Volume XX, Issue (1) (2024) 122-131

International May Conference
on Strategic Management

DOI: *10.5937/IMCSM24012B*

Original research

A RISK EVALUATION OF BULLDOZER DOWNTIMES AND ITS ECONOMIC JUSTIFICATION IN OPEN-PIT MINES

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Abstract: The mining industry has been steadily expanding annually to keep up with the increasing demands. Consequently, used machinery needs to work efficiently, which indicates that unexpected downtimes should be at the minimum possible level. Proper identification and risk evaluation of the potential breakdown is the most important element for efficient equipment maintenance and breakdown prevention. This research has focused on its reliability function determination and analyzed the consequences of downtime and the cost of repairs over a period of one year. Delays on the observed mining machine were classified according to the type of downtime: mechanical, technological, power/electricity, and downtime due to external influences. Input elements for risk assessment were severity of consequence (S), probability of occurrence (O), and failure detectability (D). The method used in this paper is based on the cost of maintenance and the impact of bulldozer breakdowns on reliability in order to maintain profitability and, by reducing the number of unwanted events caused by sudden failure of parts, increase safety during operation. Results show that the monitored bulldozer belongs to the lowest defined risk class, so its use is economically justifiable.

Keywords: risk, reliability, mining, bulldozer, profit.

1. INTRODUCTION

The mining industry, as one of the crucial suppliers of raw materials for global industry, is experiencing steady growth every year to meet demands, since the projections of demand for minerals indicate a rise of 2-3 times until 2050 (Elshkaki et al., 2016; 2018). To meet the demand, high efficiency in the extraction process necessitates continuous use of machinery. According to Bąk and Turek (2023), machine availability has a significant impact on available work time in mines. Frequent stoppages and breakdowns can reduce daily mined volume by

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50% (Bąk & Turek, 2023). With the high rate of accidents, the mining industry can be considered one of the most dangerous, with serious casualties and property losses on a yearly basis (Mahdevari et al., 2014; Miao et al., 2023). To improve the safety level and proper functioning of equipment, a new approach for risk assessment should be used (George & Renjith, 2021; Brkić et al., 2023).

Mining in open pits often involves a great variety of machinery of different sizes and applications. Large equipment is often used for main excavation, loading of material, and transport processes, for example, rotor wheel excavators, dumpers, and conveyers, but these processes are supported by different auxiliary tasks, like site planning, surface cleaning, road maintenance, building of canals and water reservoirs, etc. The machines specialized for those kinds of work are often called auxiliary equipment, and they include loaders, dozers, hydraulic excavators, graders, pipelayers, rollers, trucks, etc. (Ignjatović et al., 2018)

Numerous studies have shown that the availability and reliability of mining auxiliary equipment enable high efficiency in the entire mining process (Gomilanović et al., 2023), and the aim of this paper is to propose a reliable method for risk monitoring and assessment for dozers working in open pit mines so safety and efficiency can be upgraded while minimizing downtimes and breakdowns during the working process. This paper is structured as follows: it starts with an introduction, which is followed by a literature review, and continues with methodology, results and discussion, and conclusion sections.

