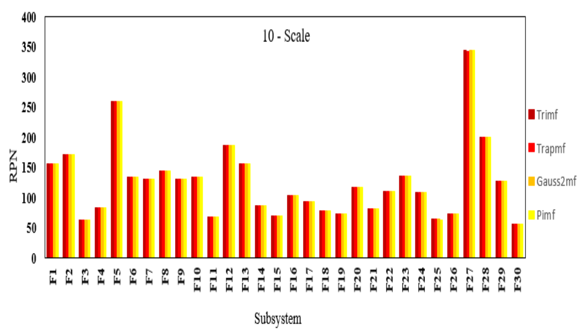

Fig. 8. The results of using 10-scale fuzzy method for different membership functions

In this respect, the best performance of the Fuzzy FMEA method is achieved with a 10-scale implementation. Here, the defuzzification methods are evaluated (Table 9). The results show that the three methods of defuzzification, namely centroid, bisector, and mom, presented the same RPN values without significant differences (at the 5% level). In addition, the two methods, lom and som, presented the highest and the lowest RPN values, respectively. In addition, the lom method generated the same values of RPN for two subsystems of 9 and 29.

Tab. 9. The results of using different defuzzification methods.

F	centroid		bisector		mom		lom		som	
	RPN	P	RPN	P	RPN	P	RPN	P	RPN	P
1	157	6	159	7	159	6	188	6	129	7
2	171	5	173	5	177	5	210	4	144	5
3	63	29	64	28	64	28	77	27	51	28
4	84	21	86	21	86	21	103	20	68	21
5	259	2	260	2	260	2	312	2	208	2
6	134	11	135	10	135	10	162	10	108	10
7	131	12	130	13	130	13	155	12	104	13
8	144	8	144	8	144	8	173	8	115	8
9	130	13	130	12	130	12	154	13	105	12
10	135	10	136	9	136	9	163	9	109	9
11	68	27	68	27	68	27	82	26	55	27
12	186	4	184	4	184	4	204	5	163	4
13	157	7	159	6	157	7	181	7	133	6
14	86	20	87	20	87	20	103	19	70	20
15	70	26	69	26	69	26	83	25	55	26
16	104	18	105	18	105	18	126	16	84	18
17	93	19	94	19	94	19	113	18	75	19
18	79	23	81	23	81	23	97	22	64	23
19	74	24	75	24	74	24	88	23	60	25
20	117	15	115	15	115	15	138	14	92	16
21	82	22	81	22	81	22	98	21	65	22
22	110	16	111	16	111	16	133	15	88	17
23	136	9	135	11	135	11	162	11	108	11
24	108	17	107	17	108	17	116	17	99	15
25	64	28	64	29	58	29	75	28	41	30
26	73	25	73	25	73	25	87	24	60	24
27	343	1	345	1	345	1	368	1	322	1
28	200	3	201	3	203	3	219	3	187	3
29	127	14	129	14	129	14	154	13	103	14
30	56	30	55	30	55	30	66	29	44	29

Fig. 9 shows the individual value plot for the RPNs' values derived from the two conventional FMEA methods, including the product of the weighted average of S, O, and D (Conv1) and the weighted average of RPN experts (Conv2), as well as the RPN derived from the Fuzzy FMEA method with 10-scale and five defuzzification methods. Accordingly, the centroid defuzzification method can be selected as the best method since the resulting RPN values have the highest resolution. In other words, the two closest subsystems have RPNs with highest differences.

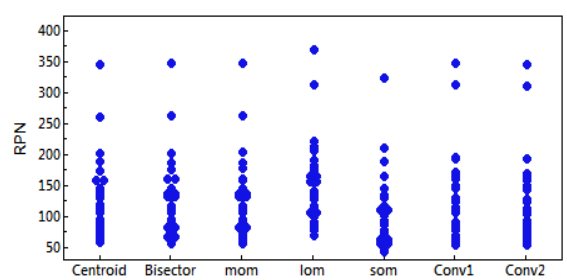

Fig. 9. Individual value plot of RPN

3-3. Sensitivity analysis

In order to verify the sensitivity of RPN and risk priority to variations in experts' opinions and,

