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Assessing Operational Damage Impact on Mining Tires (Case Study)

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Abstract

In open-pit mining operations, loading and haulage activities account for a significant portion, typically between 50% and 60%, of the operational costs of the entire mining process. Tires, in turn, rank second in terms of operating costs for most mining companies. Therefore, understanding and preserving the useful life of Off-The-Road (OTR) tires is a critical factor in ensuring the profitability of a mining project. This study focuses on a specific mine to analyze the causes of operational damage in the tires of Mining Trucks (MTs) and Front-End Loaders (FELs). It aims to identify the factors leading to the premature disposal of these tires, and propose solutions to increase their useful life. The study identifies four key aspects that influence the low performance of extraction equipment, namely operator experience, environmental condition, raw materials, and equipment condition. Additionally, the study reveals that overinflation pressure significantly contributes to the premature disposal of tires, accounting for 70.5% of MT tire damage and 52.5% of FEL tire damage (primarily affecting MT rear and FEL front tires). The use of tire chains is proposed as a solution, with the potential to decrease the unit cost per labor hour by 28% for at least 50% of the tires.

1. Introduction

In open-pit mining, loading and haulage account for approximately 50% to 60% of the operational costs of the entire mining process [1, 2, 3]. After fuel, tires hold the second position in the cost hierarchy for mining companies [4, 5]. Therefore, understanding how to preserve the lifespan of Off-The-Road (OTR) tires is crucial to ensuring efficient and safe mining operations [6], and it is also a critical factor in the profitability of a mining project [5].

In the context of a mining operation, essential equipment for conducting unit operations in the mining process includes Mining Trucks (MT), front-end loaders (FEL), and Wheel dozers. Therefore, Off-The-Road (OTR) tires play a critical role in the efficient development and execution of mining. Consequently, extending the lifespan of these tires is crucial for the successful management of a mining company [7]. To provide a reference, it is estimated that a large metal mining operation utilizes 900 OTR tires annually, with each tire weighing an average of 4 tons [8]. Similarly, a large non-metallic operation uses 90 OTR tires, with each tire weighing an average of 1.9 tons [9]. These figures highlight the significant amount of rubber waste generated by each mining operation worldwide in the form of discarded tires over one year.

A tire is a rubber component that covers a vehicle's wheel, maintaining contact with the road surface, and providing traction and support for the vehicle's weight. Its primary function is to enable the movement of the vehicle, allowing it to travel from one place to another [10]. Tires are composed of various materials including polymers, metals, and additives. These include carbon black, which provides stability and gives tires their black color, as well as elastomeric compounds, steel cords, fibers, and other organic and inorganic components. It's important to note that many of these tire components are not biodegradable [11, 12]. OTR tires, specifically designed for off-road

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applications in mining, are characterized by their robust and durable construction to withstand the harsh conditions of mining roads. Their tread depth is typically deeper compared to tires used for commercial purposes, aiming to enhance traction on loose terrain. Additionally, they are engineered to withstand heavy loads imposed by the equipment they support. However, as stated by Goode (2023), mining companies often prioritize mine production over the lifespan of OTR tires, resulting in an estimated 90% of tires experiencing premature failure [13]. Tire wear is influenced by several factors including driver skills, weather conditions, equipment maintenance, road conditions [14, 7], tread design, and inflation pressure [4].

Research conducted thus far has examined various factors associated with tire wear including pressure, temperature, and road conditions. Among the identified common failures in ultra-large mining truck tires, tread separation, and sidewall damage are frequently observed [15]. Anzabi (2012) emphasizes the significance of monitoring tire conditions as a preventive measure against equipment downtime, injuries, and decreased productivity [16]. Shakenov (2022) highlights the impact of road conditions on tire lifespan [17].

On the other hand, there is also pressure from the high degree of pollution that the production of scrap tires causes to the environment. Because mining operates on a large scale and uninterruptedly, it has become one of the most polluting industries in this regard [18]. Although there are no official figures on the amount of discarded OTR tires in the world today [19], by 2012 it was estimated that there were 17 million tons of used tires worldwide [20]. Just as an example, two of the main mining countries such as Australia and Chile discard more than 130 thousand tons of scrap tires per year [21] and 180 thousand tons of waste per year [22, 23], respectively. At the urban level, pollution from burning tires is also observed, which causes soil [24] and air pollution [25], in addition to the risk of fire [26].

Despite the existence of some methods for reusing tire waste such as incorporating them as aggregate in roads, athletics, and cycling tracks, and using them for safety elements in roads, among others, the large-scale production of tires remains a significant worldwide environmental problem [27, 28, 26, 29, 30]. Ongoing studies are being conducted to explore new technologies that can facilitate innovative uses of tires within the framework of a circular economy [31, 18, 32]. The substantial volume of waste tires has prompted governments to develop environmentally responsible policies. For example, in Canada, a protocol was implemented in 2016 under the Resource Recovery and Circular Economy Act, with a primary focus on shredding and reusing rubber materials [33]. South Africa has established a recycling program that imposes a tax on new tires to promote the use of recycled ones. In the case of Chile, the Extended Producer Responsibility Law [34] mandates that by 2026, mining companies must ensure that 100% of their tires are managed through recycling methods, shifting away from traditional collection systems.

The objective of this study is to identify the factors that contribute to operational damage to tires in loading and extraction equipment, and propose a strategy to enhance their lifespan. The research employs a case study approach conducted at an open-pit mining company. The primary causes of tire damage are identified using statistical analysis and the Pareto rule. The study aims to achieve two key benefits: (i) mitigating production waste resulting from tire damage in front-end loaders (FEL) and haul trucks (MT), and (ii) improving economic indicators associated with tire lifespan performance.

2. Methodology

The methodology employed in this study is based on a systematic and structured approach to analyze the tire loss process of MT and FEL devices during the period 2019-2021. A comprehensive analysis is conducted to identify the causes of tire loss, assess the impact of operational damage on tires, and quantify the associated losses. Furthermore, Pareto and Ishikawa diagrams are utilized to identify the primary causes of damage and analyze the parameters that affect tire performance. The obtained results and conclusions offer valuable insights for enhancing tire management of MT and FEL devices (Figure 1).

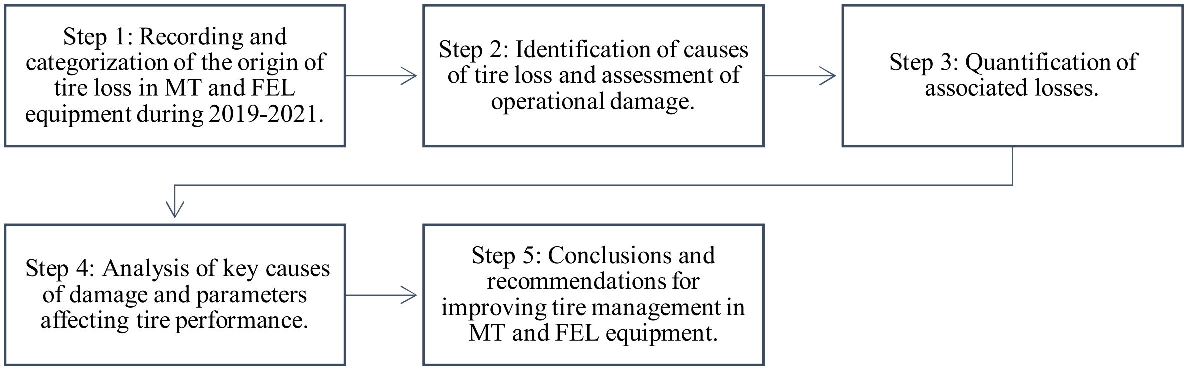

Figure 1. Flow of the methodology followed for the study.

