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Hazardous Waste Risk Analysis in Heavy Equipment Maintenance

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A B S T R A C T

The increasing frequency of heavy equipment maintenance activities has led to a significant rise in hazardous waste generation, which may pose operational, environmental, and occupational health and safety (OHS) risks if not properly managed. This study aims to identify failure modes, prioritize risks using Failure Mode, Effects, and Criticality Analysis (FMECA), determine root causes through Root Cause Analysis (RCA), and develop improvement recommendations for hazardous waste management in heavy equipment maintenance activities at PT XYZ. A case study approach was employed, with data collected through field observations, interviews, documentation, and expert judgment involving four experts. Risk assessment was conducted using Severity (S), Occurrence (O), and Detection (D) scores to calculate the Risk Priority Number (RPN). Normalized RPN (NRPN) values were classified as high risk (NRPN > 75%), moderate risk (50% < NRPN ≤ 75%), and low risk (NRPN ≤ 50%). The results identified 15 failure modes, comprising four high-risk, nine moderate-risk, and two low-risk failure modes. FM-08, involving contamination of the drainage system by used oil and dirt, had the highest RPN of 324 (NRPN = 100%). The four high-risk failure modes were further analyzed using RCA, which identified human factors, work methods, and facilities as the predominant root cause categories, with material and environmental factors also contributing to several failure modes. Improvement recommendations were subsequently developed using the 5W+1H approach. The integration of FMECA and RCA provides a systematic framework for prioritizing risks, identifying root causes, and formulating targeted improvements in hazardous waste management during heavy equipment maintenance activities.

1. INTRODUCTION

The growth of the industrial sector in Indonesia, particularly in Batam City, has driven an increase in the use of heavy equipment to support operational activities in the manufacturing, construction, and logistics sectors. According to data from the Batam City Statistics Agency (BPS), Batam City's economy grew by 6.69% in 2024, with the manufacturing sector making the largest contribution to the Gross Regional Domestic Product (GRDP), followed by the construction sector. This condition indicates a high level of industrial activity, which has implications for the increasing demand for heavy equipment and maintenance activities to maintain equipment reliability and reduce operational downtime [1], [2], [3] .

Heavy equipment maintenance activities generate hazardous and toxic waste (B3 waste), such as used oil, used filters, contaminated wiping cloths, and other chemical residues, which require proper management in accordance with applicable environmental regulations. Improper hazardous waste management has the potential to cause environmental pollution, disrupt the continuity of company operations, and increase occupational safety and health (OSH) risks. Therefore, hazardous waste management is an important aspect of maintaining the sustainability of company operations while ensuring environmental protection [4], [5] .

PT XYZ is a company engaged in heavy equipment rental, including forklifts, lorry cranes, and various other units supporting operational activities. Along with the increase in the company's assets from 31 units in 2021 to 394 units in 2025, the frequency of maintenance activities has also increased, resulting in a higher volume of hazardous waste generated. Based on observations conducted in the workshop area, several conditions with the potential to become failure modes were identified,

including oil trays left in the work area, used filters that were not immediately transferred to the designated waste storage area, oil spills on the workshop floor, and improper waste handling that did not comply with established procedures. These conditions have the potential to disrupt operational activities, increase the risk of workplace accidents, and cause environmental pollution if not promptly controlled.

To systematically assess these risks, this study employs Failure Mode, Effects, and Criticality Analysis (FMECA) and Root Cause Analysis (RCA). FMECA was selected to identify potential failure modes and prioritize risks based on Severity (S), Occurrence (O), and Detection (D), which are used to calculate the Risk Priority Number (RPN) [6], [7] . RCA was subsequently employed to investigate the underlying causes of the failure modes classified as high risk, supported by a fishbone diagram to organize potential contributing factors [8] . The complementary use of these methods allows the study to prioritize risks and investigate their underlying causes, providing a basis for developing targeted improvement recommendations.

