Volume XX, Issue (1) (2024) 111-121

International May Conference on Strategic Management

DOI: *10.5937/IMCSM24011J*

Original research

A HYBRID RELIABILITY - FMEA METHODOLOGY IN RISK ASSESSMENT OF A BELT CONVEYOR SYSTEM

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Abstract: An appropriate maintenance strategy can maximize a machine's capacity and economic lifetime and also produce yearly savings of several million euros. That being said, a risk assessment approach can help companies identify the systemic bottlenecks that are interfering with their development and cut a large portion of their profit each year. This paper presents a hybrid reliability-Failure Mode and Effects Analysis (FMEA) methodology to assess the risk associated with belt conveyor systems, particularly in open-pit mining environments. By integrating severity, occurrence, and detection indicators, a 3D risk assessment matrix was developed. Using data from conveyor system maintenance, including downtime and failure occurrences, chi-square tests to analyze system reliability and mean downtime were applied. The methodology allows for a nuanced understanding of the frequency and severity of failures, enabling more informed decision-making about maintenance strategies. The paper highlights the economic implications of system failures and the potential for substantial financial savings through optimized maintenance planning.

Keywords: risk, reliability, mining, belt conveyor.

1. INTRODUCTION

During the 1970s, an energy crisis affected the whole Western world. Implementing solutions with lower labor and energy requirements has become a fundamental goal for companies in order to stay competitive in the market. Problems in the mining industry were no different, as transportation of ores needed to be done with minimum energy and costs. Although it had been invented almost 100 years earlier, a belt conveyor finally found its spot under the sun at the time, especially in bulk material extraction such as coal. Among its low operating costs, other advantages such as safety of operation, reliability, versatility, and a broad range of capacities have led it to become a dominant transportation solution for a wide variety of engineering problems (CEMA, 2014).

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Nowadays, belt conveyors present a reliable provider of continuous material flow between operations without loss of time for loading and unloading or empty return trips (CEMA, 2014). However, factors such as aging from long-term operation, heavy or impact loads, complex operating environments and long transport distances may generate undesirable phenomena, e.g., wear or puncture. Each one of those can develop into long-range tears, forcing an unexpected downtime. Material delays may result in huge financial losses for companies in the mining industry. Therefore, the maximum effort should be put into its prevention (Guo et al., 2022).

In Serbia, coal was, is, and will be the most significant source of energy, with 85% participation in the structure of overall primary energy reserves (Pavlovic et al., 2011). Hence, the proper functioning of systems for their exploitation can be presented as not only a primary goal for the mining companies but also as a matter of highest interest at the state level. The conveyor belt, as a fundamental part of a belt conveyor system, presents *"the main artery for coal mine production and transportation"* (Hou et al., 2024). The idea of mitigating risk in such a system seems reasonable if the ultimate goal is to minimize overall costs. A methodology suggested by Spasojević-Brkić et al. (2023) will be applied in an attempt to deal with the problem adequately. At first, similar previous research was discussed. Eventually, the results will be put into a defined risk assessment framework.

2. LITERATURE REVIEW

Heavy machinery, including rubber belt conveyors, bucket-wheel excavators, dredges, and dumpers, is commonly used in modern open-pit mines for tasks such as overburden removal, transport, crushing, and loading (Ignjatović et al., 2018). Thus, much research was done to determine heavy machinery reliability and the consequences of improper maintenance. Bugarić et al. (2014) proposed a methodology used to determine the rubber belt conveyor's reliability function, operating on machines (bucket-wheel excavator, belt wagon, spreader) that remove overburden on the Tamnava – East Field open-pit mine. The research was based on the fact that the mean operating time until failure may be represented by the composition of an exponential distribution (sudden failures) and a normal distribution (gradual failure). Štatkić et al. (2019) also calculated the mean time to failure (MTTF) in order to analytically assess the reliability of a single-motor drive that powers a rubber conveyor belt at the Drmno open-pit mine. Analysis from a study by Li et al. (2019) generated a Weibull three-parameter distribution model, which has shown that the probability of belt conveyor failure or breakdown can rise to almost 25% during continuous operation for 24 hours.