subsequently, variations in determining the parameters of S, O, and D, the sensitivity analysis method was used. The results of the Fuzzy FMEA sensitivity analysis indicating the variations in S, O, and D indices are shown in Fig. 10. To perform the sensitivity analysis and determine the influences of these changes on the Fuzzy RPN and their risk priority in comparison with the original state, three quantities equal to 1, 2, and 3 units are added to or subtracted from each of S, O and D indices values from each expert. In each case, only one of the three values of S, O and D indices was changed, and the other two indices were kept unchanged.
As the results show, the increase and decrease of the S value by approximately 1 unit has no influence on RPN values and their prioritization. However, increasing S value by 2 or 3 units has the greatest positive impact on fuzzy RPN values, especially on its risk priority. Therefore, RPN value shows higher sensitivity to the higher amount of S in comparison with the lower amount of it.
However, there was no change in the first three risk priorities, and variation in index S had the least effect on RPN values in comparison with O and D indices' variations. The variations of RPN and the risk priority of the failure modes are dependent on the positive and negative changes in index O (Fig 10.b), as the increase of 3 units increasing in index O caused the substitution between the first and second priorities. Moreover, the comparison of the sensitivity analysis of the three indices shows that, in terms of the RPN variation, index O is more effective than other two indices. On the other hand, the changes in index D caused variation in RPN; thus, the increase in index D results in the increase of the RPN, and the decrease of index D results in the decrease of the RPN with the minimum change in the risk priority of the failure modes. Furthermore, the reduction of index D by 3 units had the most influence on the RPN variation. Therefore, considering the above results, O, S, and D indices, respectively, have the most effect on the variation of RPN and risk priority of the failure mode.

3-4. Risk clustering

As the results of both conventional and Fuzzy FMEA methods show, failure modes can be prioritized at 30 risk levels. However, some of the RPN values of the failure modes have small differences. Therefore, in this research, we plotted the dendrogram of RPN for the failure modes. Fig. 11 is arranged based on the Euclidian distance between the failure modes. As the results show, all of the 30 subsystems or failure modes can be clustered into three general risk groups. Two failure modes with priority of 1 and 2 are placed in the same risk cluster. Therefore, a similar maintenance policy can be used based on the dendrogram results for the failure modes that is placed in the same cluster.