Accordingly, this study aims to identify failure modes in hazardous waste management during heavy equipment maintenance activities at PT XYZ, evaluate and prioritize the associated risks using FMECA, determine the root causes of high-risk failure modes using RCA, and formulate improvement recommendations using the 5W+1H approach. The study considers operational, environmental, and occupational health and safety (OHS) aspects to support systematic improvements in hazardous waste management practices.

2. LITERATURE REVIEW

2.1. *FMECA and Root Cause Analysis*

The *Failure Mode, Effects, and Criticality Analysis* (FMECA) method is one of the risk analysis methods widely used to identify failure modes, evaluate the effects of failures, and determine risk priorities based on the parameters of *Severity* (S), *Occurrence* (O), *Detection* (D), and *Risk Priority Number* (RPN) [6], [9], [10] . However, FMECA primarily indicates risk priorities and does not fully explain the root causes of failures. Therefore, *Root Cause Analysis* (RCA) is used as a complementary method to identify the root causes of failure modes with the highest risk levels, enabling more targeted improvement recommendations to be developed [7], [8] .

2.2. *Previous Studies and Research Gap*

Previous studies have applied *Failure Mode and Effects Analysis* (FMEA), *Failure Mode, Effects, and Criticality Analysis* (FMECA), *Hazard and Operability Study* (HAZOP), and *Hazard Identification, Risk Assessment, and Risk Control* (HIRARC) to identify and evaluate risks across various industrial sectors [6], [7] . However, most of these studies have focused on specific risk aspects, such as equipment reliability, occupational safety, or environmental impacts, separately. In contrast, the application of FMECA combined with *Root Cause Analysis* (RCA) to hazardous waste management resulting from heavy equipment maintenance activities, while simultaneously considering operational, environmental, and occupational safety and health (OSH) aspects, remains limited [7], [8] . This condition indicates the need for an approach that is not only capable of determining risk priorities but also identifying their root causes as a basis for developing more effective corrective actions.

Based on this research gap, this study aims to identify failure modes in the management of hazardous waste generated from heavy equipment maintenance activities at PT XYZ, determine risk priorities using the FMECA method, analyze root causes using RCA, and develop improvement recommendations using the 5W+1H approach. This study is expected to provide an integrated risk analysis framework to support improvements in the effectiveness of hazardous waste management by considering operational, environmental, and occupational safety and health (OSH) aspects.

3. METHODOLOGY

This study employs a *mixed-methods* approach through a case study at PT XYZ, a company engaged in heavy equipment rental in Batam City. The quantitative approach is used to determine risk levels using the *Failure Mode, Effects, and Criticality Analysis* (FMECA) method, while the qualitative approach is used to identify the root causes of risks using *Root Cause Analysis* (RCA). The combination of these two approaches enables a comprehensive analysis, ranging from the identification of *failure modes* and determination of risk priorities to root cause identification and the development of improvement recommendations. The study was conducted in the workshop area of PT XYZ from February to June 2026, with the research objects consisting of hazardous waste generated from maintenance activities, including used oil, used filters, contaminated wiping cloths, and other supporting waste.

Data were collected through observations, interviews, documentation, and *expert judgment*. Observations were conducted to identify the actual conditions of hazardous waste management and the *failure modes* occurring in the workshop area. Interviews were conducted with personnel directly involved in maintenance activities and hazardous waste management to obtain information regarding work processes, potential risks, and existing control measures. Documentation was used as supporting data, including company procedures, photographs of field conditions, and operational documents. Subsequently, *expert judgment* was used to assess the *Severity* (S), *Occurrence* (O), and *Detection* (D) parameters required for the FMECA analysis [11], [12] .

The research respondents consisted of four experts, namely the Head Mechanic, Assistant Head Mechanic, Head of HSE, and Head of Facility. The respondents were selected using *purposive sampling* based on their experience, competencies, and direct involvement in heavy equipment maintenance activities and hazardous waste management. This sampling technique was employed to obtain relevant and representative information in accordance with the objectives of the study. The use of *expert judgment* in FMECA aims to obtain assessments of the *Severity*,

Occurrence, and *Detection* parameters based on the respondents' knowledge and experience of the system being analyzed [12], [13] .

