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Analysis of Causes and Consequences of Failures in Process of Andesite Crushing by Jaw Crusher

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Abstract: Mining and mineral processing are essential for the functioning of many economic sectors and for meeting human needs. Diagnostics and evaluations of faults are necessary to ensure the successful and responsible management of mining and processing processes for mineral raw materials. Fault-free operation contributes to increased efficiency, productivity, safety, and reliability, reduces the cost of the process under consideration, and reduces environmental impacts. This study aims to identify and analyze possible component failures associated with the jaw crusher used in the process of andesite crushing in an open-pit quarry and compare different approaches to their assessment. The benefit of this is using three different failure analysis methods to assess the criticality of individual jaw crusher components. This approach's novelty lies in the synergy that occurs when assessing the failures' impacts on safety, quality, and the environment.

Keywords: raw material processing; jaw crusher; fault diagnosis; process control

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1. Introduction

The mining and manufacturing industries are essential to the functioning and development of modern society and are characterized by high process and system complexity. Machines and equipment in these industries must cope with harsh working conditions; they have to operate in all seasons and in extreme temperatures, rain, snow, dust, etc. It is, therefore, essential to pay attention to ensuring the reliability and quality of their operation and optimizing individual processes. It is therefore essential to pay close attention to their regular maintenance and thus avoid problems with their unavailability caused by unexpected breakdowns. There are a number of simpler or more complex methods that can be used. The most commonly used methods include the Ishikawa diagram (Cause and effects diagnostics), the Five Whys, Poka-Yoke, and others [1–4]. These methods can be used alone or in combination to achieve an effective result. Each has its advantages, and it is important to select the one that best suits the problem at hand [5–7]. One of these methods is the Failure Mode and Effects Analysis (FMEA).

Failure Mode and Effects Analysis in the technological process of mineral processing is a critical step in ensuring the plant's efficient, reliable, and safe operation. Identifying and eliminating defects can lead to improved performance and quality, reduced costs, and reduced negative environmental impacts. This study focuses on applying defect and root cause analysis in the technological process of andesite treatment. In this method, it is crucial not only to identify potential failures but also to assess their significance. Since its inception in the 1950s, FMEA has evolved through various approaches to assessing the significance of identified failures [8,9].

Traditionally, risk assessment in FMEA has been performed using a risk priority number (*RPN*). The *RPN* calculation considers only three risk factors: severity (*S*), occurrence (*O*), and detection (D). It does not consider safety, quality, cost, or other important factors (environmental impact, customer impact, legal and regulatory consequences that may arise in the event of failure, time factor needed to correct the error, or reputational risk).

Many authors have explored alternative methods for determining the *RPN* [7,8,10]. Ouyang et al. describe the drawbacks of the classical *S*, *O*, and *D* assessment and propose a combination of *SO*, *SD*, and *OD* risk factors for risk assessment [11]. Combinations of risk variables improve the risk assessment by considering the inter-relationships between the variables. They help to better identify the most critical risks that require immediate attention. This assessment can be used in manufacturing, automotive, healthcare, and IT services.

Gargama and Chaturvedi compare two innovative approaches for prioritizing FMEA assessments in their study. The first approach uses fuzzy theory to calculate the *RPN*. The second evaluates the degree of agreement in the opinions of a team of FMEA evaluators [12]. In their study, Wu and Wu [13] propose a fuzzy beta-binomial method to evaluate *RPN* by integrating fuzzy theory, Bayesian statistical inference, and beta-binomial distribution. Yu et al. propose a new Failure Mode and Effects Analysis model using personalized evaluation linguistics and a rule-based Bayesian network [14]. Carpitella et al. proposed a modification of FMEA based on a fuzzy theory for optimizing maintenance activities. Their approach combines a reliability analysis with multi-criteria decision-making methods [15].

Unlike traditional methods, fuzzy logic allows one to work with imprecise and uncertain data. It provides a more accurate assessment because it provides a mathematical framework. It assesses risks based on linguistic variables, leading to a better understanding and management of risks. Its disadvantage is its computational complexity. There is no uniform standard for its implementation. As with traditional assessment methods, there is subjectivity in defining the rules, but less is needed [16,17].

The authors of Wu et al.'s [9] literature review also point out the need for academic research in this area to be more oriented towards the needs of industrial practice in terms of utilizing published theoretical knowledge. Paolo Mercorelli's study [18] highlights the importance of model-based and data-driven approaches in fault identification and diagnosis, emphasizing the need for hybrid methods to bridge the gap between theoretical methodologies and practical implementations.

Liu et al., in their review, present the results of examining 75 articles from international journals published from 1992 to 2012 [8]. They focused on identifying the shortcomings of the traditional methodology and newly proposed approaches and evaluating their adequacy.

Recently, there has been a significant change in the FMEA evaluation methodology. In 2019, a harmonized guide was created with the collaboration of two major automotive industry organizations, AIAG (Automotive Industry Action Group) and VDA (Verband der Automobilindustrie), along with OEMs (Original Equipment Manufacturers) like companies Bosch (Stuttgart, Germany) and Denso (Kariya, Aichi Prefecture, Japan). In the latest version of the FMEA manual, they present *S*, *O*, *and D* as an alternative way of assessing the *RPN* [5,6]. In the guide, the risk number *RPN* has been replaced with the Action Priority (AP) concept. AP gives more weight to severity and divides priorities into three groups. More emphasis is placed on preventing defects and failures before they occur.

Each approach is characterized by a different calculation complexity, the need to involve experienced experts, and the degree of objectivity of the assessment. At the same time, it brings a different perspective on the significance of identified failures. For the active use of FMEA in the monitored process, it is necessary to compare individual approaches and select the optimal one.

FMEA is used in various industries, including aerospace, automotive, nuclear, and electronics. The following text focuses on studies related to the extraction and processing of raw materials.

If we can understand the causes of common faults and how to solve them, we can better use the equipment. Sinha and Mukhopadhyay's [19] study focuses on the failure analysis of rock crushers and their critical components using the FMEA method with traditionally calculated *RPNs* and the Total Time on Test (TTT) chart. They intended to improve both performance and operational reliability by identifying critical components of the equipment that need timely replacement to avoid failures. Zhai et al. analyze the reliability and optimization of a forage crusher rotor in terms of fatigue fracture, hammer wear, and violent vibration [20]. Many authors address the problem of the operational and design parameters of crushers on their performance [21–29]. Crusher rotor reliability analysis and fatigue life prediction is also addressed in the work of Zhao et al. [24]. In their study, Okechukwu et al. say that the simulation and optimization of jaw crusher design elements must be addressed at the design stage [25]. Murithi et al. [26] and Abhishek et al. [27] pointed out that the design parameters of the swinging jaw plate are influenced by the flow stress and deformation behavior during the crushing process. Optimization of a swinging jaw plate is also dealt with in work by Deepak [28]. The optimized design increases the jaw crusher's performance and service life. Adding reinforcement to the movable jaw plate reduces its weight by 24%, resulting in lower energy consumption, increased durability, and no-failure operation. Deniz investigated the effects of selected parameters and materials on the performance and capacity of a jaw crusher under laboratory conditions. He made practical recommendations for adjusting the operating parameters of the jaw crusher, which can be applied in actual operating conditions. [29].

This study aims to identify and classify the possible failures of jaw crusher components during the andesite processing process and to assess their significance. Three selected approaches (FMEA and its modifications) are used to assess their significance. Based on a multi-criteria evaluation of the jaw crusher under study and its components in terms of quality, safety, and environmental impact, we propose preventive measures to eliminate the identified faults to improve the efficiency, sustainability, and safety of the andesite processing process.

This study extends the commonly used view of component failure assessment to include its impact on output product quality and environmental impact. This approach is original and has not previously been published in the available literature.