To prevent failures and increase reliability, we view such systems from a broader perspective and consider non-technical factors. Therefore, risk management is important. Kecojevic et al. (2008) analyzed the risk associated with fatal incidents on belt conveyors in the U.S. mining industry. Risks were identified and quantified via the Preliminary Hazard Assessment (PHA) method, and their levels were then developed using a pre-established risk matrix that ranks risks according to probability and severity. On the other hand, two studies by different authors (Burduk, 2012; Özfırat et al., 2022) applied Failure Modes and Effects Analysis (FMEA) to a belt conveyor system with the goal of identifying and ranking risks according to their RPN (Risk Priority Number). Burduk (2012) used linguistic variables to reveal risk factor cause-and-effect relationships and reduce their impact on production systems. Additionally, Özfırat et al. (2022) have done Event Tree Analysis (ETA) for each previously identified risk to display and decrease their severity degrees. A study by Moghrani et al. (2023) took a step further, proposing a RPI-MCDM-based FMEA evaluation model that classifies failure modes of systems and machines in order to enhance failure modes in belt conveyor systems and the mining industry in general. Although numerous authors analyzed risk inside a mining environment, most of the research was done from a safety perspective, where potential hazards were perceived as the main consequence. This study aims to model risk from an economic perspective, placing generated costs as the main side effect of an unplanned downtime.

3. METHODOLOGY

Based on the construction characteristics of belt conveyors and the number of existing data points for analysis, the observed belt conveyor system was divided into three sub-systems. The primary sample of the conveyor's performance consisted of recorded downtimes and times between failures. Recorded failures were separated into three different categories: failure of mechanical parts, failure of electrical parts, and other failures. Firstly, a chi-square test will be used to determine which theoretical statistical distribution best fits the data regarding downtimes and intervals between failures. The next stage is the determination of the system's reliability/unreliability functions. The method of their calculation will be selected based on the results of the statistical testing. In other words, the functions can be found analytically if the data can be represented by an exponential theoretical distribution for all types of failures and sub-systems. Otherwise, another way of proving their determination must be found. Eventually, the overall system's risk will be evaluated inside a three-dimensional risk assessment model.

4. RESULTS AND DISCUSSION

4.1. Statistical testing of the data

As has already been said, the main conveyor system (B.C.-S#0) has been divided into three different sub-systems (B.C.-S.S#1, B.C.-S.S#2, and B.C.-S.S#3). The times between failures and downtimes were perceived separately for mechanical and electrical failures in each sub-system. Other failures that were happening inside all of the sub-systems were summarized into one sample, perceiving it as a fictional additional sub-system (B.C.-S). Within all sub-systems, the data could be approximated with the exponential theoretical distribution (Figures 1-4) with a relevance threshold of $\alpha = 0.01$.

Table 1 shows the parameters of each distribution. Parameters of the TBF distribution present the failure intensity (λ) of each failure type. On the other hand, revealing the DT distribution parameter allows generating the maintenance intensity (μ).

Table 1. Results of application the $\chi 2$ – test

Object	Failure type	No. of failures	Distribution of TBF		Distribution of DT	
			Type	Parameter λ	Type	Parameter μ
B.C.-S.S#1	Mechanical	226	E1	0.003190810	E1	0.049033847
	Electrical	15	E1	0.004083211	E1	0.023637302
B.C.-S.S#2	Mechanical	202	E1	0.003574741	E1	0.054267622
	Electrical	90	E1	0.003387967	E1	0.026733403
B.C.-S.S#3	Mechanical	394	E1	0.004548413	E1	0.037638440
	Electrical	249	E1	0.005242600	E1	0.032062975
B.C.-S	Other	70	E1	0.005482600	E1	0.023120329