The analysis began with the identification of *failure modes* based on the results of observations, interviews, and documentation. Each *failure mode* was then assessed by the four experts using the *Severity* (S), *Occurrence* (O), and *Detection* (D) parameters. The value of each parameter was calculated as the average score given by all experts using Equation (1).

$$\bar{X} = \frac{(\sum_{i=1}^{n} x_i)}{n} \quad (1)$$

$\bar{X}$ = average parameter score
x_i = score assigned by the i-th expert
n = number of experts

The average score was calculated to obtain a single representative value for each parameter before conducting the FMECA analysis.

Next, the average values of *Severity*, *Occurrence*, and *Detection* were used to calculate the *Risk Priority Number* (RPN) using Equation (2) [6] .

$$RPN = S \times O \times D \quad (2)$$

S = Severity
O = Occurrence
D = Detection

The RPN values were then normalized using Equation (3) to obtain the relative risk priority for each *failure mode*.

$$NRPN = \frac{RPN_i}{RPN_{max}} \times 100\% \quad (3)$$

NRPN = Normalized Risk Priority Number
RPN_i = RPN value for the i-th failure mode
RPN_{max} = Highest RPN value

The normalized results were subsequently classified into three risk categories: *High Risk* (NRPN > 75%), *Moderate Risk* (50% < NRPN ≤ 75%), and *Low Risk* (NRPN ≤ 50%). *Failure modes* classified as *High Risk* were further analyzed using *Root Cause Analysis* (RCA), supported by a *Fishbone Diagram*, to identify their root causes based on the factors of *man, method, material, facility,* and *environment*. Based on the RCA results, improvement recommendations were developed using the 5W+1H approach to ensure that corrective actions could be implemented systematically and appropriately target [14] .

4. RESULTS AND DISCUSSION

4.1. *Failure Mode Identification*

Failure mode identification was conducted based on the results of field observations, interviews, documentation, and validation with experts. The identification process resulted in 15 failure modes related to hazardous waste management activities in the workshop area of PT XYZ. The identified failure modes covered operational, environmental, and occupational safety and health (OSH) aspects, thereby providing a comprehensive representation of the actual conditions of hazardous waste management during heavy equipment maintenance activities. The identification of failure modes served as the basis for the risk assessment using the FMECA method, as each failure mode was evaluated based on the *Severity*, *Occurrence*, and *Detection* parameters.

Table 1. List of Failure Modes

Code	Actual Condition	Rationale	Status
FM-01	The work area is poorly organized, obstructing work activities and worker movement.	This condition indicates that the principles of *Seiri* and *Seiton* have not been properly implemented, as an unorganized work area can obstruct activities, make equipment access more difficult, and reduce work process efficiency [15] .	Non-compliant
FM-02	Dismantled components and spare parts are not properly organized.	This condition is inconsistent with the *Seiton* principle, which emphasizes systematic arrangement of components so that they can be easily found, used, and returned to their designated storage locations, thereby supporting work efficiency [15], [16] .	Non-compliant
FM-03	Work equipment is not placed in its designated location.	This condition contradicts the *Seiton* principle, as each piece of equipment should be placed in a designated location to facilitate retrieval, use, and return to storage [15], [16].	Non-compliant
FM-04	Materials, equipment, and components are accumulated in the work area.	This condition indicates that the *Seiri* principle has not been properly implemented, as unnecessary items should be separated to prevent accumulation that may obstruct work activities [16].	Non-compliant
FM-05	Operational materials are not stored in an organized manner.	This condition is inconsistent with the *Seiton* principle, which requires materials to be stored in an organized manner so that they can be easily identified and accessed, thereby supporting smooth operations [16].	Non-compliant
FM-06	Oil spills or liquid waste are not	This condition contradicts the *Seiso* principle, which emphasizes maintaining	Non-compliant