2.1. Off-the-road tires

This section corresponds to Stage 1 of the methodology described in Figure 1. A structural diagram of an all-terrain radial tire (Figure 2) is presented, composed of the following elements: (1) Tread: The outer surface of the tire that contacts the road surface. It is considered the most critical part of the tire. [35]; (2) Body ply: Resistant layers of the tire that provide internal structural support; (3) Belt: Reinforces the tread to prevent excessive deflection during curves and traction. It improves tire performance and durability; (4) Sidewall: The vertical part of the tire that offers structural support and protection by absorbing impacts; (5) Bead: The innermost part of the tire, forming a groove that allows the tire to fit the rim; (6) Inner liner: The inner layer of the tire that retains air and resists the penetration of external elements; (7) Cap-ply: The upper layer that provides additional resistance and protection to the tread. It contributes to tire stability and helps dissipate heat generated during operation; (8) Apex: Provides additional support to the sidewall by distributing the stresses generated by the tire during operation; (9) Shoulder: The area of the tire located between the tread and the sidewall, responsible for dissipating heat and reducing tire heating.

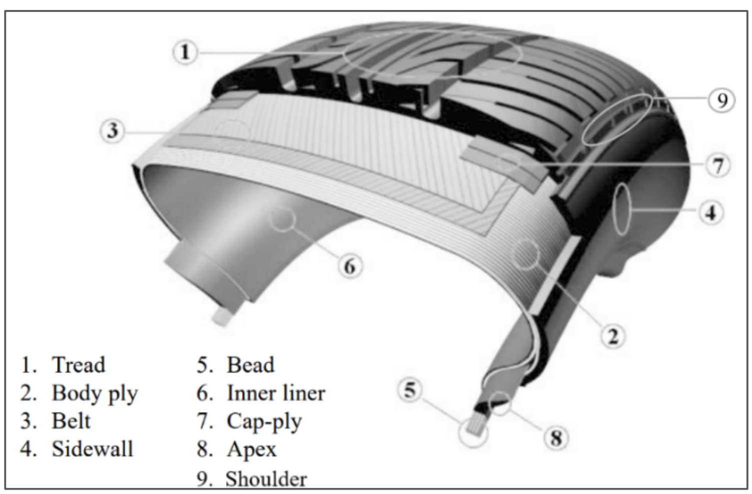

Figure 2. Tire cross-section, modified from [35].

Tire construction can be classified into two types: radial or bias. This classification refers to the Body ply (Figure 2, component 2), which consists of plies that provide resistance to the internal structure of the tire. These plies can be arranged in two directions: radially or diagonally. Radial tires have their plies parallel to the carcass and are crossed at 90°. This arrangement enables the tire to absorb shocks, impacts, and road irregularities [36, 37]. On the other hand, bias tires have a ply parallel to the tire carcass at angles between 35° to 40°. This configuration results in a stiffer tire [36].

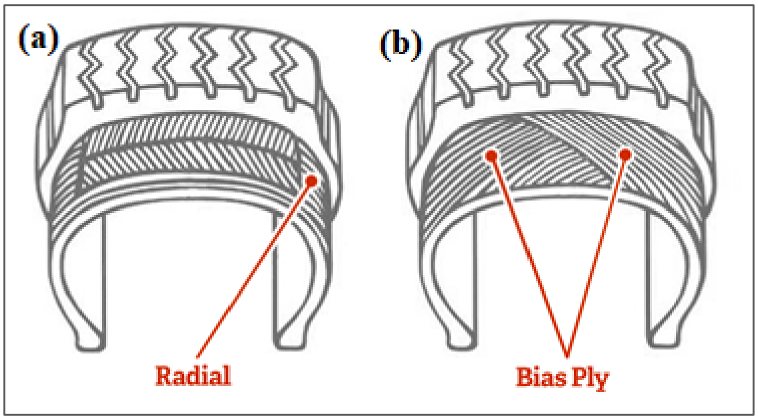

Figure 3. Tire ply arrangement (a) Radial tire, (b) Bias tire. Rescued from [38].

3. Operational Damage to Tires

Operational damage can be defined as the consequence of an event that causes a tire to become damaged or require repair. This damage may or may not be due to human error and occurs during full equipment operation, hence its name. Such damage affects not only the integrity of the tire but also that of the equipment, individuals, production, and costs due to premature tire failures.

When equipment supported by tires is loaded, it not only affects the suspension and steering system but also significantly impacts the performance and durability of the tire's tread and sidewall. Consideration of controllability and driving stability is crucial as tires are subject to dynamic and thermal loads, wear, and damage [39]. Despite the tire's resistance to properties such as abrasion, cuts, and impact, the mining environment, and operators' work practices contribute to a reduced tire lifespan, leading to irreparable damage and/or operational setbacks. Table 1 presents the risks and operational damage to which tires are exposed.

Table 1. Tire removal reasons. Own elaboration.

	Wear	Retired	Wear and tear
Tire removal reasons	Operational damage	Cuts	Sidewall cutting (component 4, Figure 1)
			Tread cut (component 1, Figure 1)
			Butyl cut
		Impact	Impact on the sidewall (component 4, Figure 1)
			Tread impact (component 1, Figure 1)
		Separation	Separation by cutting
			Sidewall separation (component 4, Figure 1)
			Tread separation (component 1, Figure 1)
			Shoulder separation (component 9, Figure 1)
			Mechanical separation
			Separation by temperature
		Detachment	Detachment of tread (component 1, Figure 1)
		Other	Repair failure

Cuts are incisions in the tire caused by driving over angular or semi-angular rocks with significant granulometry compared to the tire. These incisions can occur on the sidewall (Figure 4a), tread or butyl. Impacts are deep damages that typically perforate the tire structure, breaking the top and carcass ply. They result from collisions with obstacles on the road such as rocks or when encountering a large rock. The location of impacts can be identified as sidewall (Figure 4b) or tread. Both shear and impact failures can be catastrophic, especially when the tire's temperature is high at the time of the failure, often resulting in a blown tire [14]. Separation refers to the partial detachment of one of the tire plies. It is classified based on the area of involvement such as sidewall (Figure 4c), tread (Figure 4d), cut or shoulder. Separation can also be categorized based on its origin such as mechanical or temperature separation. In some cases, separation can be total, referred to as "detachment," which commonly affects the tread. "Repair failure" refers to tires that are sent for repair, but due to environmental conditions, experience detachment of the implemented patch. In such extreme conditions, the tire cannot be repaired.

