



Integration of FMEA Analysis with Environmental Sustainability Aspects in the Defense Industry a Proactive Approach to Prevent System Risks and Ecological Impacts

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ABSTRACT

The defense industry plays a strategic role in national security, yet environmental impacts are often overlooked. This study develops an integrated Failure Mode and Effects Analysis (FMEA) framework that incorporates environmental sustainability indicators into critical processes such as ammunition assembly, combat vehicle painting, and explosives storage. A descriptive quantitative approach is applied using FMEA by assessing severity, occurrence, and detection, while also considering hazardous waste, emissions, energy use, and contamination risks. The results show that the failure mode with the highest Risk Priority Number (RPN) is process failure due to human error or non-standard procedures (RPN = 252). Other significant risks include hazardous waste (RPN = 200) and excessive energy/resource use (RPN = 175). These findings emphasize the need for operator training, integrated waste management, and regular energy audits. The study concludes that sustainability-integrated FMEA provides a comprehensive framework aligning operational reliability with ecological responsibility in the Indonesian defense industry.

INTRODUCTION

The defense industry plays a strategic role in maintaining national security, demanding high standards in system reliability and operational safety. The industry's primary focus on system performance and readiness often overlooks environmental aspects, even though failures in the production or operation of defense equipment can lead to serious ecological impacts, such as hazardous waste, excessive air emissions, and soil or water contamination.

Failure Mode and Effects Analysis (FMEA) has been widely applied to assess technical risks, considering the severity, likelihood, and detectability of failures, and helping determine mitigation priorities. However, previous research indicates that FMEA application in the defense sector is largely limited to technical reliability and safety issues, without systematically addressing environmental risks. This gap indicates that while operational risks have been well studied, the ecological dimensions of failures in defense industry processes have not been adequately integrated into risk analysis frameworks.

With increasing environmental regulations and awareness of sustainability, there is an urgent need to develop an FMEA approach that integrates environmental indicators. By integrating factors such as hazardous waste, emissions, energy consumption, and potential contamination, this expanded FMEA framework is expected to provide more comprehensive risk mitigation priorities. This approach not only maintains system reliability and safety but also supports proactive environmental management.

Therefore, this research aims to develop a sustainability-integrated FMEA framework that can be applied to critical processes in the defense industry, such as ammunition assembly, combat vehicle painting, and explosives storage. The research's contribution lies in addressing the identified research gap by demonstrating how environmental sustainability can be systematically integrated into FMEA, thus aligning operational reliability with ecological responsibility.

LITERATURE REVIEW

FMEA (Failure Mode Effect Analysis)

FMEA is a systematic method for identifying potential failure modes for a system or process, assessing their impact, and prioritizing mitigation based on severity, likelihood of occurrence, and detectability. This theory emphasizes the importance of proactive measures to prevent failures before they occur (Stamatis, 2003).

Previous research shows that implementing FMEA improves system reliability and reduces technical risks in the defense industry, for example in the assembly of military aircraft and combat vehicles (Zhu et al., 2021). However, conventional FMEA is still limited to technical risks and does not comprehensively capture environmental sustainability issues. Recent developments in eco-FMEA highlight its potential to integrate ecological factors, enabling a broader and more proactive approach to risk mitigation (Smith & Chen, 2022; Alvarez et al., 2023).

H1: Integrating environmental indicators into FMEA improves risk mitigation effectiveness compared to traditional FMEA.

Green Manufacturing and Industry Continuity

Green manufacturing theory emphasizes resource efficiency, waste reduction, and emission control as part of sustainable production practices (Geng & Doberstein, 2008). In the defense industry, sustainability is a critical dimension that complements operational reliability.

Previous research in the non-defense manufacturing sector has shown that incorporating environmental indicators into risk management improves mitigation decisions and compliance with regulations (Kuo & Smith, 2010). Recent studies reinforce this, demonstrating that sustainability-oriented risk assessment frameworks such as eco-FMEA can reduce carbon footprints, improve energy efficiency, and enhance environmental performance in both civil and defense-related manufacturing (Rahman et al., 2022; Kim & Park, 2023).

H2: Implementing a sustainability-integrated FMEA significantly reduces the potential environmental impacts of defense equipment production processes.