	properly handled.	workplace cleanliness, and is also inconsistent with the Hazardous Waste Management SOP, which requires proper waste handling to prevent environmental pollution [17].	
FM-07	Used oil waste is stored in inadequate containers.	This condition is inconsistent with the Hazardous Waste Management SOP, as hazardous waste must be stored in containers that meet technical requirements to prevent leaks, spills, and environmental pollution [17].	Non-compliant
FM-08	The drainage system is contaminated with used oil and dirt.	This condition indicates that waste management has not been carried out in accordance with the Hazardous Waste Management SOP, as waste entering the drainage system has the potential to cause environmental pollution [17].	Non-compliant
FM-09	Hazardous waste management is not carried out optimally.	This condition constitutes non-compliance with the Hazardous Waste Management SOP, as all waste management stages should be carried out systematically to minimize risks to the environment and occupational safety [17].	Non-compliant
FM-10	The waste storage area does not meet housekeeping standards.	This condition contradicts the principles of 5S, which emphasize workplace organization and cleanliness, and does not meet the waste storage requirements stipulated in the Hazardous Waste Management SOP [17].	Non-compliant
FM-11	Oil spills on the floor are not cleaned up immediately.	This condition is inconsistent with the *Seiso* principle, which emphasizes maintaining workplace cleanliness, and contradicts the Hazardous Waste Management SOP because it may increase the risk of environmental pollution and workplace accidents [17].	Non-compliant
FM-12	Materials, hoses, or components are located along work pathways.	This condition contradicts the *Seiton* principle, as work pathways should be free of obstructions to ensure that work activities can be carried out safely, effectively, and efficiently [18].	Non-compliant
FM-13	Maintenance activities are carried out in a narrow and poorly organized work area.	This condition indicates that the *Seiri* and *Seiton* principles have not been properly implemented, as a narrow and poorly organized work area can obstruct maintenance processes and increase potential hazards in the workplace [16].	Non-compliant
FM-14	Heavy components are placed in an unsafe manner.	This condition is inconsistent with the *Seiton* principle, as materials and components should be arranged systematically and stored safely to facilitate handling and reduce the potential for workplace accidents [16].	Non-compliant
FM-15	Used oil waste and flammable materials are stored improperly.	This condition contradicts the Hazardous Waste Management SOP, as hazardous waste must be stored in accordance with technical requirements to prevent the risks of fire, environmental pollution, and hazards to workers [17].	Non-compliant

Source: Authors' analysis based on field observations, interviews, and documentation (2026).

4.2. *FMECA Analysis Results*

Risk assessment was conducted by four experts using the *Severity* (S), *Occurrence* (O), and *Detection* (D) parameters. The average value of each parameter was used to calculate the *Risk Priority Number* (RPN), which was subsequently normalized to determine the risk priority level. The analysis identified 15 *failure modes*, consisting of 4 *High Risk*, 9 *Moderate Risk*, and 2 *Low Risk* categories. These results indicate that most of the *failure modes* fall into the *Moderate Risk* category, while the four *High Risk failure modes* represent the highest priorities for the development of corrective actions.

Table 2. FMECA Calculation Results

Failure Mode	S	O	D	RPN	NRPN (%)	Risk Category
FM-01	6	7	4	168	52%	*Moderate Risk*
FM-02	5	6	4	120	37%	*Low Risk*
FM-03	5	7	4	140	43%	*Low Risk*
FM-04	6	7	4	168	52%	*Moderate Risk*
FM-05	6	7	5	210	65%	*Moderate Risk*
FM-06	8	7	5	280	86%	*High Risk*
FM-07	7	6	5	210	65%	*Moderate Risk*
FM-08	9	6	6	324	100%	*High Risk*
FM-09	8	5	5	200	62%	*Moderate Risk*
FM-10	8	7	5	280	86%	*High Risk*

FM-11	6	7	5	210	65%	*Moderate Risk*
FM-12	7	6	4	168	52%	*Moderate Risk*
FM-13	6	7	5	210	65%	*Moderate Risk*
FM-14	8	6	6	288	89%	*High Risk*
FM-15	9	4	6	216	67%	*Moderate Risk*

