Jurnal Perkeretaapian Indonesia (Indonesian Railway Journal) Vol.8 No. 2 Oktober, 2024
p-ISSN 2550-1127/e-ISSN 2656-8780

Risk Analysis of Railway Infrastructure Asset using Hazard Identification and FMEA Analysis on Track Asset

Angga Tri Maulana[1]*, Satrio Wicaksono[1],
Fakultas Teknik Mesindan Dirgantara, Institut Teknologi Bandung, Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat 40132, Indonesia[1]
*) corresponding author: Angga Tri Maulana / 23122037@mahasiswa.itb.ac.id

ABSTRAK

Kereta api di Indonesia menjadi pilihan utama dalam transportasi karena kapasitasnya yang besar dan tingkat keselamatan yang tinggi. Namun, menjaga keandalan sistem prasarana memerlukan perawatan yang fokus pada keselamatan dan manajemen risiko secara cermat. Oleh karena itu, penelitian ini bertujuan untuk menyelidiki risiko terkait prasarana kereta api, dengan fokus pada identifikasi bahaya dan analisis FMEA (Failure Mode and Effects Analysis) pada jalur kereta api. Melalui pengumpulan data primer berupa kuesioner, wawancara serta diskusi dan data sekunder berupa studi literatur, analisis mengungkap 28 bahaya signifikan terkait prasarana kereta api. Ditemukan bahwa sebelas modus kegagalan memiliki nilai RPN pada level high risk dan sembilan modus kegagalan pada level moderate risk, sementara hanya 8 modus kegagalan pada level low risk. Empat besar modus kegagalan dengan risiko tertinggi adalah rel patah, skilu, rel spaten dan rel retak. Rekomendasi perbaikan diberikan sehingga menurunkan nilai RPN pada level high dan moderate risk menjadi level moderate dan low risk serta meningkatkan keamanan jalur kereta api. Analisis ini memberikan dasar yang kokoh untuk pengembangan strategi manajemen risiko yang lebih efektif di masa depan dan berkontribusi pada pemahaman dan peningkatan keamanan prasarana jalur kereta api serta memfasilitasi strategi perawatan yang efektif untuk operasi kereta api yang berkelanjutan.
Kata Kunci: Identifikasi bahaya, FMEA, aset jalur kereta api, Risiko.

ABSTRACT

Railway transportation in Indonesia is the primary choice due to its large capacity and high safety standards. However, maintaining the reliability of the infrastructure system requires careful safety-focused maintenance and risk management. Therefore, this research aims to investigate the risks associated with railway infrastructure, focusing on hazard identification and Failure Mode and Effects Analysis (FMEA) on railway tracks. Through the collection of primary data via questionnaires, interviews, discussions, and secondary data from literature studies, the analysis revealed 28 significant hazards related to railway infrastructure. It was found that eleven failure modes had RPN values at the high-risk level and nine at the moderate-risk level, while only eight failure modes at the low-risk level. The best four failure modes with the highest risk were broken rail, *skilu*, buckling rail on railway geometry and cracked/defective rail. Recommendations for improvement were provided to reduce the RPN values from high and moderate-risk levels to moderate and low-risk levels and enhance railway safety. This analysis provides a solid foundation for developing more effective risk management strategies in the future, contributing to the understanding and improvement of railway infrastructure safety and facilitating effective maintenance strategies for sustainable railway operations.
Keywords: *Hazard Identifiaction, FMEA, Railway Track Asset, Risk.*

1 INTRODUCTION

The mobility of people and goods relies heavily on efficient transportation. Railways in Indonesia are the leading choice because they have a large capacity, utilise land efficiently, and offer a high level of safety [1]. The railway transportation system involves infrastructure, facilities, human resources, and specific rules, whereas railway infrastructure, which includes tracks, stations, and operational facilities, plays a crucial role in ensuring safety and comfort. In maintaining the reliability of the railway infrastructure system, infrastructure maintenance is carried out with the main focus on safety, which requires careful risk management for safe and reliable operations [2]. Among the various infrastructure components that make up a railway track asset, railway geometry, rails, Railway turnout, fasteners, concrete sleepers, and ballast are potential risks that need to be thoroughly analysed.

The challenge in managing railway infrastructure assets is an in-depth understanding of the complexity of railway infrastructure network components, interactions between components, and their impact on network performance by maximising system performance and safety [3]. Safety standard guidelines are used to prevent railway system accidents by meeting the railway regulator's technical requirements. Railway components such as rails, Railway turnout, fasteners, and sleepers have technical requirements. Wear standards apply to rails and Railway turnout, while fasteners and sleepers must be installed correctly according to the rules [4]. Despite safety standard guidelines, the potential danger of train accidents can still occur due to a lack of compliance with procedures and a lack of guidance and supervision of risks. These risks can be effectively monitored, evaluated and reported through decisions regarding safety risk reporting and safety management systems [5].

Safety is directed at the existence of risk-free conditions in the system, while risk itself reflects the hazard's probability and intensity level. Safety analysis involves hazard identification and risk evaluation using Failure Mode and Effect Analysis (FMEA) methods. Integration of safety in RAMS (Reliability, Availability, Maintainability, Safety) involves understanding and assessing risks in system reliability, availability, and maintainability, optimising maintenance strategies and maintaining operational safety and other infrastructure [6]. RAMS is used throughout the system lifecycle, considering the needs of various parties such as suppliers, project implementers, project owners, and railway operators. It helps detect, analyse, and control potential hazards and ensures long-term optimal availability and selection of the best maintenance solutions. Thus, RAMS provides a crucial methodological framework for engineers, system designers, clients, and operators to address safety and reliability issues throughout the life cycle of rail systems [7]. The characteristics of RAMS are closely interrelated in that improving product reliability can reduce the likelihood of catastrophic failures, and product maintenance can improve safety, but it also has the potential to cause failures if not appropriately performed [8].

Railway companies face various operational risks, from management level to field operations. Risk identification and evaluation are essential to establish an acceptable level of risk because railway operational safety has a broad impact [9]. Based on train accidents from 2020 to 2023, there have been three accidents in Indonesia, where 66.67% of the leading causes of these accidents are infrastructure factors [10]. The graph of the leading causes of train accidents in 2020 - 2023 can be seen in Figure 1.

Risk analysis on railways involves recognising, evaluating, and controlling potential hazards during operations. Good design and maintenance are required to meet the high safety standards governed by guidelines such as EN 50129 and EN 50126-2 [7]. The railway sector has been steadily increasing in recent decades, yet limited infrastructure capacity leads to traffic disruptions. To maintain the attractiveness of railways, sustainable economical safety performance is required. One approach is reliability-based maintenance with the support of formal risk analysis recognised by regulators [11]. The company's priority is to identify risks related to infrastructure maintenance, using methods such as FMEA for in-depth risk analysis and taking preventive actions [9].

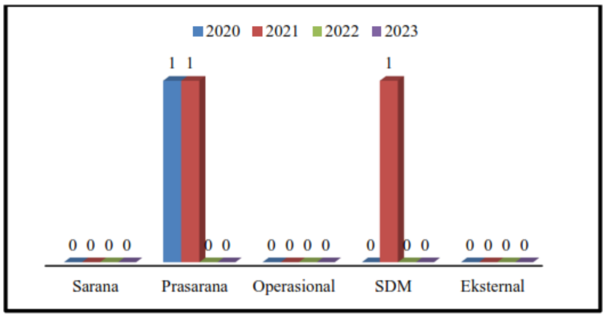

Figure 1. Leading Factors of Train Accidents 2020 - 2023 [10]

FMEA is a systematic method used to evaluate items or processes by identifying potential failures and their impact on performance and the surrounding environment to support decision-making that reduces the likelihood of failure and its impact and improves outcomes. FMEA must comply with applicable laws and be used by those directly involved in the analysis [12]. In risk analysis, FMEA is performed by identifying and assessing potential failures using the parameters of severity, likelihood of occurrence, and probability of detection. A Risk Priority Number (RPN) is then formed to determine the criticality level. This technique is applied in various industries to analyse systems, products, assembly, and services [13].