2. Materials and Methods

This study was conducted at a company that operates an open-pit quarry to extract andesite. The quarry body consists of a hypabyssal intrusion of diorite porphyrite within the confines of a 780 × 540-m quarrying area. The thickness of the deposit varies from 24 m to 74 m, depending on the surface. The andesite is dark grey, locally greenish, and irregularly grained to massive, with feldspar, pyroxenes, and amphiboles. The detachment is predominantly boulder-shaped and locally platinum (Figure 1).



Figure 1. Andesite before treatment.

2.1. Description of the Technological Process

The entire technology used in extracting and producing natural crushed andesite in the quarry can be divided into quarrying, primary crushing, secondary crushing, and tertiary crushing.

Drilling and blasting are used to extract the andesite. Holes are drilled using drilling machines into which blasting material is inserted. After blasting, the rock is disturbed. Oversized pieces are mechanically broken up using a hydraulic hammer. The raw material is removed from the quarry by an electric excavator on a crawler chassis and transported by lorries for further processing.

Crushing is the breaking of solid material into small fragments or parts. Jaw and cone crushers are used for crushing. This study deals with the crushing of the material by jaw crusher.

The jaw crusher is used for primary crushing, and the material to be crushed is relatively large (up to 1100 mm max). The excavated material from the hopper falls through the sorting grate into the jaw crusher hopper. The jaw crusher uses a pressure force to break the material. The material is compressed and crushed in a crushing chamber composed of a moving and a fixed jaw plate. The device's output slot is up to 180 mm. A sensor controls the material level in the crusher hopper. An illustration of the crusher with the essential parts marked is shown in Figure 2. These parts are further analyzed to determine the occurrence of potential failures.

From the jaw crusher, the crushed material falls onto the conveyor and is transferred to the vibrating screen for final sorting. The vibrating screen's input is material up to 180 mm in size. The output is three fractions of size: 80–180 mm, 32–80 mm, and 0–32 mm. Screens with a grain diameter of 63 mm are also used depending on customer needs and requirements, ensuring process flexibility. These fractions can be manually diverted to the outer slip and to the outer dump by means of a flap in the classifier chute or further processed in the cone crusher.

A part of the material flow with the jaw crusher is shown in Figure 3.

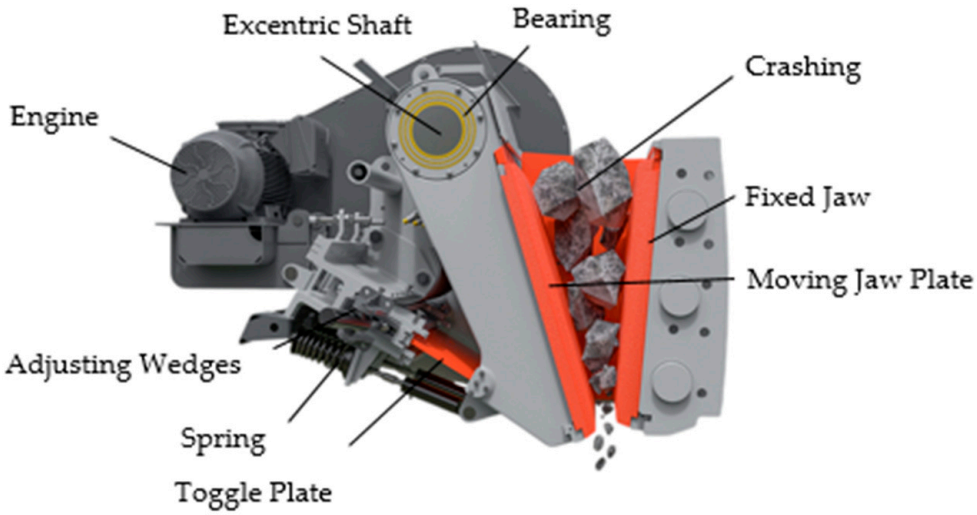


Figure 2. An illustration of the jaw crusher with the essential parts marked [30].

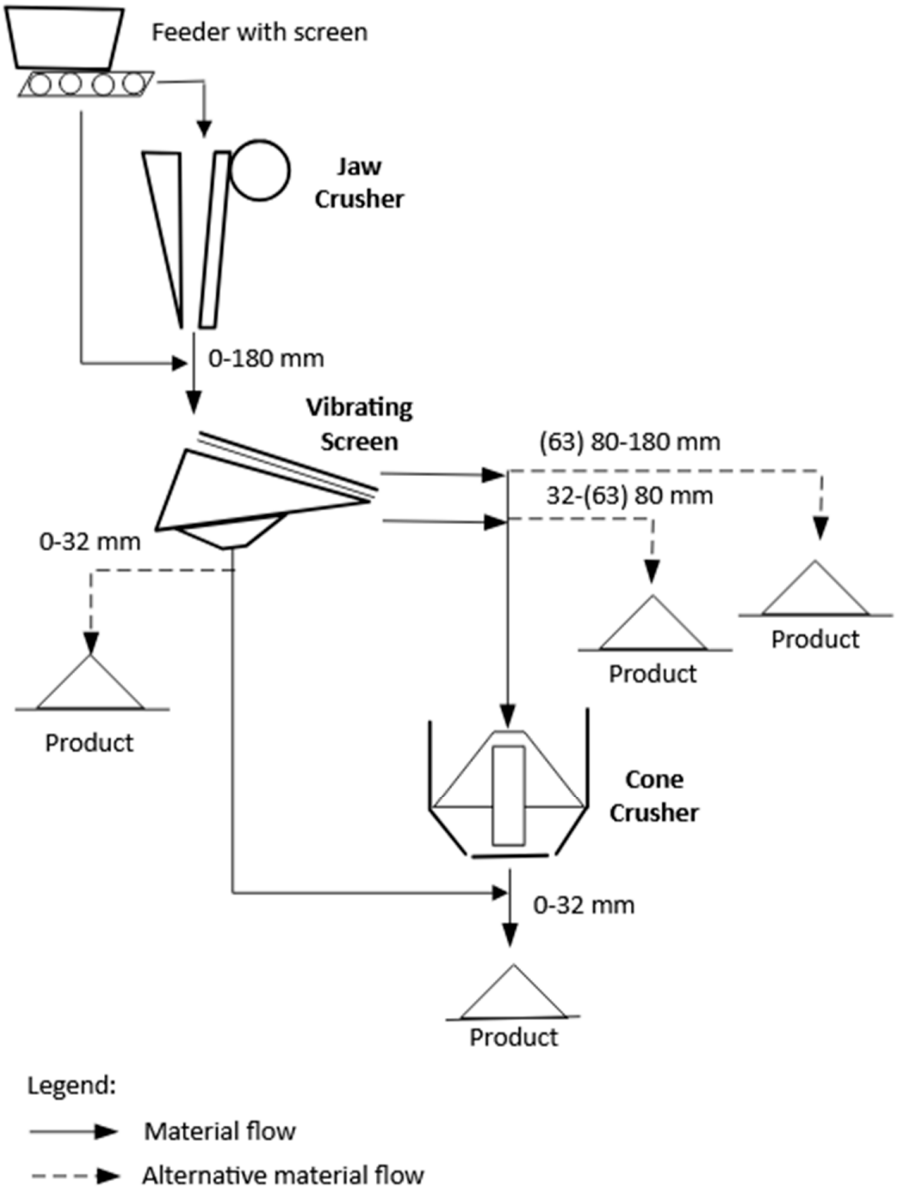


Figure 3. A part of the material flow with the jaw crusher.

