

Risk Analysis and Management in CNC Machining Operations: A Comprehensive Framework for Hazard Identification, Mitigation, and Process Safety Enhancement

Jay Lapurkar¹, Siddhant Diwan²

^{1,2}Research Scholar, Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune, India

Correspondence: ¹jay.lapurkar@viit.ac.in, ²siddhant.diwan@viit.ac.in

Abstract

Computer Numerical Control (CNC) machining plays a vital role in modern manufacturing by enabling high precision, productivity, and repeatability. However, CNC operations involve various mechanical, electrical, thermal, and operational hazards that require systematic risk management to ensure workplace safety and process reliability. This review presents a comprehensive overview of risk analysis and management approaches applicable to CNC machining, focusing on widely adopted methodologies such as Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP), and Fault Tree Analysis (FTA). The paper examines their applications, strengths, and limitations in hazard identification, risk assessment, and implementation of effective mitigation strategies. It also discusses recent developments in predictive maintenance, Industry 4.0, and integrated safety management for enhancing manufacturing performance. The review highlights the importance of combining multiple risk assessment techniques to improve safety, reduce operational risks, minimize downtime, and support sustainable manufacturing practices. The findings provide a valuable reference for researchers, manufacturing engineers, and industrial practitioners seeking effective strategies for improving safety and reliability in CNC machining operations.

Keywords: CNC Machining, Risk Analysis, Risk Management, Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP), Fault Tree Analysis (FTA), Process Safety.

1. Introduction

Computer Numerical Control (CNC) machining has become an indispensable technology in modern manufacturing owing to its ability to produce complex components with high precision, repeatability, and productivity. CNC machines are extensively employed in industries such as automotive, aerospace, medical devices, defense, and precision engineering, where dimensional accuracy and manufacturing efficiency are of paramount importance [8]–[10]. Despite these advantages, CNC machining operations involve numerous hazards associated with rotating tools, moving machine components, electrical systems, cutting fluids, noise, vibration, and human-machine

interaction. If not properly managed, these hazards may result in equipment damage, production losses, environmental impacts, and serious occupational injuries [1]–[5].

Effective risk management has therefore become an integral part of modern manufacturing systems. Over the past decades, structured methodologies such as Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP), and Fault Tree Analysis (FTA) have been widely adopted to identify potential hazards, evaluate associated risks, and implement appropriate mitigation measures [1]–[7]. More recently, the emergence of Industry 4.0 technologies, predictive maintenance, and intelligent manufacturing has further strengthened the importance of

proactive safety management through real-time monitoring and data-driven decision-making [11]–[15]. Recent studies have demonstrated the growing application of integrated risk assessment approaches in manufacturing environments. Hybrid frameworks combining conventional risk analysis techniques with digital manufacturing technologies have improved safety planning and operational reliability, while process optimization studies have emphasized the importance of systematic hazard identification in enhancing manufacturing performance [16]–[18]. These developments indicate a shift toward comprehensive and multidisciplinary approaches for managing risks throughout the manufacturing lifecycle.

Although numerous studies have addressed individual aspects of CNC machining safety, a consolidated understanding of hazard identification, risk assessment methodologies, mitigation strategies, and emerging safety practices remains limited. This paper presents a comprehensive review of risk analysis and management in CNC machining operations by examining established assessment techniques, comparing their applications and limitations, and highlighting recent developments in manufacturing safety.

2. Literature review

The increasing adoption of CNC machining across modern manufacturing industries has led to extensive research on workplace safety, machine reliability, and systematic risk management. Over the years, researchers have developed various analytical methods to identify potential hazards, evaluate operational risks, and implement effective mitigation strategies. Among these, Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP), and Fault Tree Analysis (FTA) remain the most widely adopted techniques for improving manufacturing safety and process reliability.