Source: Authors' calculations based on expert assessments (2026)

Based on the RPN normalization results, FM-08 had the highest risk level, with an RPN of 324, followed by FM-14 (288), FM-06 (280), and FM-10 (280). These four *failure modes* were classified as *High Risk* and therefore required further analysis using the RCA method. The high RPN values indicate that these *failure modes* have a combination of severity, occurrence frequency, and likelihood of detection that warrants higher control priority compared with other *failure modes*. This finding is consistent with the FMECA concept, in which control priorities are determined based on the highest RPN values [6] .

4.3. *Root Cause Analysis (RCA)*

RCA was conducted on the four *failure modes* classified as *High Risk*, namely FM-06, FM-08, FM-10, and FM-14. The selection of these four *failure modes* was based on the RPN normalization results, allowing analytical resources to be focused on risks with the greatest potential impacts on operational, environmental, and occupational safety and health (OSH) aspects. The analysis was performed using a *Fishbone Diagram* with five categories of potential causes: *man, method, material, facility,* and *environment.*

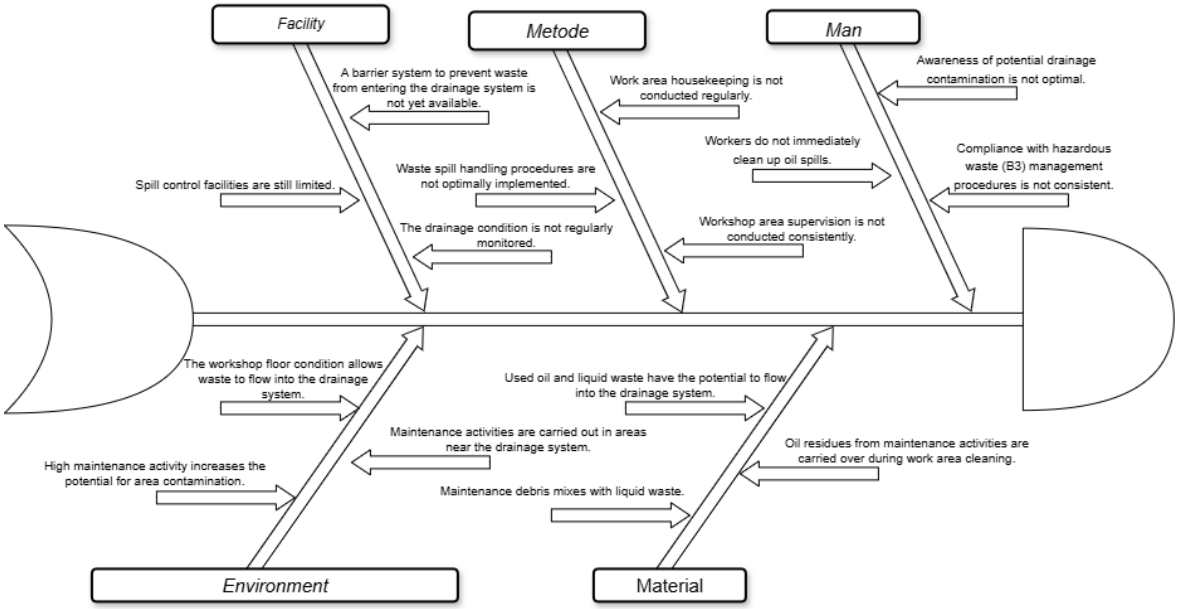


Figure 1. Fishbone Diagram of FM-08

Source: Authors' analysis based on field observations and interview results (2026).