2.2. The Procedure for Analysis of Failures

The procedure for analysis and evaluation of faults in the monitored crushing process consists of the following steps:

1. Establishment of a multidisciplinary working team. The team needs to include experts from different fields to ensure that the assessment is made from the point of view of technology, quality, safety, maintenance, and operation, as well as an expert in applying the FMEA method.
2. Analysis of possible failures and their causes with respect to jaw crusher components. This step determines the location, manifestation, consequence, and cause of the error in the chosen piece of equipment.
3. Risk quantification and risk assessment. The severity of the failure *S* shall be assessed for the identified failure causes. The occurrence of the failure *O* and the probability of detection *D* shall be determined.
   Risk assessment was conducted using calculation of risk priority numbers (*RPNs*) and their division into three critical categories, including determination of action priorities (*APs*) and modified calculation of *RPNs* using critical numbers (*CNs*).
4. Assessment of the impact of detected failures on quality, safety, and the environment.
5. Comparison of the results of the risk assessment methods used.
6. Practical implications. This includes proposal of recommended measures to reduce or prevent the occurrence of failures. The following section elaborates on the above procedure in detail. It also explains all the procedures and terms used.

3. Results and Discussion

3.1. Establishment of a Multidisciplinary Working Team

The working team was made up of five experts. The process engineer knows the process and is responsible for optimizing and improving the production processes. The safety engineer identifies worker and equipment safety risks and ensures that all operations are conducted according to safety regulations and standards. The quality engineer monitors how failures can affect the quality of production and ensures that the product meets established quality standards. The maintenance engineer has hands-on maintenance experience and can identify risks associated with wear and failure. The final member of the team is an expert in the application of the FMEA method.

This multidisciplinary team allowed for a comprehensive and practical risk assessment because each team member brought their expertise and experience to the table, which contributed to a better understanding and management of potential failures.

3.2. Analysis of Possible Failure Modes, Their Effects, and Their Causes for the Jaw Crusher

This study defines “Failure” as any deviation from regular operation that reduces crushing efficiency, safety, or quality.

Failures can occur in the engine part of the shredder, mainly due to overheating. Motor overheating occurs due to overloading the crusher and insufficient cooling if the ventilation holes become clogged. External environmental conditions, such as temperature and humidity, also affect motor overheating. A thermal fuse protects the engine against overheating. However, the primary cause of overheating is excessive electric current. When the engine overheats, the engine is switched off, and the shredder should still be able to finish the material with inertial force. However, in the device under study, under natural conditions, such a condition does not occur when the crusher is overloaded. Significant problems then arise when the crusher is restarted. The overloaded crusher cannot be started up. In this case, it is necessary to manually eject the processed raw material from

the crusher and start it up empty. The bigger problem would be engine stalling due to engine burn.

Excessive vibration can have several causes. Impurities in the pulley, poor belt tension, or loosening of the pulley can lead to increased noise and reduced crusher performance. A broken pulley can even cause the crusher to become inoperative.

Overloading the crusher or loosening the belt reduces the crusher's performance, which is manifested by belt slippage. High belt wear can lead to belt breakage, which will render the crusher inoperable.

In the crushing chamber, the smooth flow of material can stop due to one oversized piece of andesite or the wedging of several smaller pieces into each other. This situation can be dealt with either by using an overhead crane or a remotely controlled hammer. In the past, a specific case was recorded during an operation where non-crushable material that did not belong in the crusher entered the crusher. To solve this problem, a so-called "toggle plate" is a safety device that is shown in Figure 4.

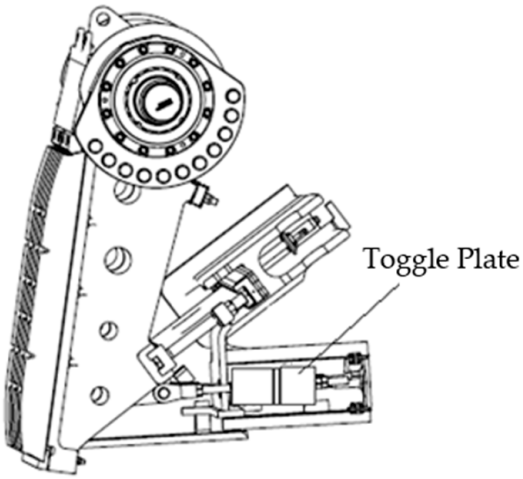


Figure 4. The toggle plate of the jaw crusher [30].

Another significant cause is the failure of the rotary sensor. The rotary sensor is not part of the crusher, but its failure affects its functionality. This issue arises during voltage fluctuations, causing the conveyor belt to trip. In order to prevent the reverse running of this loaded belt at a particular inclination, this circuit is secured by a brake. In the event of this brake's failure, a condition may occur where the brake is released while the belt is running, yet the engine will keep going. In this case, there will be no stopping the previous equipment, and the material will accumulate on the line. In the jaw crusher, the probe will overflow, and due to the excess material in the first part of the line, damage to the equipment will occur.

Should this condition occur, and non-crushable material gets into the crushing section, it could damage the crushing parts and render the crusher inoperable. This plate will crack at the weakened point in this case, enlarging the crusher outlet slot and thus reducing the risk of damage to the crushing section.

The most significant disadvantage of a jaw crusher is the wear of the jaw plates. The moving part of the jaw plate wears out more. Due to this uneven wear, the moving jaw plate must be replaced roughly three times more frequently than the fixed plate. The jaw crusher is mostly overloaded with material in the lower part of the crushing chamber. The crushing jaws can be rotated and used with the less worn side down, possibly optimizing their use (Figure 5). With more frequent rotation of the jaw plates, the jaws wear more uniformly and, hence, have less impact on the nip angle.

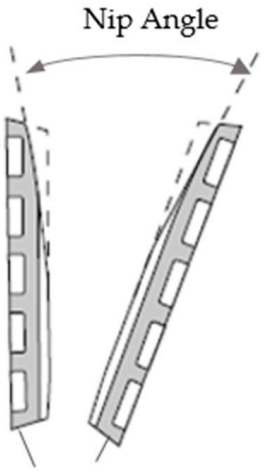
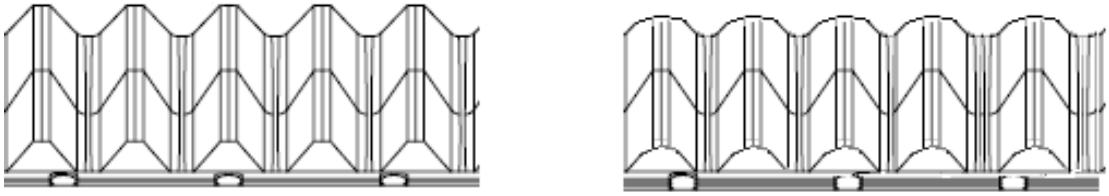


Figure 5. The nip angle between the fixed and the moving jaw plate.

When replacing the jaw with a new one, it is necessary to observe the exact tooth pattern of the jaw plate to ensure suitability for crushing the specified material. In the past, the wrong tooth pattern was used in the quarry, which immediately affected the quality of the output product. The crusher usually worked, but the input material was not crushed. Examples of an appropriate and inappropriate tooth pattern are shown in Figure 6.



(**a**) (**b**)

Figure 6. Examples of appropriate (**a**) and inappropriate (**b**) tooth patterns in andesite processing [30].

The output slot may also enlarge due to the loosening of the jaw plate, release screw, or side wedge, or from insufficient spring tension. The effect of the size of the output slot on the output fraction is shown in Figure 7. The frequency of this operation is dependent on the size of the raw material being processed.