In the rail industry, rail infrastructure assets, as the foundation of the rail system, are critical to maintaining safe and efficient operations. To achieve this, lifecycle management is required to ensure effective asset management, considering all asset lifecycle phases. The asset hierarchy of railway infrastructure includes railways, civil engineering/structure, and systems/promises [3]. FMEA can be conducted on all aspects of railway infrastructure, but it can also be applied to one asset hierarchy, such as on the railway aspect, where the FMEA analysis process is carried out through the stages of identification, assessment, and recommendations [14].

The FMEA technique involves a worksheet that records failure modes, RPN values, and countermeasures to reduce risk and improve failure detection. The parameters to be evaluated in FMEA analysis related to railway components include damage or failure of track geometry, rails, Railway turnout, fasteners, sleepers, and ballast to ensure the safety and security of trains [13].

The FMEA method is used systematically to analyse components and systems in railway infrastructure by performing risk assessment considering factors such as severity, likelihood of occurrence, and detectability. FMEA thus helps identify potential risks associated with railway infrastructure and design appropriate corrective actions. Implementing these actions can reduce the risk of failure, improve service, and enhance operational safety and reliability. While various risk identification methods exist, FMEA and its components are considered one of the most suitable and practical approaches. Risk priority values are calculated based on occurrence, fault detection, and severity indicators, which help establish priorities for action [9]. Thus, FMEA provides an understanding of the risks in railway infrastructure and a concrete framework for improving safety and reliability.

Risk methodology in railway infrastructure maintenance programs is critical to effectively improving system safety and performance to ensure that maintenance changes do not compromise safety levels, availability, and timeliness while maintaining or improving maintenance cost efficiency [11]. Preventive and corrective maintenance is essential to maintain stability and reduce losses. The FMEA method determines maintenance policies by assessing damage's potential types, consequences, and causes based on severity, occurrence, and detection criteria. This evaluation helps set maintenance priorities based on risk priority number (RPN), which reflects the level of risk of damage that may occur, thus helping to optimise maintenance strategies and improve the performance and safety of the railway [15]. Therefore, this study aims to investigate and analyse the risks associated with railway infrastructure, focusing on hazard identification and the application of FMEA analysis on railways to railway infrastructure, such as track geometry, rails, Railway turnout, fasteners, sleepers, and balances. Through the application of FMEA, this research identifies potential failure modes, evaluates the impact of failures on the performance of railway infrastructure, and assesses risks related to the severity, likelihood of occurrence, and detectability of failures. In addition, it formulates appropriate corrective action recommendations to reduce the risk of failure, improve service, and enhance the overall safety and reliability of the railway infrastructure. As such, this research provides a deep insight into the risks associated with railway infrastructure and provides a concrete framework for improving its safety and operational performance.

2 LITERATURE STUDY

2.1 Risk Management Concepts in the Context of Infrastructure Assets

Risk management is a systematic, structured, and comprehensive process for identifying, analyzing, evaluating, and managing risks in an organization to assure stakeholders that risks have been identified and managed effectively, according to context, and with an evidence-based approach [16]. Risk management involves identifying, classifying, analyzing, attitude, and responding to risks. Risks are identified and documented using various methods in Risk Identification. Sources of risk are understood and categorized in Risk Classification. Risk impacts are assessed, and priorities are set for risk analysis. Strategies to increase opportunities and reduce threats are developed in Risk Response. Consideration of controls, capabilities, and responsibilities of relevant parties is done in Risk Allocation [17].

As per ISO 31000, risk assessment involves identifying, analyzing, and evaluating risks. Identification involves recognizing sources of risk and material events using evidential methods or a team approach. The analysis aims to understand the risk and provide input for decision-making. The evaluation compares risks with established criteria, considering risk tolerance, and uses frequency, severity, and detection values to compile a comprehensive analysis result [6]. Risk control is carried out with four steps: elimination, substitution, engineering control, and administrative control, which aim to reduce potential hazards in the work environment [18]. Each step in the risk assessment process should be applied relevantly considering the complexity of the problem, the degree of uncertainty, the resources required, and the ability to provide quantitative outputs [16]. The risk management process can be seen in Figure 2.

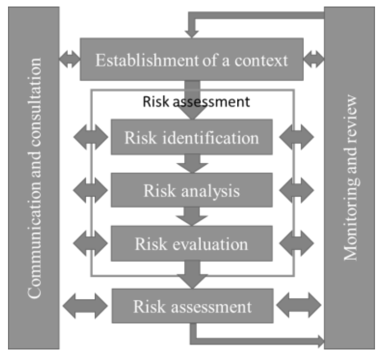

Figure 2. Risk management process [16]

2.2 Risk Assessment and Hazard Identification Techniques

Risk assessment enables decision-makers to make informed decisions on how to treat specific risks. Effective communication and consultation with stakeholders is essential in this process. In selecting risk assessment techniques, justifiable techniques must be considered according to the situation and an understanding of the increased risk that can be traced and verified. After that, factors such as study objectives, decision-maker needs, type of risk, potential consequences, available expertise, and availability of information influence the selection of techniques. Then, the technique meets the needs of the risk assessment well, is consistent with the level of potential risk being analyzed, and can be modified or improved as needed. In addition, attention is required to applicable regulatory and contractual requirements. Evaluation of each step in the risk assessment process is necessary to determine the methods' applicability [16]. Table 1 shows the applicability of some of the tools and techniques used for risk assessment.

Table 1. Application of tools and techniques for risk assessment

Alat Bantu dan Teknik	Proses Penilaian Risiko				
	Identifikasi risiko	Analisis risiko			Evaluasi risiko
		Konsekuensi	Probabilitas	Tingkat risiko	
Hazard and Operability Study	HA	HA	A	A	A
Root Cause Analysis	NA	HA	HA	HA	HA
Failure Mode and Effect Analysis	HA	HA	HA	HA	HA
Fault Tree Analysis	A	NA	HA	A	A
Cause and Effect Analysis	A	HA	HA	A	A
Event Tree Analysis	A	HA	A	A	NA
Reliability Centered Maintenance	HA	HA	HA	HA	HA
Markov Analysis	A	HA	NA	NA	NA
Monte Carlo Simulation	NA	NA	NA	NA	HA
Bayesian Statistics and Networks	NA	HA	NA	NA	HA

Note: HA = Highly Acceptable, A = Acceptable, NA = Not Acceptable
Source: [16]

Hazard identification is a critical step in railway safety analysis. It involves observing and analyzing systems to recognize potential failures or hazardous conditions and establish safety requirements, including understanding high-level hazards and their causes. The hazard control stage focuses on determining the underlying causes of hazardous events. Various hazard identification techniques such as FMEA, FTA, and ETA are used to evaluate risks that may affect the reliability and safety of railway systems. Therefore, proper hazard identification is essential to ensure optimal operational safety [7].