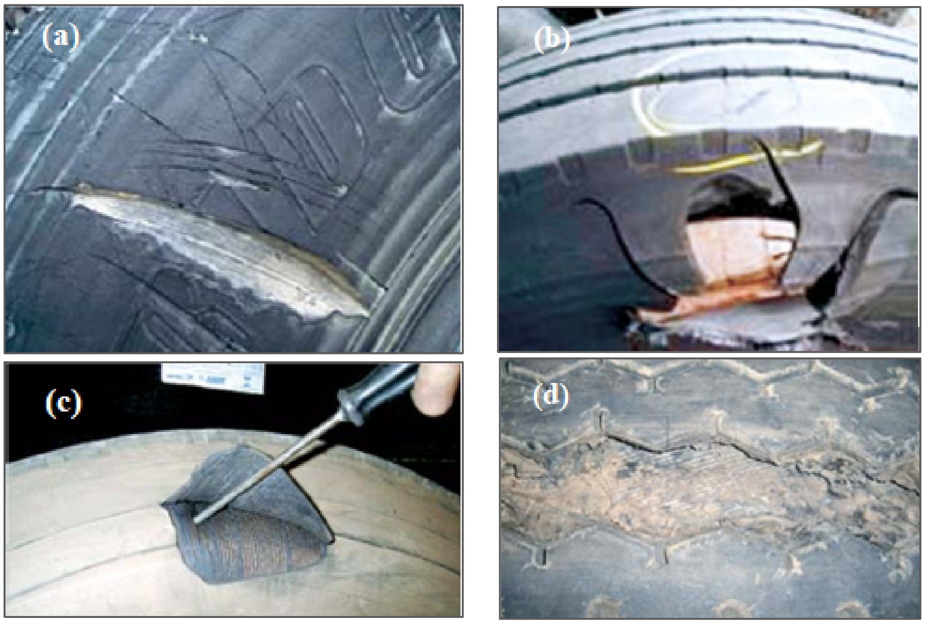

Figure 4. Types of operational damage. (a) Sidewall shear; (b) Sidewall impact; (c) Sidewall separation; (d) Tread separation. Rescued from [40].

4. Tire Chains

Chains can be defined as dense steel mesh that adapts to the shape of the tire, providing protection to its vulnerable parts and forming a barrier against potential damage during mining operations [4]. Regarding tire chains, they can be categorized into two types: (i) protection chains and (ii) traction chains. These components significantly contribute to enhancing tire lifespan, operational productivity, and cost-effectiveness.

Protection chains serve the purpose of safeguarding the tire's tread surface and various sidewall areas. The utilization of protective chains offers several advantages including a reduction in operational cost per hour, decreased expense for tire repair, prevention of unscheduled stops, and improved traction while minimizing tire slippage. On the other hand, traction chains are specifically designed to enhance tire traction in areas with poor adherence such as on icy or muddy surfaces [41].

5. Case Study

This section corresponds to Step 2 of the Methodology described in Figure 1. The mining company under study is in Chile. It is an open-pit mine that extracts iodine and potassium nitrate at a rate of 11,000 tons of iodine per year and 4 million tons of nitrates per year. For ore processing, the company has a network of roads that are 25 m wide, with a maximum slope of 10%. However, due to the nature of the deposit, most of the roads are horizontal or sub-horizontal. To maintain the roads in good condition and ensure their proper operation, the company follows maintenance protocols. These protocols involve using water trucks to irrigate the roads once a day. This practice helps maintain road conditions by improving compaction and controlling suspended dust. The lifespan of the roads varies between 2 to 6 months, depending on the life of the mining polygons and the cold leach heaps they connect. The mining equipment required for operation includes drills, front loaders, extraction trucks, motor graders, water trucks, and other auxiliary equipment. The mining equipment under study that uses OTR (Off-The-Road) tires are mining trucks (MT) and front-end loaders (FEL). The MT equipment varies in make and model (Komatsu, model HD-785-7; Hitachi, model EH1700-3; Komatsu, model HD-1500-8; and Caterpillar, model 785-D). However, all these models use only two tire sizes: 27.00R49 and 33.00R51. These tires are radial and have a tread groove depth that ranges between 66.5 and 73 mm [42]. The FEL equipment, specifically the Caterpillar model 993K, uses 50/65-51 size bias tires with a tread depth of 124 mm. The Komatsu model WA900 uses 45/65R45 size radial tires with a tread depth of 116 mm [43].

In Chile, approximately 180,000 tons of tires larger than 57" are produced each year [22, 23]. Unfortunately, only 17% of these tires are managed in an environmentally sound manner [23]. This underscores the urgency of achieving the recovery goals outlined in Law 20290 [44]. Therefore, maximizing efforts to increase the lifespan of tires contributes to waste reduction, the proper management of discarded tires, and environmentally and economically responsible operations in line with the directives of law 20290. In this context, the company under study has recorded the disposal of 48 FEL tires and 223 MT tires between the years 2019 and 2021. Considering that each tire has an approximate value of 19,000 USD, the total value involved is estimated to be around 5.1x10^6 USD. Of the FEL tires (Table 2) and MT tires (Table 3), 87.5% and 79.8%, respectively, have been prematurely discarded due to operational damage without reaching their full useful life. To address this issue, the company records specific reasons for tire loss based on the type of operational damage suffered, aiming to reverse this negative trend.

Table 2. Tire scrap registration FEL.

Year	2019	2020	2021
Operational damage	13	16	11
Wear	0	3	3
Total	13	19	14

Table 3. Tire scrap registration MT.

Year	2019	2020	2021
Operational damage	68	67	59
Wear	16	15	22
Total	84	82	81

Although there is no agreement on a wear limit for OTR tires, at the urban level, the legal limit for tread grooves is 1.6 mm [45]. Despite this, some manufacturers recommend not going below 3 mm [46]. In the case of the mining company under study, the proposed goal is not to use the tires beyond 95% of tread groove wear. For example, considering the 45/65R45 tire with a tread groove depth of 116 mm, the maximum self-imposed wear allowed by the mining company would be until the tread groove depth reaches 110.2 mm. When a tire must be discarded due to operational damage, it is usually found to have less than 95% wear. Therefore, it is possible to determine the percentage of the tread that is no longer used in operation due to early tire disposal, also known as loss of service life. According to the problems presented in the case study and the provided background information, it is necessary to analyze the distribution of the data and determine the most common type of damage in OTR tires. This section corresponds to Step 3 of the Methodology described in Figure 1.

Figures 5 to 10 show the percentage of wear that tires have before being discarded due to operational damage (blue color), and the percentage of loss of use of the tire by having a tread with less than 95% wear (orange color). Regarding the wear of MV equipment tires, they show a 74% measure in the year 2019 (Figure 5), 56.8% in 2020 (Figure 6), and 70% in 2021 (Figure 7). This means that 50% of the discarded tires are used until this percentage of tread groove wear is reached. The loss of useful life of MT equipment tires is 26% in 2019 (Figure 5), 43.2% in 2020 (Figure 6), and 30% in 2021 (Figure 7). The FEL equipment presents a median tread wear of 44.8%, 40.5%, and 52.6% for the years 2019 (Figure 8), 2020 (Figure 9), and 2021 (Figure 10), respectively. The loss of service life (median) for the FEL equipment is 55.2%, 59.5%, and 47.4% for the years 2019 (Figure 8), 2020 (Figure 9), and 2021 (Figure 10), respectively. Based on the above, it is observed that MT equipment loses on average 33% of its useful life, and FEL equipment loses on average 54% of its useful life. This demonstrates a considerable loss of useful life, including the existence of several tire units that do not wear out and must be removed due to operational damage.