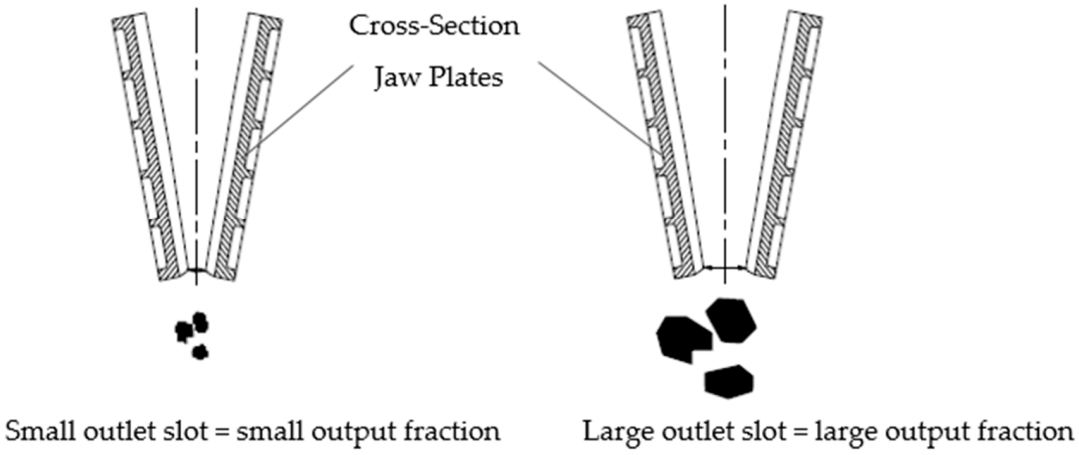


Figure 7. Effect of output slot on final product [30].

Another problem may be the immobility of the movable jaw. The cause may be a broken pressure plate, a damaged connecting rod, or a broken spring.

Insufficient bearings lubrication in the crusher can lead to severe consequences. Increased temperature in the bearing section, unusual noises, vibrations, and reduced equipment performance manifest this problem. The crusher equipment is equipped with an automatic system, which supplies the required amount of petroleum jelly to the necessary mechanical parts at regular intervals. However, if this system fails, the crusher will lose its functionality within a few minutes. The lubrication system is located in the upper part of the crusher shell, where the inlet valves for lubricating the parts that need lubrication lead through tubes of petroleum jelly to the parts that need lubrication. A problem that can occur in this automated lubrication system is the rupture of the end cap due to high vibrations or the rupture of the inlet tubing. Damage to the bearing may occur due to vibrations caused by incorrect adjustment of the height and speed of feeding the crushed material into the crusher chamber. To prevent these failures, it is essential to regularly inspect and maintain the lubrication system and use a quality lubricant designed for jaw crushers.

The shaft may experience an impact sound caused by excessive wear on its eccentric sleeve.

The possible failure modes of the jaw crusher, their consequences, and their causes are listed in Table 1.

Table 1. Failure modes and effects analysis for jaw crusher.

Component	Failure Mode	Failure Effect	Failure Cause	Label
Crusher engine	Engine overheating	Engine shuts down	Thermal fuse blows—increased current due to crusher overload	JC1
	Engine shutdown	Jaw crusher not working	Engine failure	JC2
Pulley	Excessive vibration	Increased noise, reduced crusher power	Impurities in the pulley	JC3
			Poor belt tension	
			Pulley release	
			Incorrect operating speed	
		Jaw crusher not working	Pulley broken	
V-belt	Belt slippage due to overload	Low crusher power	Crusher overload Release of belt	JC4
	Belt breakage	Jaw crusher not working	Belt wear	JC5
Crushing chamber	Stopping the continuous flow of material	Clogging of the crushing chamber	Oversized piece	JC6
			Jamming multiple pieces	JC7
	Backfilling of the crushing chamber	Increased noise, reduced crusher power	Rotary sensor failure	JC8
	Damage to the toggle plate	High pressure on the jaws crusher plate	Presence of non-crushable material	JC9
Crusher jaws	Enlargement of the exit slot—another fraction	Abrasion of the material on the jaw during crushing	Wear of the jaws teeth	JC10
	Fixed jaw plate movement	Noise, inefficient operation	Loosening of the jaw plate Insufficient spring tension	JC11
	Stopping the continuous flow of material	Crusher overload with crushed material	Broken pressure plate Connecting rod is damaged Spring is broken	JC12
Bearing	High temperature	Noise, inefficient operation	Insufficient/contaminated lubricant	JC13
			Wrong bearing clearance	
			Bearing damage	JC14
	Bearing damage	Vibrations caused by incorrect material feed height and speed	Excessive height and speed of material feeding	JC15
			Lubricant leakage through a burst hose or end cap	JC16
Shaft	Shock sound	Inefficient operation	Eccentric shaft bushing is worn	JC17

3.3. Quantification and Risks Assessment

3.3.1. Risk Assessment Using Calculation of Risk Priority Numbers and Their Division into Categories

After analyzing the causes of possible errors arising during material crushing, the severity, occurrence, and probability of defect removal were evaluated. All three factors evaluated can take values between 1 and 10. The specific ratings are determined based on existing tables [31].

A team of procedural experts composed of five members (see Section 3.1) assessed the identified failures [5,6]. To increase the evaluation's objectivity, a maximum and minimum value were excluded for each failure and for each factor evaluated. The value of each factor, S, O, and D, was determined as the median of the remaining values.

The risk priority number RPN was calculated by the formula

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

where the "S" rating indicates the severity of the effect of the fault, the "O" rating reflects the probability with which a possible failure cause will occur, and the "D" rating reflects the probability with which the failure in the cause–effect chain will be detected.

The values for the risk priority number can range from 1 to 1000, being a variable with an exponential distribution. In order to identify those failures that need to be addressed immediately, i.e., to propose appropriate measures to reduce the corresponding risk priority number, it is necessary to determine the so-called critical risk priority number. As Nenadál et al. [31] point out, the customer usually determines this value, or a Pareto analysis can be used to identify the vital causes of failures.

Table 2 shows the values of the three factors, S, O, and D, identified by the expert team. The calculated risk priority numbers are given for the failures from Table 1. The table is sorted according to the risk priority numbers of the values in descending order.

In this study, a team of process experts determined a critical value of $RPN = 90$. In the next step, a team of process experts determined recommended actions for every failure. They are listed in Table 2.

The study of the criticality of individual failures in equipment is an important complement to the FMEA method. In the next part of this thesis, individual emerging failures in the monitored equipment will be classified into groups according to criticality. The RPN values in this study, determined by a team of process experts, are divided into three criticality categories, namely the following:

- Critical: Involves injury, damage to equipment, and conditions requiring an immediate remedy; ≥ 90.
- Marginal: No significant impairment to the function of the equipment or injury to persons; $RPN \in \langle 21; 89 \rangle$.
- Negligible: No damage to the equipment, no injury to persons, and no immediate remedy is required; $RPN \leq 20$.

Based on the above classification, identified failures in the monitored equipment were divided into individual categories (Table 2). Four identified failures belong to the critical category, five are in the marginal category, and eight are in the negligible category. Failures of lubricant leakage through a burst hose or end cap, jamming multiple pieces, rotary sensor failure, and bearing damage, classified as critical, were also confirmed by Pareto analysis with the 70% criterion (Figure 8).

Table 2. Risk assessment using *RPN* for jaw crusher and recommended actions.

