JKIE (Journal Knowledge Industrial Engineering) Vol. 13, No. 2, August 2026, pp.175-190

http://jurnal.yudharta.ac.id/v2/index.php/jkie

Journal Knowledge Industrial Engineering

E-ISSN: 2541-4461 | P-ISSN: 2460-0113

Causes Analysis of Scrap Tire Damage to Improvement Recommendations Design for Heavy Equipment Tire at PT ZGA

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Article Info

Article history
Received : June 10, 2026
Revised : August 13, 2026
Accepted : August 25, 2026
Published : August 31, 2026

Keywords:
Awareness;
FMEA;
FTA;
OTR;
Tire.

ABSTRACT

Open-pit coal mining uses haul trucks as the main equipment to transport material from the loading front to the dumping point, with operating costs reaching 50–60%. Poor OTR tire maintenance can cause premature damage, reduce tire service life, and increase operating costs, resulting in unmet KPI targets. Tire costs are the second-largest expense in the mining industry. In this study, tire waste due to premature scrap reached IDR 1,383,090,656.87 with 12 types of tire damage. This research aims to identify root causes and contributing factors of tire damage based on failure types to extend tire life and reduce operating costs. The study integrated maintenance analysis framework Reliability Centered Maintenance (RCM) using Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA). FTA shows that the main cause of inner liner separation is low operator tire awareness (9%). FMEA results indicate that Inner Liner Separation has the highest Risk Priority Number (RPN) of 343. Recommended improvements include proper tire inflation control, rim maintenance, good operating practices, and improved housekeeping. Achieving optimal tire life is a shared responsibility across all departments.

DOI: https://doi.org/10.35891/jkie.v13i2.7009

1. Introduction

Coal mining carried out by PT ZGA at the FOF site is open pit mining. The activity of moving material from front loading to the dumping point contributes 50% - 60% of operational costs in open pit mining (E. Tapia et al., 2021; Mamani et al., 2024). Heavy equipment used in mining operations is of the track and wheel types. Haul trucks are wheeled units used to transport mined materials from the front-loading area to the dumping point and are vital in these activities (Anshori et al., 2018; Mnzool et al., 2024; Skoczylas et al., 2023). Heavy equipment has several supporting components, one of which is tires. Tires function to support the vehicle's load, absorb shocks (suspension), transmit braking and traction, and provide manuverability and stability for changes in direction (Achekuogene et al., 2020; K. Waluś & J. Warszczyński, 2022). Suboptimal tire maintenance can result in damage with the following impacts: reduced service life and increased operational costs. Operational costs of tire use rank second in the mining industry (Hia & Laksono Singgih, 2025; Mamani et al., 2024; Nanang S et al., 2025).

The tires in this study were sized 27.00R49 with 12 types of damage. Based on the data, 53 tires experienced premature scrap (cannot be operated again with a lifespan below the KPI target) out of 83 scrap tires. The resulting tire waste costs reached IDR 1.38 billion. The average Tread Utilization Ratio (TUR) was 44% of the new tire tread thickness, while the safe usage limit according to the company's SOP is 80%. Average tire wear rate is 309 (h/mm).

OTR tire damage can reduce tire life and cause increased tire waste if not handled systematically (A. Shakenov et al., 2022; Galatia, 2020). Previous studied identified several factors contributed premature tire failures in mining industries, including operational conditions, tire pressure, haul-road conditions, load, TKPH, and operator practices. For example, main factors causing tire damage include operational conditions, operator behavior, inappropriate tire pressure, and the quality of mine road maintenance (Malakoutikhah et al., 2022; Saadaari et al., 2024). Tire damage that occurs before reaching its design life is called premature scrap and has a direct impact on wasted operational costs (Joseph et al., 2025; Lindeque, 2016; Tabuni et al., 2024). Tire bursting and prioritized risk factors using the Fuzzy Best-Worst Method specifically focussed analyzed (Mamani et al., 2024). Evaluated tire performance using KPI, TKPH, road condition, and road maintenance availability (Sari, 2020). However, these studies generally focus on a particular failure mechanism, operational parameter, or prioritization technique. These approaches are informative but don’t fully link the root causes of tire failures to risk priorities and maintenance improvements in open-pit hauling.