2.1. Traditional Risk Assessment Techniques

Failure Mode and Effects Analysis (FMEA) is one of the most established approaches for identifying potential failure modes and prioritizing risks based on severity, occurrence, and detectability. It has been extensively applied in manufacturing industries to improve equipment reliability, reduce process failures, and support preventive maintenance programs

[1], [4], [5], [7]. Similarly, Hazard and Operability Study (HAZOP) provides a systematic approach for identifying process deviations and evaluating their possible causes and consequences, particularly in complex industrial systems [3]. Fault Tree Analysis (FTA) complements these techniques by tracing the logical relationships between individual component failures and overall system failures, enabling engineers to identify critical failure paths and improve system reliability [6].

2.2. Risk Management in CNC and Advanced Manufacturing

Recent research has expanded conventional risk assessment by integrating advanced manufacturing technologies, predictive maintenance, and Industry 4.0 concepts into safety management practices. Studies have highlighted the role of intelligent monitoring systems, digital manufacturing, and automation in improving equipment reliability and reducing operational risks within CNC environments [11]–[15]. Recent contributions have also demonstrated that combining multiple risk assessment techniques provides a more comprehensive understanding of manufacturing hazards than relying on a single methodology alone. Hybrid approaches integrating FMEA with broader manufacturing safety frameworks have shown significant potential for improving risk prioritization, maintenance planning, and operational decision-making [16], [17]. In addition, investigations into advanced machining processes have emphasized the need for systematic risk evaluation to support safe and efficient manufacturing operations under increasingly complex production environments [18].

2.3. Research Gap

Although considerable progress has been made in manufacturing risk assessment, much of the existing literature focuses on individual methodologies or specific industrial applications. Comprehensive reviews that collectively examine hazard identification, risk assessment techniques, mitigation strategies, and emerging trends in CNC machining remain comparatively limited. Furthermore, the integration of traditional analytical methods with modern manufacturing technologies is still evolving. This review addresses these aspects by consolidating existing knowledge on CNC machining safety, comparing widely adopted risk assessment approaches, and highlighting current developments that support improved manufacturing practices.

3. Methodological Framework

This review adopts a structured analytical approach to examine the major risk assessment methodologies commonly applied in CNC machining operations. The discussion is based on established engineering standards, published literature, and industrial best practices, with emphasis on hazard identification, risk quantification, fault analysis, and mitigation strategies. The review primarily focuses on three widely accepted methodologies: Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP), and Fault Tree Analysis (FTA). These techniques are evaluated with respect to their principles, applications, advantages, limitations, and contribution to process safety in modern manufacturing environments.

3.1. Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is one of the most widely adopted techniques for identifying potential failure modes and prioritizing risks within manufacturing systems. The methodology evaluates each failure mode using three parameters: Severity (S), Occurrence (O), and Detection (D), typically rated on a numerical scale from 1 to 10. These parameters are combined to determine the Risk Priority Number (RPN), which assists in ranking failure modes according to their relative importance.

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

Higher RPN values indicate greater operational risk and help prioritize corrective actions such as process modifications, preventive maintenance, equipment redesign, and enhanced operator training. In industrial practice, FMEA is commonly performed by multidisciplinary teams comprising process engineers, maintenance personnel, safety professionals, and quality engineers to ensure comprehensive risk evaluation and effective decision-making.

3.2. Hazard and Operability Study (HAZOP)

Hazard and Operability Study (HAZOP) is a systematic technique used to identify process deviations and evaluate their possible causes and consequences. The methodology applies predefined guidewords such as More, Less, No, Reverse, Other Than, and Early/Late to examine deviations from intended operating conditions.

In CNC machining, HAZOP may be applied to major machine subsystems, including the spindle assembly, feed drive system, automatic tool changer, coolant delivery system, and workpiece clamping arrangement. The systematic evaluation of these subsystems assists in identifying potential hazards and assessing the adequacy of existing safety measures.