Label	S	O	D	*RPN*	Criticality Category	Recommended Action
JC16	8	5	4	160	Critical	Better and more flexible fixing of the hoses and use of a better quality material for the hoses as vibrations affect them.
JC7	8	6	3	144	Critical	Removal of jammed material by overhead crane. Enlargement of the outlet slot. Adjusting the feed rate of the input material.
JC8	7	5	4	140	Critical	Sound/light indication of voltage fluctuations.
JC14	8	3	4	96	Critical	Continual inspection of noise, everyday checks for lubricant quantity.
JC12	9	2	2	36	Marginal	Continual inspection of noise and maintenance once a week.
JC1	7	5	1	35	Marginal	Increase engine cooling efficiency. Cleaning filters and changing oil.
JC3	4	3	2	24	Marginal	During operation—continuous visual inspection of the pulley.
JC4	6	4	1	24	Marginal	During operation—control by the control system and continuous visual inspection.
JC5	6	4	1	24	Marginal	During operation—continuous visual inspection of the belt.
JC17	5	2	2	20	Negligible	Continual inspection of noise and maintenance once a week.
JC2	8	2	1	16	Negligible	Cleaning filters and changing oil.
JC13	7	2	1	14	Negligible	Regular filter change and checks of lubricant quantity.
JC15	6	2	1	12	Negligible	Regular checks of conveyor belt speed daily.
JC9	10	1	1	10	Negligible	Control of the amount of material in the crusher and the speed of feeding.
JC11	9	1	1	9	Negligible	Visual inspection after sheet metal replacement.
JC6	8	1	1	8	Negligible	Use a different amount of explosive. Removal of jammed material by overhead crane. Breaking an oversized piece with remotely controlled hammer.
JC10	3	1	1	3	Negligible	Continuous visual inspection of the jaws and checking with a spirometer. Rotation of the jaw plates every two months. Using better quality jaw plates. Calibrate the equipment every 2–3 months.

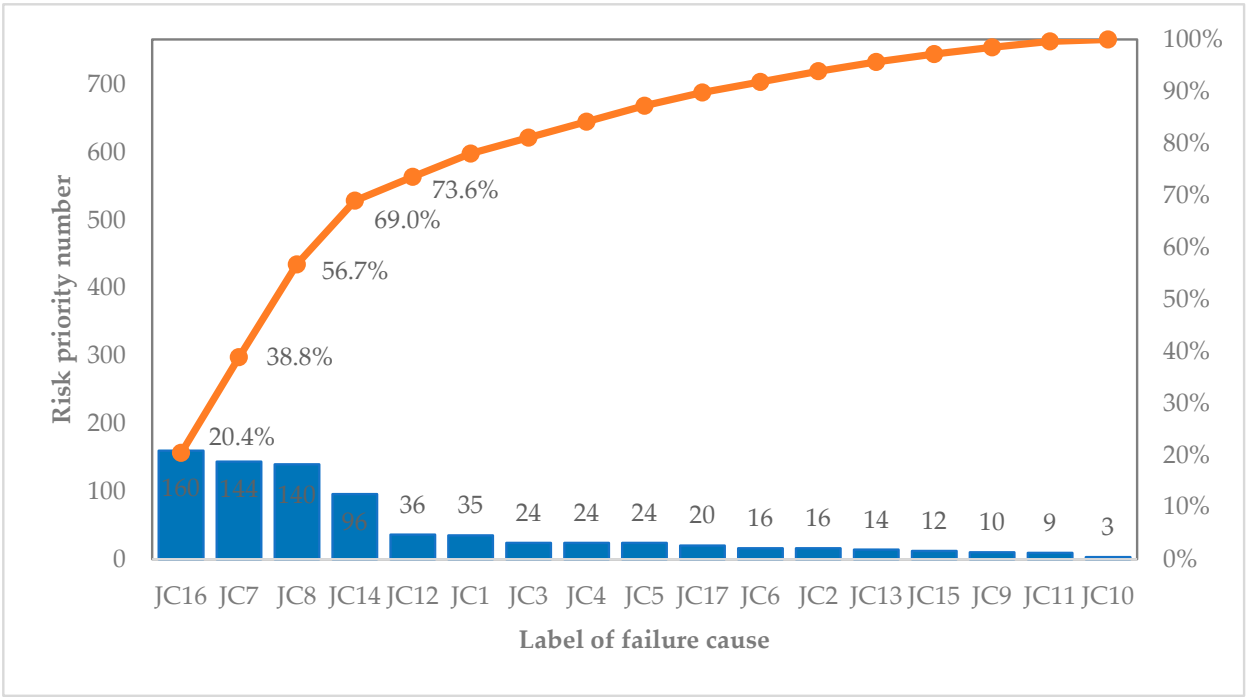


Figure 8. Pareto analysis with Lorenz curve of *RPNs*.

3.3.2. Risk Assessment Using Determination of Action Priority Method

When calculating the *RPN* value, *S*, *O*, and *D* are weighted as equal factors. When evaluated using the Action Priority method (AP), more emphasis is placed on the severity of the problem, then the frequency of occurrence, and finally the detectability [5,6].

The resulting AP rating is divided into three levels:

- High: Prevention and/or detection action must be taken, or justification must be provided.
- Medium: Prevention and/or detection action should be taken, or justification must be provided.
- Low: Action can be taken to improve prevention.

Based on this approach, our identified failures were divided into three categories (Table 3). One failure belongs to the High level, six to the Medium level, and ten to the Low level.

Table 3. Risk assessment using Action Priority and critical number.

Label	S	O	D	AP	CN	SO	SD	OD
JC1	7	5	1	Medium	Medium	35	7	5
JC2	8	2	1	Low	Low	16	8	2
JC3	4	3	2	Low	Low	12	8	6
JC4	6	4	1	Low	Low	24	6	4
JC5	6	4	1	Low	Low	24	6	4
JC6	8	1	1	Low	Low	8	8	1
JC7	8	6	3	High	Medium	48	24	18
JC8	7	5	4	Medium	Medium	35	28	20
JC9	10	1	1	Medium	Low	10	10	1
JC10	3	1	1	Low	Low	3	3	1
JC11	9	1	1	Medium	Low	9	9	1
JC12	9	2	2	Medium	Low	18	18	4
JC13	7	2	1	Low	Low	14	7	2
JC14	8	3	4	Low	Low	24	32	12
JC15	6	2	1	Low	Low	12	6	2
JC16	8	5	4	Medium	Medium	40	32	20
JC17	5	2	2	Low	Low	10	10	4

Severity is a key factor in all three methods (*RPN*, *AP*, and *CN*) because it determines how severe a failure's impact on a system or process can be. A high severity value means that the failure can have serious consequences, so it is important to pay attention to it. Occurrence is important to determine how often a failure occurs. Repeated failures may indicate a need for process or system improvement. Detection is important for identifying failures before they cause serious problems. A high detection capability means failures can be quickly identified and corrective action taken.

The significance of *SO*, *SD*, and *DO* assessments (Figure 9) lies in the fact that each method assesses risk from different points of view. *SO* is the simplest method because the criteria used are easier to evaluate, unlike *SD* and *DO*, which also include the detection criterion.

The figure below illustrates the proportions of the individual products *SO*, *SD*, and *OD* in their sum. In the graph of Figure 10, it can be seen that, in our case, in almost all failures (except JC14), the product *SO* forms the largest share of the sum (more than 40%). For this reason, we used the critical number assessment, which is based on an assessment using the *S* and *O* factors, as another method for risk assessment.