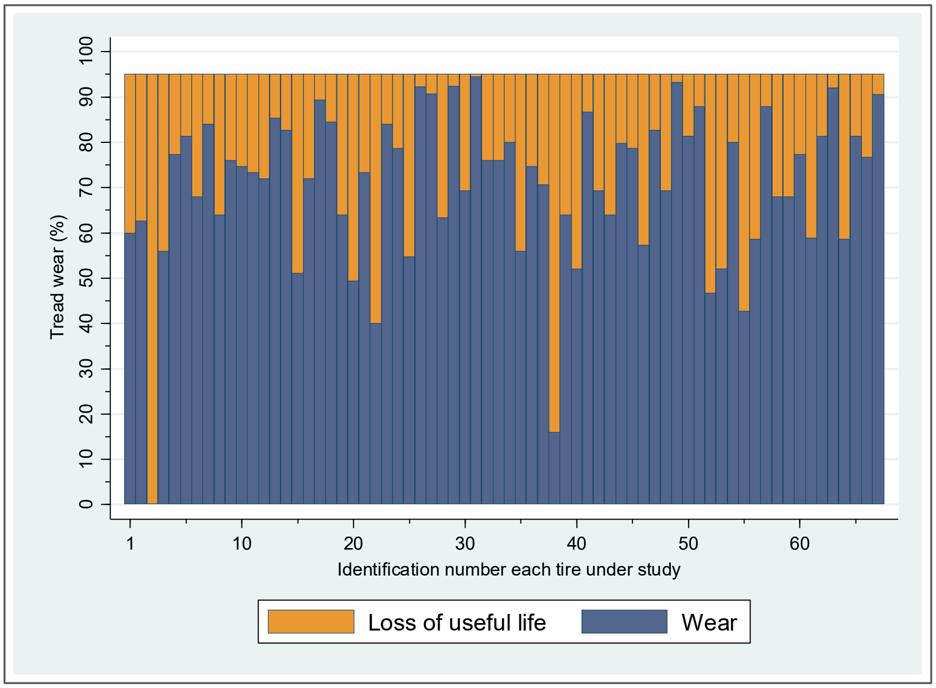

Figure 5. MT tire wear, 2019.

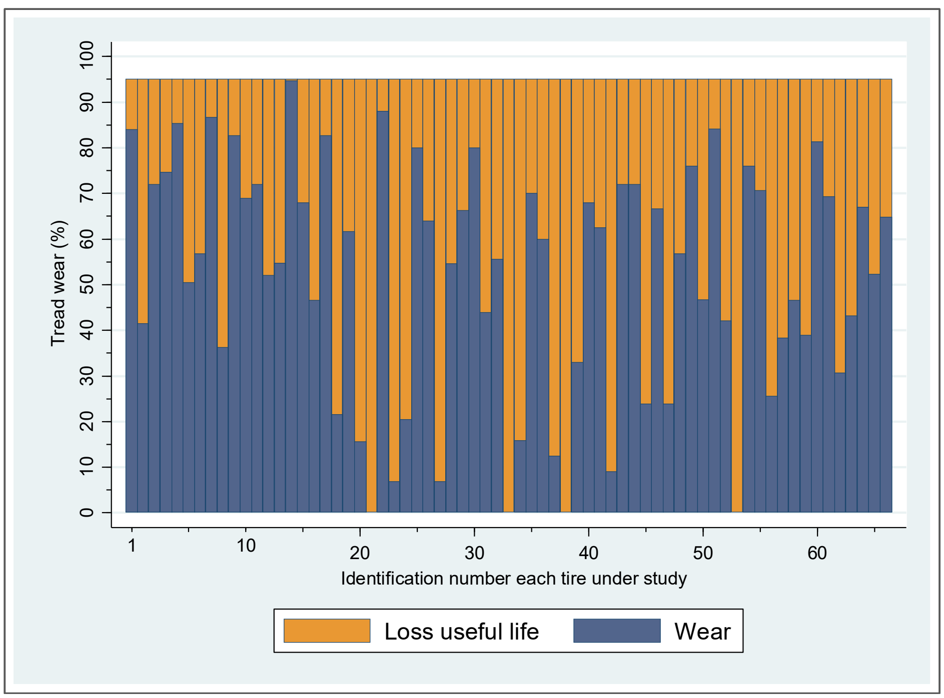

Figure 6. MT tire wear, 2020.

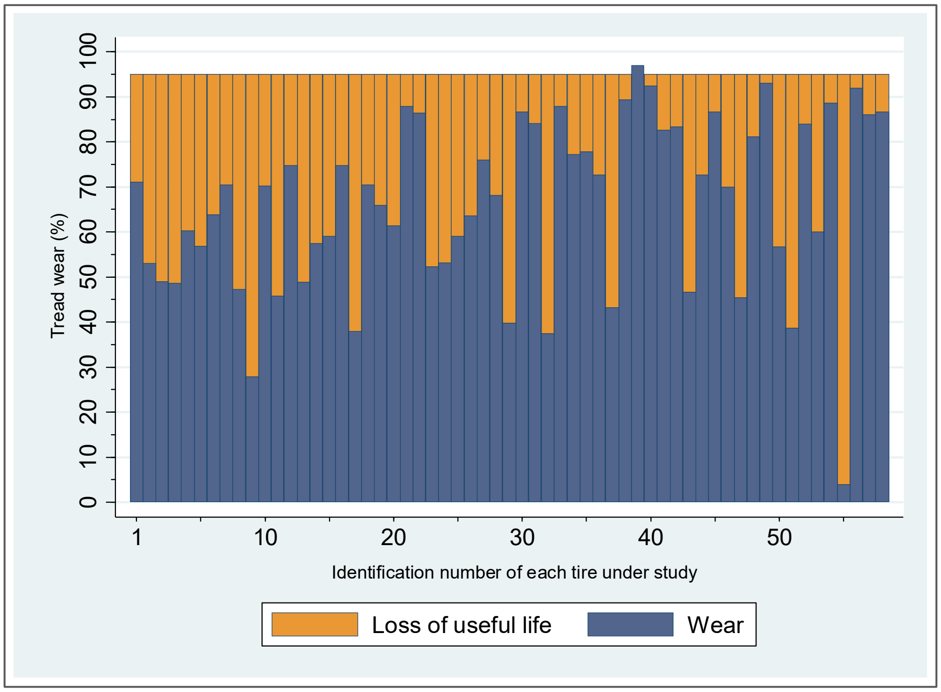

Figure 7. MT tire wear, 2021.

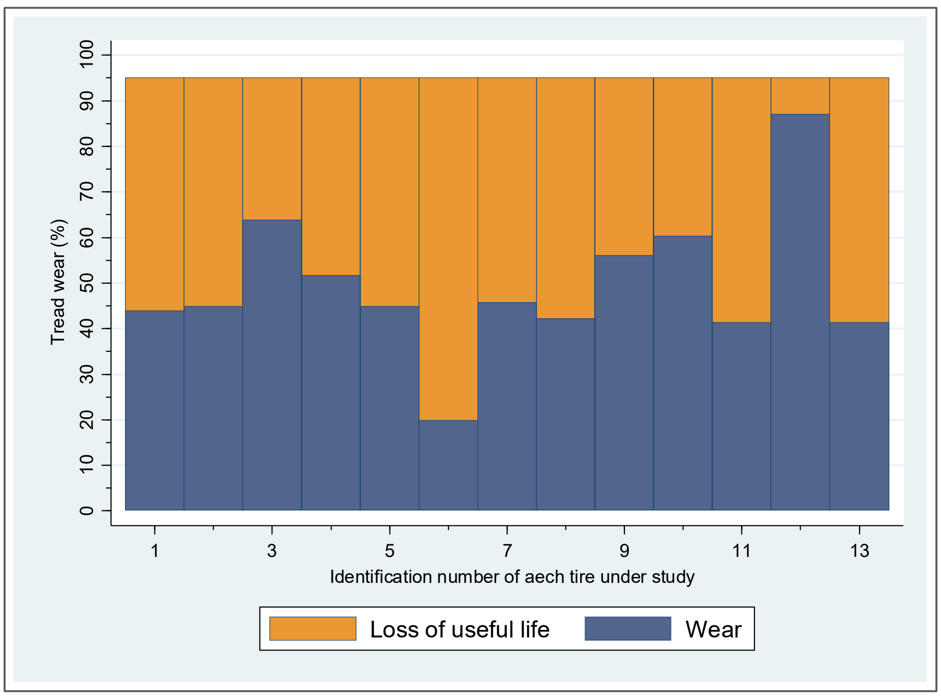

Figure 8. Tire wear FEL, 2019.