2.3 FMEA Analysis in Railway Infrastructure Asset Management

FMEA produces quantitative outputs, with factors such as resources, uncertainty, and complexity influencing their relevance, which are used to identify and address potential failures in systems, designs, and processes. The critical variables in FMEA are Severity, Occurrence, and Detection, which determine the risk rating of the failure. The rating scale ranges from 1 to 10, with 1 indicating the lowest impact and 10 the highest impact, tailored to the potential failure and relevant literature [19]. FMEA analysis helps prevent failures by identifying possible failure modes and developing appropriate control strategies. By analyzing possible failures and their consequences, FMEA improves the safety of railway operations and becomes a valuable tool in ensuring optimal safety [7]. Implementing FMEA involves identifying, assessing, and addressing failure modes. It involves reviewing potential failures, determining their impact, and recommending handling actions. Reassessment is done to evaluate the actions' effectiveness by checking the RPN value after handling to ensure that the risk of failure has been effectively managed and remains acceptable [13]. Risk priority number (RPN) calculation is based on fault occurrence, detection, and severity indicators. Furthermore, the calculation of an action plan is recommended based on the results of the RPN value [9]. FMEA is used as one of the explicit risk estimation methods, especially in the context of railway systems, where it is calculated based on the probability of hazard occurrence (O), the consequence of hazard occurrence (S), and the probability of hazard detection (D) [20]. The severity and occurrence rate criteria can be based on historical statistics from the infrastructure information system of the railway company's safety department [9]. The table of severity and occurrence rate in railway service can be seen in Tables 2 and 3.

Table 2. Criteria for Severity

Severity of the disorder	Description	Pts.
Extremely serious	The impact of the danger is very serious and can lead to a drastic decrease in safety (eg serious railway accident, death) / in case of death or property damage by € 2,000,000 in points 9, above € 2,000,000 in points 10.	10
		9
High	The impact of the danger is serious and leads to a reduction in safety (railway accident and serious injury) / in the case of personal injury or property damage up to € 750,000 in points 7, over € 750,000 in points 8.	8
		7
Moderately significant	The impact of the hazard is significant and can lead to a reduction in the level of safety (for example: incident, injured people) / in case of injury or property damage up to € 100,000 in points 4, up to 250,000 in points 5 and up to 500,000 in points 6.	6
		5
		4
Little significant	The impact of the danger is small and leads to a reduction in the level of safety (eg failures during operation) / in the case of property damage up to € 10,000 in points 2, up to € 50,000 in points 3.	3
		2
Insignificant	The effect of the hazard has no significance for safety. No cost.	1

Source: [9]

Table 3. Criteria for Occurrence

Accident occurrence	Description (frequency of accident)	Points
Very high	Once in 3 months	10
	Once in 6 months	9
	Once in a year	8
High	Once in 2 years	7
	Once in 3 years	6
Moderate	Once in 4 years	5
	Once in 5 years	4
Low	Once in 6 years	3
	Once in 7 years	2
Negligible	Once in 8 years	1

Source: [9]

The hazard identification potential parameter determines how likely potential hazards can be diagnosed. Early detection of hazards through advanced onboard diagnostic systems or advanced test methods during inspection or maintenance significantly influences the high safety level [20]. A table of detection rates for railways can be seen in Table 4.

Table 4. Criteria for Detection

Risk detection	Description	Points
Very low	Minimal probability of hazard detection. It is practically impossible to identify the cause of the error.	10
		9
Low	There is a low probability of hazard detection. It is very likely that the control measures which are applied will not make it possible to identify the cause of the error. It is very difficult to identify the cause of the error.	8
		7
Average	There is an average probability of hazard detection. The control measures may enable the identification of the cause of the error. Symptoms may be established and identified which indicate the possibility of hazard occurrence.	6
		5
High	The probability of hazard detection is high. The control measures which are applied enable the identification of the cause of the error. Symptoms for the occurrence of the cause are noticeable.	4
		3
Very high	The probability of hazard detection is very high. Identification of the cause of the error is certain.	2
		1

Source: [20]

Risk evaluation is carried out using a risk matrix, where hazards with an RPN value above 120 are considered relevant, and hazards with an RPN value above 150 are considered a direct threat to the rail system's safety. Preventive and corrective measures are applied to hazards with high RPN values [20]. Mathematically, the relationship between parameters and RPN is formulated as follows:

$$RPN = S \times O \times D \qquad (1)$$

Where RPN is Risk Priority Number, S is Severity, O is Occurance, and D is Detection

When determining the S, O, and D parameters, there are differences in numerical values in the team's decision results, where the numerical value is between two numbers, so always choose the higher number. If teams experience disagreements in value judgments, the following steps may help [21]:

1. If the different values are close together, average the differences. For example, if values are 5 and 6, the final value is 6.
2. If differences in scores jump one category, reach a consensus. All team members must feel responsible for the decision.

Based on the RPN results, risk effects are evaluated according to the data listed in Table 5, and from these results, recommended steps for improvement are carried out [9].

Table 5. Evaluate of RPN

Evaluation	Measure	RPN total
High risk	Necessary intervention in the process is required.	>150
Moderate risk	Process control is required.	121-150
Low risk	No special measures required.	120

Source: [9]

3 METHOD

The research analysis method begins by collecting primary data through questionnaires, interviews, or discussions and secondary data from literature studies. The next step is hazard identification, followed by determining the Severity (S), Occurrence (O), and Detection (D) parameters. Then, FMEA analysis is carried out to obtain the RPN value. After that, an RPN value is evaluated, and if it exceeds tolerance, a risk response is carried out by making improvements. The final step is to draw up conclusions to complete the analysis. The research flow chart can be seen in Figure 3.

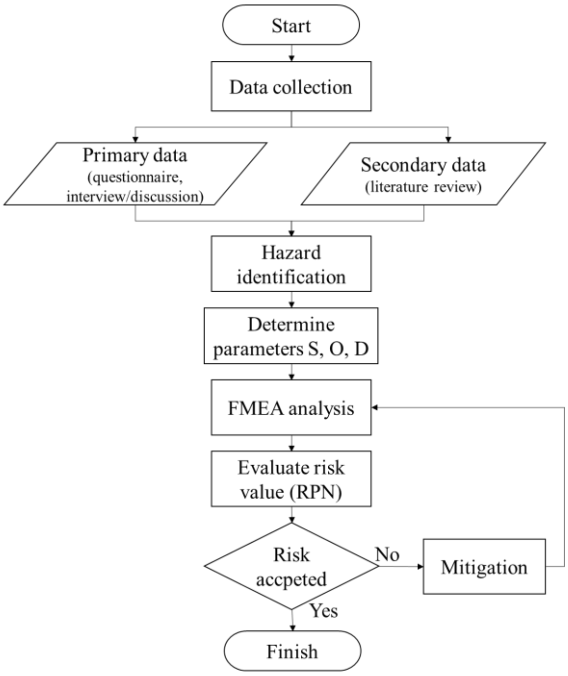

Figure 3. Research method for risk analysis of railway infrastructure

4 RESULT AND DISCUSSION

4.1 Hazard Identification

The results of the analysis of hazard identification data are based on questionnaires and interviews conducted with 30 respondents who are experienced workers in railway infrastructure where the infrastructure investigated includes railway geometry, railway turnout, rails, fasteners, sleepers and ballast. A comparison of respondents' experiences can be seen in Figure 4.

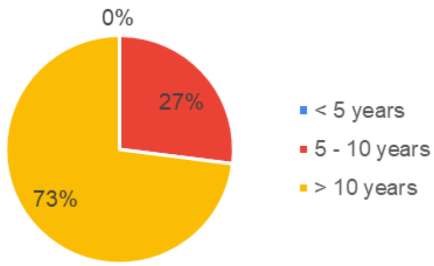

Figure 4. Respondents' experience in railway infrastructure

Based on the results of the questionnaire, a hazard identification list for each railway line component was obtained. The hazard identification list is based on respondents' choices with a reasonably high percentage. Hazard identification for railway track components can be seen in Figures 5, 6, 7, 8, 9, and 10.