2. LITERATURE REVIEW

A dozer is a crawler-type tractor with a front blade, and thanks to its capability to efficiently move large quantities of material, it is one of the most common pieces of auxiliary equipment in open pit mines (Jankovic et al., 2019; Munda & Widodo, 2021). On a mine site, it is used for: extending land stuffing, road maintenance, opening mountain roads, and transferring land (Ignjatović et al., 2018; Munda & Widodo, 2021). Because it is widely used equipment, numerous risks are associated with its exploitation. However, research has shown that most of the published papers focus on assessing the health risk for serious injuries to occur (Md-Nor et al., 2008; Rosanti et al., 2022) or downtime cost evaluation (Bhushan et al., 2022; Bugaric et al., 2022). As stated in Spasojević-Brkić et al. (2015), safety and sustainable business success cannot be viewed separately. Proper equipment maintenance can improve overall throughput by up to 7 percent, as the cost of mining vehicle maintenance can contribute to 30–40 percent of total mining costs (Sharma et al., 2022). The most frequent causes of failure, according to the results of the Pareto analysis, from the aspect of failure risk are heating repair, oil change, bulldozer cleaning, screw replacement, tonsil adjustment, filter replacement, part repair, hose replacement, and bearing replacement (Spasojević-Brkić et al., 2022). Bhushan et al. (2022) analyzed the crawler dozer transmission's reliability, availability, and maintainability (RAM) using the Markov method and total productive maintenance (TPM) and found that applying preventive maintenance (PM) can increase the dozer's availability by 9 percent. FMEA and FMECA can effectively evaluate the risk of failure based on quantitative data (Kumar & Kumar, 2016), leading to more efficient equipment maintenance (Jafarpisheh et al., 2020). Tanasijevic et al. (2019) have used a fuzzy-based decision support model for bulldozers' effectiveness evaluation and shown that the experts opinions lead to results comparable to measurements (Tanasijevic et al., 2019). Similarly, Djenadic et al. (2019) used fuzzy theory to provide a conceptual and mathematical model for the bulldozer's availability evaluation based on expert opinion, together with the related analytic hierarchy process (AHP) multi-criteria analysis.

This paper utilizes a method that considers the cost of maintenance and the impact of bulldozer breakdowns on reliability. The goal is to maintain profitability and enhance operational safety by reducing the number of unwanted events caused by sudden part failures.

3. METHODOLOGY

This research's central idea has evolved into a four-phase methodology. The primary database, which consists of recorded bulldozer's downtimes over a period of six months, presents the basis for all further analysis. The first step is to examine and categorize the collected data based on the type of downtime. The Pareto diagram will be used for this purpose. In the second phase, a chi-square test will be used to determine the number of failures over a specific time period.

Next, it will be tested for downtime as a random variable using the Kolmogorov-Smirnoff test. The goal of testing is to determine which theoretical statistical distribution best fits the data. The approach of reliability/unreliability function determination in the third phase shall be chosen based on the statistical testing results. To put it another way, if the number of failures in a given period of time can be represented by the Poisson theoretical distribution, referring functions can be calculated analytically. Whereas, the downtime distribution will define the equation that generates the mean downtime, which is needed in the last phase of the study. Finally, the overall bulldozer's risk will be evaluated using a three-dimensional risk assessment model.

4. RESULTS AND DISCUSSION

4.1. Data analysis and classification

A Pareto chart was created with the goal of representing the distribution of failure types and identifying which ones are most significant (Figure 1). Delays in the observed auxiliary machinery were categorized according to the type of downtime: mechanical downtime, technological downtime, power/electricity downtime, downtime due to external influences, misuse and organizational downtime.