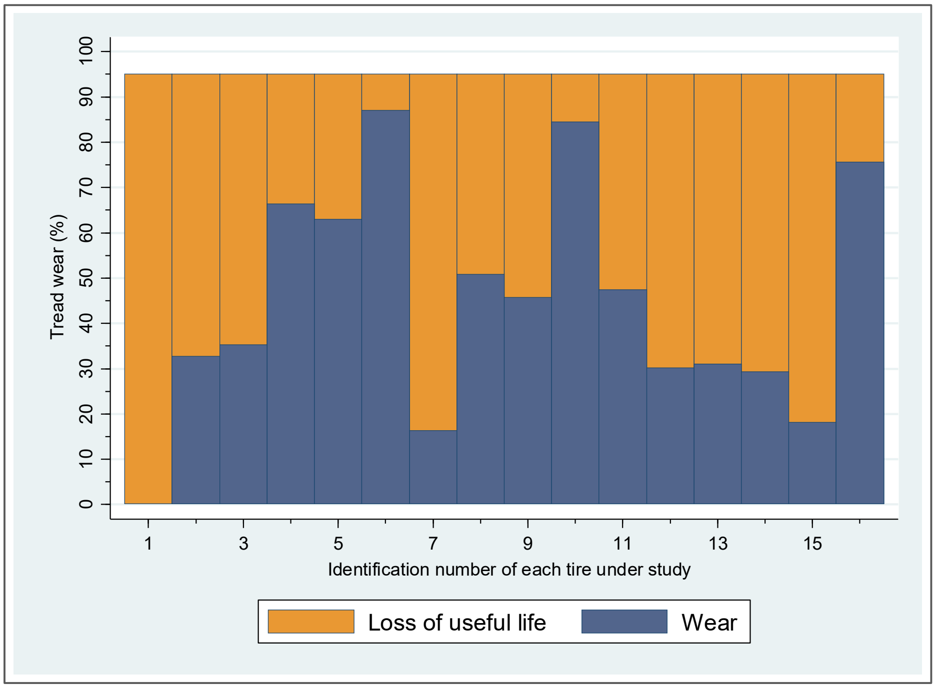

Figure 9. Tire wear FEL, 2020.

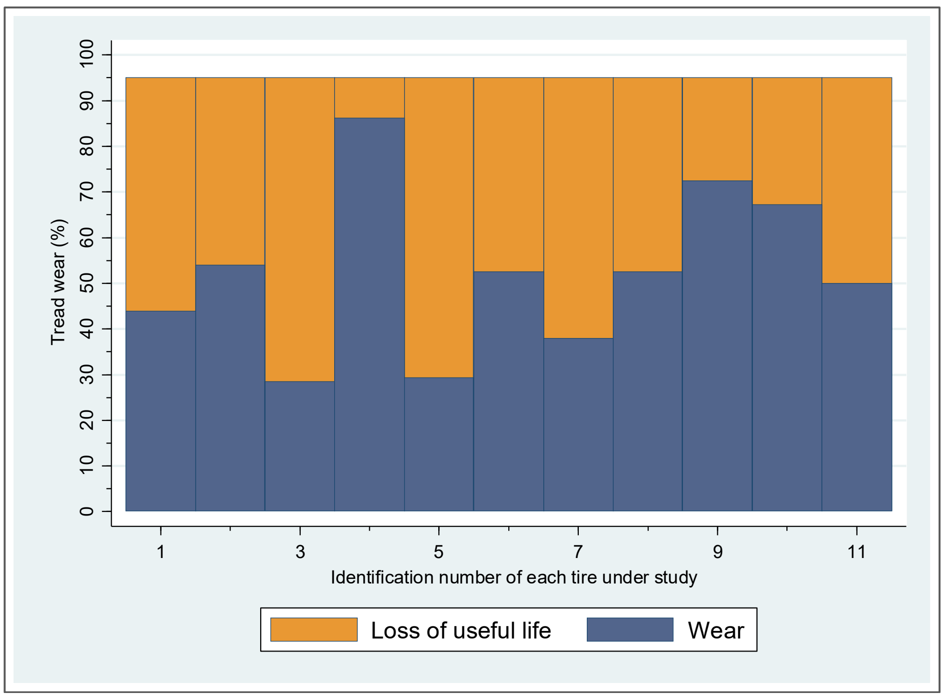

Figure 10. Tire wear FEL, 2021.

The persistence over the years in the situation of premature retirement of tires on loading and transport equipment induces the need for a careful examination of the incidence of operational damage. The operational cause with the highest incidence in the period 2019-2021 is impacts (Figure 11), which mainly occurs in the tread, followed by cuts and separation in different tire components. Similarly, it is determined (Figure 11) that the most affected tire parts are the tread and sidewall in the case of MT equipment, and in the case of FEL equipment, the most affected tire area is the tread. Both impacts (45.3% in MT equipment and 35% in FEL equipment) and cuts (25.2% in MT equipment and 17.5% in FEL equipment) are operational damages that occur due to high inflation pressure, which also reduces the traction of the tire [4]. This type of failure corresponds mainly to lax practices on the part of operators, who do not check for damage to their tires and/or do not give notice of the need for repair, causing the damage to increase to the point of being unrepairable.

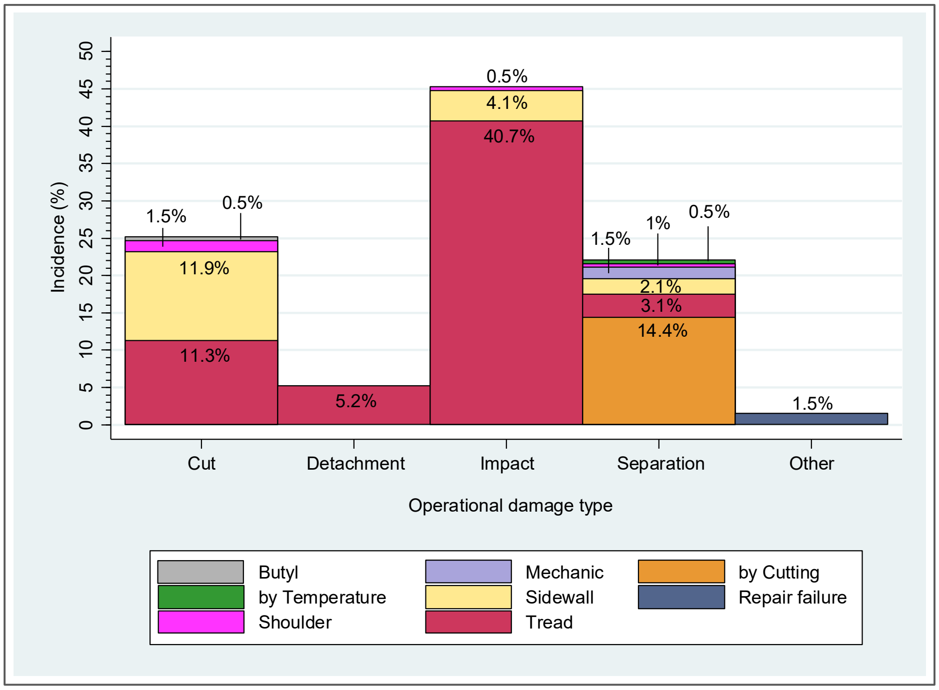

Figure 11. Distribution of the incidence according to the type of damage in MV equipment, 2019-2021.