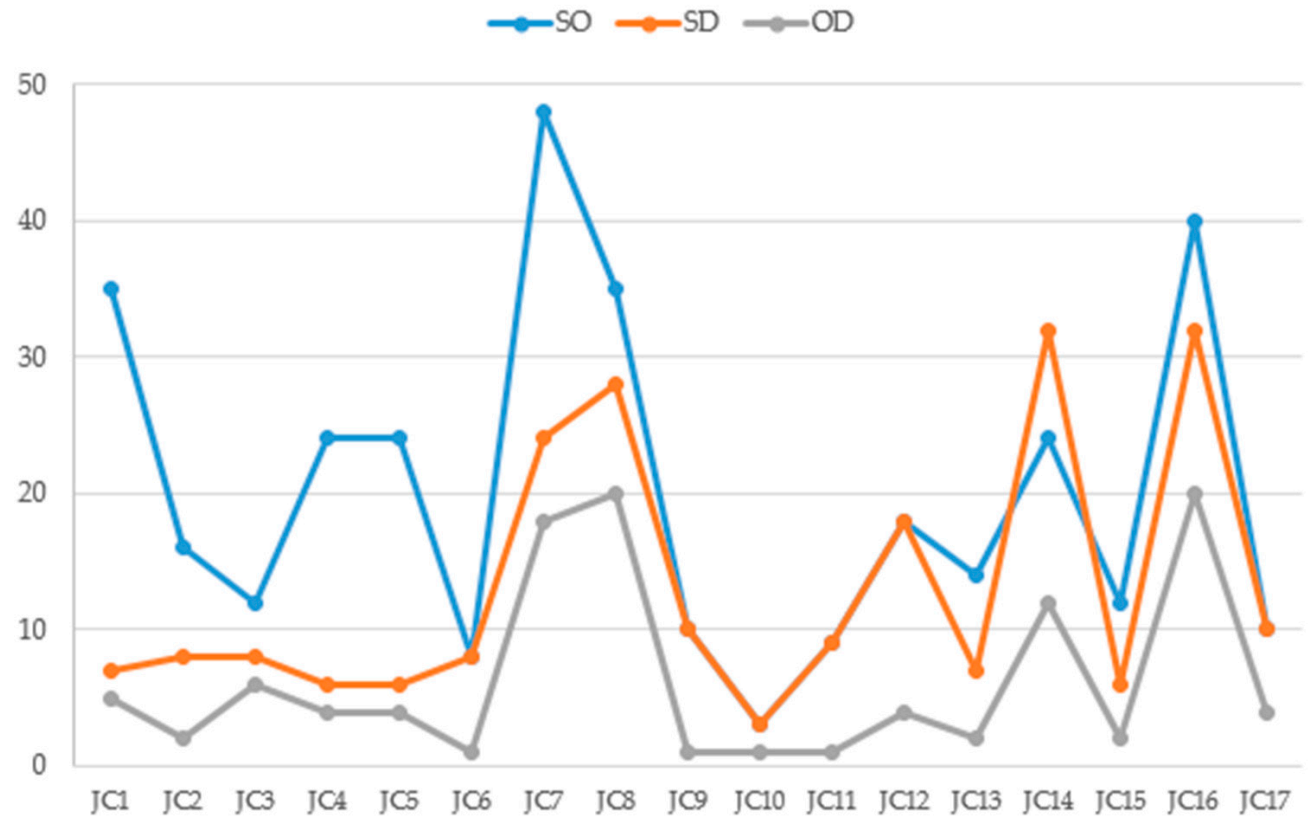


Figure 9. Risk assessment using *SO*, *SD*, and *OD*.

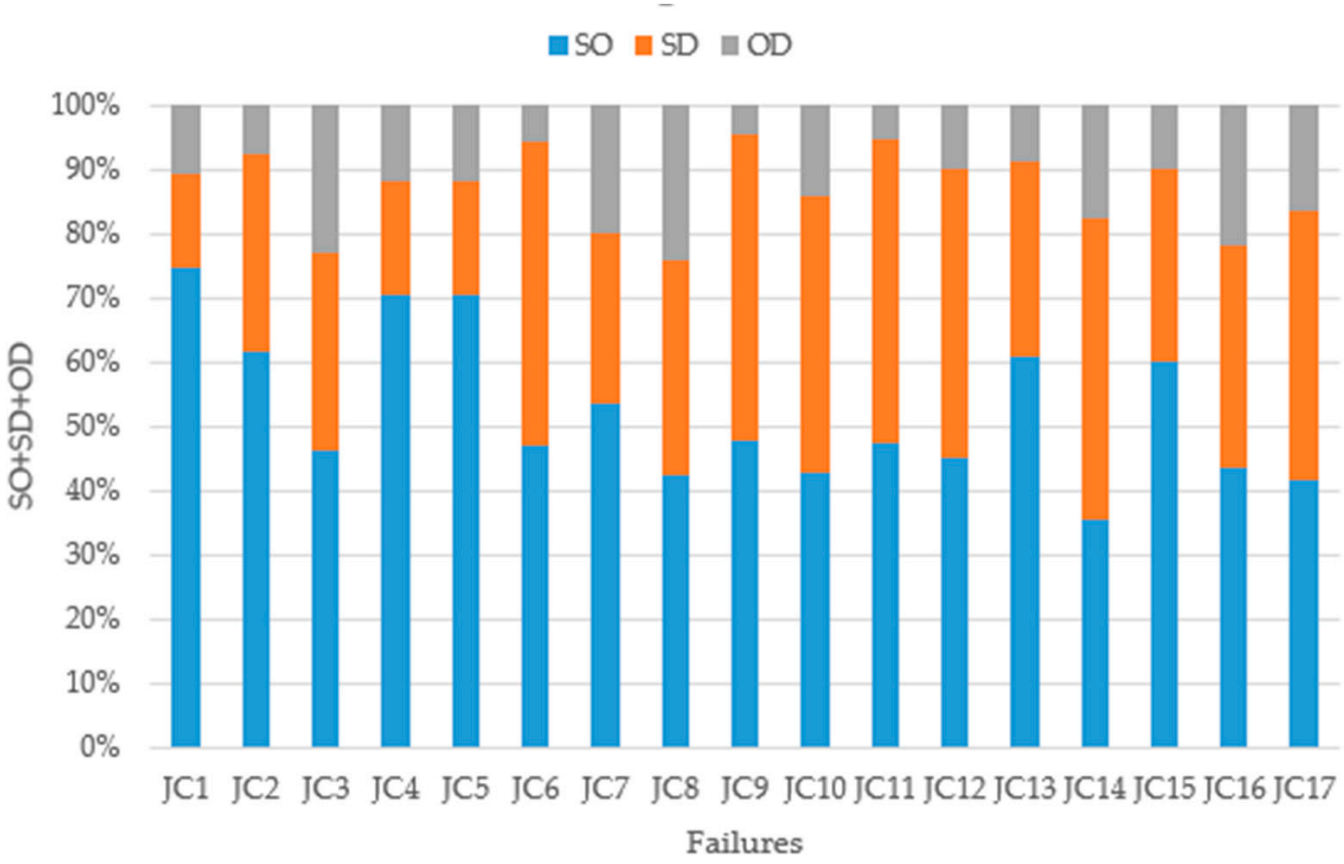


Figure 10. Proportions of products of factors *SO*, *SD* and *OD* for individual failures.

3.3.3. Risk Assessment Using Modified Calculation of *RPNs* Using Critical Numbers

Sometimes it is difficult to evaluate the detection factor (*D*). In this case, the critical number (CN) is calculated as follows:

$$CN = S \times O \tag{2}$$

By determining the CN, the severity of the failure can be quickly determined, which helps in prioritizing corrective actions. The division into categories of priority according to the CN value is as follows:

- High: Action must be taken; $CN \in \langle 70; 100 \rangle$.
- Medium: Action should be taken; $CN \in \langle 30; 69 \rangle$.
- Low: Action can be taken; $CN \leq 29$.

The *CN* values were calculated for each failure and assigned to individual categories accordingly. Four failures fall into the Medium priority category, and thirteen into the Low priority category (Table 2).

A comparison of the criticality categories (Figure 11) shows that the *AP* approach is more rigorous than the *CN* approach in terms of assessing the significance of failures. Based on the *CN* approach, no failures fall into the High priority category, and four failures fall into the Medium priority category (JC1, JC7, JC8, and JC16). In contrast to the *AP* approach, where one failure (JC7) belongs to the High priority category and six failures belong to the Medium priority category (JC1, JC8, JC9, JC11, JC12, and JC16).