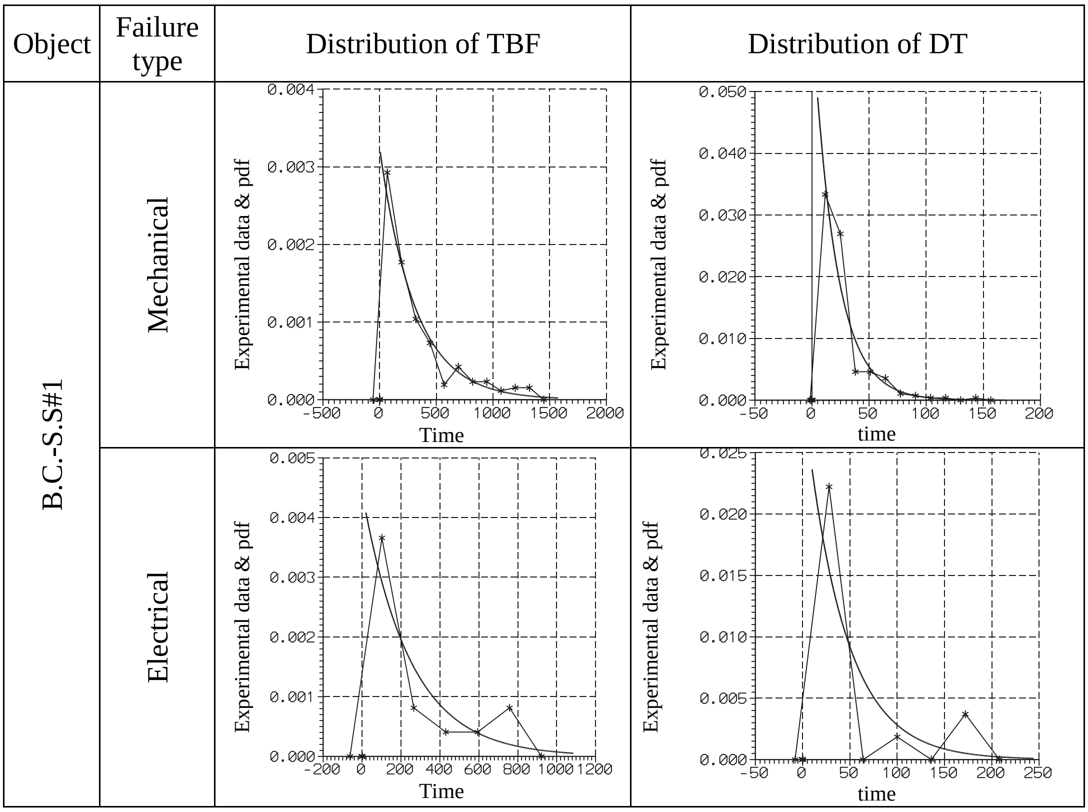


Figure 1. Distribution of TBF and DT for B.C.-S.S#1

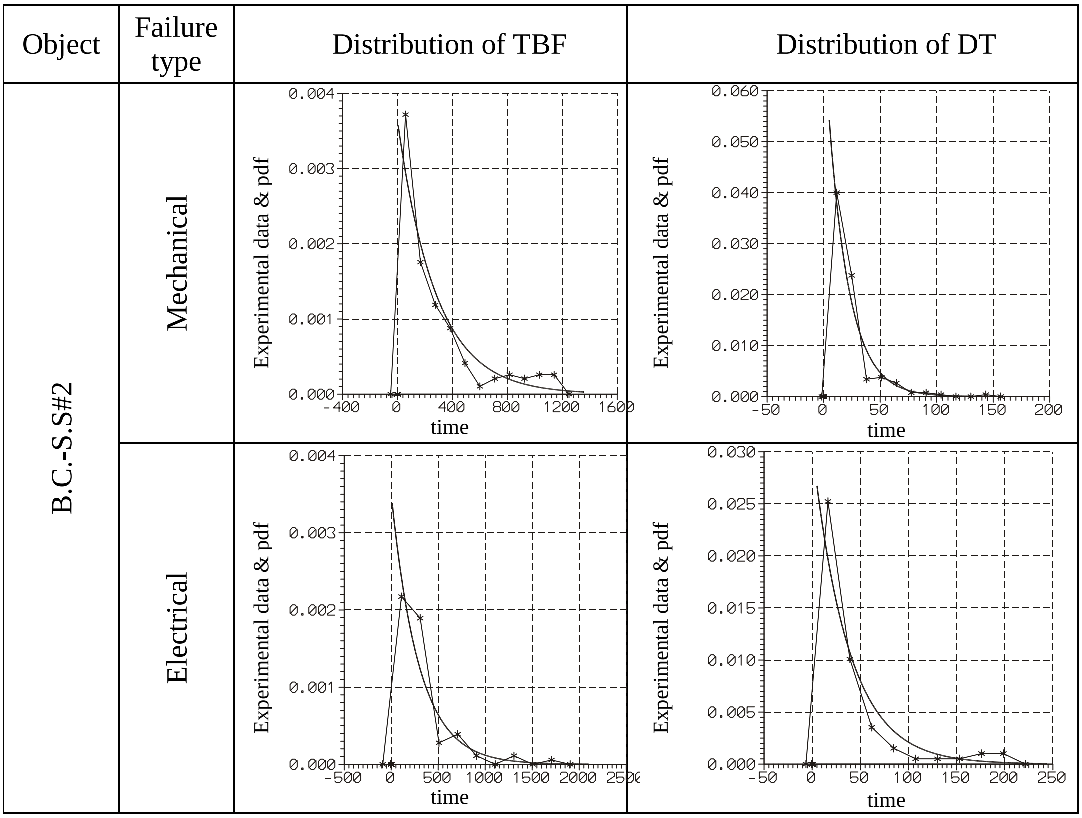
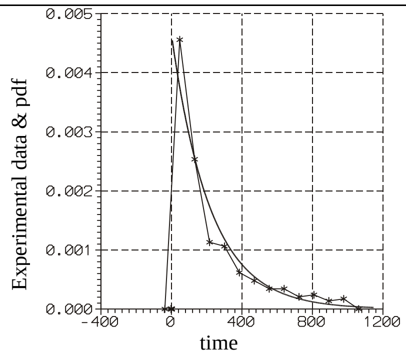
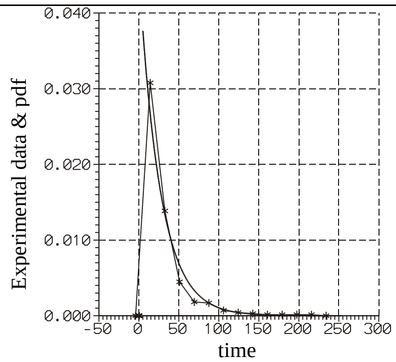


Figure 2. Distribution of TBF and DT for B.C.-S.S#2

<table>
<tr><th>Object</th><th>Failure type</th><th>Distribution of TBF</th><th>Distribution of DT</th></tr>
<tr><td rowspan="2">B.C.-S.S#3</td><td>Mechanical</td><td>
</td><td>
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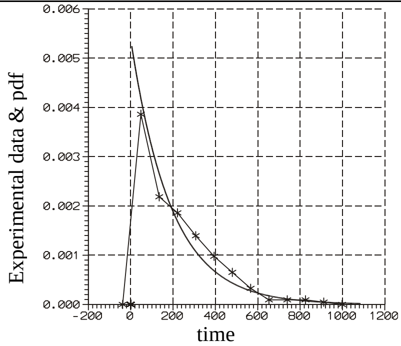
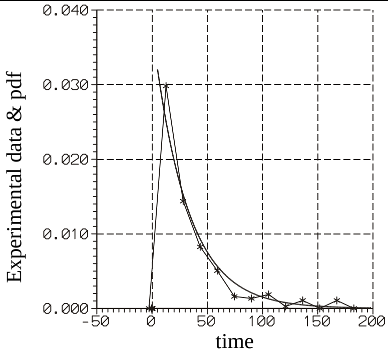
<tr><td>Electrical</td><td>
</td><td>
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Figure 3. Distribution of TBF and DT for B.C.-S.S#3