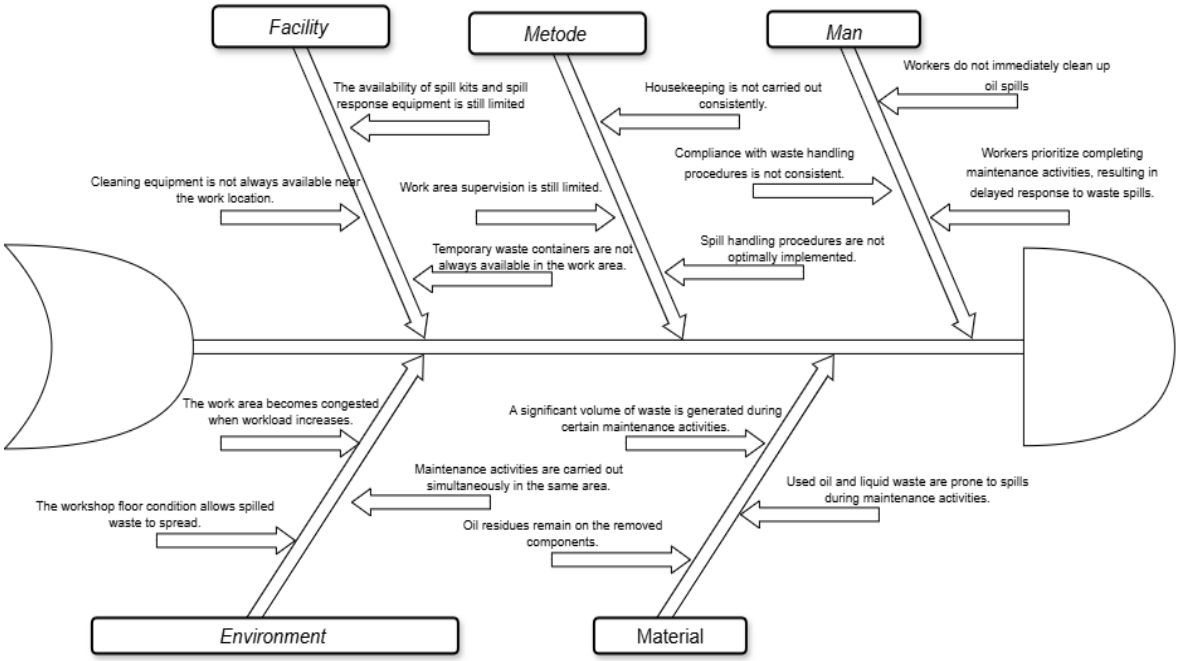


Figure 2. Fishbone Diagram of FM-06

Source: Authors' analysis based on field observations and interview results (2026).