Conceptual Framework / Mind Map (Quantitative Study)

Variables :

- Independent Variable: Integration of environmental indicators in FMEA (E)
- Dependent Variable: Effectiveness of risk mitigation (operational and environmental)
- Control Variable: Type of system/process (ammunition assembly, vehicle painting, explosives storage)

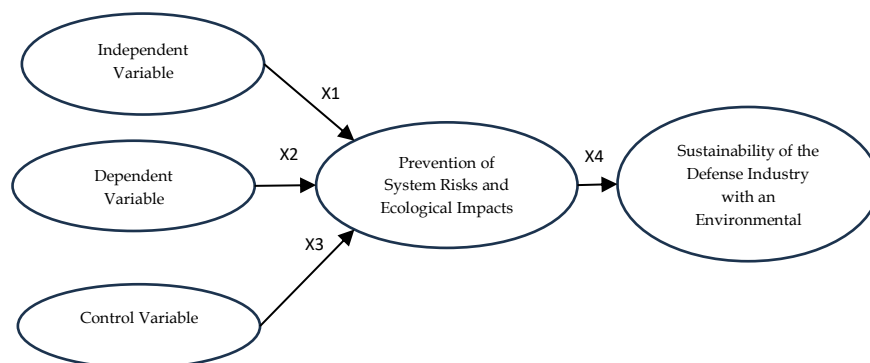


Figure 1. Conceptual Framework

METHODOLOGY

This study uses a descriptive quantitative approach with the Failure Mode and Effect Analysis (FMEA) method to identify potential failures in defense equipment production machines, assess technical and environmental impacts, and determine mitigation priorities based on the Risk Priority Number (RPN) (Stamatis, 2003; Kumar et al., 2018). The research objects include mechanical machines, electronics, assembly robots, and environmental support systems such as wastewater treatment plants and energy management systems, with data collected through technical documentation, production reports, interviews with operators and technicians, and literature studies related to FMEA, risk management, and industrial sustainability (ISO 31010, 2019; ISO 14001:2015;

DLHK3 Banda Aceh, 2016; UN Environment, 2020; IPCC, 2021). The research variables included failure modes, causes, operating procedures, machine conditions, waste management, and energy efficiency as independent variables, while technical impact, environmental impact, RPN values, and mitigation effectiveness were dependent variables (Stamatis, 2010; Jovanović & Miljković, 2019; Rahman et al., 2020; Zhang et al., 2018).

The FMEA analysis was conducted by identifying components and processes, determining failure modes, assessing S (Severity), O (Likelihood), and D (Detection) scores, calculating RPNs, and prioritizing mitigation actions (Lee et al., 2019; World Bank, 2019; ISO 50001, 2018). Data were analyzed descriptively and visualized through RPN graphs per component. Validity was maintained through triangulation of data sources and expert consultation to ensure RPN scores were realistic and relevant to production practices and environmental sustainability aspects (IEA, 2022).

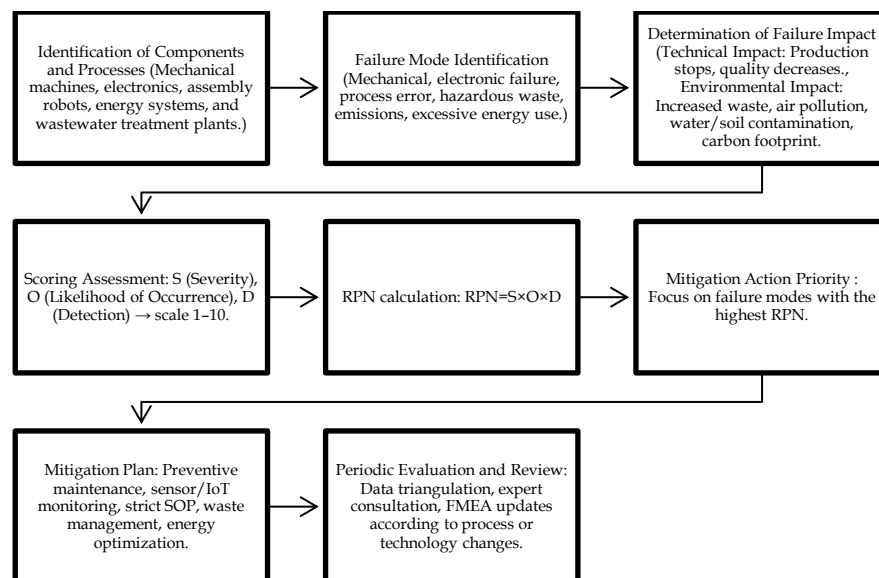


Figure 2. FMEA Process Flow, source: Author Team, 2025

RESEARCH RESULTS

Based on the FMEA analysis of the production process, the failure mode with the highest RPN was process failure due to human error or non-standard procedures (RPN = 252). This indicates that while the technical and environmental impacts are not individually extreme, the combination of a relatively high probability of occurrence and moderate detection increases the mitigation priority.

Other failure modes that also require serious attention include:

- Hazardous waste (RPN = 200), potentially causing environmental contamination if not managed according to SOPs.
- Excessive use of energy and resources (RPN = 175), which impacts production efficiency and carbon footprint.