The solution to this research is to identify the factors causing heavy equipment tire scrap based on the type of damage integrated maintenance analysis framework in Reliability Centered Maintenance (RCM), Fault Tree Analysis (FTA), and Failure Mode and Effects Analysis (FMEA) to map failure causes to risk based improvement planning. This studied is applying integrated framework to 27.00R49 OTR tires on haul trucks at an open-pit coal mine, tying failure causes to tire life performance and practical maintenance recommendations. The contribution is not only identifying dominant tire failure causes but also providing a maintenance focused decision framework applicable to related tire failure modes.

2. Literature Review

Mining industry activities in carrying out production require support for smooth running at optimal costs. Tire maintenance activities will not run smoothly without standard tire maintenance management (Wibowo & Santosa, 2021). Implementation of tire maintenance management includes midlife (rotation) tire activities to prepare rear spare tires, tire matching, Ton Kilometer Per Hour (TKPH) studies, tire pressure maintenance, load control, road condition monitoring, and tire awareness (Lindeque, 2016; Sari et al., 2022; Yusupov et al., 2022).

Mining heavy equipment truck tires, commonly known as Giant Off the Road Tires (OTR), have two types of construction, namely radial and bias construction. In general, the difference between radial tires and bias tires is that radial tires have a construction consisting of steel wire arranged at a 90° angle to the circumference of the tire which forms the casing. Meanwhile, bias tires have a nylon woven construction that crosses each other forming an angle of 25° to 40° to the circumference of the tire that forms the carcass (Sadjiep Tchuigwa et al., 2021; Sari, 2020; Zhou et al., 2022) .

Several components of tire wihich generally consist on Figure 1:

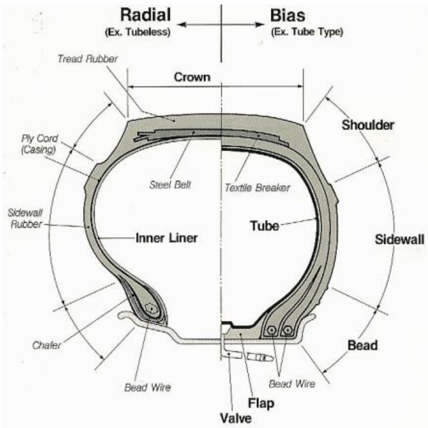

Figure 1. Radial and Bias Tire Parts
Source: PT. Bridgestone Mining Solutions Indonesia Material, 2015

1) Tread/Crown : the part that is in direct contact with the road surface with traction, wear resistance and cut resistance capabilities.
2) Carcass/Casing : the part that functions as the frame of the tire and holds the pressurized air that enters the tire.
3) Breaker/Belt : the part located between the belt and the casing with the ability to withstand punctures from foreign objects as a casing protector.
4) Bead : part of the tire formed from coils of steel wire which functions as an anchor between the tire and rim when installed.
5) Sidewall : the part of the tire wall made of rubber that functions as a protector for the side casing and is resistant to cracking due to flexing and cutting due to exposure to foreign materials (Goodyear, 2021; K. Waluś & J. Warszczyński, 2022; PT. Bridgestone Mining Solutions Indonesia Material, 2015; Sadjiep Tchuigwa et al., 2021).

The service life of heavy equipment tires is influenced by several factors from operational activities including: tire pressure, road conditions from front loading to dumping point, load, average unit speed, site Ton Kilometer per Hour (TKPH) value against tire TKPH, and tire awareness (Lindeque, 2016; Sari et al., 2022; Yusupov et al., 2022).

Scrap tire performance can be analyzed by calculating Key Performance Indicator (KPI) parameters. These parameters include Tread Utilization Ratio (TUR) (%), wear rate (hours/mm), and lifetime (hours) (Anshori et al., 2018; Yoga Achmad Rynaldy et al., 2025). The projected lifespan of scrap tires if premature damage does not occur can be calculated from the KPI parameter values. The following is the calculation formula for these parameters:

a. Lifetime calculating (hours):

$$\mathrm{LT} = \mathrm{HM\ remove} - \mathrm{HM\ install} \quad (1)$$

b. TUR calculating (%):

$$\mathrm{TUR} = \frac{(\mathrm{OTD} - \mathrm{RTD})}{\mathrm{OTD}} \mathrm{\ X\ } 100\% \quad (2)$$

c. Wear rate calculating (hours/mm):

$$\mathrm{WR} = \frac{\mathrm{LT}}{(\mathrm{OTD} - \mathrm{RTD})} \quad (3)$$

d. Projected life span:

$$\mathrm{PL} = \mathrm{LT} + (\mathrm{WR} * \mathrm{RTD}) \quad (4)$$

Description:

LT	=	Lifetime (hours)
HM	=	Hours Meter (hours)
TUR	=	Tread Utilization Ratio (%)
RTD	=	Remain Tread Depth (mm)
OTD	=	Original Tread Depth (mm)
WR	=	Wear Rate (hours/mm)
LE	=	Projection Life (hours)

Work area conditions and tire pressure maintenance also affect the average tire lifespan until scrap. Table 1 and Figure 2 shows factors that influence average tire lifespan (A. Shakenov et al., 2022; Bridgestone Off The Road Tires, 2007).

Table 1. Reduction Average Tire Life Span

Factor	Condition	Reduce Life (%)
Tire Air Pressure	As Recommendation	0%
	10% Below Recommendation	10%
	20% Below Recommendation	25%
	30% Below Recommendation	70%
	10% Above Recommendation	10%
Road Condition	Without Rocks	0%
	With Scattered Rocks	10%
	Well Maintained with Fine Gravel	10%
	Poor Maintenance with Unleveled Gravel	30% or More
	Scattered Blasted Rocks	40% or More
Road Grade	Flat	0%
	>6%	10%
	>15%	30%
Road Bend	No Bends	0%
	Smooth Bends	10%
	Sharp turn	20% or More

Source: A. Shakenov et al., 2022

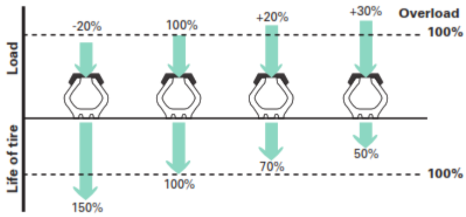

Figure 2. Load Affecting Tire Life Span
Source: Bridgestone Off The Road Tires, 2007

Reliability Centered Maintenance (RCM) is a process for determining the steps that need to be taken so that physical assets can operate as expected (Aprilianto et al., 2025; Patil et al., 2022; Suresh Kumar Sahani et al., 2023). This method combines preventive maintenance and corrective maintenance strategies to ensure the reliability of equipment function under operational conditions with a systematic approach (Maulana & Aribowo, 2024; Patil et al., 2022). RCM is also a method that can be applied to increase maintenance effectiveness (Andrian & Wahyudin, 2024; da Silva et al., 2023). Fault Tree Analysis (FTA) is used to identify the root causes of the factors causing scrap tires for each type of damage resulting from literature studies.

Failure Mode and Effect Analysis (FMEA) is used to determine the type of damage that is a priority for repair based on the results of the highest Risk Priority Number (RPN) calculation (Febriana & Hasbullah, 2021; Hasan et al., 2019).

The Fault Tree Analysis (FTA) is an analytical method for identifying the root cause of a failure by identifying the cause-and-effect relationships between various events. Failures can be caused by hardware, human error, or other events. FTA shows the logical relationship between the root causes that contribute to the failure, with the root cause being the one above (Febriana & Hasbullah, 2021; Zakaria et al., 2025). The relationship between events is indicated by the gate symbol. The causes of other events can be individual or group (Syarifudin & Putra, 2021).

FMEA (Failure Mode and Effect Analysis) method is widely used to analyze machine productivity decline and functional failures (Febriana & Hasbullah, 2021; Zakaria et al., 2025). Failure modes consist of components in the system and analyzing their impact on the reliability of the system (Hasan et al., 2019; Syarifudin & Putra, 2021). FMEA also plays a role in anticipating damage by providing repair recommendations so that problems do not impact customers (Turgay et al., 2024; Zakaria et al., 2025).

FMEA analysis requires a Risk Priority Number (RPN) value. This value is determined by a questionnaire completed by experienced individuals with a deep understanding of the process being studied. The RPN value consists of severity (S), likelihood of occurrence (O), and detection (D) (Zakaria et al., 2025). Risk Priority Number (RPN) is a relative measure of risk. RPN is determined before implementing recommendations from corrective actions, and it is used to determine which part is the top priority based on the highest RPN value (Febriana & Hasbullah, 2021; Syarifudin & Putra, 2021). RPN calculation formula:

$$RPN = Severity\ x\ Occurance\ x\ Detection \quad (5)$$

The value of RPN is used to determine the risk level. There are three risk categories: high risk with an RPN value ≥ 100, medium risk with an RPN value of 50-99, and low risk with an RPN value < 50. Risks with a high RPN value will be subject to maintenance (Awsan Mohammed et al., 2022; Bashir Salah et al., 2023; Syarifudin & Putra, 2021).