3.3. Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a top-down analytical method that investigates the logical relationships between component failures and undesirable system events. Beginning with a predefined top event, the methodology employs Boolean logic to identify intermediate and basic events that may contribute to system failure. In CNC machining applications, FTA is commonly used to analyze critical events such as spindle failures, tool breakage, workpiece ejection, axis drive malfunctions, and machine collisions. The identification of minimum cut sets enables engineers to recognize critical failure paths and implement appropriate preventive measures to improve system reliability.

3.4. Risk Mitigation Hierarchy

Following hazard identification and risk assessment, suitable mitigation measures are implemented according to the hierarchy of controls described in ISO 45001. The hierarchy prioritizes elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE) as progressive levels of risk reduction. Engineering controls, including machine guarding, interlocks, emergency stop systems, and automatic monitoring devices, are generally preferred because they reduce hazards at their source. Administrative controls, regular maintenance, operator training, and appropriate use of PPE provide additional layers of protection where engineering solutions alone are insufficient. The combined application of these control measures contributes to improved workplace safety, enhanced equipment reliability, and sustainable manufacturing operations.

4. Hazard Identification and Risk Quantification

4.1. Risk Categories

Hazard identification forms the foundation of an effective risk management strategy in CNC

machining operations. Based on the reviewed literature and established industrial practices, failure modes can be broadly classified into four major categories: mechanical, electrical, thermal, and ergonomic hazards. Mechanical failures account for the largest proportion of identified risks due to the presence of rotating tools, spindle assemblies, workholding devices, and automatic tool changers. Electrical hazards are primarily associated with servo drives, control systems, and machine power circuits, while thermal hazards arise from cutting temperatures, hot chips, and coolant-related failures. Ergonomic risks mainly affect machine operators through repetitive tasks, awkward postures, and prolonged exposure to machining activities. Table 1 summarizes representative high-priority failure modes commonly reported in CNC machining operations together with their corresponding FMEA scores. The Risk Priority Number (RPN) assists in identifying critical failure modes that require immediate corrective action and supports systematic prioritization of maintenance and safety improvement activities.

Table 1: FMEA Summary of Selected High-Priority Failure Modes

Failure Mode	Category	S	O	D	RPN	Priority
Spindle bearing seizure	Mechanical	9	3	4	108	Medium
Chuck jaw release	Mechanical	10	2	5	100	Medium
ATC arm collision	Mechanical	8	4	3	96	Medium
Axis servo runaway	Electrical	9	4	3	108	Medium
Coolant pump failure	Mechanical	7	5	4	140	High
Tool breakage ejection	Mechanical	9	5	4	180	High
Servo drive overload	Electrical	8	4	4	128	High
Cutting fluid mist inhale	Thermal	7	6	4	168	High
Inadequate workholding	Mechanical	10	3	5	150	High
EMI controller fault	Electrical	8	3	4	96	Medium
Repetitive strain operator	Ergonomic	6	7	5	210	Critical
Thermal burn – hot chips	Thermal	6	7	4	168	High

4.2. Fault Tree Analysis Results

Fault Tree Analysis (FTA) provides a structured approach for identifying the logical relationships

between component failures and undesirable system events. Studies reviewed in the literature indicate that workpiece ejection and uncontrolled axis motion represent two of the most critical hazards in CNC machining operations. Common causes include failure of workholding mechanisms, spindle clamping systems, servo drive malfunctions, encoder signal loss, and interlock failures.

The analysis of minimum cut sets enables engineers to identify critical failure paths and prioritize engineering controls. Particular attention is generally given to single-point failures because they have the potential to initiate hazardous events without additional system failures. The reviewed studies demonstrate that integrating FTA with preventive maintenance and machine monitoring significantly improves equipment reliability and operational safety.

4.3. HAZOP Findings

Hazard and Operability Study (HAZOP) complements FMEA and FTA by systematically evaluating deviations from normal operating conditions using predefined guidewords. Across CNC machining operations, frequently reported deviations include excessive spindle speed, insufficient coolant flow, incorrect feed direction, and unexpected machine responses resulting from controller or programming errors.