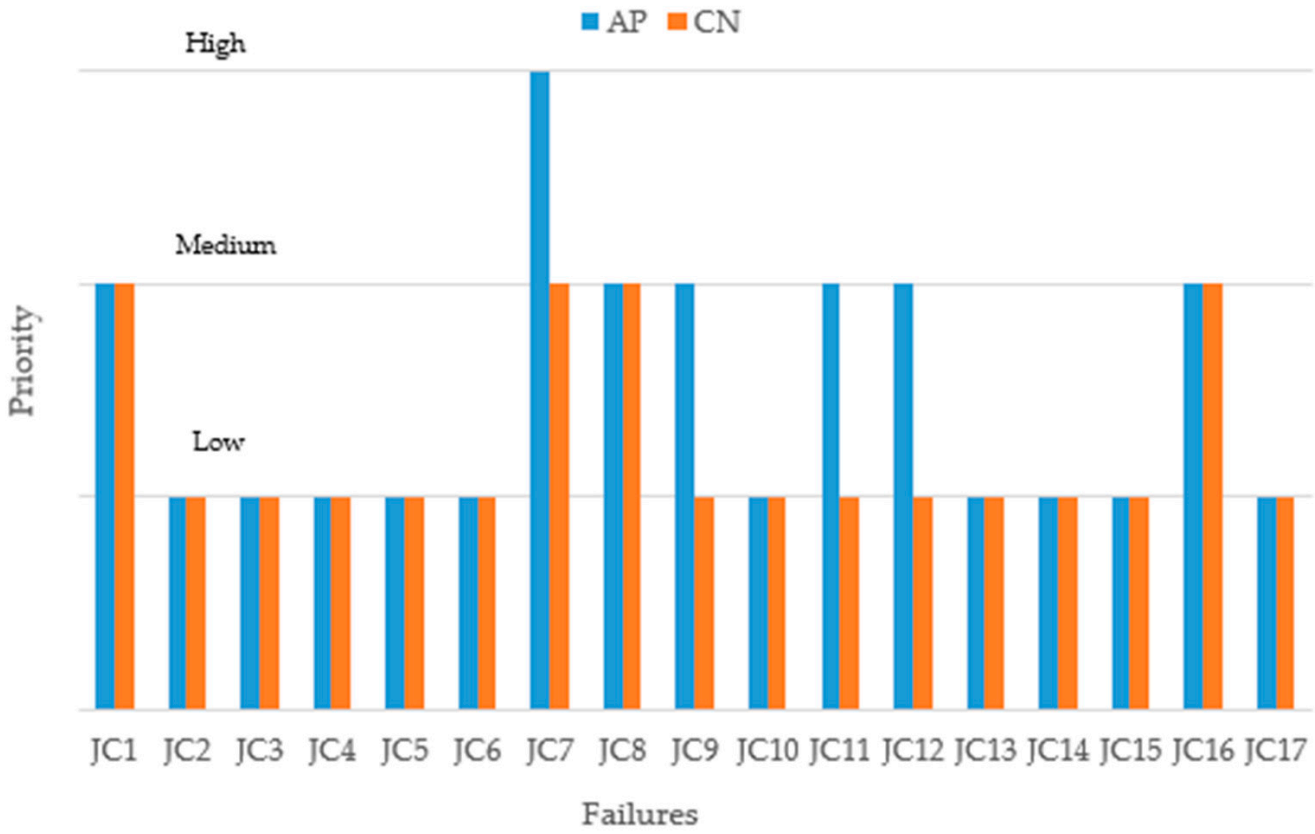


Figure 11. Comparison of categorization of failures based on *AP* and *CN* approaches.

3.4. The Impact of the Failure Effects of the Jam Crusher on Quality, Environment, and Safety

Based on the identified failures that may occur in the equipment under investigation, it is possible to assess the impacts of these failures on quality, occupational health and safety, and the environment. The impacts identified may affect any combination of the

three, or they may not affect any of them, and only represent equipment malfunctions. However, it should be borne in mind that the quarry itself, by its very activity, is causing an impact on the environment. Apart from the fact that it directly affects the surface structure of the natural terrain, there are several other factors, such as noise, increased dustiness, and interference with the natural habitat of various species of fauna and flora, which must be taken into account to ensure that the quarry does not affect the natural environment.

It can be concluded that the loosening of the jaw plate is a defect affecting safety. It results in excessive noise, which can cause permanent damage to the health of employees (their hearing). Another safety issue is a seemingly unrelated problem, namely the ingress of oversized material into the crusher. However, this can result in material spilling over the crushing area and causing damage to both the equipment itself and affecting the safety of persons in the vicinity of the crusher. The abnormal noise generated when the jaw plate is loosened also has an environmental impact, as does vibration in the jaw crusher, for example, when the pulley is set incorrectly. A burst lubrication hose or its seal also has an environmental impact due to the leakage of lubricating fluid and its penetration into the soil.

The quality of the final product is also affected by the wear of the serrations on the jaws, which causes the output slot of the crusher to enlarge. The loosening above the jaw plate has the same effect on the final product. Similarly, the occurrence of non-crushable material will cause the buckling of the buckling plate and thus significantly alter the output slot of the crusher.

The impacts on quality, safety, and the environment of the identified failures occurring in the individual components of the jaw crusher are shown in Figure 12.

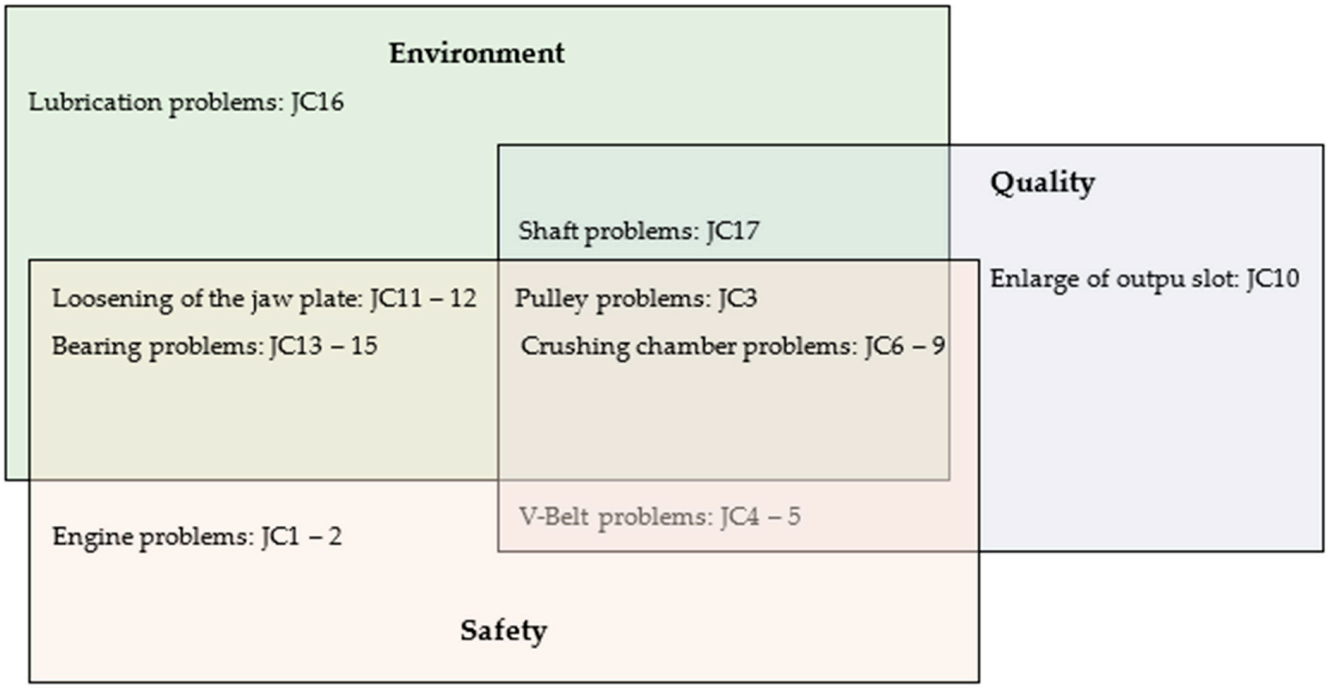


Figure 12. The impact of the identified failures in the components of the jaw crusher on quality, environment, and employee safety.