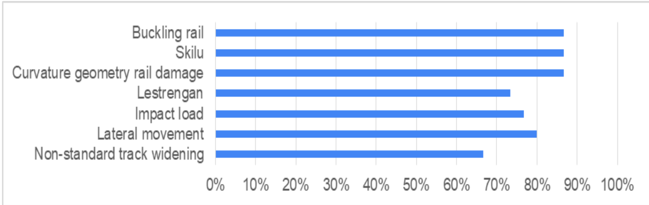

Figure 5. Hazard Identification of Railway Geometry

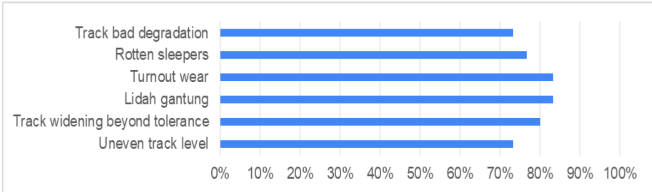

Figure 6. Hazard Identification of Railway turnout

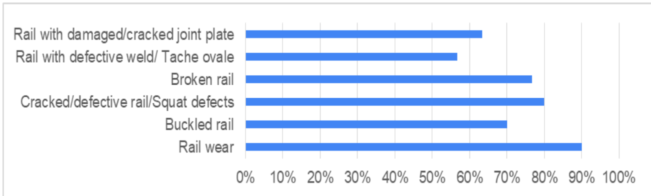

Figure 7. Hazard Identification of Rails

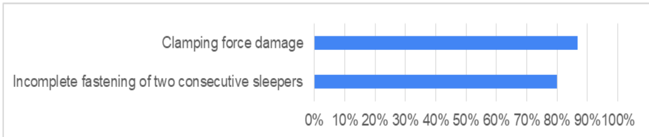

Figure 8. Hazard Identification of Railway Fasteners

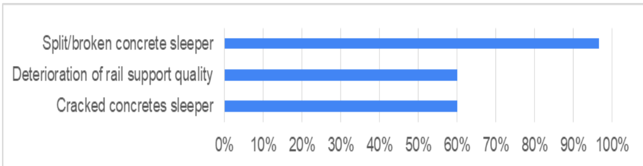

Figure 9. Hazard Identification of Concrete Sleepers

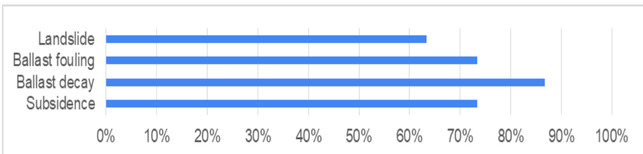

Figure 10. Hazard Identification of Ballast

It can be seen that more than 50% of respondents have the same assessment regarding identifying hazards on railway track components. A recap of hazard identification on railway lines can be seen in Table 6.

Table 6. Recap of Hazard Identification on Railway Track Components

No	Components	Hazard Identification
1	Railway geometry	Non-standard track widening
		Lateral movement
		Impact load
		Lestrengan
		Curvature geometry rail damage
		Skilu
		Buckling rail
2	Railway turnout	Uneven track level
		Track widening beyond tolerance
		Lidah gantung
		Turnout wear
		Rotten sleepers
		Track bad degradation
3	Rails	Rail wear
		Buckled rail
		Cracked/defective rail/Squat defects
		Broken rail
		Rail with defective weld/ Tache ovale
		Rail with damaged/cracked joint plate
4	Fasteners	Incomplete fastening of two consecutive sleepers
		Clamping force damage
5	Concrete Sleepers	Cracked concretes sleeper
		Deterioration of rail support quality
		Split/broken concrete sleeper
6	Ballast	Subsidence
		Ballast decay
		Ballast fouling
		Landslide

4.2 Determine Severity (S), Occurance (O), dan Detection (D) Parameters

The criteria for severity level, occurrence level, and detection level were established through an extensive review of hazard identification and risk control systems employed by railway companies in Indonesia, along with relevant literature on FMEA. These criteria are made in a table showing a scale for each level with a numerical value of 1 - 10, where 1 is the lowest and 10 is the highest. Based on the results of development and discussion sessions with railway company personnel in Indonesia, the criteria for severity level, incident level and detection level can be seen in Tables 7, 8 and 9.

Table 7. Classification of Severity

Severity Rating	Based on Financial (loss)	Based on Train Operations (single track)	Based on Facilities and Infrastructure	Based on Safety
1	< 25 million rupiah	< 30 minutes	Slightly damaged	No victims required medical treatment
2	25 – 100 million rupiah	30 – 45 minutes	Damaged ≤ 10%	Minor injuries without hospitalization
3	100– 250 million rupiah	45 minutes – 1 hours	Damaged ≤ 20%	
4	250 – 500 million rupiah	1 – 1 hours 15 minutes	Damaged ≤ 30%	Minor injuries with total hospitalization < 30 days
5	500 juta million – 1 billion rupiah	1 hours 15 minutes – 1,5 hours	Damaged ≤ 40%	
6	1 – 2 billion rupiah	1,5 – 1 hours 45 minutes	Damaged ≤ 50%	Serious injuries with inpatient treatment > 30 days
7	2– 3 billion rupiah	1 hours 45 minutes – 2 hours	Damaged ≤ 60%	
8	3 – 4 billion rupiah	2 – 2,5 hours	Damaged ≤ 75%	
9	4– 5 billion rupiah	2,5 – 3 hours	Damaged ≤ 90%	The victim is permanently disabled
10	> 5 billion rupiah	> 3 hours	Damaged > 90%	The victim died

Table 8. Classification of Occurrence

Occurrence Rating	The possibility of an event occurring	Indicators based on history	Indicators based on future possibilities
1	0 – 10%	Never happened	There is no indication in the assessment
2	> 10 – 20%	Occurs < 2 in a year	
3	> 20 – 30%	Occurs < 2 in a year	

Occurrence Rating	The possibility of an event occurring	Indicators based on history	Indicators based on future possibilities
4	> 30 – 40%	Occurs < 4 in a year	There are indications but they are not convincing enough for the assessment
5	> 40 – 50%	Occurs < 6 in a year	There are indications in the assessment and they are quite convincing
6	> 50 – 60%	Occurs < 8 in a year	
7	> 60 – 70%	Occurs < 12 in a year	There are strong indications in the assessment and are quite convincing
8	> 70 – 80%	Occurs < 20 in a year	
9	> 80 – 90%	Occurs < 30 in a year	There are strong indications in the assessment and are convincing
10	> 90 – 100%	Often occur	

Table 9. Classification of Detection

Detection Rating	Probability of failure to detect	Criteria based on control design	Detection Criteria
1	Almost certainly	The controls can almost certainly detect potential failures	There is a high probability that a defect will be detected. Verification and/or control will almost certainly detect damage or defects
2	Very high	Has very high control capabilities to detect failures	
3	High	Has high control capabilities to detect failures	There is a high probability that a defect will be detected. Verification and/or controls have a good chance of detecting damage or defects
4	A bit high	Having high control capabilities tends to detect failure	
5	Currently	Has sufficient control capabilities to detect failures	Medium probability that a defect will be detected. Verification and/or control will most likely detect damage or defects
6	Low	Has low controllability to detect failure	
7	Very low	Has very low controllability to detect failure	
8	Slight	There are few controls to detect potential failures	It is unlikely that defects will be detected. Verification and/or control may not detect any damage or defects
9	Very slight	There are very few controls to detect potential failures	
10	Almost impossible	There are no controls to detect potential failures	There is a very low (or zero) chance that a defect will be detected. Verification and/or control will not or cannot detect any damage or defects

4.3 FMEA Analysis

The next step after identifying hazards and determining the S, O, and D parameters is to conduct FMEA analysis by determining the S, O, and D values and calculating the RPN value for each identified hazard. Determining these values is essential to measure the level of potential risk and prioritize the actions needed to reduce risk. The determination of these values was carried out using a questionnaire to 39 respondents who are experienced workers in railway infrastructure. A comparison of respondents' experience can be seen in Figure 11.