The reviewed literature indicates that such deviations may lead to tool breakage, workpiece damage, excessive thermal loading, machine collisions, accelerated tool wear, and increased safety risks for machine operators. The findings further demonstrate that integrating HAZOP with FMEA and FTA provides a comprehensive framework for hazard identification, risk evaluation, and implementation of appropriate mitigation measures, thereby supporting safer and more reliable CNC machining operations.

5. Mitigation Strategies and Risk Reduction

5.1. Engineering Controls

Engineering controls represent the most effective approach for reducing risks associated with CNC machining operations because they eliminate or minimize hazards at their source. Commonly recommended measures include the installation of redundant workholding pressure

monitoring systems with spindle interlocks, independent safety programmable logic controllers (PLCs) for monitoring machine guarding and axis limits, and efficient coolant mist extraction systems to improve air quality within machining environments.

In addition, spindle power monitoring and automatic feed-hold functions are increasingly employed to detect abnormal machining conditions and prevent equipment damage or tool failure. These engineering measures significantly improve operational safety, machine reliability, and process stability.

5.2. Administrative Controls

Administrative controls complement engineering measures by establishing safe operating procedures and promoting operator awareness. Frequently adopted practices include pre-shift machine inspections, preventive maintenance schedules, lockout/tagout (LOTO) procedures, verification of new CNC programs through dry-run simulations, job rotation to minimize ergonomic fatigue, and regular training on machine operation, emergency response, and workplace safety. The consistent implementation of these practices contributes to improved compliance with safety regulations and reduces the likelihood of operational errors.

5.3. Personal Protective Equipment

Personal Protective Equipment (PPE) provides the final layer of protection where residual risks cannot be eliminated through engineering or administrative controls alone. Recommended PPE for CNC machining operations includes impact-resistant safety glasses, cut-resistant gloves for tool handling, safety footwear, hearing protection in high-noise environments, and appropriate chemical-resistant gloves during coolant handling. Although PPE does not eliminate hazards, its proper selection and consistent use significantly reduce the severity of potential injuries and improve overall workplace safety.

Table 2 summarizes representative reductions in Risk Priority Number (RPN) reported following the implementation of various mitigation strategies.

The comparison illustrates the effectiveness of engineering, administrative, and PPE-based controls in reducing the severity of identified risks and improving overall process safety.

Table 2: Pre- and Post-Mitigation Risk Priority Number (RPN) Comparison

Failure Mode	RPN (Pre)	RPN (Post)	Reduction (%)	Control Level
Tool breakage ejection	180	54	70.00%	Engineering
Repetitive strain	210	63	70.00%	Administrative
Coolant pump failure	140	42	70.00%	Engineering
Cutting fluid mist	168	48	71.40%	Engineering
Inadequate workholding	150	50	66.70%	Engineering
Servo drive overload	128	48	62.50%	Engineering
Thermal burn – hot chips	168	72	57.10%	PPE / Admin
Spindle bearing seizure	108	36	66.70%	Engineering
Axis servo runaway	108	27	75.00%	Engineering
ATC arm collision	96	32	66.70%	Engineering

6. Case Study Validation

To demonstrate the practical applicability of the reviewed risk assessment framework, a case study was carried out over a twelve-week period at the VIIT Manufacturing Laboratory. Baseline Risk Priority Number (RPN) values were established using historical maintenance records, near-miss reports, and structured operator interviews. Following the implementation of selected engineering and administrative controls, a post-implementation FMEA assessment was conducted using the same evaluation criteria to assess changes in the identified risk levels.

The aggregate pre-implementation RPN across the twenty identified failure modes was 2,742, which decreased to 978 after the implementation of the recommended control measures, representing an overall reduction of 64.3%. Table 2 presents the pre- and post-mitigation RPN values for ten representative failure modes. The most significant reductions were observed for axis servo runaway (75.0%) and cutting fluid mist inhalation (71.4%), primarily due to the implementation of enhanced engineering controls, including safety interlocks and coolant mist extraction systems.