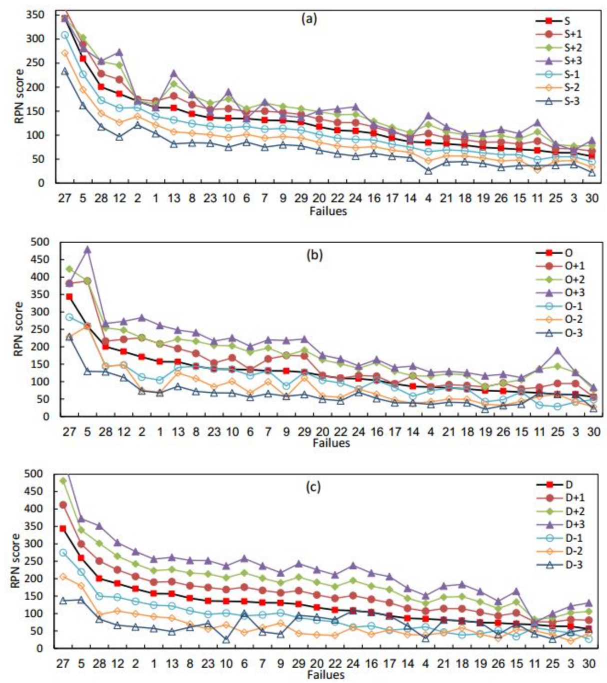

Fig. 10. Sensitivity analysis results for S, O, and D

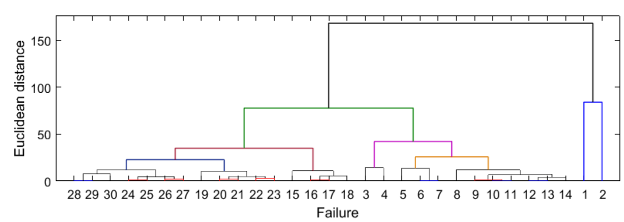

Fig. 11. The clustering of subsystems RPN

4. Conclusion

FMEA is a method for the reliability planning that identifies all system failures mods' accordance with the specified guidelines and leads to improvement of reliability by preventing failures. In this paper, by using the FMEA method and the analyst team, three parameters for estimating the effect severity, occurrence, and detection of each failure were determined to assess each failure mode of the electrical and control components of CNC lathe machines. In this paper, the performances of two conventional FMEA methods and Fuzzy FMEA method were investigated and compared with each other; for each expert, the weighted values were defined according to their characteristics. The results showed that the conventional FMEA method, using the weighted average, generated different RPN values for the 30 subsystems subjected to study. The results of using the Fuzzy FMEA method for three modes of definition for S, O, and D indices, in the form of 3-scale, 5-scale, and 10-scale, by using four membership functions, showed that the type of membership function did not have a significant effect on the RPN value. In addition, the results showed that the values of RPN obtained from the Fuzzy FMEA method had significant dependence on the number of scales used in S, O, and D definitions. The best result for the Fuzzy FMEA method was obtained for 10-scale mode. In addition, the centroid method was chosen as the best defuzzification method. The sensitivity analysis of the Fuzzy FMEA model showed that the RPN values were sensitive to higher values of S rather than to its low value. In addition, the comparison of the sensitivity analysis of all three indices shows that index O affects RPN variation greater than the two other indices do; in addition, O, S, and D indices have the most effect on the RPN value and the risk priority of failure modes, respectively. The results of clustering of risks using Euclidean distance between failure modes in 30 subsystems showed that all failure modes could be clustered into three risk groups. As a result, the same maintenance policy can be used based on dendrogram results for failure mods in the same cluster.

5. Recommendations and The Concept of Future Research

It is recommended to develop these study types for entire CNC Machine considering the collaborative decision-making method; for proper and complete analysis of performance and results and of the CNC machine failure modes, we can use robust data with high accuracy. Future research is required to use the Fuzzy FMEA assessment with operated priority to solve problems, and taking corrective actions should be assessed again to check whether the FRPNs of each failure can be reduced or not.

Acknowledgment

This research has been supported by the Scientific Research Project in collaboration with Ferdowsi University of Mashhad (Project Number: 19561) and Iranian Cylinder Bush manufacturer (Keyhan Sanat Ghaem Company). The authors would like to thank the Maintenance Department at the Keyhan Sanat Ghaem Company to provide the opportunity for this research, especially Mahdi Akbarpuor and Mr. Dolat doost for their valuable time spent on this research, and other Maintenance staff members who provided us with useful technical information**Appendix A.**

See Table A for details.

Tab. A. Main Failure Modes of Electrical and control systems of a CNC Lathe.

NO.	Subsystem	Potential failure modes	Potential effect(s) of failure	Potential cause (s)/failure mechanism
S1	NC	Defined errors, The desired accuracy in production is not provided.	The accuracy of production is lost, The machine stops.	Internal causes: Mechatronic tools failure due to power voltage fluctuation, External causes: Disruptions in Machine-related units like encoder, positioning Actuators failure like servo motor failure.
S2	Controller	Appearance Symptoms like breaking the keys of screen and so on. Delay startup or Hang up the controller.	Causing the collision of axes and clash of them with each other. Failure to move one or more axis. Workpiece failure. Breaking the tool (colett, and ...).	Voltage level changes at input and output. The failure of electronic components inside the controller such as: IC, optocoupler. Problems in cnc parameters like speed, acceleration and so on.

				Bug in ICs program. Stopping of input keys due to utilization.
S3	PLC	The PLC does not turn on Problem in the running of PLC program,	Stopping of machine, destroying the work piece.	Power voltage fluctuation, short circuit of input or output, Entry of particles or dust to PLCs Increasing of temperature in PLC,
S4	HMI	The screen is not displayed. HMI does not work.	Moving restriction and the problem in screen.	Failure in collectors and sockets. Failure of HMI Touch screen. Bug in internal programs.
S5	Servo motor	Servo motor does not work. Mistake on movement. Change in size in product.	The axis does not work. Causing of wrong size in product. Collision between axis and framework.	Encoder failure. Power supply with too much ampere. Z axis brake problems.
S6	Spindle drive	The drive does not work. Output was not provided.	Stopping of machine spindle.	Entry of dust into electronic circuit through the fan. Increase of environmental temperature. Power voltage fluctuation. Power supply with too much ampere. End of useful life of workpiece.
S7	micro switch	The axis does not move and alarm limit is displayed. The axis go until the end of path but the switch does not work and collision happens. The device is not referenced.	Collision between the axis and end of its path. The device is not referenced.	inappropriate condition: Pouring of water soap on it. Inappropriate setting. switch with Low quality. End of useful life of workpiece.
S8	Proximity Sensor	Replacement of work pieces is not done. The device is not referenced.	The workpieces are not selected correctly.	inappropriate condition: Pouring of water soap on it. Inappropriate setting. switch with Low quality. End of lifetime of the piece itself .
S9	Pressure sensor.	Hydraulic motor does not work. If the motor is induction motor, its phase changes. Disconnecting of a phase.	The System or device does not work. Alternatively, if the device's operating pressure is low, the device stops and gives alarm.	End of useful life of workpiece.
S10	Oil sensor.	The lubricant is finished. Lubrication is not done.	Causing damage to device seriously due to lack of lubrication.	End of useful life of workpiece.
S11	temperature sensor	Temperature alarm.	Temperature was not detected and Related units would be damaged.	End of useful life of workpiece.