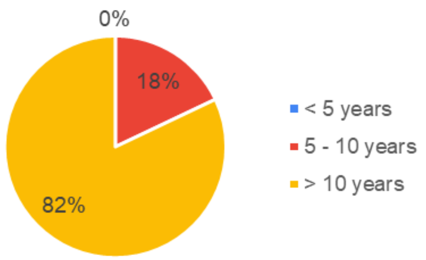

Figure 11. Respondents' experience to determine S, O, D

The analysis involved using descriptive statistics to determine the selected value from the 39 options provided by respondents in the questionnaire. In cases where variations occurred among respondents regarding certain parameters (S, O, and D), the average value was utilized based on findings from the literature review. For this study, the absolute mean value derived from the 39 responses was employed as the value for parameters S, O, and D. Mean, or average, denotes the central value of a dataset obtained by dividing the sum of all data points by the total count of data points. Typically, two central values are recognized: the mean for the entire population and the mean for a sample. Mean, or average, serves as a key indicator of central tendency in datasets [22]. After completing hazard identification and calculating S, O, and D parameters, the highest RPN was observed for broken rail (252) and *skilu* (224), while the lowest was for incomplete fastening of consecutive sleepers (60). A comprehensive FMEA analysis was conducted for railway track components, detailed in Table 10.

Table 10. Result of FMEA Analysis in Railway Track Components

Component	***No***	***Potential Failure Mode***	***Potential Failure Effect***	***S***	***Potential Causes***	***O***	***Current Process Controls***	***D***	***RPN***
Rails	1	Rail wear	Degradation of rail components	7	Dynamic loads from high frequency trains	6	Process with wear gauge	3	126
	2	Buckled rail	Degradation of rail components	7	Axle loads and inconsistencies train traffic speed and defects in rail materials	5	Periodic visual inspection and penetrant	3	105
	3	Cracked/defective rail/Squat defects	Rail failure, rail breaks	8	Dynamic loads from high frequency trains	6	Periodic visual inspection for ultrasonic detection	4	192
	4	Broken rail	Rail failure, derailment	9	High shear stress loading cycles	7	ultrasonic detection, eddy current test, and penetrant	4	252
	5	Rail with defective weld/ Tache ovale	Rail failure, increased maintenance costs	7	Excessive hydrogen in the joints and incorrect welding procedures	6	ultrasonic detection, eddy current test, and penetrant	4	168
	6	Rail with damaged/cracked joint plate	Deterioration in track condition causes derailments	7	Insufficient support of rail sleepers and corrosion	5	Visual observation	3	105
Railway turnout	7	Uneven track level	Rails wear unevenly	7	Ballast is not solid	6	with rail scales	3	126
	8	Track widening beyond tolerance	wear	7	Fasteners are loose and rails wear	7	with rail scales	3	147
	9	*Lidah gantung*	Tongue rail does not close tightly until derailment occurs	7	Fasteners are rotted and ballast is not solid	6	with rail scales	3	126
	10	Turnout wear	The train wheels are not oriented properly	7	The rail height is not level and the train track width exceeds tolerance	6	Rail scales and wear gauges	3	126
	11	Rotten sleepers	Railway track widening and impact load	8	Sleepers age	7	Visual observation	2	112
	12	Track bad degradation	Impact load and derailment	7	ballast is thin and and drainage is inadequate	5	Visual observation	3	105
Fasteners	13	Incomplete fastening of two consecutive sleepers	Widening of railway tracks	6	The decreasing gripping force capability of the fastening clamp	5	Visual observation	2	60
	14	Clamping force damage	The fastener comes off very easily	6	The fastening being hammered and torqued improperly	5	Visual observation	4	120
Concrete Sleepers	15	Cracked concretes sleeper	Structural failure and train derailment	6	Affected by tamping machine and increased loading	5	Visual observation	3	90
	16	Deterioration of rail support quality	Increased maintenance costs	6	Abrasion of rail fastening base and wearing of fasteners	5	Visual observation	4	120
	17	Split/broken concrete sleeper	Structural integrity compromised,	8	Uneven compaction from the compactor	6	Visual observation	2	96

Component	***No***	***Potential Failure Mode***	***Potential Failure Effect***	***S***	***Potential Causes***	***O***	***Current Process Controls***	***D***	***RPN***
			failure and derailment		machine and load from supports				
Ballast	18	Subsidence	Subsidence of the railway and disruption of the railway structure	8	The load beneath the ballast layer	5	Visual observation	4	160
	19	Ballast decay	Loss of durability and alignment of railway tracks	8	The ballast material is mixed with other substances and the drainage is poor	6	Visual observation	3	144
	20	Ballast fouling	Ballast deformation and misalignment between rails	7	The mixing of ballast with external/inherent materials, and the degradation of ballast particles	6	Visual observation	2	84
	21	Landslide	Structural failure and train derailment	8	Erosion, earthquakes, and steep slopes	5	Visual observation	4	160
Railway Geometry	22	Non-standard track widening	Damage to railway materials, up to derailments	8	Worn rails, non-standard concrete sleepers, and missing isolators	6	Visual observation and rail scales	3	144
	23	Lateral movement	Damage to railway materials, loss and derailment	8	Loose ballast, thin ballast, and trackbed movement	7	Visual observation and rail scales	3	168
	24	Impact load	Damage to railway materials, loss and derailment	8	Loose ballast, thin ballast, and trackbed movement	7	Visual observation and rail scales	3	168
	25	*Lestrengan*	Damage to railway materials, loss and derailment	8	Loose ballast, thin ballast, and trackbed movement	7	Visual observation and rail scales	3	168
	26	Curvature geometry rail damage	Damage to railway materials, up to derailments	8	The lengthening of the curve, track widening, and more ballast on the outer	7	Visual observation and rail scales	3	168
	27	*Skilu*	Damage to railway materials, up to derailments	8	The height difference of the rail inside and outside the three-meter span	7	Visual observation and rail scales	4	224
	28	Buckling rail	Damage to railway materials, up to derailments	8	Loose ballast, thin ballast, and experiencing extreme high temperatures	6	Visual observation	4	192

4.4 Evaluate Risk Value

Risk value evaluation is carried out after the RPN value of all failure modes has been obtained. A risk value below 120 is still in a reasonable condition, so it is still safe with the control and measurement methods used currently. Meanwhile, a tighter control process is required for RPN values of 120 – 150. For RPN values of more than 150, process intervention is necessary to reduce risk within reasonable limits and control better. Based on the results of the FMEA analysis, it was found that eleven failure modes were at the high-risk level, nine failure modes at the moderate-risk level, and eight failure modes at the low-risk level. In this case, the best four failure modes at the high-risk level are:

1. Broken rail, RPN = 252 (S = 9, O = 7, D = 4)
2. *Skilu*, RPN = 224 (S = 8, O = 7, D = 4)
3. Buckling rail on railway geometry, RPN = 192 (S = 8, O = 6, D = 4)
4. Cracked/defective rail, RPN = 192 (S = 8, O = 6, D = 4)

Overall, the detection level ranges from 2 to 4, with 3 being more dominant, severity level ranges from 6 to 9 with 8 being dominant, and occurrence level ranges from 5 to 7 with no dominant value. The overall RPN value dominates above 150. The presentation of the FMEA analysis results can be seen in Figures 12 and 13.