3.5. The Comparison of Approaches to Assessing the Significance of Component Failures

The results of the three approaches will be compared to compare the significance of the detected failures of the jaw crusher components.

When the failures were categorized into three criticality categories based on the *RPN* value, the following failures were placed in the most critical category: JC7, Stopping

the continuous flow of material; JC8, Backfilling of the crushing chamber; JC14, Bearing damage; JC16, Lubricant leakage through a burst hose or end cap.

The *RPN* calculation does not take into account the priority of the individual factors *S*, *O* and *D*. Therefore, a harmonized FMEA approach using AP was used in the evaluation. Based on that approach, only one failure, JC7 (stopping the continuous flow of material), fell into the High Priority category.

The third approach, based on the *CN* methodology, does not take into account criterion *D* (detection) in the evaluation. Not a single failure identified was included in the High priority category (Table 4).

Table 4. Comparison of significance of failures by selected methods.

Label	Priority Importance			Total for		Impact to		
	RPN	**AP**	**CN**	**Failure**	**Component**	**Quality**	**Environment**	**Safety**
JC1	xx	xx	xx	6	9			•
JC2	x	x	x	3				•
JC3	xx	x	x	4	4	•	•	•
JC4	xx	x	x	4	8	•		•
JC5	xx	x	x	4		•		•
JC6	x	x	x	3	22	•	•	•
JC7	xxx	xxx	xx	8		•	•	•
JC8	xxx	xx	xx	7		•	•	•
JC9	x	xx	x	4		•	•	•
JC10	x	x	x	3	12	•		
JC11	x	xx	x	4			•	•
JC12	xx	xx	x	5			•	•
JC13	x	x	x	3	18		•	•
JC14	xxx	x	x	5			•	•
JC15	x	x	x	3			•	•
JC16	xxx	xx	xx	7			•	
JC17	x	x	x	4	4	•	•	
xxx High	xx Medium	x Low					• Impact of failure	

The impact of the failures on quality, environment, and safety, as shown in Table 4, supports the conclusion that the crusher chamber is the most critical component of the jaw crusher. For this reason, prevention and maintenance activities need to be focused on its components as a priority.

Sinha and Mukhopadhyay also address the same issue. Their study confirmed that the jaw plate is the most important component of the jaw crusher [32]. Based on the maximum failure rate estimation and the Total Time on the Test chart, they found that the failure rate of the jaw plate decreases when the correct tooth shape is used [33].

3.6. Practical Implications

The emphasis on regular inspection and maintenance of the machine and equipment is positively reflected in the low frequency of their downtime due to failure. The case study aims to evaluate and propose measures to eliminate existing or prevent potential failures and defects in selected equipment for rock processing. The most important components include the crusher chamber, jaw plates, bearings, and pulley.

Proposal for measures to reduce the incidence of identified failures are as follows:

- Create a checklist of components that require regular inspection and maintenance. The maintenance checklist is usually set daily (8 h), weekly (40 h), monthly (200 h), and

yearly (2000 h). Regular maintenance can extend the life of the machine and maximize its performance in the crushing process.

- Proper execution of drilling and blasting operations will ensure fewer oversized pieces that can cause material to become wedged in the crushing chamber.
- Control of the amount of material in the crusher and the feed rate.
- Adherence to the prescribed tooth type of the jaw plates for the material to be crushed (Figure 6).
- Removal of fine particles is necessary to reduce the wear of jaw liners and improve the overall performance of the crushing equipment [34].
- Regularly lubricate bearings and moving parts with grease.
- Proper lubrication with specified lubricant minimizes friction during operation, extends machine life, and improves crushing efficiency.
- Various sensors, such as lubricating oil temperature sensors and lubricating oil filter condition indicators, can monitor the current condition of the component to prevent damage and failure. As Yan et al. stated, it is also necessary to ensure the accuracy of the data obtained by the sensors. Unreliable sensors can affect diagnostic decisions [35].

4. Conclusions

Various methods have been used to analyze and identify the component failures of a jaw crusher used for crushing andesite. After identifying the causes of possible failures of the components, an assessment of the severity (S), occurrence (O) and detection (D) factors was carried out. The traditional calculation of the risk priority number (*RPN*) provides a quantitative assessment of the risk. The causes, according to the *RPN* value, were divided into three critical categories—critical, negligible, and marginal. Pareto analysis also confirmed the critical category with a criterion of 70/30. The *RPN* value may not reflect the actual level of risk. Therefore, a harmonized FMEA approach using Action Priority (AP) was also used in the assessment. This approach considers the prioritization of risks and the importance of individual factors. It places importance on determining severity, a critical risk assessment factor. Using AP, the identified failures were divided into three categories—High, Medium and Low. Another method used was the determination of the critical number (CN) or the calculation of SO. This method is used to identify risks quickly. It focuses on the severity and occurrence of failures. However, it does not consider detection. The SO method was compared with the SD method and the DO method. SD helps to improve detection mechanisms but is not as suitable for rapid identification as SO. DO focuses on detection and frequency of occurrence but does not consider the severity of failures.

This study also assessed the impact of the identified failures on quality, safety, and the environment. The components whose failures impact all three areas assessed are the crushing chamber and the pulley. The crushing chamber and bearings were also identified as the most critical components of the crusher in terms of the significance of failures. A similar conclusion was reached in their works by Sinha and Mukhopadhyay, who dealt with the problem of failure analysis of jaw crushers and their components [19,32,33].

A scope for further research can be found in reducing the subjectivity of evaluating factors such as severity, prevalence and detection by the expert team members; other statistical tools could be used, e.g., analysis of variance (ANOVA). Instead of the procedure used in this study, after statistically insignificant differences in ratings demonstrated by one-factor analysis of variance, a simple arithmetic mean of the ratings could be used instead of their median. Narayanagounder and Gurus address the limitations of the traditional FMEA approach by using ANOVA to compare means of risk priority number (*RPN*) values. This

approach more effectively identifies failure modes, especially when there is a mismatch in severity, occurrence, and detection rates [36].

Focusing this study on the jaw crusher limited its scope. Further research should extend the identification of failures occurring on other equipment in the andesite processing process, such as cone crushers and vibratory screeners.

The traditional FMEA approach can be combined with more modern methods, such as machine learning (ML) algorithms. Fernandes et al., in their review paper [37], highlight the increase in the use of ML for fault diagnosis and prognosis. Simulation models or advanced analytical tools and software can be used to analyze and identify failures in the raw material processing process to help predict failures and optimize maintenance. IoT sensors can also be used for continuous condition monitoring or early prediction of unplanned failures, enabling real-time monitoring and control of processes and equipment. In a review article, Yan et al. [35] analyze industrial manufacturing use of the Industrial Internet of Things (IIoT), Cyber-Physical Systems, Artificial Intelligence (AI), cloud computing, and big data storage for process monitoring and real-time fault diagnosis. Paul Mercorelli highlights the importance of integrating intelligent algorithms and hybrid approaches for fault detection and diagnosis strategies [18].

Attention should also be paid to analyzing sociological, natural, technogenic, and other risks related to worker safety and environmental protection in the andesite processing process.

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