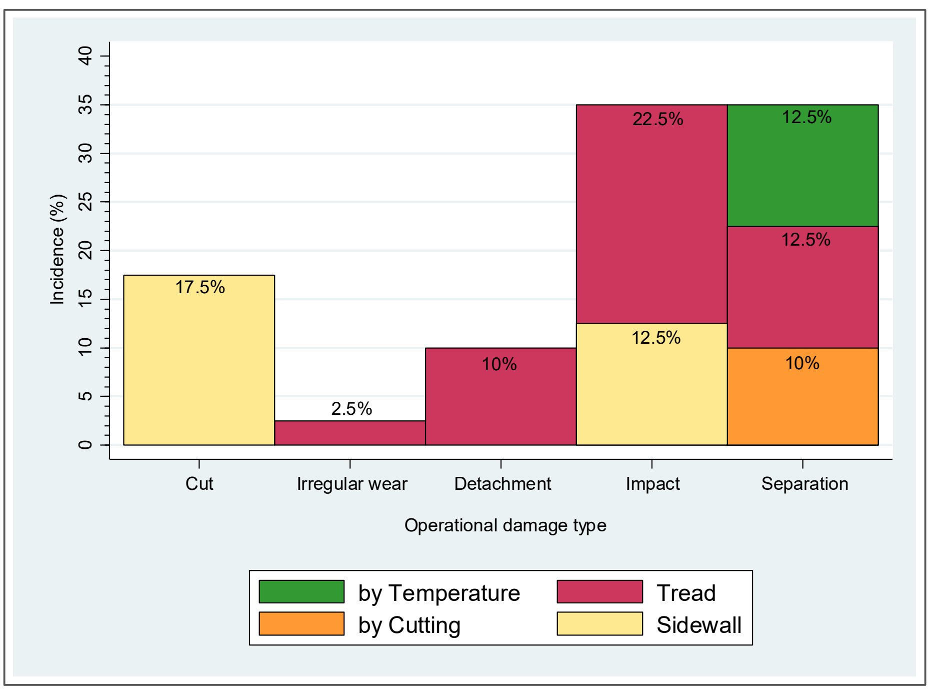

Figure 12. Distribution of incidence according to type of damage in FEL equipment, 2019-2021.

Based on the aforementioned information, the tire positions most affected by operational damage in the period 2019-2021 are determined as follows: 94.3% of operational damage in MT tires belongs to the rear positions (positions 21, 22, 23, 24). In contrast, 75% of discarded FEL tires belong to the front positions (positions 11, 12), as shown in Figure 13. Additionally, the latest results (year 2021) represented in Figure 14 reveal that 99% of MT tires belong to the rear positions, while 81% of FEL tires belong to the front positions. These results reflect the continuation of historical trends in the most recent period. It is inferred from these records that the weight supported by each piece of equipment, which is specific to each function, has a significant impact on the useful life of the tires. However, when analyzing the type of damage (Figure 11 and Figure 12) and the location of the tire (Figure 13 and Figure 14) together, it is possible to infer that both factors have a significant impact on the useful life of the tires. Furthermore, it can be inferred from Figure 14 that different triggering factors cause tire scrap: (i) Negligent operational practices with the life of the inputs, which worsen when the equipment is in the process of loading and transportation; (ii) The condition of the roads is a critical factor in preventing the occurrence of operational damage; (iii) The quantity, availability, and use of auxiliary equipment to carry out road maintenance; (iv) The coarse granulometry of the material at the time of loading, since the FEL equipment spills material close to the rear wheels of the MT equipment, thus increasing the probability of operational damage.

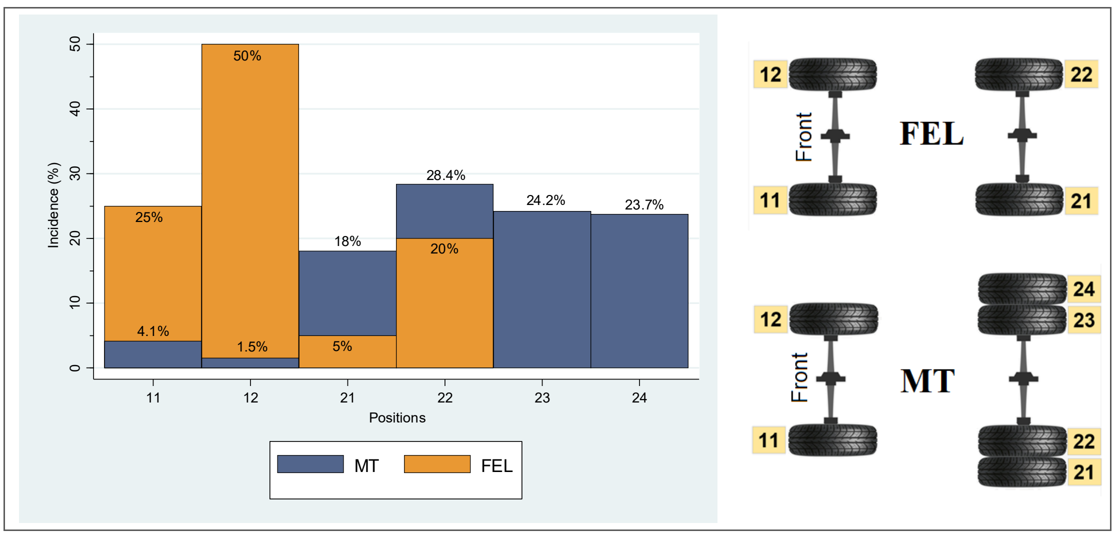

Figure 13. Incidence by position, operational damage of FEL and MT equipment, 2019-2021.

