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Troubleshoot and Root Cause Analysis of CNC Machine Failures Using FMEA Tool in Terms of Reliability Maintenance

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Abstract
This paper aims to identify the root causes of failures in Computer Numerical Control (CNC) machines and analyze them using the Failure Mode and Effects Analysis (FMEA) technique in the modern automotive industry. CNC machines play a crucial role in manufacturing by ensuring high precision, efficiency, and repeatability. However, frequent failures result in significant downtime, reduced productivity, and increased maintenance costs. This study adopts a systematic approach by integrating Root Cause Analysis (RCA) with FMEA to identify critical failure modes and assess their impact. The associated risks are evaluated using the Risk Priority Number (RPN) method, enabling prioritization of failure modes. Based on the findings, appropriate corrective actions are proposed to improve machine reliability, minimize operational disruptions, and enhance overall efficiency in manufacturing processes.

Keywords: *CNC Machine; Root Cause Analysis (RCA); Failure Mode and Effects Analysis (FMEA); Maintenance; Reliability; RPN.*

1. Introduction

CNC machines are widely used for precision machining in automotive, aerospace, and manufacturing industries. Despite their advanced technology, CNC machines are prone to mechanical, electrical, and software-related failures. Traditional maintenance approaches often rely on reactive strategies, which result in unplanned downtime. Reliability-centered maintenance (RCM) integrates proactive methods, and FMEA serves as a key tool in identifying and mitigating risks. CNC machines play a vital role in modern manufacturing industries due to their ability to produce complex parts with high precision [1] and repeatability. However, machine failures can severely disrupt operations, reduce productivity, and increase operational costs. Failures in CNC systems arise from multiple sources, including mechanical wear, electrical faults, environmental conditions, and human errors. Recent studies emphasize that identifying and addressing root causes of failures is essential for improving reliability and minimizing downtime. Reliability-centred maintenance (RCM) combined with Failure Mode and Effects Analysis (FMEA) [2], provides a systematic approach to analyse failures and prioritize maintenance actions.

2. Literature Review

The literature indicates that reliability maintenance plays a crucial role in ensuring efficient operation of CNC machines. FMEA has been widely recognized as an effective tool for identifying potential failure modes and prioritizing maintenance actions. When combined with root cause analysis techniques, FMEA provides a structured approach for troubleshooting CNC machine failures and improving system reliability. Future research should focus on integrating FMEA with advanced technologies such as predictive maintenance, condition monitoring, and machine learning to enhance reliability maintenance strategies in modern manufacturing environments Shown in Table 1.

Table 1 Schematic Literature Review

Author/Year	Research Focus	Methodology/ Tools Used	Key Findings	Research Gap
Shafiee, Mahmood and et. al. (2019)	Application of FMEA in reliability engineering [3]	Failure Mode and Effects Analysis	Demonstrated that FMEA helps identify potential failure modes and prioritize corrective actions through Risk Priority Number (RPN).	Limited application in complex CNC manufacturing systems.
West, Jye, et al (2024)	Reliability Centered Maintenance (RCM)[4]	Preventive and predictive maintenance strategies	RCM improves system availability and reduces unexpected equipment failures in industrial systems.	Integration with CNC machine diagnostics requires further research.
Yazdi, Mohammad, et al. (2023)	Engineering maintenance and reliability [5]	Reliability analysis techniques such as FMEA and fault tree analysis	Maintenance planning improves system reliability and operational efficiency.	Lack of specific studies focusing on CNC machine failure mechanisms.
Pazhayattil, Ajay Babu, and Sanjay Sharma. (2025)	Failure analysis in manufacturing equipment [6]	FMEA and Root Cause Analysis (RCA)	Identified critical machine components and recommended preventive maintenance strategies.	Need for more case studies on CNC machine failure data.
Huang, Jia, et al. (2022)	Reliability assessment of manufacturing systems [7]	FMEA combined with reliability modeling	Improved failure prediction and maintenance planning in manufacturing systems.	Limited application in CNC machining environments.
Wang, Xiaoyan (2024)	CNC machine fault diagnosis [8]	Failure analysis techniques and reliability maintenance	Found that spindle systems and servo drives are major sources of CNC machine failures.	Need for structured troubleshooting frameworks.
Sun, Junkai, et al. (2023)	Maintenance optimization in CNC machines [9]	FMEA and risk priority number analysis	Identified high-risk failure modes and improved machine reliability by prioritizing maintenance tasks.	Integration with predictive maintenance technologies not explored.

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Windarto, Rofi Brianpratam, et al. (2023)	Root cause analysis of industrial machine failures [10]	Fishbone diagram and FMEA	RCA techniques help identify fundamental causes of machine failures.	Limited research focusing on CNC machines specifically.

2.1. FMEA History & CNC Machine Analysis

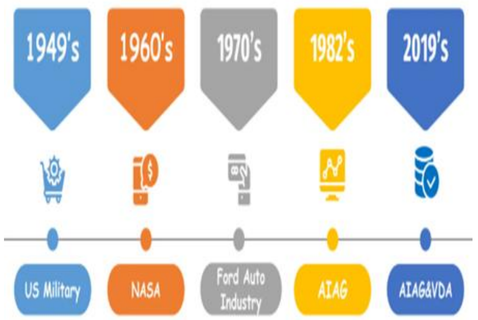

Figure 1 **History of FMEA**

- **1949s:** Developed by the U.S. military for reliability analysis
- **1960s:** Adopted by NASA for space missions (e.g., Apollo Program)
- **1970s:** Introduced in the automotive industry by Ford Motor Company
- **1982s:** Widely adopted in manufacturing and quality systems Shown in Figure 1
- **2019s:** Used across industries for risk analysis and continuous improvement

FMEA is widely used in industrial systems to identify potential failure modes and evaluate their impact based on severity, occurrence, and detectability. It helps prioritize risks using the Risk Priority Number (RPN). Recent research shows that FMEA is increasingly adopted in CNC machine reliability analysis [11] due to its structured approach to evaluating multiple failure dimensions.A 2025 study on CNC lathe machines applied FMEA to identify critical components and prioritize maintenance actions, demonstrating its effectiveness in reducing breakdown risks.