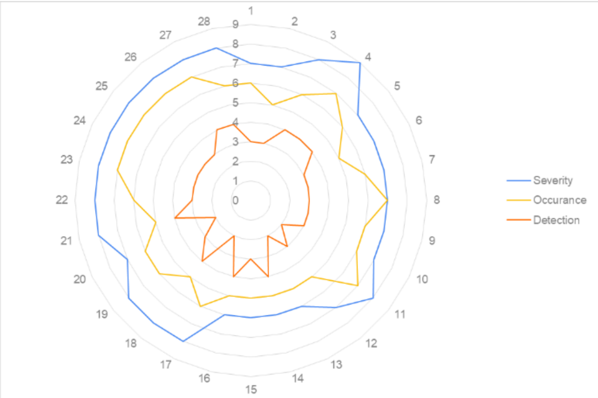

Figure 12. FMEA amalaysis result in S,O,D parameter presentation

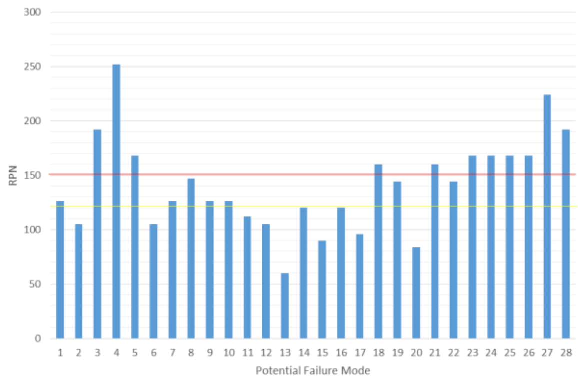

Figure 13. FMEA analysis result in RPN presentation

4.5 Risk Response

After conducting an FMEA analysis and identifying failure modes that require control and repair, the next step is to respond to the discovered risks. Risk response refers to a series of recommended actions to reduce the Risk Priority Number (RPN) value to an acceptable tolerance limit. These improvement recommendations aim to reduce the likelihood of a failure occurring, reduce its impact if it happens, or improve failure detection. Effective risk response ensures that risks are managed well and within established tolerance limits. Risk response was carried out by distributing questionnaires and discussions with railway company employees in Indonesia who had experience in the field of railway infrastructure. Based on the risk response carried out, all failure modes have an RPN value below 120. The results of the overall risk response can be seen in Table 11.

Table 11. Risk Respon Analysis of Failure Modes with High-risk and Moderate-risk levels

Component	***No***	***Potential Failure Mode***	***Existing***				***Action Recommended***	***Improvement***			
			S	***O***	***D***	***RPN***		***S***	***O***	***D***	***RPN***
Rails	1	Rail wear	7	6	3	126	Maintenance on curves, routine inspections, periodic upkeep, cyclic replacement of worn-out rails, lubrication, employing resilient rails, and collaborative efforts are crucial for ensuring the safety and reliability of railway operations	7	5	3	105
	3	Cracked/defective rail/Squat defects	8	6	4	192	Utilize flashbutt welding to prevent cracks at welding points, maintain joint geometry, and perform routine maintenance. Monitor the thermit welding process, inspect with ultrasonics, ensure compliance with procedures, conduct daily checks, enhance welding quality, and compact welding points.	7	5	3	105
	4	Broken rail	9	7	4	252	Ensure joint geometry is maintained, use ultrasonics during USM, install joint plates on potentially fractured rails, and complete joint bolts. Conduct daily inspections with officer, and replace rails if cracked. Monitor closely during welding, improve welding quality, and compact welding points. Adjust train loads according to routine inspection cycles, and utilize rail strength detection tools to inspect welded joints.	9	6	2	108
	5	Rail with defective weld/ Tache ovale	7	6	4	168	Ensure strict supervision of the welding process and quality, adhere to specified methods and SOPs, grind faulty rail surfaces with MP12, use stud welding at damaged spots, avoid welding old joints or defective rails, conduct routine inspections with ultrasonic equipment, and inspect track sections on foot for welded joint integrity	7	5	3	105

Component	***No***	***Potential Failure Mode***	***Existing***				***Action Recommended***	***Improvement***			
			S	***O***	***D***	***RPN***		***S***	***O***	***D***	***RPN***
Railway turnout	7	Uneven track level	7	6	3	126	Conduct routine maintenance cycles on switches using quality-tested Matisa equipment, ensuring adherence to SOPs and established cycles. Adjust switch construction for inadequate height, replace wooden with concrete or composite sleepers, address any leveling issues, and periodically lift surrounding ballast for proper compaction.	7	5	2	70
	8	Track widening beyond tolerance	7	7	3	147	Perform regular inspections and maintenance cycles on switches by adjusting the turnout construction to the required height, ensuring the track gauge meets standards by tightening fastening devices, documenting the number of deteriorated sleepers for replacement, replacing wooden turnuot sleepers with robust concrete ones, conducting routine inspections, and frequently surveying switches using Matisa equipment.	7	6	2	84
	9	*Lidah gantung*	7	6	3	126	Coordinate daily checks on the position of switch tongues for early detection and repair of any *lidah gantung*, and conduct regular surveys for periodic monitoring. Routinely maintain switches by compacting the tongue and sleeper areas. Ensure the stability of the track bed by modifying the rail track and using ballast tamping. Conduct detailed inspections with the Signaliing unit to test switch jams and maintain a level 0. Collaborate with the signaling and track maintenance units to detect hanging turnout.	7	5	2	70
	10	Turnout/ switches wear	7	6	3	126	Conduct routine switch inspections and maintenance cycles with periodic assessments. Maintain track geometry and width to standard specifications. Compact ballast and maintain switch tongue area for stability. Coordinate daily switch tongue position checks for early detection and resolution of any issues. Evaluate passing tonnage and speed on switch curves, replace worn switch tongues, and collaborate with Sintel units and track teams to address hanging switches. Perform ongoing maintenance on switch components, ensure track width, and lubricate regularly.	7	5	2	70
Fastener	14	Clamping force damage	6	5	4	120	Replace worn-out sleepers and fasteners with new and quality ones, regularly inspect to prevent wear and loose fasteners. Add insulators, conduct daily and monthly cross inspections, and check areas prone to vandalism. Ensure that fastener repairs are done regularly with quality materials and proper installation according to procedure. Replace fasteners according to their technical lifespan and ensure strong installation. Ensure that fasteners are not covered by ballast and avoid the use of hammers during installation.	6	4	3	72
Concrete sleepers	16	Deterioration of rail support quality	6	5	4	120	Perform routine inspections and periodic maintenance to maintain the geometry and condition of the track, ballast, and sleepers. Use rubber pads during sleeper installation and replace regularly. Replace fastening accessories and worn-out concrete sleepers regularly, and carry out tamping when damaged. Maintain proper elevation and level, and execute compaction cycles using specialized equipment	6	4	3	72
Ballast	18	Subsidence	8	5	4	160	Conduct routine inspections and planned maintenance on the track bed, including examination of soil characteristics. Construct sturdy structures to maintain track stability, including managing water flow. Reinforce the track bed according to technical standards and maintain cleanliness and condition. Ensure track geometry and ballast compaction are uniform to specifications using quality materials. Ensure a solid sub-ballast and install ballast retainers such as stop blocks or gabions to prevent settling.	8	4	3	96

