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Risk in Active Manufacturing Plants: A Practical Multi-Hazard Approach

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Abstract

Manufacturing plants are complex environments where ongoing production exposes workers, equipment, and nearby communities to various types of risks. This study analyzes these risks during active production and presents a structured approach for identifying and evaluating them. A combination of established methods, including Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Bow-Tie analysis, was used to assess hazards across mechanical, chemical, electrical, ergonomic, and environmental domains. Data were collected from five large-scale manufacturing facilities in India, covering automotive, pharmaceutical, chemical, and electronics sectors. The analysis identified a total of 1,697 hazards, with mechanical hazards (28.4%), chemical exposure (22.1%), and process-related deviations (19.7%) emerging as the dominant risk categories, together accounting for over 70% of the total identified risks. The study further shows that the implementation of proactive strategies such as real-time monitoring, predictive maintenance, and anomaly detection can lead to a significant reduction in overall risk levels (approximately 40–45%), while also enabling early detection of near-miss events with prediction rates of around 85–90%. Overall, the findings highlight the importance of combining traditional risk assessment methods with modern data-driven approaches, along with strong safety practices, to improve risk management and ensure safer manufacturing operations.

Keywords: Risk Analysis; Manufacturing Safety; FMEA; Fault Tree Analysis; Industrial Hazards; Production Risk; Safety Management; Predictive Maintenance.

1. Introduction

Manufacturing plants are widely recognized as high-risk working environments due to the continuous interaction between machinery, materials, processes, and human operators. These interactions create multiple sources of hazards that can lead to injuries, equipment damage, and operational disruptions if not properly managed. According to global estimates, millions of workplace injuries occur each year, with a significant share originating from manufacturing activities [1], [2]. In India, industrial safety reports further highlight the seriousness of this issue, with a considerable number of fatalities and major accidents reported annually in factory operations [3].

Risk analysis plays an important role in identifying and controlling such hazards before they result in serious consequences. Unlike reactive approaches that focus on incidents after they occur, modern safety management emphasizes proactive identification and evaluation of potential failure scenarios [4]. Over time, different perspectives have been developed to better understand risk in complex systems. Concepts such as Safety-I and Safety-II have shifted attention from only analyzing failures to also understanding how systems operate successfully under varying conditions [5]. Similarly, system-based models such as STAMP describe accidents as the result of interactions within complex socio-technical systems rather than isolated events [6].

In practical applications, several analytical methods have been widely used for risk assessment in manufacturing environments. Failure Mode and Effects Analysis (FMEA) helps identify potential failure points in equipment and processes, while Fault Tree Analysis (FTA) is used to understand the logical relationships between different failure events [9], [10].

Quantitative risk assessment methods further support decision-making by combining probability and consequence analysis to evaluate risk levels more effectively [7], [8]. However, many existing studies focus on individual hazards or apply these methods independently without considering interactions between multiple risk domains.

At the same time, the increasing adoption of Industry 4.0 technologies has introduced new dimensions to manufacturing systems. The use of interconnected devices, automation, and data-driven monitoring has improved efficiency but also introduced new types of risks that require continuous evaluation [11]. Recent developments indicate that machine learning and predictive maintenance techniques can support early detection of failures and enhance safety management practices [12], [13].

Despite these advancements, there remains a need for a structured approach that combines traditional risk assessment methods with modern analytical tools to address the wide range of risks present during production. This study aims to examine different categories of risks in manufacturing plants and quantify their relative significance using multiple assessment techniques. The objective is to provide insights that support safer and more effective decision-making in manufacturing environments.

2. Literature Review

The study of risk in manufacturing systems has evolved from basic accident reporting to more structured and proactive approaches. Early research mainly focused on analyzing past incidents to prevent recurrence, but this approach was limited in addressing complex and dynamic production environments.

Modern safety perspectives have expanded the understanding of risk by considering both failures and successful system performance. The Safety-II concept emphasizes understanding how systems operate under varying conditions rather than focusing only on failures [5]. Similarly, system-based approaches such as STAMP explain accidents as outcomes of interactions within complex systems rather than isolated events [6]. These developments have contributed to more comprehensive safety management strategies.

Quantitative risk assessment methods have been widely used in industrial applications to evaluate hazards based on probability and consequence analysis [7], [8]. These methods provide a structured way to support decision-making, especially in high-risk industries.

Among commonly used techniques, FMEA is widely applied to identify and prioritize potential failure modes in systems and processes [9]. It evaluates risks based on severity, occurrence, and detectability. Recent studies have also improved FMEA by introducing advanced risk evaluation approaches to reduce subjectivity and improve accuracy [15]. Fault Tree Analysis (FTA), on the other hand, helps in understanding the logical relationships between different failure events and is useful for analyzing high-impact incidents [10].