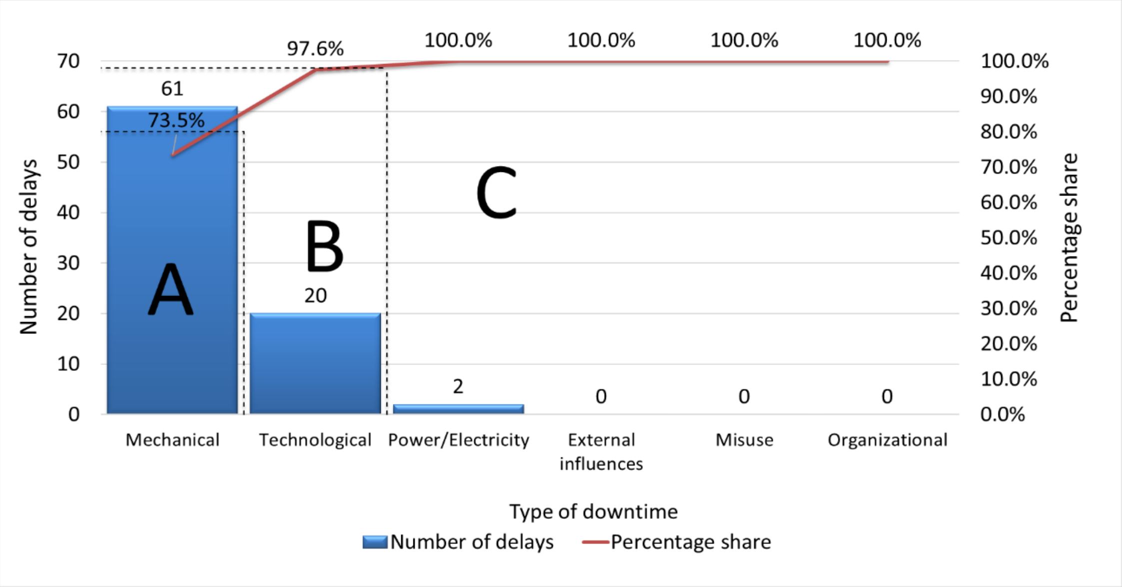

Figure 1. Pareto chart of downtime types

As it can be seen in Figure 1, mechanical and technological downtimes represent an almost complete majority, with 97.6% of the whole sample (zones A and B). Thus, from a maintenance and risk management point of view, the two types should be the most crucial factors.

4.2. Statistical testing of the data

Utilizing the chi-square test, it was determined that the number of failures in a given time was associated with the Poisson theoretical distribution characterized by the rate parameter $\lambda_1 = 0.360827375$ with the relevance threshold of $\alpha = 0.01$ (Figure 2). The Poisson distribution can be described by its probability density function, which is given in Equation 1:

$$\mathrm{f(x)} = \mathrm{P(X = x)} = \frac{(\lambda \cdot \mathrm{t})^{X} \cdot e^{-\lambda \cdot \mathrm{t}}}{x!}, x = 0,1,2,3. \tag{1}$$

The random discrete variable *x* (number of failures in a day) can take values from 0 to 3, meaning there is possibility that there are no failures in a day, but also 1, 2 or 3. The probability that there will be no failures in a given period of time is nothing else but the reliability of the system.

$$\mathrm{f(0)} = \mathrm{P(X = 0)} = \frac{(\lambda \cdot \mathrm{t})^{0} \cdot e^{-\lambda \cdot \mathrm{t}}}{0!} = e^{-\lambda \cdot \mathrm{t}} = R(t) \tag{2}$$

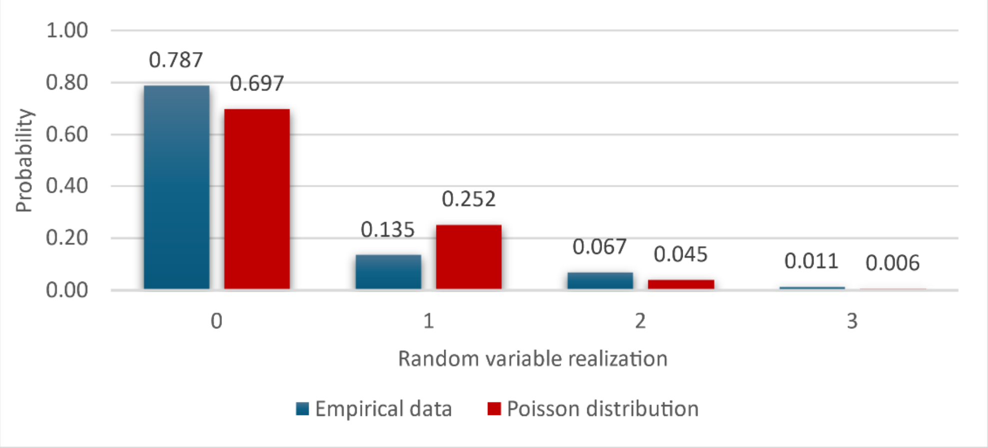

Figure 2. Probability distribution of a number of failures in a day

When it comes to downtime distribution, the results of K-S testing showed that it can be approximated with The 2nd order Erlang theoretical distribution defined by the rate parameter $\lambda_2 = 0.046362906$ (and shape parameter $k = 2$) with the relevance threshold of $\alpha = 0{,}01$ (Figure 3). Delays were recorded and measured in minutes.