Table 2. Research Gap on Off the Road Tire Analysis

Study	**Focus**	**Method**	**Strength**	**Limitation Compared with the Present Study**
Sari (2020)	Tyre performance of HD-785	KPI, TKPH, and road condition evaluation	Linked tyre performance with operational conditions	Does not perform hierarchical root-cause analysis or risk prioritization
Galatia (2020)	Premature tyre failure	Qualitative and quantitative analysis	Identifies TKPH mismatch as a key contributing factor	Does not integrate a causal tree with FMEA-based risk prioritization
Malakoutikhah et al. (2022)	Dump truck tyre bursting	Fuzzy Best-Worst Method	Strong multi-criteria risk prioritization approach	Focuses specifically on tyre bursting rather than multiple tyre scrap failure mechanisms
Mamani et al.	Operational	Pareto and	Identifies dominant	Does not

(2024)	tyre damage	Ishikawa analysis	operational contributing factors	quantitatively link root causes to RPN-based maintenance priorities
Saadaari et al. (2024)	Haul truck tyre failures	Supervisor–Field Engineering Approach (S-FEA)	Provides strong field-based identification of tyre failure causes	Does not establish maintenance priorities using FMEA

Source: Data Processing

Research gap previous study then present study is present study using integrated maintenance analysis RCM framework, FTA, and FMEA to integrates root-cause analysis, risk prioritization, and targeted maintenance recommendations.

3. Methodology

The research using integrated maintenance analysis framework Reliability Centered Maintenance (RCM) method with research data from damaged tires that have been scrapped (cannot be operated again) measuring 27.00R49 with Komatsu HD 785-7 series, Caterpillar 777D and 777E series units. The analysis methods that will be used are Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA).

The FTA data collection method was carried out by interviewing specialist tire mining maintenance implementers, where respondent is senior tire technician and tire engineer. The thing asked in the interview is the factors that cause tire damage. The factors causing scrap tire damage for each type of damage are shown in Table 3.

Table 3. Factors Causing Scrap Tire Damage

Factor	1	2	3	4	5	6	7	8	9	10	11	12
Sudden Braking or Acceleration	√	√		√								
Turning at High Speed			√	√							√	√
Overspeed					√				√		√	√
Improper Unit Operation					√					√		√
Spinning									√			√
Sliding									√			√
Combing the Road Divider										√		
Heavy Impact with Material					√	√		√				√
Tire Contact with Sharp Material					√			√	√	√		√
Tire Not Sitting Perfectly on Rim	√	√		√								
Improper Use of Equipment	√											
Not being Careful when Removing and Installing Tires on the Rim	√											
Foreign Objects Trapped Between Bead and Flange	√											
Product Failure in Tire Construction			√	√					√		√	
Rim and Component Problems (Deformation, Rust, etc.)	√	√		√				√				
Mismatched Rim Components	√	√	√	√								
Excessive Heat Braking Result from the Brake Drum		√										
Valve Problem								√				
O-Ring Problem								√				

Factor	1	2	3	4	5	6	7	8	9	10	11	12
Excessive Heat in Tires Due to Operation					√	√			√		√	√
The Site's TKPH (Ton Kilometer Per Hour) Value is Greater than Tire's TKPH Value (Tire Specifications Do Not Match the Work Area)									√			√
Stone Trapped in Dual Fitment										√		
Low Tire Pressure	√	√	√	√	√			√	√	√	√	√
Over-Inflated tires					√				√			√
Poor Tire Pressure Maintenance					√			√			√	√
Improper Tire Storage												√
Tire Repair Failure							√					√
Poor Tire Repair Quality							√					
Air Trap During Repair Process							√					
Overload on Tires	√	√	√	√	√				√	√	√	√
Excessive Flexing in Tires			√	√						√	√	
Poor Housekeeping/Work Area Maintenance					√				√	√	√	√
Undulations (Wavy Roads)			√	√	√					√	√	√
Sharp Turn									√		√	√
Work Area Flooded										√		