Component	***No***	***Potential Failure Mode***	***Existing***				***Action Recommended***	***Improvement***			
			S	***O***	***D***	***RPN***		***S***	***O***	***D***	***RPN***
	19	Ballast decay	8	6	3	144	Rutin inspecting and planned maintenance are conducted on the trackbed, including soil checks and drainage adjustments. Drainage flow is ensured, while ballast thickness normalization is performed beneath the sleepers. Declogging is followed by ballast replacement and compaction in declogged areas. For marshy areas, ballast replacement and geotextile installation are carried out	8	5	2	80
	21	Landslide	8	5	4	160	Conduct regular inspections and planned maintenance on the track bed, including checking embankments that do not meet specifications and steep slopes, with effective preventive measures. Construct structures to maintain track bed stability and normalize areas with retaining walls, as well as planting trees to prevent landslides. Identify landslide-prone points through SAP data collection, and install ballast stoppers at risky points to keep them stable. Perform periodic repairs of drainage channels to prevent potential landslides, and early detection through analysis of track bed excavation conditions to determine appropriate retaining constructions.	8	4	3	96
Railway Geometry	22	Non-standard track widening	8	6	3	144	Conduct routine inspections and scheduled maintenance tasks, ensuring consistent checks of measurement equipment and adherence to track profile standards. Install additional insulators for enhanced protection and promptly repair fastening devices and supporting accessories. Implement periodic maintenance routines for insulators, replacing them when necessary. Monitor and address any issues with lifts and linings to correct geometric damage. Conduct comprehensive inspections with measuring instruments and routine checks by officer.	8	5	2	80
	23	Lateral movement	8	7	3	168	Rutin inspecting and planned maintenance are conducted using locomotive or track measurement vehicles, ensuring track profile normalization per regulations. Routine maintenance with track machines and uniform consolidation prevent waterlogging. Tamping maintains track quality, while regular geometric maintenance ensures optimal track conditions	8	6	2	96
	24	Impact load	8	7	3	168	Rutin inspecting and planned maintenance are conducted using locomotive or track measurement vehicles, ensuring track profile normalization per regulations. Routine maintenance with track machines and uniform consolidation prevent waterlogging. Tamping maintains track quality, while regular geometric maintenance ensures optimal track conditions	8	6	2	96
	25	*Lestrengan*	8	7	3	168	Rutin inspecting and planned maintenance are conducted using locomotive or track measurement vehicles, ensuring track profile normalization per regulations. Routine maintenance with track machines and uniform consolidation prevent waterlogging. Tamping maintains track quality, while regular geometric maintenance ensures optimal track conditions	8	4	3	96
	26	Curvature geometry rail damage	8	7	3	168	Conduct regular inspections and planned maintenance of curves, including visual checks by officers and recording cycle inspections with lokomotive ride/bordes ride, as well as repairs according to SOP. Ensure the ballast remains functional through proactive measures and periodic maintenance.	8	6	2	96
	27	*Skilu*	8	7	4	224	Perform regular track inspections with rail vehicles and conduct periodic maintenance. Ensure thorough track packing is carried out. Check rail temperatures using Matisa equipment and water the rails if temperatures exceed the limit. Perform regular elevation adjustments and track maintenance. Continuous preventive measures are taken to avoid ballast issues by maintaining track alignment using tamping machines.	7	5	3	105

Component	*No*	*Potential Failure Mode*	*Existing*				*Action Recommended*	*Improvement*			
			S	*O*	*D*	*RPN*		*S*	*O*	*D*	*RPN*
	28	Buckling rail	8	6	4	192	Conduct routine inspections and planned maintenance on the ballast, including periodic tamping at intervals to adjust rail expansion. Install RPM joints every 300 meters and check the availability of fastening devices. Always inspect during hot weather conditions and detect rail heat, and prepare for tamping if necessary. Maintain ballast construction to standard and monitor its condition, especially during extreme weather. Identify track irregularities, particularly on curves with small radii, and perform geometry repairs according to standards with additional ballast if needed.	7	5	3	105

4.6 Discussion

Risk analysis with the FMEA method has been widely used to map potential risks and has good analysis results. Based on the results of the analysis, there are several serious problems: broken rails, buckling rail, and *skilu*. The analysis shows these issues have high RPN values, indicating a high risk associated with these events. Reports from the NTSC support the evidence that these factors are the cause of train accidents that occur in Indonesia. On October 17, 2023, there was a train 17 (Argo Semeru) derailment accident at KM 520+4 downstream of the Daop 6 Yogyakarta area due to buckling rail [23]. On December 10, 2020, there was a derailment of KA 3772A at Talangpadang Station Emplacement, which the KNKT concluded to be due to a *skilu* so that the vertical weight pressure of the wheels was reduced and caused the train wheels to rise to the surface of the rail and the derailment occurred [24]. In addition, on August 4, 2019, there was a train 2511A derailment on the KM 48+600 downstream line in the Daop 4 Semarang area due to the poor quality of the railroad so that it could not withstand the lateral movement of the railroad and the failure to determine the neutral temperature of the rail during rail installation resulting in buckling rail [25]. Then, on March 7, 2018, a broken rail at KM 49+3/4 Daop 1 Jakarta Region disrupted KRL travel [26].

On the other hand, the findings related to missing fasteners on two consecutive sleepers showed the lowest RPN value in the analysis, indicating that this failure mode is at a low-risk level and falls into the lowest priority category. In 2015, PT KAI (Persero) submitted a response that the loss of fasteners did not reach tens and did not affect the robustness of the rail condition [27]. Although cases of missing fasteners do not directly cause accidents, they can cause inconvenience during train travel.

Responses to the identified risks through interventions and process controls have significantly reduced the risks. This is reflected in reducing the RPN value to a low-risk category. However, more detailed follow-up observations are needed to ensure the effectiveness of these interventions and controls. Additional data on impact, occurrence rate, and detection effectiveness need to be collected to evaluate further the effectiveness of the risk control measures that have been implemented. This step is essential to continuously improve the safety and reliability of the rail network system.

5 CONCLUSION

The results of risk analysis with hazard identification and FMEA on railway lines reveal several important aspects in understanding and improving the safety of this infrastructure. There are 28 significant hazard identifications related to railway track geometry, Railway turnout, rails, fasteners, sleepers and ballast based on a hazard identification process using questionnaires and interviews with workers with experience in the railway infrastructure. Development of evaluation criteria based on discussions with experts from railway companies in Indonesia strengthens the foundation of risk evaluation

FMEA analysis determined the level of potential risk with 11 failure modes showing RPN values at the high-risk level, 9 failure modes at the moderate-risk level, and 8 failure modes at the range of reasonable RPN values (low risk). The best four failure modes that are at the high-risk level are broken rail (RPN = 252), *skilu* (RPN = 224), buckling rail on railway geometry (RPN = 192), and cracked/defective rail (RPN = 192). Meanwhile, the failure mode at the low-risk level with the lowest RPN value is incomplete fastening of two consecutive sleepers (RPN = 60). Risk response is carried out to follow up on analysis findings on failure modes at the high-risk and moderate-risk levels by recommending a series of corrective actions to reduce the RPN value at the low-risk level or moderate-risk level (RPN under 150) and increase the overall safety of the railway track.