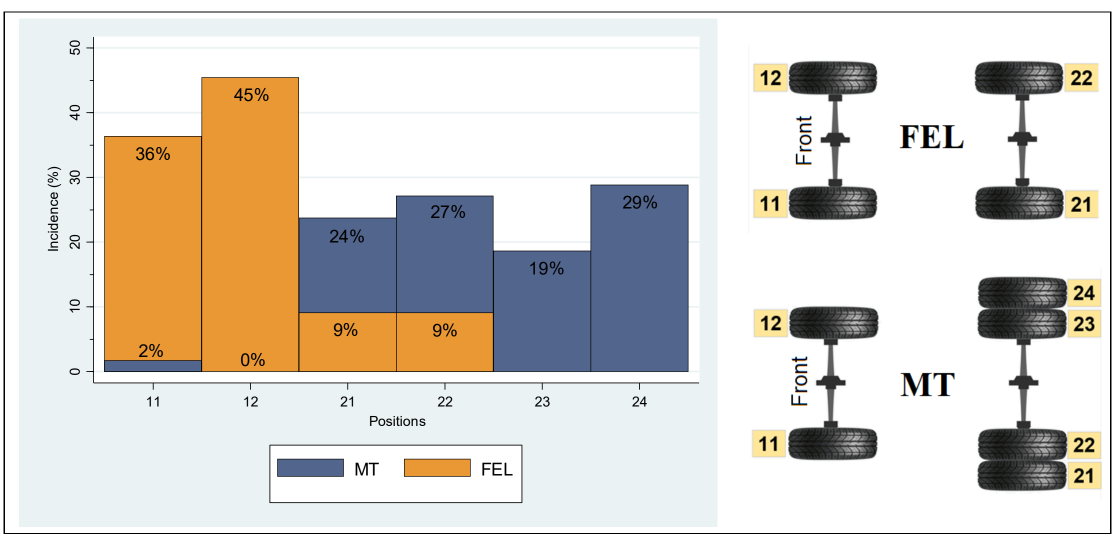

Figure 14. Incidence by position, operational damage of FEL and MT equipment, 2021.

After identifying the operational causes that lead to the premature disposal of tires, a Pareto diagram (following the 80/20 rule) is prepared for MT equipment (Figure 15). It identifies that 80% of MT tire losses are due to five causes, four of which are related to the sidewall and tread, coinciding with the known information about this tire type as reported by [15]: sidewall cut, tread cut, tread impact, tread separation, and tread detachment. Thus by addressing the aforementioned causes, it is expected to mitigate 80% of the total tire losses. Meanwhile, the Pareto diagram for FEL equipment (Figure 16) indicates that 91% of the tire losses are associated with four causes of operational damage: separation by cutting, tread separation, separation by temperature, and tread impact. By addressing these causes, a 90% reduction in total losses in loading equipment can be achieved. This section corresponds to Step 4 of the Methodology described in Figure 1.

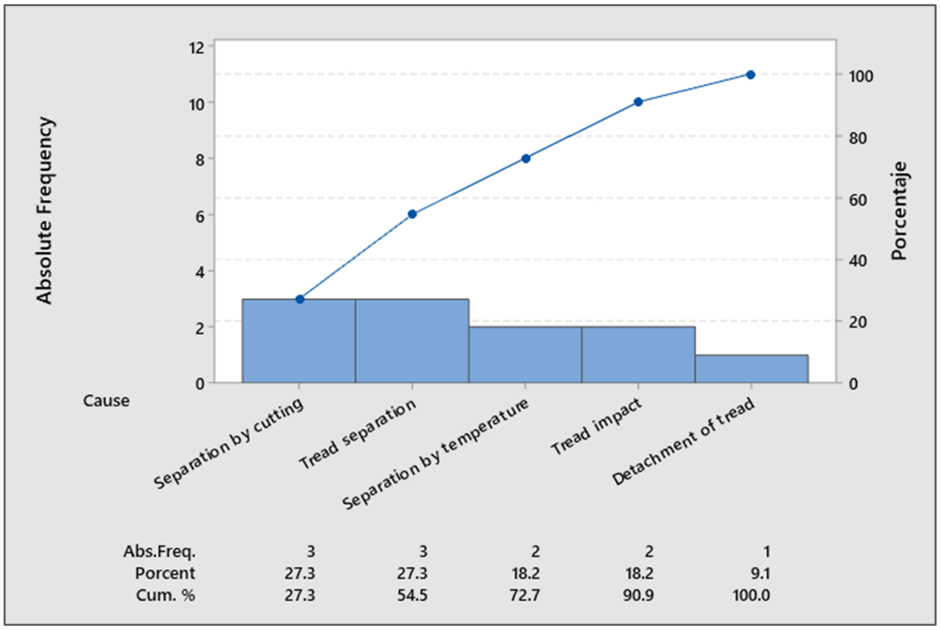

Figure 15. Pareto diagram - MT equipment tire scrap.

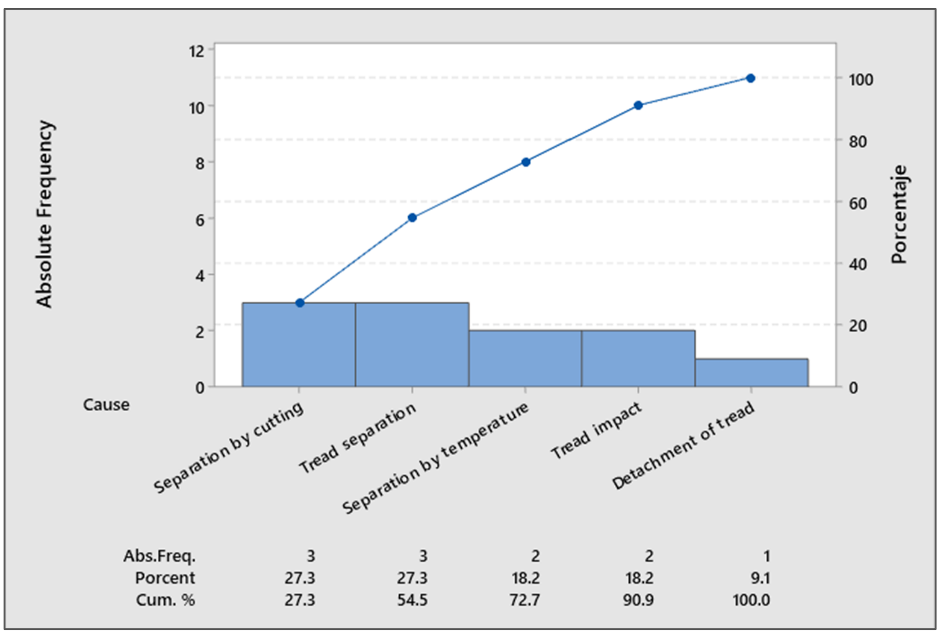

Figure 16. Pareto diagram - FEL equipment tire scrap.

Thus, it is determined that the tires of FEL equipment are the ones whose useful life is most affected. Therefore, an evaluation of the use of protective chains for this type of tire is undertaken, and it is suggested to implement a pilot plan using protective chain in FEL equipment. In this case, an investment is made in the purchase of chains for US$11,200 each. These chains have a nominal life of 12,000 hours for FEL tires of size 45/65R45, and are valued at US$19,000 each. The 50th percentile (P50) of FEL tires yields 5435 hours, representing 53% of their tread wear. However, without these incidents, a tire at the P50 wear rate should have a useful life of more than 9700 hours (to reach 95% tread wear). In other words, at least 50% of the tires are losing more than 4300 hours of operational use. By implementing chains on equipment tires, it is expected that tire life will exceed the current duration. In other words, using chains will slow down tread wear compared to tires that do not use chains. However, this hypothesis should be tested once the proposed pilot plan is implemented.