Source: (Goodyear OTR Tyres Australia, 2002; Internal Perusahaan, 2017; PT. Bridgestone Mining Solutions Indonesia Material, 2015)

Description:

1 = Bead Damage
2 = Bead Rupture/Burst
3 = Bulging
4 = Chafer Damage
5 = Impact Sidewall
6 = Inner Liner Separation
7 = Repair Failure
8 = Run Flat
9 = Shoulder Separation
10 = Sidewall Cut
11 = Sidewall Separation
12 = Tread Separation/Lifting

FMEA questionnaire development to each tire damage. Respondent criteria only expertise on tire maintenance and analysis. Expert in this case respondent work on PT XYZ because all of tire technician has certified from Bridgestone or Goodyear, or respondent have experienced as tire engineer. Severity assessment is conducted based on the degree of damage associated with the specific type of scrap tire failure. The severity assessment categories regarding the impact resulting from these factors are presented in the table 4.

Table 4. Severity Ranking

Ranking	Category	Description Effect
10	Dangerous (No Warning)	Could Harm Consumers; Non-Compliant with Government Regulations; Without Warning
9	Hazardous (With Warning)	May Harm Consumers; Non-Compliant with Government Regulations; Contains a Warning
8	Very high	Disrupting 100% of Production; all products become scrap; customers extremely dissatisfied

Ranking	Category	Description Effect
7	High	Major Production Disruption; High Volume of Scrap Products; Dissatisfied Customers
6	Moderate	A small fraction of products were scrap; the rest were good and required no sorting; the customer was dissatisfied
5	Low	100% of products are repairable; guaranteed to be returned by consumers
4	Very Low	Most products can be repaired; the rest are in good condition; returns are possible
3	Minor	Only a few things were fixed; the rest were fine; on average, customers complained.
2	Very Small	Complaints Only from Certain Customers.
1	Null	There is absolutely no effect on consumers.

Source: Zakaria et al., 2025

An occurrence assessment is conducted regarding the factors causing specific types of tire damage. The categories for assessing the frequency with which the causes of scrap tire damage result in specific damage types are presented in the table 5.

Table 5. Occurance Ranking

Ranking	Occurance Failure	Occurance Failure Level
10	Very High	1 in 2
9		1 in 3
8	High	1 in 8
7		1 in 20
6	Moderate	1 in 80
5		1 in 400
4		1 in 2.000
3	Low	1 in 15.000
2		1 in 150.000
1	Very Low	1 in 1.500.000

Source: Zakaria et al., 2025

The detection assessment evaluates the difficulty level associated with the specific type of scrap tire damage. The categories for assessing the difficulty of detecting these damage types are presented in the table 6.

Table 6. Detection Ranking

Ranking	Detection Description
10	Undetectable
9	Most Likely Undetectable
8	Complex Inspection and Dissassembly Required
7	Inspection and Dissassembly Required

Ranking	Detection Description
6	Helped Tools/Simple Disassembly Required
5	Highly Careful Inspection Using Human Senses
4	Careful Inspection Using Human Senses
3	Requires Inspection
2	Clearly visible to human senses
1	Always clear, very easy to understand.

Source: Zakaria et al., 2025

4. Results and Discussion

The object of this research is 27.00R49 tires that have been scrapped (cannot be operated again) from January to June 2025 at PT ZGA site FOF located in Muara Enim Regency, South Sumatra Province, Indonesia. There were 83 scrap tires with 12 types of damage and three manufacturers, namely, Bridgestone, Michelin, and Goodyear. Data was obtained from the results of downloading the PT ZGA site FOF report.

The results of the Fault Tree Analysis (FTA) analysis of the causes of overall tire scrap obtained five factors causing the highest tire damage, namely lack tire awareness from operator (8%), operator habits (6%), chasing production targets (4%), lack tire awareness from tire-man (4%), and unit availability (4%) from 121 factors causing tire damage. The percentage result indicates how often the factor appears on all tire damage. A summary of the highest tire damage factors for each type of damage can be seen in Table 3.