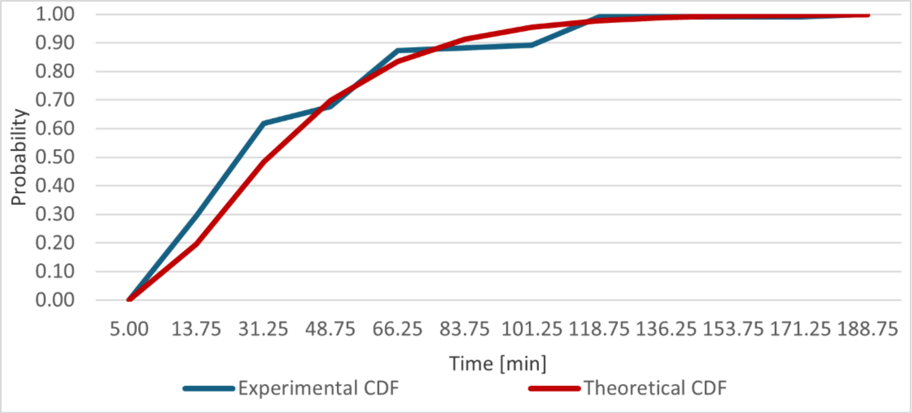

Figure 3. Bulldozer's downtime distribution

4.3. Reliability analysis

As has already been said, the reliability of the bulldozer (the probability that it will perform its specified function for a given time) can be derived from Poisson's PDF and has an exponential distribution form. Therefore, the parameter of the distribution (λ_1) will be equal to the failure intensity (λ_1 = 0.360827375 1/day = 0.015034474 1/h).

$$R(t) = e^{-\lambda_1 \cdot t} = e^{-0.015034474 \cdot t} \tag{3}$$

Conversely, the concept of unreliability (or failure function) includes the probability that the system will fail within a specified time frame, which can be determined by following Equation 4.

$$F(t) = 1 - e^{-\lambda_1 \cdot t} = 1 - e^{-0.015034474 \cdot t} \tag{4}$$

Figure 4 provides a graphical representation of the change in the bulldozer's reliability and unreliability over a period of one month, approximately 30 days (720 h).

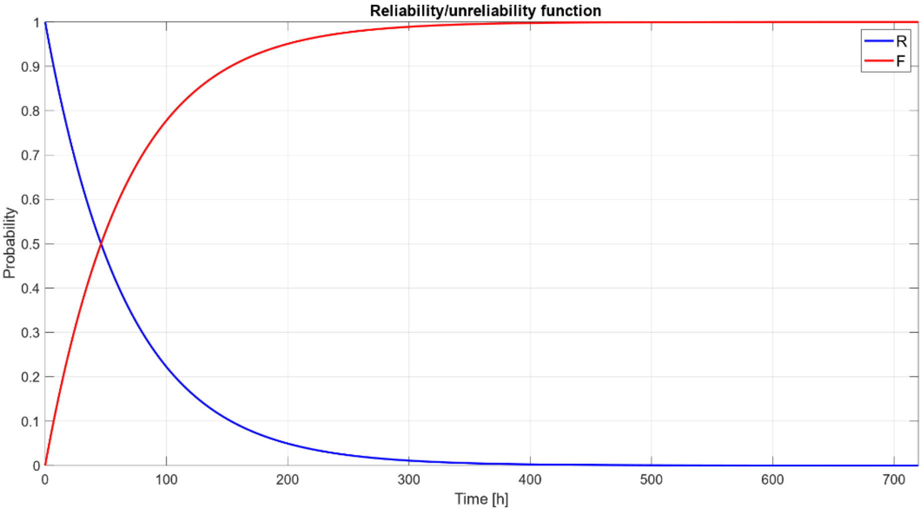

Figure 4. System's reliability and unreliability over time

The average delay time due to the failures (MDT) is equal to the expected value of the downtime distribution:

$$MDT = \frac{k}{\lambda_2} = \frac{2}{0.046362906} = 43.14\ \text{min} \approx\ 0.72\ \text{h} \tag{5}$$

4.4. Risk assessment model

The FMEA method, or Failure Modes and Effects Analysis, is one of the most widely used instruments for risk assessment and management in complex technical systems. It was officially defined and detailed by the international standard ISO/IEC 31010. The method evaluates the risk level using the risk performance number (RPN). Three component indicators, each graded on a scale of 1 to 5, comprise the risk performance, accurately characterizing risk as a whole (Đenadić, 2022).