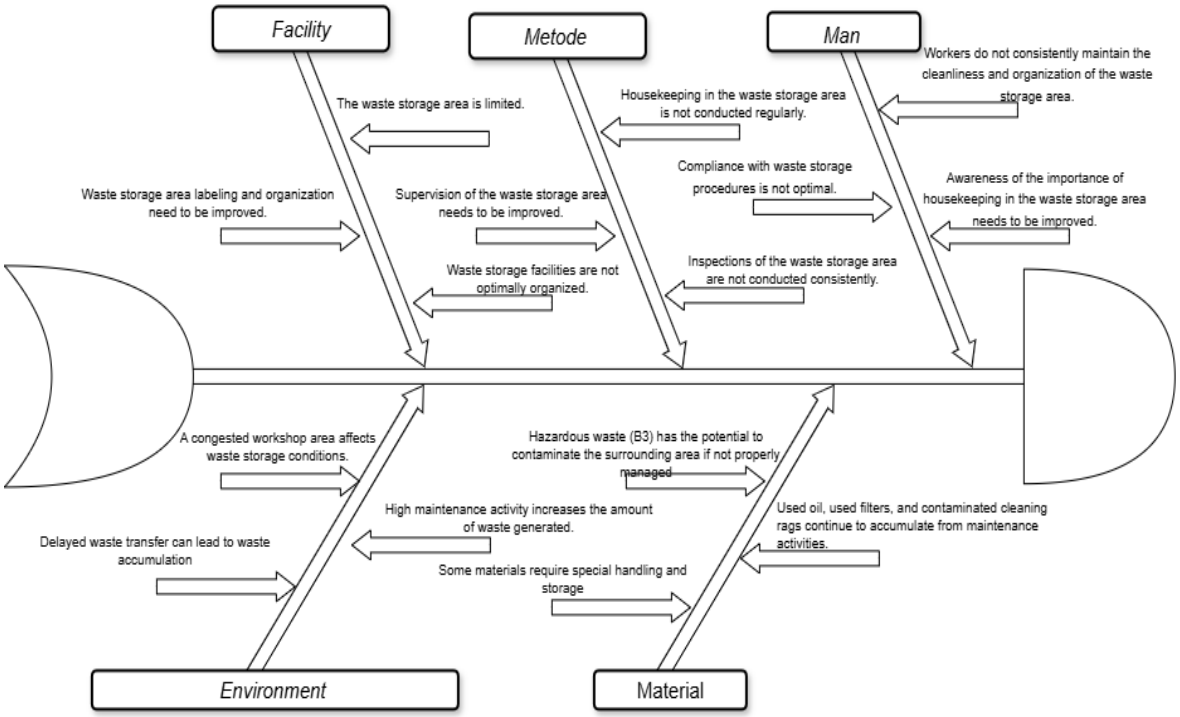


Figure 3. Fishbone Diagram of FM-10

Source: Authors' analysis based on field observations and interview results (2026)

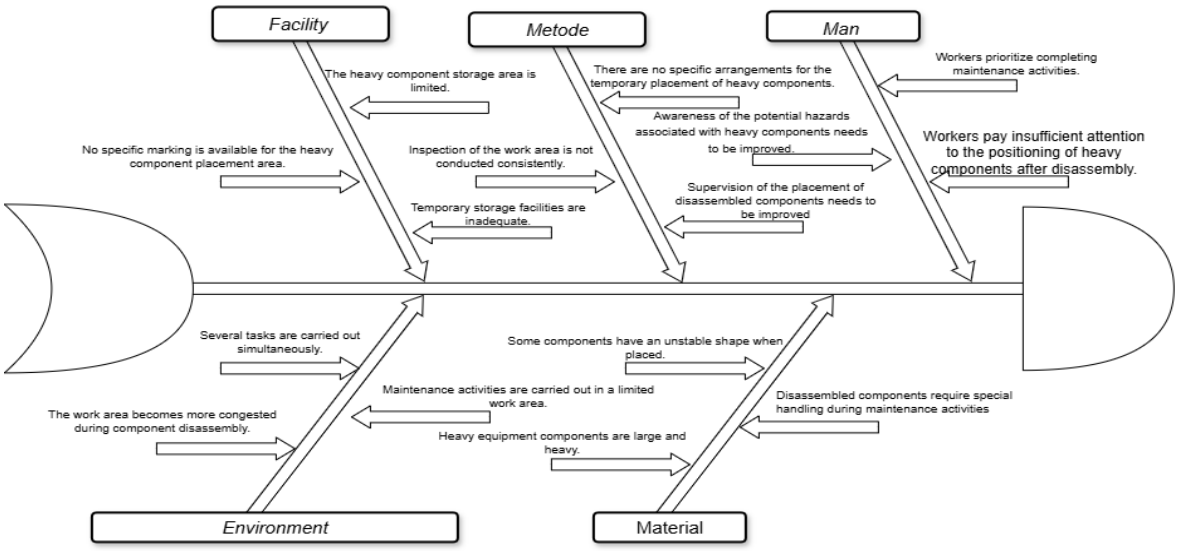


Figure 4. Fishbone Diagram of FM-14

Source: Authors' analysis based on field observations and interview results (2026)

The RCA results indicate that the root causes of the risks were predominantly associated with the *man, method,* and *facility* factors. The *man* factor was related to low compliance with work procedures and *housekeeping* practices. The *method* factor was attributed to the inconsistent implementation of hazardous waste management procedures, while the *facility* factor was associated with limitations in supporting facilities for waste storage and handling. In addition, the *material* and *environment* factors also contributed to several *failure modes*, particularly those related to oil spills and drainage system contamination. These findings indicate that improving the effectiveness of hazardous waste management requires not only improvements in supporting facilities but also stronger work discipline and enhanced supervision of procedure implementation.