2.2. Root Cause Analysis in CNC Failures

Root cause analysis (RCA) aims to identify underlying causes rather than symptoms of failure. Common tools include:

- Fishbone Diagram
- Pareto Analysis
- Fault Tree Analysis

Recent work combining FMEA with RCA techniques found that spindle overheating, servo motor failure, and tool handling errors are major contributors to CNC failures.

2.3. Reliability Maintenance Approaches

Reliability-centred maintenance (RCM) focuses on optimizing maintenance strategies based on equipment criticality and failure behaviour. Studies indicate that integrating FMEA into computerized maintenance systems improves equipment effectiveness and reduces downtime [12].

3. Methodology

3.1. Research Framework

The methodology consists of the following steps:

- Identification of CNC machine components
- Detection of failure modes
- Determination of failure causes and effects
- Risk evaluation using FMEA
- Root cause analysis
- Development of corrective actions

3.2. Failure Mode and Effects Analysis (FMEA)

FMEA evaluates failures using three parameters:

- **Severity (S):** Impact of failure
- **Occurrence (O):** Frequency of failure
- **Detection (D):** Likelihood of detecting failure

$$RPN = S \times O \times D$$

Higher RPN values indicate higher priority risks.

3.3. Data Collection

Data sources include:

- Maintenance logs
- Operator feedback
- Machine performance records
- Historical failure data

4. Common CNC Machine Failures

Based on recent studies and industrial observations, the most common failures include:

4.1. Mechanical Failures

- Spindle wear or seizure

- Bearing failure
- Tool breakage

Spindle failure is often caused by poor lubrication and overload conditions

4.2. Electrical Failures

- Servo motor burnout
- Sensor malfunction
- Power supply instability

4.3. Pneumatic and Hydraulic Failures

- Valve leakage
- Air contamination
- Pressure fluctuations

Leakage in pneumatic systems is often linked to poor air quality and humidity Shown in Table 2.

4.4. Human Errors

- Incorrect programming
- Improper machine setup
- Lack of operator training

Human error is a significant contributor to CNC failures in modern manufacturing environments.

5. FMEA Analysis of CNC Machine Failures

Table 2 Common Failure list in CNC Grinding Machine Table with RPN Calculations

Component	Failure Mode	Cause	Effect	S	O	D	RPN
Spindle	Overheating	Poor lubrication	Machine shutdown	9	7	6	378
Servo Motor	Burnout	Overload	Production halt	8	6	5	240
Tool System	Breakage	Improper tool selection	Poor quality	7	5	4	140
Pneumatic Valve	Leakage	Air contamination	Pressure loss	6	7	6	252

6. Root Cause Analysis [13-15]

6.1. Fishbone Analysis

Key root causes include:

- **Machine:** Wear and tear
- **Method:** Poor maintenance schedules
- **Man:** Lack of training
- **Material:** Poor quality inputs
- **Environment:** Temperature and humidity

6.2. Pareto Analysis

Studies show that:

- 80% of failures are caused by 20% of issues
- Spindle, servo motor, and tool errors dominate failure causes.

7. Troubleshooting Strategies

7.1. Preventive Maintenance

- Scheduled lubrication
- Regular inspection of components
- Cleaning and calibration

7.2. Condition-Based Monitoring

- Vibration analysis
- Temperature monitoring
- Oil analysis

7.3. Operator Training

- CNC programming skills
- Machine handling
- Troubleshooting techniques

7.4. Use of Smart Maintenance Systems

Modern systems integrate FMEA with predictive analytics to reduce failure risks and improve reliability Shown in Figure 2.

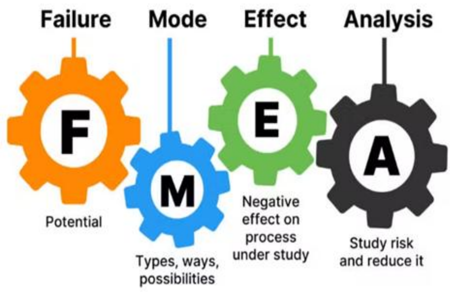

Figure 2 Schematic Representation of the Failure Mode and Effects Analysis (FMEA) Process

Conclusions and Future Research Direction

The integration of FMEA with root cause analysis provides a powerful framework for improving CNC machine reliability. By prioritizing high-risk components using RPN, maintenance teams can focus on critical areas and optimize resource allocation. Recent advancements include:

- AI-assisted FMEA generation
- Integration with IoT-based monitoring systems
- Advanced decision-making models

These approaches significantly enhance predictive maintenance capabilities. This study demonstrates that FMEA is an effective tool for troubleshooting and root cause analysis of CNC machine failures. By systematically identifying failure modes and prioritizing risks, organizations can improve reliability, reduce downtime, and optimize maintenance strategies. Future research should focus on integrating machine learning and real-time data analytics with FMEA for enhanced predictive maintenance.

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