Equation 6 provides the overall RPN for all failures, which ultimately represents the overall risk level of bulldozers.

$$RPN = S \cdot O \cdot D \tag{6}$$

The severity of the consequences (S) is the first partial indicator. In order to accurately assess the incident's intensity, this indicator seeks to quantify its impacts. The total costs (TC) incurred due to the bulldozer not operating are used to determine the severity of the failure. These includes lost revenue and repair expenses. Bugaric et al. (2022) state that the company loses 66.6125 EUR for each hour when a machine is out of commission, or that ATC = 66.6125 [EUR/wh]. In light of this, Table 1 presents a ranking of the event's severity.

Table 1. Severity of consequences evaluation

Criterion	Severity of consequences	Rank
$TC \leq 100$ [EUR]	Very Low	1
$100 < TC \leq 300$ [EUR]	Low	2
$300 < TC \leq 600$ [EUR]	Medium	3
$600 < TC \leq 900$ [EUR]	High	4
$TC > 900$ [EUR]	Very High	5

The overall severity rank is evaluated by calculating the average total cost per failure:

$$ATC \cdot MDT = 66.6125 \cdot 0.72\ = 47.96\ \text{EUR} \tag{7}$$

Thus, the overall severity of the consequences is evaluated as Very Low (S = 1).

O stands for the probability of occurrence, which is another partial indicator. It represents the degree of uncertainty, or the likelihood that an unforeseen event, a failure, will transpire. Table 2 outlines the evaluation procedure based on the system’s unreliability. Table 3 examines the chance of failure in four different scenarios to show how this indicator changes over time. The bulldozer enters a phase with a "Very High" likelihood of occurrence during the 5th day of operation, meaning that a failure is almost unavoidable.

Table 2. Probability of occurrence evaluation

Criterion	Probability of occurrence	Rank
$F(t) \leq 0.2$	Very Low	1
$0.2 < F(t) \leq 0.4$	Low	2
$0.4 < F(t) \leq 0.6$	Medium	3
$0.6 < F(t) \leq 0.8$	High	4
$F(t) > 0.8$	Very High	5

Table 3. Four scenarios that illustrate how second risk dimension (O) changes through time

Scenario	Operating time	Probability of failure	Rank
I	1 work shift = 8 h	$F(8) = 0.1133$	1
II	1 day = 24 h	$F(24) = 0.3029$	2
III	3 days = 72 h	$F(72) = 0.6612$	4
IV	5 days = 120 h	$F(120) = 0.8354$	5

The third partial indicator, detection rate (D), shows how a failure mode will be identified by controls and inspections and also quantifies its impact based on how simple it will be to identify the problem's cause when a failure happens (Wang et al., 2012). Table 4 presents the ranking of the detection rate of events according to the type of failure.

Table 4. Detection rate indicator evaluation

Criterion	Detection rate	Rank
/	Very High	1
Failure type is mechanical.	High	2
Failure type is technological or due to external influences.	Medium	3
Failure type is due to power/electricity.	Low	4
/	Very Low	5

The general detection rate of failures in bulldozers is estimated based on an expected value of ranks:

$$EV(R_D) = \sum_{i=1}^{4} p_i \cdot R_{Di} = \frac{61}{83} \cdot 2 + \frac{2}{83} \cdot 3 + \frac{0}{83} \cdot 3 + \frac{20}{83} \cdot 4 = 2.51 \tag{8}$$

The final detection rate will be rounded up to a larger figure, $D = 3$, in accordance with the previously established process, which prioritizes safety and calls for evaluating each indicator with a whole number.