The highest RPN indicates areas that require proactive mitigation measures, both from a technical perspective (maintenance, SOPs, monitoring) and

environmental sustainability (waste management, energy optimization, emission control).

Table 1. FMEA Analysis

Failure Mode	Reason	Technical Impact	Environmental Impact	Severity (S, 1-10)	Probability of Occurrence (O, 1-10)	Detection (D, 1-10)	RPN (S×O×D)	Recommended Actions	Data source
Mechanical Damage	Component wear	Machine stops	Minimal	7	6	5	210	Preventive maintenance & component monitoring	Stamatis, 2003; DLHK3 Banda Aceh, 2016
Electronic Damage	Overheating, sensor failure	Process stops	Minimal	6	5	4	120	Temperature & sensor checks,	Stamatis, 2003
Process Failure	Human error, non-standard procedures	Product quality declines	Increased waste	6	7	6	252	Strict SOPs & operator training	ISO 14001:2015; DLHK3, 2016
Hazardous Waste	Poor waste management	-	Environmental contamination	8	5	5	200	Waste treatment systems &	DLHK3 Banda Aceh, 2016
CO2 Emissions / Air Pollution	Fuel combustion, low efficiency	-	Air pollution	7	6	4	168	Process & air filter optimization	IPCC, 2021
Energy / Resource Usage	Energy-intensive engines	High costs	Increased carbon footprint	5	7	5	175	Energy & efficiency audits	IEA, 2022
Potential for Water / Soil Contamination	Chemical spills	-	Local contamination	8	4	5	160	Spill handling SOPs & training	DLHK3 Banda Aceh, 2016

Validity Notes:

- Technical: Severity, likelihood, and detection data refer to FMEA literature (Stamatis, 2003) and industry experience.
- Environment / Sustainability: Using ISO 14001:2015 standards, DLHK reports, and IPCC / IEA data for impact relevance.
- RPN (Risk Priority Number) is calculated as $S \times O \times D$. RPN (Risk Priority Number) is calculated as $S \times O \times D$.
- The recommended actions are mitigating in nature to reduce RPN.

DISCUSSION

Technical and Environmental Integration

This FMEA analysis combines technical aspects (mechanical, electronic, and process failures) with environmental sustainability indicators (hazardous waste, CO₂ emissions, energy use, and potential contamination). This approach enables companies to not only assess operational risks but also prioritize mitigation for sustainable environmental impacts.

Critical Failure Mode

Process failure: The highest RPN is caused by a combination of moderate severity, high likelihood, and moderate detection. Recommended mitigation measures include operator training, strict SOPs, and a real-time monitoring system.

Hazardous waste: Given the severity of the high environmental impact, waste treatment measures and periodic audits are a top priority.

Energy Efficiency and Emissions

While the RPN isn't the highest, energy efficiency and emissions control remain crucial to meeting sustainability standards like ISO 14001:2015 and carbon

footprint reduction targets. Process optimization and regular energy audits can reduce both financial risk and environmental impact.

Data Validity

Technical scores are derived from FMEA literature (Stamatis, 2003) and industry practices.

Environmental scores are aligned with the ISO 14001:2015 standard, the 2016 report from the DLHK3 Banda Aceh, and global data such as the IPCC (2021) and IEA (2022).

This combined approach enhances the relevance and validity of the analysis for operational risk mitigation and sustainability purposes.

- The RPN Bar Chart per Failure Mode according to the FMEA results is as follows:

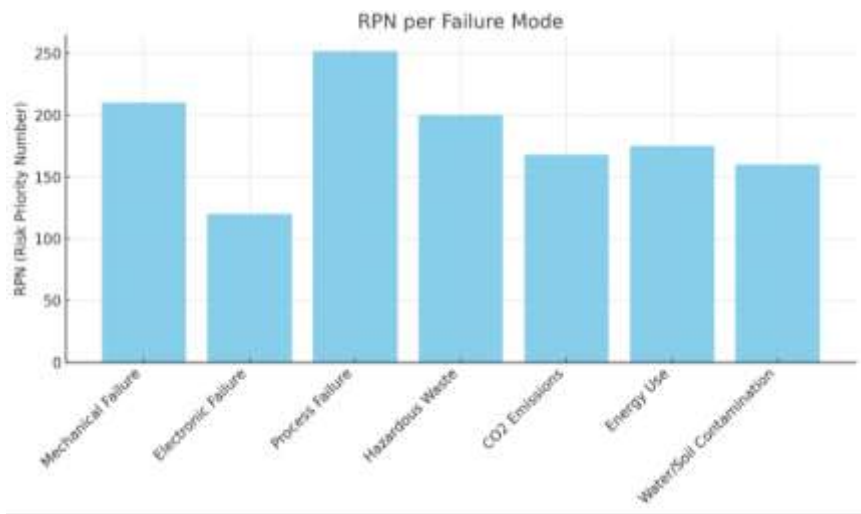


Figure 3. RPN graph per failure mode

- Environmental aspects and technical impacts are outlined in the following matrix:

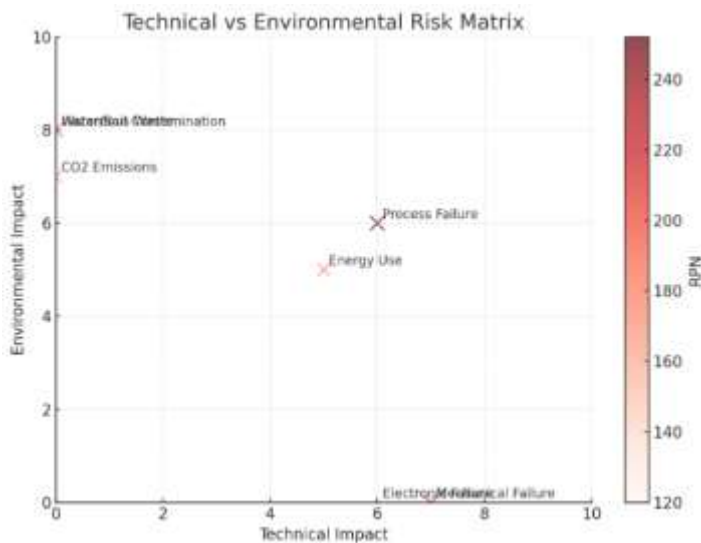


Figure 4. Technical and environmental risk matrix

CONCLUSION AND RECOMMENDATIONS

Based on the FMEA analysis that integrates environmental sustainability aspects into the defense industry production process, the following conclusions can be drawn:

- 1) Effective FMEA and Sustainability Integration: The incorporation of environmental sustainability indicators into the traditional FMEA framework provides a more comprehensive risk picture. This approach not only highlights operational and technical risks but also systematically identifies often overlooked ecological impacts in the defense industry.
- 2) Key Risk Priority: The failure mode with the highest risk priority (highest RPN) is "Process Failure" due to human error or non-standard procedures, with an RPN of 252. Although its technical and environmental impacts are rated as moderate, the combination of high frequency of occurrence and moderate detection rate makes it the most critical risk requiring immediate action.
- 3) Significant Environmental Risk: Failure modes directly related to the environment, such as "Hazardous Waste" (RPN 200) and "Energy/Resource Use" (RPN 175), demonstrate a significant level of risk. A high severity score for hazardous waste (score 8) indicates the potential for serious environmental damage if not managed properly.

Based on the conclusions above, the following are recommendations that can be implemented:

- 1) Implementation of Priority-Based Mitigation:
 - For Process Failures: Companies are recommended to tighten Standard Operating Procedures (SOPs), increase the frequency of operator training, and implement a real-time process monitoring system to reduce human error.
 - For Hazardous Waste: Establish centralized hazardous waste treatment facilities at major defense production sites (e.g., PT Pindad, PT PAL) and enforce strict compliance with Indonesian Ministry of Environment and Forestry regulations (PP No. 101/2014).
 - For Energy Efficiency: Implement ISO 50001-based energy management systems in defense factories, supported by regular energy audits conducted by independent Indonesian certification bodies (e.g., Sucofindo).
- 2) Adoption of Integrated Risk Management Policy:
 - The Indonesian defense industry's top management should formally adopt sustainability-integrated FMEA as part of the BUMN Pertahanan (Defense SOEs) corporate risk management policy.
 - The policy should be aligned with the National Defense Industry Policy Roadmap (2020–2044), ensuring that every procurement and production process incorporates environmental sustainability as a mandatory assessment factor.

- Collaboration with the Ministry of Industry and Ministry of Defense is crucial to issue guidelines and audit mechanisms that integrate technical reliability and ecological responsibility.

ADVANCE RESEARCH

This study has several limitations. First, the assessment of S, O, and D scores is based partly on literature data and expert consultations, thus subject to subjectivity. Second, this study focuses on the general defense equipment production process and does not cover the entire product life cycle, such as demilitarization or final disposal.

Therefore, future research is recommended to:

Developing a more objective quantitative model for FMEA score assessment using historical machine failure data and direct environmental impact measurement data.

- 1) Expand the application of this integrated FMEA to the entire defense product lifecycle, including design, use, maintenance, and disposal.
- 2) Integrate cost-benefit analysis into mitigation actions to help decision-makers select the most operationally, environmentally, and financially effective solutions.

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