S12	Electric Hydraulic Valve.	Electricity will not reach bobbin and the electronic order will not command the valve. Oil leakage (Oring's failure).spool Failure.	It affects clamp and unclamp.	- Bobbin failure - Oring's failure - spool Failure
S13	Pneumatic Solenoid Valve.	The desired electrical device such as hydraulic jack does not perform properly	Interruptions in the function of the components that control give commands by solenoid valve.	End of useful life of workpiece. Entry of undesired materials to wind parts Loose bobbins.
S14	Electrical brake of Z axis	The brake is not released. Due to axis rigidity, The drive alarms	The engine will be hot. The engine burns. It does not brake and the axis hits the end of the way due to excessive movement.	Problems in plc programming. Electrical relay failure. Failure wiring to I / O.
S15	Power supplies	No output voltage. The input voltage is not converted to the desired voltage.	It stops the circuit that uses the power supply.	power voltage fluctuation Power supply with too much ampere

Tab. A. (Continued)

NO.	Subsystem	Potential failure modes	Potential effect(s) of failure	Potential cause (s)/failure mechanism
S16	Inverter	The motor does not work. IGBT error. Not having the output corresponding current.	Causing stop in the motor that is under control.	Pass high current from output. wear out.
S17	Contactor	The motor does not work. The engine works with Two-phase. The control circuit does not work properly.	Failure of machine setup. Burning if not protected.	Entry of dust into bobbin Under the blade. Problems in determining of proper range.
S18	Fuse (electrical)	Connect and disconnect the current continuously. If phase 3's current becomes phase 2.	Disconnect the corresponding circuit.	Current fluctuation. The 3-phase current become 2 phases.
S19	Thermal Switch	The ampere range does not work properly.	It causes burning of an electric motor. Causing of problems in moving of motor.	Long working. Current fluctuation.
S20	Relays and Bases	The corresponding circuit command is not applied.	Stopping circuit.	Long working. Drag a large current.
S21	Transformer	No output voltage.	It causes to stop the machine.	Much heat Power supply with too much ampere
S22	Electrical switch	The machine is off The key does not connect Cutting off without any reason	Problems in turn on the machine.	Too much connect and Disconnect Applying in inappropriate current

				range. Extreme Short circuit in output
S23	Board I/O	Alarm error.	The machine will stopped completly.	Problems in input supply. Short circuit in output.
S24	Servo drive	IGBT. Drive error, e.g., IGBT	It causes to interrupt the servo.	Power supply with too much ampere. the engine is stuck. Entry of the dust into electronic circuit and increasing the Temperature.
S25	Brake Resistance	Power drive part is damaged seriously.	Causing of stop in the motor that is under control.	Passing of current over than allowed Limit on machine's instruction
S26	Encoder	Position error.	The position is not recognized correctly; thus, the axis does not move properly.	Moisture. Impact. Water soap leakage. Oil leakage.
S27	micro switch	The device is not referenced. Overtravel Error, yet the axis is not out of position.	The device is not referenced. The position does not recognize correctly and the axis may hit to end of the course.	Moisture. Impact. water soap leakage. Oil leakage.
S28	Proxy switch	The arm tool change does not work properly. Spindle gearbox does not work properly.	The device is not referenced. The position is not recognize correctly and the axis may hit to end of the course.	Moisture. Impact. water soap leakage. Oil leakage.
S29	Spindle motor	There are electronic and mechanical failures. Spindle does not spin. Rotation with sound and vibration.	Depending on the type of failure: The precision comes down. Does not work (does not rotate).	Error in cooling system. High pressure during machining. Bearing failure. Failure and loose belt. Check nut damage or loose.
S30	Conveyor motor	Do not spin the Conveyor.	The lathe location is not emptied of the particle.	Stuckking the conveyor. Power supply with too much ampere.

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