Table 7. Factors Causing Each Type of Scrap Tire Damage

Type of Damage	Root Cause	%
Bead Damage	Lack Tire Awareness from Operator	6%
Bead Rupture/Burst	Lack Tire Awareness from Operator	7%
Bulging	Lack Tire Awareness from Operator	7%
Chafer Damage	Lack Tire Awareness from Operator	7%
Impact Sidewall	Lack Tire Awareness from Operator	8%
Inner Liner Separation	Lack Tire Awareness from Operator	9%
Repair Failure	Poor Tire Repair Quality	22%
Run Flat	Lack Tire Awareness from Operator	7%
Shoulder Separation	Lack Tire Awareness from Operator	8%
Sidewall Cut	Lack Tire Awareness from Operator	8%
Sidewall Separation	Lack Tire Awareness from Operator	8%
Tread Separation Lifting	Lack Tire Awareness from Operator	9%

Source: Processing Data

Used data for FMEA analysis, such as: severity, occurrence, and detection for the type of heavy equipment scrap tire damage, were obtained through questionnaires from 22 respondents with a work experienced of more than 10 years, amounting to 68%. Figure 3 given detail demographic map.

P-ISSN: 2460-011 3 I JKIE (Journal of Knowledge Industrial Engineering) I E-ISSN: 2541-4461
DOI: https://doi.org/10.35891/jkie.v13i2.7009 I Vol. 13 , No. 2, August 2026, pp. 67-82

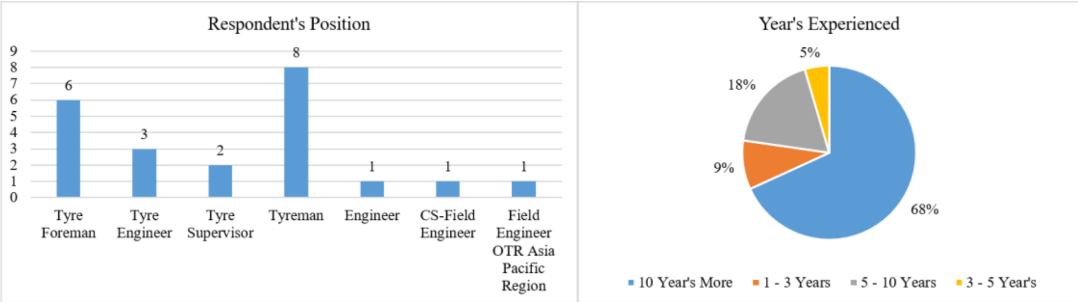

Figure 3. Demographic Map
Source: Processing Data

Results of the Risk Priority Number (RPN) calculation show that the type of heavy equipment tire damage that has the highest value is Inner Liner Separation with a value of 343. The severity level of this type of damage is 7, obtained from the average assessment scores of 22 respondents. Meaning it causes operational stops and has the potential for premature scrap on the tire. Occurance level of this type damage is 7, obtained through the average assessment scores of 22 respondents for each causal factor. Meaning high probably factor causes failure. While a detection level is 7, obtained through the average assessment scores of 22 respondents. Mean that inspection and dissassembly are required to detect failure. This type of damage will be continued to be planned for repair recommendations. Details of RPN calculations are in Table 8.

Table 8. RPN Calculation Results

Risk Event	Severity (S)	Occurance (O)	Detection (D)	SxOxD
Bead Damage	5	6	5	150
Bead Rupture/Burst	6	6	5	180
Bulging	6	6	4	144
Chafer Damage	5	6	4	120
Impact Sidewall	8	7	5	280
Inner Liner Separation	7	7	7	343
Repair Failure	6	8	5	240
Run Flat	9	6	5	270
Shoulder Separation	6	7	5	210
Sidewall Cut	5	8	3	120
Sidewall Separation	6	6	5	180
Tread Separation Lifting	6	7	4	168

Source: Processing Data

Results of the RPN calculation show that the damage to the inner liner separation has the highest RPN value of 343, so the damage is a priority for improvement action. Design of Improvement recommendations is obtained through the results of the Failure Mode and Effect Analysis (FMEA) questionnaire and Focus Group Discussion (FGD) with the PT ZGA tire section regarding the factors causing the damage from the Fault Tree Analysis (FTA) diagram. The FTA diagram of the inner liner separation damage is as follows Figure 4:

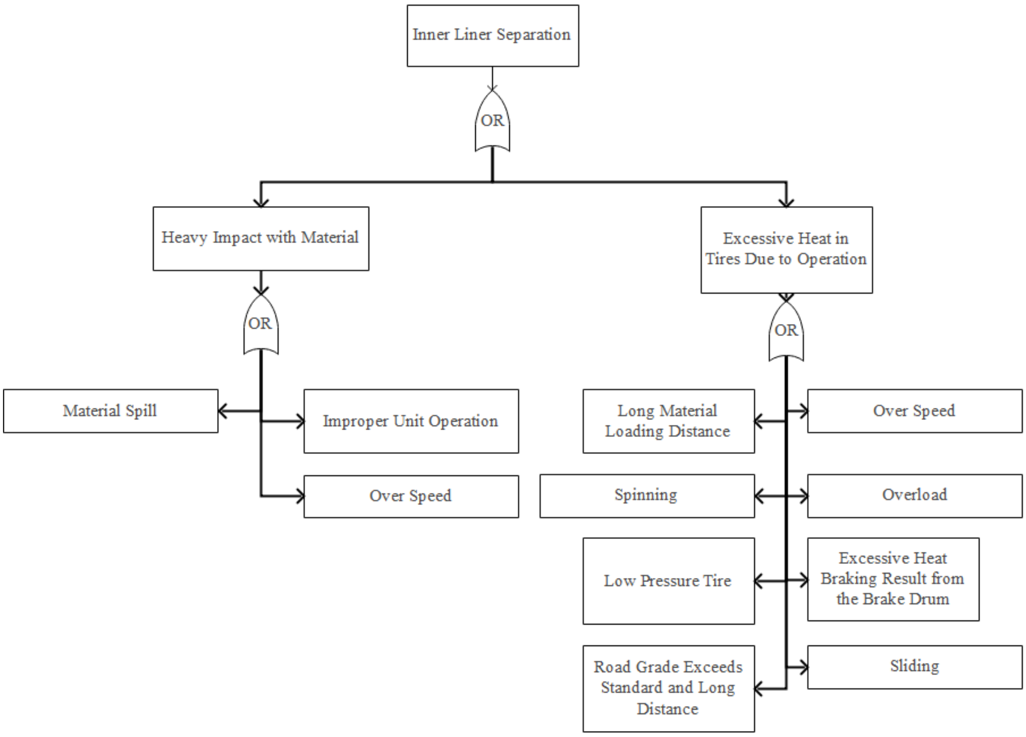

Figure 4. FTA Inner Liner Separation Diagram
Source: Processing Data

The FTA inner liner separation diagram shows that there are two main causal factors that can influence the damage with 16 derivative factors. Figure 4 shown only main causal factor (derivative factors number 1) and derivative factor number 2 containing material spill, improper unit operation, and over speed from factor heavy impact with material and long material loading distance, over speed, spinning, overload, low pressure tire, excessive heat braking result from the brake drum, road grade exceeds standard and long distance, and sliding from factor excessive heat in tires due to operation. There are several factors that appear in the various derivative factor terms, example over speed. The most influential causal factor inner liner separation is that lack tire awareness from operator at 9%, which the value is derived based on how frequently the factor appears.

Design of improvement recommendations to reduce the occurrence of inner liner separation tire damage whether from the main factors heavy impact with material and excessive heat in tires due to operation. Especially to avoid premature scrap, namely improving tire air pressure maintenance to meet standards and calculations, improving rim and component maintenance, good unit operation, improving housekeeping/work area maintenance, and maintaining load standards on the unit. Overall, the improvement recommendations are steps to anticipate the occurrence of factors that cause damage, both based on the results of the analysis and previous research. There are also factors that influence each other towards the factors that cause damage based on the results of the FTA, so if a potential cause of damage from one type of damage is repaired it will reduce the potential for other types of damage.

Mines must establish road maintenance teams that are independent from the mining department to avoid conflicts of interest. The tire maintenance team should be strengthened by involving tire experts to lead the existing team, and it is also important for mines to increase tire awareness among tire-man and operators (Galatia, 2020). Despite implementing credible tire maintenance practices such as tire rotation, tire pressure adjustment during installation, road maintenance, and dust control, these measures are considered insufficient to prevent premature tire failure, so a more robust tire management system is needed (Saadaari et al., 2024). Achieving tire service life is not only the responsibility of the tire team but is a shared responsibility of all departments.