From the narrative and considering that the operational damages occur in both MT and FEL equipment, an Ishikawa diagram is created to efficiently analyze the root causes of the problem (Figure 17). Among the categories "Materials," "Equipment," and "Environment," the identification of two common factors is observed. These factors are the operational availability of support equipment necessary for safe operation and the granulometric result of the blasting operation, which appears to be too coarse for loading or transport equipment to detect and avoid accidentally passing over. Both factors are significant; however, further in-depth studies are required to determine the underlying causes of these circumstances, which are beyond the scope of this investigation. On the other hand, the reasons identified in the category of "Equipment Operators" appear to be more manageable in the short term. These reasons include (1) a lack of a culture of care and awareness regarding the value of tires; (2) overloading of materials and/or unbalanced loads causing excessive strain on the tires; (3) inadequate control of tire inflation pressure. These three reasons can be addressed through a policy aimed at raising awareness about the economic value of tires, their environmental impact, and how responsible operational and environmental behaviors can help mitigate their negative impact. Examples such as Coeur Rochester [47] demonstrate the importance of prioritizing communication and interdisciplinary team responsibility, promoting awareness, and encouraging performance improvement through economic incentives. Simultaneously, it is necessary to implement clear and rigorous maintenance and prevention protocols that include daily inspection of inflation pressure. It is presumed that the company uses excessively high pressures, which affect 70.5% of MT tires and 52.5% of prematurely discarded FEL tires due to operational damage (those discarded due to Impact and Cut) [4, 48].

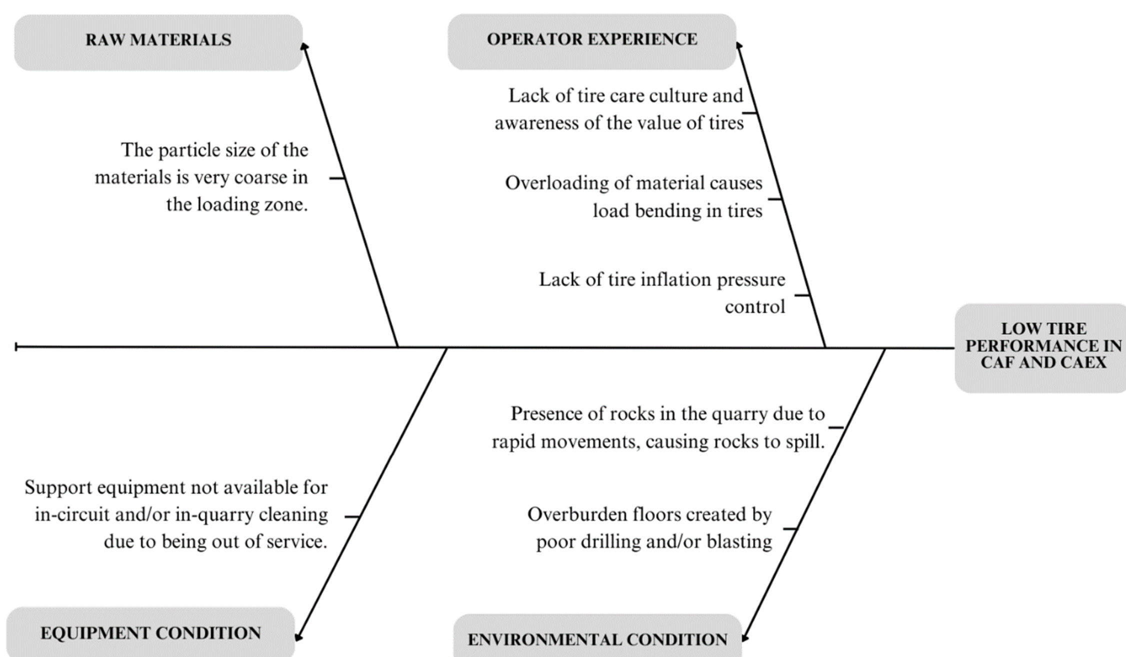

Figure 17. Ishikawa diagram explaining FEL and MT equipment performance. Own elaboration.

6. Conclusions

- In the case study, an average tire takes 6395 hours of operation to wear out 95% of its tread. However, 50% of the tires in the study take 5435 hours to reach this level of wear.
- The rear tires of the MT equipment are the most affected (positions 21, 22, 23, 24), primarily in the sidewall and tread. Meanwhile, the front tires of the FEL equipment are the most affected (positions 11, and 12), primarily in the tread. It is recommended to protect the equipment tires through appropriate measures and behaviors, with special emphasis on the front tires for FEL equipment and the rear tires for MT equipment.
- The unit cost of an average FEL tire is 2.97 [USD/h], and the unit cost of an FEL tire belonging to the 50th percentile is 3.50 [USD/h]. The use of chains represents an improvement, as the unit cost is reduced to 2.52 [USD/h], resulting in a 28% improvement compared to the unit cost of 50% of the tires. This translates to over 200k USD in tire expenses due to the premature loss of their service life during the study period.
- It is recommended to implement an awareness program about the economic and environmental impact of tires. The implementation of such policies in the mining company can lead to significant economic savings, considering that the number of MT equipment is much higher than FEL equipment.
- The company has been advised to periodically monitor tire inflation pressure, as excessive pressure influences the premature disposal of 70.5% of MT tires and 52.5% of FEL tires due to operational damage. It is also recommended to implement this improvement before initiating any pilot plan involving the use of chains.

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ارزیابی تأثیر خسارت عملیاتی بر تایرهای معدنی (مطالعه موردی)

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چکیده:

در عملیات معدن روباز، فعالیت‌های بارگیری و حمل و نقل، بخش قابل توجهی، معمولاً بین ۵۰ تا ۶۰ درصد از هزینه‌های عملیاتی کل فرآیند معدن را تشکیل می‌دهند. لاستیک‌ها به نوبه خود از نظر هزینه‌های عملیاتی برای اکثر شرکت‌های معدنی رتبه دوم را دارند. بنابراین، درک و حفظ عمر مفید تایرهای خارج از جاده (OTR) یک عامل حیاتی در تضمین سودآوری یک پروژه معدنی است. این مطالعه بر روی یک معدن خاص برای تجزیه و تحلیل علل آسیب عملیاتی در تایرهای کامیون‌های معدن (MTs) و بارگذارهای جلویی (FELs) تمرکز می‌کند. هدف آن شناسایی عواملی است که منجر به دفع زودهنگام این لاستیک‌ها می‌شود و راه حل‌هایی برای افزایش عمر مفید آنها پیشنهاد می‌کند. این مطالعه چهار جنبه کلیدی را شناسایی می‌کند که بر عملکرد پایین تجهیزات استخراج تأثیر می‌گذارند، یعنی تجربه اپراتور، شرایط محیطی، مواد خام و شرایط تجهیزات. علاوه بر این، این مطالعه نشان می‌دهد که فشار بیش از حد به طور قابل‌توجهی به دفع زودهنگام لاستیک‌ها کمک می‌کند و ۷۰.۵ درصد آسیب تایر MT و ۵۲.۵ درصد از آسیب تایر FEL را تشکیل می‌دهد (که عمدتاً بر لاستیک‌های عقب و جلوی MT تأثیر می‌گذارد). استفاده از زنجیر چرخ به عنوان یک راه حل پیشنهاد شده است، با پتانسیل کاهش هزینه واحد در هر ساعت کار تا ۲۸ درصد برای حداقل ۵۰ درصد لاستیک‌ها.

کلمات کلیدی: خارج از جاده، لاستیک، OTR، کامیون معدن، لودر جلو.