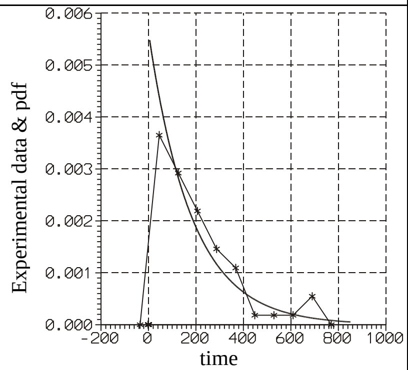
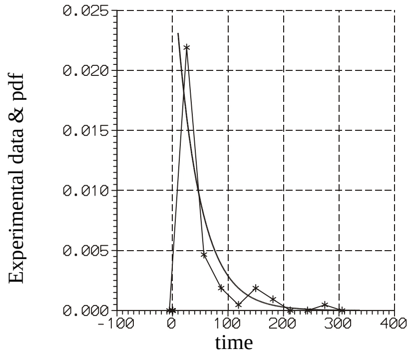
<table>
<tr><th>Object</th><th>Failure type</th><th>Distribution of TBF</th><th>Distribution of DT</th></tr>
<tr><td>B.C.-S.</td><td>Other</td><td>
</td><td>
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Figure 4. Distribution of TBF and DT for other failures

4.2. Reliability analysis

As it has been proven that the samples can be affiliated with the exponential theoretical distribution, the belt conveyor system's reliability will be calculated analytically as the reliability of a system with serially connected elements, where each sub-system presents an element from a theory standpoint. In other words, Equation (1) can be used for its calculation:

$$R_{BCS}(t) = R_1(t) \cdot R_2(t) \cdot \ldots \cdot R_7(t) = e^{-\lambda_1 \cdot t} \cdot e^{-\lambda_2 \cdot t} + \cdots + e^{-\lambda_7 \cdot t}$$
$$R_{BCS}(t) = e^{-(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_6+\lambda_7)\cdot t} = e^{-\lambda_{BCS}\cdot t} = e^{-0.029510342\cdot t} \quad (1)$$

Where:

λ_1 – mechanical failure intensity for B.C.-S.S#1,
λ_2 – electrical failure intensity for B.C.-S.S#1,
λ_3 – mechanical failure intensity for B.C.-S.S#2,
λ_4 – electrical failure intensity for B.C.-S.S#2,
λ_5 – mechanical failure intensity for B.C.-S.S#3,
λ_6 – electrical failure intensity for B.C.-S.S#3,
λ_7 – other failure intensity (B.C.-S), and
λ_{BCS} [1/h] – failure intensity of a whole system.

Conversely, the unreliability of a system presents the probability of its failure in a given period of time and it can be determined by the following Equation (2):

$$F_{BCS}(t) = 1 - e^{-\lambda_{BSC}\cdot t} = 1 - e^{-0.029510342\cdot t} \quad (2)$$

Figure 5 reveals a graphical representation of the change in the conveyor's reliability and unreliability over a period of one week or 7 days (168 h).