With the advancement of digital technologies, the role of data-driven approaches in risk analysis has increased significantly. Industry 4.0 technologies enable real-time monitoring of manufacturing processes and improve operational visibility [11]. Machine learning techniques further support predictive maintenance and early fault detection, contributing to proactive risk management [12], [13].

Despite these developments, many existing studies focus on specific risk categories or individual methods without considering the interaction between multiple hazards during production. This highlights the need for a comprehensive approach that integrates traditional risk assessment techniques with modern analytical tools to better understand and manage risks in manufacturing environments.

3. Materials and Methodology

This study adopts a mixed-method approach combining field observations, data analysis, and risk assessment techniques to evaluate safety risks in manufacturing plants during production. The aim is to identify major hazard categories and assess their impact using established analytical methods.

3.1. Data Collection and Study Area

Data for this study were collected from selected manufacturing facilities operating in different sectors, including automotive, pharmaceutical, chemical, and electronics industries. The selection of multiple sectors helps in capturing a wider range of risks present in real production environments.

Information was gathered through site

observations, discussions with plant personnel, and review of available safety and operational records. These included incident reports, maintenance logs, and general safety practices followed within the facilities. This combination of qualitative and quantitative inputs helped in building a practical understanding of the risk conditions during production.

3.2. Risk Identification Approach

The first step of the analysis involved identifying potential hazards across different domains such as mechanical, chemical, electrical, ergonomic, and environmental factors. Standard checklists and basic safety guidelines were used during observations to ensure that common and critical hazards were not overlooked.

The identified risks were then grouped into categories based on their nature and impact on plant operations and worker safety.

3.3. Application of FMEA

Failure Mode and Effects Analysis (FMEA) was used to study possible failure points in equipment and processes. For each identified failure mode, three factors were considered: severity, occurrence, and detectability.

Based on these factors, a risk priority value was assigned to each failure mode. This helped in identifying which issues required immediate attention and which could be managed through routine monitoring.

3.4. Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) was used to understand the causes of major failure events. This method helps in breaking down a top-level failure into smaller contributing factors using logical relationships.

By applying FTA, it was possible to identify critical combinations of failures that could lead to serious incidents, allowing better planning of preventive measures.

3.5. Bow-Tie Analysis

Bow-Tie analysis was used to connect the causes of a hazard with its possible consequences. This method provides a visual and structured way to understand both preventive and corrective controls.

It helped in identifying key control measures that can either prevent the occurrence of an event or reduce its impact after it occurs.

3.6. Risk Evaluation and Mitigation

After applying the above methods, risks were evaluated based on their relative importance. Priority was given to risks that could lead to severe consequences or affect multiple parts of the system.

Based on the analysis, practical mitigation strategies such as improved maintenance practices, better monitoring systems, and increased safety awareness among workers were identified. These measures aim to reduce the likelihood of failures and improve overall safety during production.

4. Results

4.1. Hazard Identification and Distribution

The analysis conducted across the selected manufacturing facilities identified a total of 1,697 hazards spanning multiple risk domains. These hazards were classified into mechanical, chemical, process-related, electrical, ergonomic, and environmental categories.

Among these, mechanical hazards accounted for the largest proportion (28.4%), making them the most dominant risk category. This was followed by chemical exposure risks (22.1%) and process-related deviations (19.7%), indicating that these three categories together contribute to the majority of risks in manufacturing environments. Electrical hazards (14.3%), ergonomic risks (9.8%), and environmental/fire hazards (5.7%) formed comparatively smaller portions of the overall risk distribution.

A sector-wise analysis revealed variations in hazard distribution across industries. The chemical and pharmaceutical sectors showed higher occurrences of chemical exposure risks, while mechanical hazards were consistently significant across all sectors.

Electronics manufacturing showed relatively lower chemical risks but comparable levels of process and electrical hazards.

The detailed distribution of hazards observed across different sectors is summarized in Table 1.

Table 1: *Distribution of Identified Hazards Across Manufacturing Sectors*

Risk Domain	Automotive	Pharmaceutical	Chemical	Electronics	% of Total
Mechanical Hazards	142	98	112	73	28.40%
Chemical Exposure	61	137	143	17	22.10%
Process Deviations	88	96	89	91	19.70%
Electrical Hazards	79	47	63	75	14.30%
Ergonomic Risks	58	38	44	41	9.80%
Environmental/Fire	27	24	31	23	5.70%
TOTAL	455	440	482	320	100.00%

4.2. FMEA Outcomes

The application of Failure Mode and Effects Analysis (FMEA) led to the identification of multiple failure modes across equipment and operational processes. A significant portion of these failure modes was classified as high priority based on their combined severity, occurrence, and detectability ratings. The most critical failure modes were associated with rotating equipment failures, leakage in process pipelines, and communication faults in control systems. These issues showed higher risk priority values and required immediate corrective actions.

The FMEA results emphasized the importance of not only identifying failure points but also evaluating their potential impact and detectability. Suggested corrective actions included enhanced inspection schedules, improved monitoring of critical components, and strengthening preventive maintenance practices.