Implementation of improvement recommendations can reduce the potential for premature tire damage. So that it can increase the tire life, from the existing scrap tire data, it can be projected the tire life that can be achieved if there is no premature damage. If improvement recommendation inner liner separation is carried out optimally, then there is potential for increasing tire life what fail with this damage. Projected tire life maximum that can be achieved with a TUR of 80% on inner liner separation damage is as follows Table 9:

Table 9. Projected Life Maximum of Scrap Tires Improvement

Type of Damage	Average Tire Life (h)	TUR (%)	Wear Rate (h/mm)	Average Tire Life Projection (h)	Improvement
Inner Liner Separation	13.981	49%	378	22.672	62%

Source: Processing Data

The projected tire life with a TUR of 80% after the improvements action was carried out increased by 62% to a tire life of 22.672 hours. If improvement recommendation not implement optimally, so the projection tire life can be shown on Table 10:

Table 10. Scrap Tire Performance Projection Based on Actions

Action	Reduction	Average Tire Lifetime (Hours)
All Improvement Recommendations	0%	22.672
Improvement Recommendations but Load Still Over Capacity until 20%	30%	15.870
Improvement Recommendations but Poor Haul Road Maintenance	30%	15.870
Improvement Recommendations but Tire Pressure 10% Below Recommendation Value	10%	20.405
Improvement Recommendations but Tire Pressure 20% Below Recommendation Value	25%	17.004
Improvement Recommendations but Tire Pressure 20% Above Recommendation Value	10%	20.405
Improvement Recommendations but Load Still 20% Over Capacity and Tire Pressure 10% Below Recommendation Value	40%	13.603
Improvement Recommendations but Load Still 20% Over Capacity and Tire Pressure 20% Above Recommendation Value	40%	13.603
Improvement Recommendations but Poor Haul Road Maintenance and Tire Pressure 10% Below Recommendation Value	40%	13.603

Source: Processing Data

5. Conclusion

The causes of scrap tire damage based on each type of damage based on FTA analysis obtained the root cause is that lack tire awareness from operator in almost all types of damage, namely: bead damage (6%), bead rupture/burst (7%), bulging (7%), chafer damage (7%), impact sidewall (8%), inner liner separation (9%), run flat (7%), shoulder separation (8%), sidewall cut (8%), sidewall separation (8%), tread separation lifting (9%). Meanwhile, repair failure was caused by poor quality tire repairs (22%). It is possible that operators have less tire awareness because they have not received the training.

The type of damage to scrap tires that is a priority for improvements action is inner liner separation with a Risk Priority Number of 343. If this damage is ignored, it will result in premature scrap, where the tire should still be repairable but must be scrapped and cause tire waste.

This study connected analytical framework linking failure event identification, hierarchical causal analysis, risk prioritization, maintenance action formula to inner liner separation failure on off the road tire. This study demonstrated integrated framework maintenance analysis using RCM with FTA explains why a failure occurs, while FMEA identifies which failure mode should receive priority for intervention.

Recommendations to reduce the occurrence of inner liner separation tire damage, especially to avoid premature scrap, include improving tire pressure maintenance to meet standards and calculations, improving rim and component maintenance, proper unit operation, improving housekeeping/work area maintenance, and maintaining unit load standards. These recommendations are intended to reduce premature tyre scrap and improve tyre service life.

Limitations on this study likely analysis was conducted at a single mining site and focused on 27.00R49 tyres; therefore, the results should not be generalized directly to all mining operations or tyre sizes. Second, FTA developed by study literature on internal company file, goodyear removal analysis and bridgestone tire damage inspection, also interview with specialist mining tire maintenance implementer. Percentage value of the factors causing failure is obtained from how often the factors appear in the analysis.

Future research needs to validate the proposed recommendations through longitudinal implementation and compare tire reliability indicators before and after the intervention. Furthermore, future research should incorporate a formal analysis of inter-rater agreement, a sensitivity analysis regarding FTA assumptions, and methods that account for uncertainty—such as fuzzy or interval FMEA. Integrating real time data on tire pressure and temperature using technology Tire Pressure Monitoring System (TPMS) that are combined with load, and operating conditions could further support the development of predictive tire maintenance models and simplify when analyze causes of tire damage.

Acknowledgements (if any)

The author would like to thank PT ZGA, especially the FOF site, which has provided data support, to PT ZGA employees and tire experts who have been willing to be sources in this research.

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