This risk analysis can still be further developed, where potential further research could include developing more efficient hazard identification methods, further evaluation of the level of risk in specific failure modes, and implementation and evaluation of the effectiveness of recommended risk responses. In addition, the results of this research can be used as part of RAMS analysis on railway tracks so that more optimum maintenance of railway infrastructure can be carried out based on risk and reliability analysis data. With a significant contribution to understanding and improving railway infrastructure safety, this research provides a solid foundation for developing more effective risk management strategies in the future.

ACKNOWLEDGEMENTS

We sincerely thank PT Kereta Api Indonesia (Persero) for their valuable assistance in finalizing this paper. Their support in managing time and costs significantly contributed to the paper's effectiveness and efficiency. We highly value the collaboration between PT Kereta Api Indonesia (Persero) and our writing team. Your contribution and support are greatly appreciated.

REFERENCES

[1] Y. Kristian and T. Roesdiana, "Analisis Kerusakan Jalan Rel Wilayah UPT Resor Jalan Rel 3.13 Tanjung Berdasarkan Hasil Kereta Ukur," 2016.

[2] Menteri Perhubungan Republik Indonesia, "Peraturan Menteri Perhubungan Republik Indonesia Nomor 67 Tahun 2012," 2012

[3] A. Tri Maulana and L. Gunawan, "Railway Infrastructure Asset Management Optimization: Comparative Analysis of RAMS, LCC, and their Integration Approaches on Track Asset," *J. Perkeretaapi. Indones. (Indonesian Railw. J.*, vol. 7, no. Oktober, p. p, 2023.

[4] Menteri Perhubungan Republik Indonesia, "Peraturan Menteri Perhubungan Republik Indonesia Nomor 24 Tahun 2015," Feb. 03, 2015

[5] PT Kereta Api Indonesia (Persero), "Risk Assesment Register," Apr. 21, 2017

[6] I. Ansori, "Analisis Reliability Availability Maintainability Safety (RAMS) dan Life Cycle Cost (LCC) Kereta Cepat Indonesia," Universitas Indonesia, Jakarta, 2022.

[7] M. A. Muhammed Nor, A. F. Yusop, M. A. Hamidi, M. N. Omar, N. A. A. Ha-Mid, and W. M. W. Mohamed, "Alternative Railway Tools and Sustainability in RAMS: A Review," 2022.

[8] V. Keulen, "Integrating RAMS into the design process using CENELEC 50126 and MIR analysis," Eindhoven University of Technology, Eindhoven, 2008.

[9] E. Nedeliaková, M. P. Hranický, and M. Valla, "Risk identification methodology regarding the safety and quality of railway services," *Prod. Eng. Arch.*, vol. 28, no. 1, pp. 21–29, Mar. 2022, doi: 10.30657/pea.2022.28.03.

[10] Komite Nasional Keselamatan Transportasi, "Laporan Statistik Investigasi Kecelakaan Transportasi Tahun 2023 Semester 2," Jakarta, 2024.

[11] P. Söderholm and T. Nilsen, "Systematic risk-Analysis to support a living maintenance programme for railway infrastructure," *J. Qual. Maint. Eng.*, vol. 23, no. 3, pp. 326–340, 2017, doi: 10.1108/JQME-09-2016-0042.

[12] The British Standar Institution, *Failure modes and effects analysis (FMEA and FMECA)*, BS EN IEC 60812:2018. BSI Standar Publication, 2018.

[13] A. Alijoyo, Q. B. Wijaya, and I. Jacob, "Failure Mode Effect Analysis (Analisis Modus Kegagalan dan Dampak)," in *31 Teknik Penilaian Risiko Berbasis ISO 31010*, Bandung: LSP MKS, 2020. [Online]. Available: www.lspmks.co.id

[14] B. R. Saputra, "Analisis Pengendalian Risiko Keselamatan dan Kesehatan Kerja (K3) pada Proses Pembuatan dan Pengecoran Logam dengan Metode Failure Mode and Effect Analysis (FMEA) pada PT Aneka Adhilogam Karya," Yogyakarta, Jun. 2023.

[15] I. A. Tamba, A. Suryatman Margana, and B. Y. Prasetyo, "Analisis Manajemen Perawatan Menggunakan Perhitungan Distribusi Weibull dan Metode FMEA pada AC Package Di Gerbong PT. KCI Juanda," *IRWNS*, Jul. 2023.

[16] C. R. Vorst, D. S. Priyarsono, and A. Budiman, *Manajemen Risiko Berbasis SNI ISO 31000*. Jakarta: Badan Standardisasi Nasional, 2018.

[17] A. I. Hadiyanti, "Analisis Risiko pada Proyek Pembangunan Jalur Ganda (Double Track) Lintas Surabaya-Solo," Institut Teknologi Sepuluh Nopember, Surabaya, 2018.

[18] M. Afifussolih, "Manajemen Risiko K3 Pemasangan Pipa Petragas dengan Metode Hazard Identification Risk Assessment and Risk Control (HIRARC)," Jember, 2018.

[19] A. Rachman, H. Adianto, and G. P. Liansari, "Perbaikan Kualitas Produk Ubin Semen Menggunakan Metode Failure Mode and Effect Analysis dan Failure Tree Analysis di Institusi Keramik," *J. Online Inst. Teknol. Nas.*, vol. 4, Apr. 2016.

[20] M. Szkoda and M. Satora, "The application of failure mode and effects analysis (FMEA) for the risk assessment of changes in the maintenance system of railway vehicles," *Czas. Tech.*, no. 8, pp. 159–172, 2019, doi: 10.4467/2353737XCT.19.086.10865.

[21] D. H. Stamatis, *Failure mode and effect analysis : FMEA from theory to execution*. ASQ Quality Press, 2003.

[22] R. T. Mauli, C. Simorangkir, and O. Syahputra, "Menganalisis Ukuran Pemusatan," Jakarta, Sep. 2022. [Online]. Available: https://www.researchgate.net/publication/363859618

[23] Komite Nasional Keselamatan Transportasi, "INVESTIGASI KECELAKAAN ANJLOKAN KA 17 (ARGOSEMERU) DI PETAK JALAN SENTOLO – WATES, DAOP 6 YOGYAKARTA," *Web page KNKT*, Feb. 16, 2024. https://knkt.go.id/news/read/investigasi-kecelakaan-anjlokan-ka-17-(argosemeru)-di-petak-jalan-sentolo-—-wates%2C-daop-6-yogyakarta (accessed Mar. 31, 2024).

[24] Komite Nasional Keselamatan Transportasi, "Laporan Akhir KNKT.20.12.02.02," Jakarta, Jun. 2023.

[25] Komite Nasional Keselamatan Transportasi, "Laporan Akhir KNKT.19.08.05.02," Jakarta, Jul. 2022.

[26] Komite Nasional Keselamatan Transportasi, "Laporan Akhir KNKT.18.03.04.02," Jakarta, May 2019.

[27] Sugiyarto, "PT KAI Nilai Hilangnya Penambat Rel Belum Ganggu Keamanan Kereta Api Artikel ini telah tayang di Tribunnews.com dengan judul PT KAI Nilai Hilangnya Penambat Rel Belum Ganggu Keamanan Kereta Api," *Tribun news*, Jun. 22, 2015. https://www.tribunnews.com/regional/2015/06/22/pt-kai-nilai-hilangnya-penambat-rel-belum-ganggu-keamanan-kereta-api (accessed Mar. 31, 2024).