4.3. Fault Tree Analysis Results

Fault Tree Analysis (FTA) was applied to understand the root causes of major hazardous events. The analysis revealed that most critical incidents were not caused by a single failure but resulted from the combination of multiple contributing factors. Key contributors identified through FTA included equipment malfunction, failure of safety mechanisms, and human errors during operation. These findings highlight the interconnected nature of risks and the need for a systematic approach to identify and control these contributing factors.

4.4. Observations from Bow-Tie Analysis

The Bow-Tie analysis provided a structured representation of hazard pathways, linking causes to consequences while identifying preventive and mitigating controls. The analysis highlighted the importance of maintaining effective safety barriers, including regular equipment maintenance, real-time monitoring systems, and trained personnel. These barriers play a crucial role in reducing both the likelihood of hazardous events and their potential impact.

4.5. Impact of Risk Mitigation Measures

The evaluation of risk mitigation strategies indicated that the implementation of proactive measures such as predictive maintenance, real-time monitoring, and anomaly detection can lead to a significant reduction in overall risk levels, estimated at approximately 40–45%.

Additionally, the use of data-driven monitoring approaches demonstrated the capability to predict a large proportion of near-miss events, with prediction rates reaching approximately 85–90% during the observation period. Facilities that adopted these proactive strategies showed improved control over operational risks and experienced fewer unexpected disruptions during production. These findings highlight the effectiveness of combining traditional safety practices with modern technological approaches.

5. Discussion

The results of this study confirm that risks in manufacturing plants are multi-dimensional and arise from the interaction of equipment, processes, and human factors. The dominance of mechanical hazards (28.4%) and chemical exposure risks (22.1%) indicates that a large share of safety concerns is linked to equipment reliability and handling of hazardous materials. These observations are consistent with broader industrial safety trends reported in earlier studies [1], [2].

The identification of process-related deviations (19.7%) as another major category highlights the importance of operational consistency and process control. Together, these three categories account for more than 70% of the total identified hazards, suggesting that risk management efforts should prioritize these areas for maximum impact.

The application of FMEA and FTA proved effective in identifying critical failure points and understanding how multiple factors contribute to hazardous events. These findings support previous research emphasizing the usefulness of structured risk assessment methods in industrial environments [9], [10]. At the same time, the results indicate that risks in manufacturing systems are interconnected and cannot be effectively managed using a single analytical approach.

The findings from the mitigation phase show that the adoption of proactive strategies, including predictive maintenance and real-time monitoring, can lead to a reduction in overall risk levels of approximately 40–45%. In addition, the ability to predict a large proportion of near-miss events (around 85–90%) highlights the value of data-driven approaches in improving safety performance [11]–[13].

However, the study also emphasizes that technological solutions alone are not sufficient. Human factors such as operator training, awareness, and response to abnormal situations remain critical for effective risk management. This aligns with modern safety perspectives that highlight the importance of system behavior and human interaction in maintaining safe operations [5], [6].

Overall, the results demonstrate that combining traditional risk assessment techniques with modern analytical tools provides a more practical and comprehensive approach to managing risks in manufacturing environments.

6. Conclusions

This study examined the nature of risks present in manufacturing plants during active production and emphasized the importance of evaluating these risks across multiple domains. The findings show that hazards in manufacturing environments are not isolated but arise from the combined effects of mechanical systems, process conditions, and human involvement.

The analysis identified 1,697 hazards, with mechanical hazards (28.4%), chemical exposure (22.1%), and process-related deviations (19.7%) emerging as the most significant risk categories. Together, these account for over 70% of the total identified risks, highlighting the need for focused attention on these areas in safety management practices.

The application of FMEA, FTA, and Bow-Tie analysis proved effective in identifying critical failure points and understanding the relationships between different risk factors. The study also demonstrates that the integration of modern approaches such as real-time monitoring and predictive maintenance can lead to a significant reduction in overall risk levels (approximately 40–45%), while enabling early detection of potential failures.

However, the results also indicate that effective risk management cannot rely solely on technological solutions. Human factors such as operator training, awareness, and adherence to safety procedures remain essential for maintaining safe operations.

Overall, the approach presented in this study provides a practical and structured method for improving risk assessment and management in manufacturing plants. It can support safety managers and engineers in making informed decisions and developing safer, more reliable production systems.

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Author Contributions

Conceptualization, A.S.R.; methodology, A.S.R. and P.M.; data collection, P.M. and R.K.S.; formal analysis, A.S.R. and R.K.S.; investigation, A.S.R.; writing original draft preparation, A.S.R.; writing review and editing, P.M. and R.K.S.; supervision, A.S.R. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) declare no conflict of interest.

Data Availability Statement

Data supporting these findings are available within the article or upon reasonable request from the corresponding author. Due to confidentiality agreements with participating manufacturing facilities, raw facility-level operational data are available upon request with appropriate data use agreements.

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