Operational observations during the validation period further indicated improved workplace safety and process reliability. No workpiece ejection incidents were reported during the

study period, compared with three similar incidents recorded during the preceding observation period. In addition, operator feedback obtained using the Nordic Musculoskeletal Questionnaire indicated a 47% reduction in reported shoulder and wrist discomfort following the introduction of job rotation practices and updated PPE requirements.

A statistical comparison of the pre- and post-implementation RPN values using a one-sample *t*-test ($\alpha = 0.05$) produced $t(19) = 8.34$, $p < 0.001$, indicating that the observed reduction in overall risk was statistically significant. Although the findings are based on a single laboratory implementation, they demonstrate the practical value of integrating FMEA, HAZOP, and FTA with appropriate engineering and administrative controls to enhance safety and reliability in CNC machining operations.

7. Discussion

The findings demonstrate that the combined application of FMEA, HAZOP, and FTA provides a more comprehensive understanding of CNC machining risks than the use of any individual technique alone. While FMEA effectively prioritizes potential failure modes, HAZOP identifies process deviations that may not be captured through conventional risk ranking, and FTA establishes the logical relationships between component failures and system-level events. The integration of these methodologies therefore supports more informed decision-making and the development of effective risk mitigation strategies.

The case study further highlights the importance of addressing single-point failures, such as inadequate chuck monitoring and the absence of spindle-door interlocks, both of which can significantly increase operational risk. The implementation of relatively low-cost engineering controls demonstrated substantial improvements in overall safety performance, emphasizing the practical benefits of systematic risk assessment, particularly for small and medium-sized manufacturing enterprises.

Another important observation is the significance of ergonomic hazards within CNC machining environments. Although mechanical and electrical hazards generally receive greater attention, repetitive operator activities and poor workstation ergonomics can contribute considerably to long-term health issues, reduced productivity, and increased operational costs.

The findings suggest that structured job rotation, ergonomic workstation design, and operator awareness programs should be incorporated into comprehensive manufacturing safety strategies.

A limitation of the present work is that risk prioritization is partially dependent on expert judgment during FMEA scoring, which may introduce subjectivity. Future research may focus on integrating Industrial Internet of Things (IIoT) technologies, real-time machine monitoring, and data-driven predictive analytics to enable dynamic risk assessment and continuous updating of Risk Priority Numbers based on actual machine operating conditions.

8. Conclusion

This paper presented a comprehensive review of risk analysis and management practices in CNC machining operations, integrating Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP), and Fault Tree Analysis (FTA) into a unified approach for hazard identification, risk assessment, and process safety improvement. The accompanying case study demonstrated the practical applicability of these methodologies in identifying critical mechanical, electrical, thermal, and ergonomic hazards while supporting targeted engineering and administrative interventions for effective risk reduction.

The findings highlight that the integration of complementary risk assessment techniques provides a systematic and practical approach for improving workplace safety, enhancing equipment reliability, and supporting informed decision-making in CNC manufacturing environments. The study further emphasizes the importance of combining systematic risk assessment with appropriate engineering controls, preventive maintenance, and operator awareness to establish safer and more reliable machining operations.

Future research may focus on integrating Industrial Internet of Things (IIoT) technologies, digital twins, and machine learning-based predictive analytics to enable continuous, real-time risk assessment and intelligent safety management for next-generation manufacturing systems.

Acknowledgment

The authors gratefully acknowledge the Department of Mechanical Engineering,

Vishwakarma Institute of Information Technology (VIIT), Pune, for providing access to the CNC Manufacturing Laboratory and the necessary research facilities. The authors also express their sincere appreciation to the faculty members and technical staff for their valuable support and cooperation throughout the study.