Following the suggestions in a previously defined methodology by Spasojević-Brkić et al. (2023), the overall risk classification along with suggested actions is given in Table 5. The overall risk of the bulldozer's performance, including the worst-case scenario when it comes to unreliability, is equal to:

$$RPN = S \cdot O \cdot D = 1 \cdot 5 \cdot 3 = 15 \tag{9}$$

Table 5. RPN interpretation

Criterion	Risk level	Suggested actions
$RPN \leq 25$	Very Low	Regular cost analysis once in a year.
$25 < RPN \leq 50$	Low	Cost analysis once in 6 months.
$50 < RPN \leq 75$	Medium	Cost analysis once in 3 months.
$75 < RPN \leq 100$	High	Cost analysis every month.
$RPN > 100$	Very High	Cost analysis as soon as possible.

The rental cost of a machine at a market rate of 70 EUR/wh is the main boundary that determines its economic lifetime (Bugaric et al., 2022). Consequently, the machine is no longer economically viable, and its replacement is advised when the cost analysis results show that the machine maintenance is more expensive than the rental price, i.e., ATC ≥70 [EUR/wh].

To conclude, overall risk can be evaluated as "Very Low", which implies that cost analysis should be done once a year. A graphical representation of the highlighted bulldozer's RPN in a three-dimensional risk matrix is shown in Figure 5.

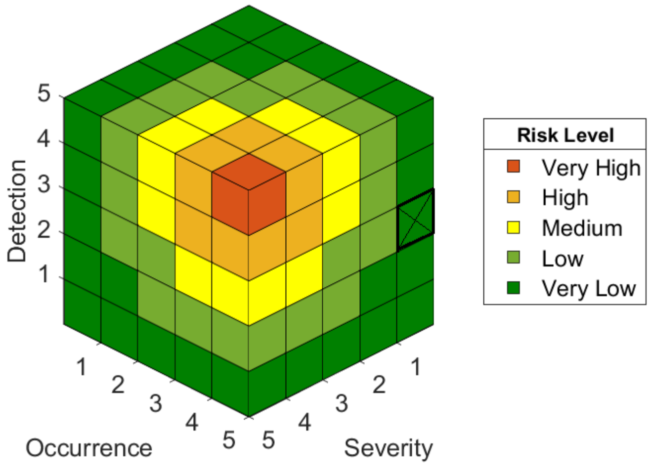

Figure 5. Bulldozer's RPN in a 3D Risk Assessment Matrix

5. CONCLUSION

Suggestions from recent studies have shown that risk in the mining industry should be examined from the perspectives of strategy and operations, in addition to the already well-known safety-centred view. Based on the Pareto analysis, it was found that the majority of downtime can be attributed to mechanical and technological factors. The chi-square test revealed a correlation between the data and a Poisson distribution. Subsequent reliability analysis revealed that the MDT amounts to 0.72 hours. The FMEA analysis determined that the bulldozer's overall performance risk is 15. Based on the rating provided, it is recommended that the cost analysis be conducted on an annual basis.The study's findings demonstrated that, because the monitored bulldozer belongs to the lowest defined risk class, its use is currently economically justifiable. In other words, it brings in more revenue than it costs to operate. The probability that the machine will turn a profit decreases as its risk level rises through years of operation. Not only do unplanned machine breakdowns generate direct economic consequences for the company, but after each of them occurs, the amortization process speeds up. Hence, the risk evaluation method can be a useful way to gain more awareness of the possibilities that old machine replacement generates, either by outsourcing or purchasing a new one. The main limitations of this research are the small sample size at first and the absence of reference risk scores for other auxiliary machines. Therefore, in order to maximize the utility of the remaining equipment, research efforts should concentrate on growing the current sample (or collecting a new, larger one) and applying the established methodology to it.

ACKNOWLEDGMENT

This research was supported by the Science Fund of the Republic of Serbia, #GRANT No. 5151, Support Systems for Smart, Ergonomic and Sustainable Mining Machinery Workplaces – SmartMiner and the Ministry of Science, Technological Development and Innovation of the RS according to the Agreement on financing the scientific research work of teaching staff at accredited higher education institutions in 2024, no. 451-03-65/2024-03/200105 of February 5, 2024. years.

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