4.4. *Improvement Recommendations*

Improvement recommendations were developed based on the RCA results using the 5W+1H approach. This approach was employed to formulate corrective actions systematically by considering the objectives, rationale, location, implementation timing, responsible parties, and implementation steps. The recommendations focused on controlling *High Risk failure modes* and were therefore expected to reduce potential risks to operational, environmental, and occupational safety and health (OSH) aspects.

Table 3. Improvement Recommendations Using the 5W+1H Approach

Failure Mode	What	Why	Where	When	Who	How
FM-08 The drainage system or wastewater channel is contaminated with oil waste and dirt generated from maintenance activities.	Improve waste control in drainage areas	To prevent environmental pollution through wastewater drainage channels.	Workshop area and drainage channels.	Regularly and after maintenance activities.	HSE, Head Mechanic, and Head of Facility.	Conduct regular drainage inspections, clean the drainage system routinely, and install barriers or control systems to prevent waste from entering the drainage channels.
FM-14 Unsafe placement of heavy components may cause workers to be struck by or trapped beneath components.	Improve the control of heavy component storage and placement.	To reduce the risk of workers being struck by or trapped beneath components.	Workshop area and component storage area.	During unit disassembly and repair activities.	Mechanics, Head Mechanic, and HSE.	Designate a specific storage area for heavy components, provide area markings, and supervise the placement of dismantled components.
FM-06 Oil spills or liquid waste are not properly handled, resulting in contamination of the work area.	Improve the control and handling of waste spills.	To prevent contamination of the work area and reduce the potential for accidents caused by slippery floors.	Workshop area and maintenance locations.	Whenever a waste spill occurs.	Mechanics, Head Mechanic, and HSE.	Provide spill kits in work areas, conduct spill response training, and ensure that spills are cleaned immediately after occurrence.

FM-10 The waste storage area does not meet housekeeping standards, increasing the potential for contaminant spread.	Improve housekeeping and organization of the waste storage area.	To maintain the cleanliness of the storage area and prevent the spread of contaminants.	Hazardous waste storage area.	Regularly according to the housekeeping schedule.	Head of Facility, HSE, and relevant workers.	Establish a housekeeping schedule, conduct periodic inspections, and organize the waste storage area in accordance with applicable standards.

Source: Authors' analysis based on RCA results (2026).

5. CONCLUSION

This study successfully identified 15 failure modes in the management of hazardous waste generated from heavy equipment maintenance activities at PT XYZ. Based on the analysis using the Failure Mode, Effects, and Criticality Analysis (FMECA) method, four failure modes were classified as High Risk, nine as Moderate Risk, and two as Low Risk based on the Severity (S), Occurrence (O), Detection (D), and Risk Priority Number (RPN) values. The highest-priority failure mode was FM-08, involving contamination of the drainage system by used oil and dirt generated from maintenance activities, with an RPN of 324 and a normalized RPN (NRPN) of 100%, followed by FM-14 (RPN = 288), FM-06 (RPN = 280), and FM-10 (RPN = 280).

The Root Cause Analysis (RCA) results indicated that the root causes of the risks were predominantly associated with the man, method, and facility factors, while the material and environment factors also contributed to several failure modes. Based on these findings, improvement recommendations were developed using the 5W+1H approach to support the effectiveness of hazardous waste management, reduce potential operational risks, minimize environmental impacts, and improve occupational safety and health during heavy equipment maintenance activities.

This study contributes to the integrated application of FMECA and RCA for risk analysis in hazardous waste management by simultaneously considering operational, environmental, and occupational safety and health (OSH) aspects. The findings can serve as a reference for companies in establishing risk control priorities in a more systematic manner.

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