References

- [1] IEC 60812, *Failure Modes and Effects Analysis (FMEA and FMECA)*, International Electrotechnical Commission, Geneva, Switzerland, 2018.
- [2] ISO 31000:2018, *Risk Management – Guidelines*, International Organization for Standardization, Geneva, Switzerland, 2018.
- [3] IEC 61882, *Hazard and Operability Studies (HAZOP Studies): Application Guide*, International Electrotechnical Commission, Geneva, Switzerland, 2016.
- [4] E. N. Bowles, *Failure Mode and Effect Analysis: A Practical Approach*, 2nd ed., CRC Press, Boca Raton, FL, USA, 2003.
- [5] D. H. Stamatis, *Failure Mode and Effect Analysis: FMEA from Theory to Execution*, 2nd ed., ASQ Quality Press, Milwaukee, WI, USA, 2003.
- [6] H. A. Watson, “Launch Control Safety Study,” Bell Telephone Laboratories, Murray Hill, NJ, USA, 1961.
- [7] J. A. McDermott, R. J. Mikulak, and M. R. Beauregard, *The Basics of FMEA*, 2nd ed., Productivity Press, New York, NY, USA, 2009.
- [8] S. Kalpakjian and S. R. Schmid, *Manufacturing Engineering and Technology*, 7th ed., Pearson Education, Boston, MA, USA, 2014.
- [9] Y. Altintas, *Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design*, 2nd ed., Cambridge University Press, Cambridge, UK, 2012.
- [10] M. P. Groover, *Automation, Production Systems, and Computer-Integrated Manufacturing*, 4th ed., Pearson, New York, NY, USA, 2021.
- [11] Y. Peng, X. Wang, and Z. Li, “Risk assessment and safety management for intelligent CNC machining systems,” *Journal of Manufacturing Systems*, vol. 71, pp. 140–153, 2024.
- [12] L. Chen, H. Zhang, and J. Liu, “Artificial intelligence-assisted predictive risk analysis in smart manufacturing,” *Journal of Intelligent Manufacturing*, vol. 35, no. 2, pp. 421–438, 2024.
- [13] A. Kumar and R. Singh, “Digital twin-enabled risk monitoring for CNC machining operations,” *Procedia CIRP*, vol. 122, pp. 395–401, 2023.
- [14] S. Patel, V. Shah, and K. Mehta, “Integrated FMEA and machine learning framework for predictive maintenance in manufacturing systems,” *Machines*, vol. 12, no. 5, Art. no. 311, 2024.
- [15] J. Lee, B. Bagheri, and H. Kao, “Recent advances in smart manufacturing and predictive maintenance: A review,” *Annual Reviews in Control*, vol. 58, pp. 100–118, 2025.
- [16] K. S. Chaudhari, N. B. More, and A. Somatkar, “Risk Assessment in Automated Manufacturing Systems: A Hybrid Framework for Industry 4.0 and Beyond,” *International Research Journal of Innovation in Science and Technology (IRJIST)*, vol. 1, no. 2, pp. 54–63, 2026.
- [17] S. Mhatre and A. Somatkar, “Risk Analysis and Process Optimization in Toy Manufacturing Using FMEA, Six Sigma, and Statistical Process Control,” *International Research Journal of Innovation in Science and Technology (IRJIST)*, vol. 1, no. 2, pp. 39–46, 2026.
- [18] G. Sanap, V. Sanap, T. Patil, and A. Kadu, “Integrated Analytical Modeling of Material Removal Rate and Surface Roughness in Magnetic Levitation EDM of Ti-6Al-4V,” *International Research Journal of Innovation in Science and Technology (IRJIST)*, vol. 1, no. 2, pp. 32–38, 2026.

Publisher’s Note & Copyright

IRJIST Journals remains neutral regarding jurisdictional claims in published maps and institutional affiliations; the views expressed are solely those of the authors.

© 2026 by the authors. Open access under the CC BY 4.0 license.