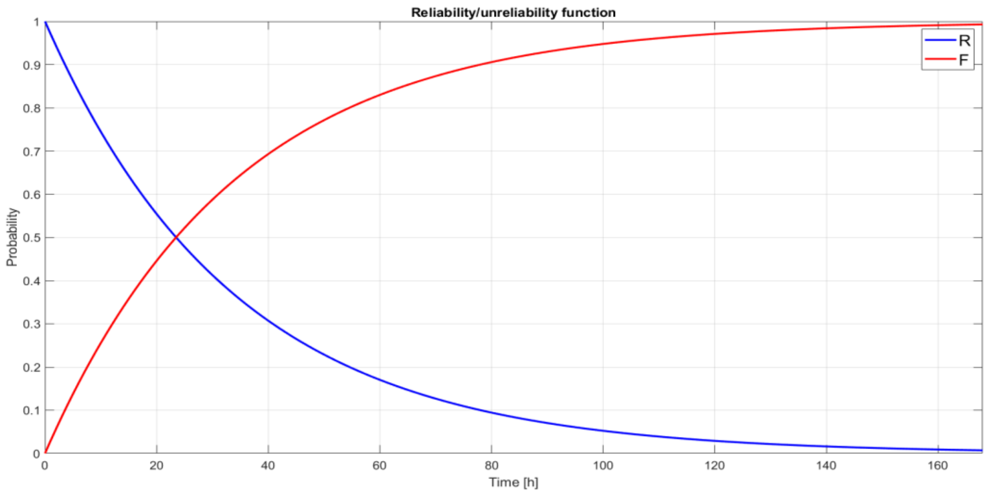

Figure 5. The change of system's reliability and unreliability in a period of one week

In order to differentiate the impact each type of failure has on a system, three mean downtimes (MDT) will be calculated, each based on the type of failure that caused it. MDT due to mechanical failures (MDT_M) can be calculated as an expected value of downtimes generated from each distribution:

$$MDT_M = \left(\frac{226}{822}\cdot MDT_{M1} + \frac{202}{822}\cdot MDT_{M2} + \frac{394}{822}\cdot MDT_{M3}\right) = 22.87 \text{ min} \approx 0.38 \text{ h} \quad (3)$$

Accordingly, mean downtime due to electrical failures (MDT_E) will be calculated as:

$$MDT_E = \left(\frac{15}{354}\cdot MDT_{E1} + \frac{90}{354}\cdot MDT_{M2} + \frac{249}{354}\cdot MDT_{E3}\right) = 33.24 \text{ min} \approx 0.55 \text{ h} \quad (4)$$

When it comes to other failures, mean downtime is calculated using equation 5:

$$MDT_O = \frac{1}{\mu_7} = \frac{1}{0.023120329} = 43.25 \text{ min} \approx 0.72 \text{ h} \quad (5)$$

4.3. Risk assessment model

One of the most approved tools for identifying and eliminating potential failures to enhance the reliability and safety of complex technical systems is the Failure Modes and Effects Analysis (FMEA) method (Liu et al., 2013). The international standard ISO/IEC 31010 officially shaped the method's definitions and principles. FMEA uses the risk performance number (RPN) to determine the risk level (Djenadic et al., 2022).

Equation 7 gives the total RPN for all failures, which ultimately indicates the total risk level in a belt conveyor system. The risk performance comprises three component indicators that accurately portray risk as a whole. On a 5-point rating system, each component indicator can be evaluated.

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

The severity of the consequences (S) is calculated in order to precisely determine the intensity of the incident. This metric aims to quantify the financial impact that the current delay has on a company. The severity of the failure is assessed using the total costs (TC) incurred as a result of the belt conveyor malfunction, among which lost revenue and repair costs are the most prevalent ones. A study conducted by Bugaric et al. (2012) found that the company loses 9232.33 EUR for every hour of material delay, i.e., the malfunction costs of the overburden excavation system per hour are equal to ATC=9232.33 [EUR/h]. Thus, Table 2 presents the defined rankings of the event's severity.

Table 2. Severity of consequences evaluation

Criterion	Severity of consequences	Rank
$TC \leq 1000$ [EUR]	Very Low	1
$1000 < TC \leq 3000$ [EUR]	Low	2
$3000 < TC \leq 5000$ [EUR]	Medium	3
$5000 < TC \leq 10000$ [EUR]	High	4
$TC > 10000$ [EUR]	Very High	5

The severity ranks of each type of failure are given inside Table 3 and evaluated by calculating the average total cost per failure ($ATCF = ATC \cdot MDT$).

Table 3. Evaluated ranks for each type of failure

Type of failure	*ATCF* [EUR]	Severity of consequences	Evaluated Rank
Mechanical	3519.10	Medium	3
Electrical	5114.78	High	4
Other	6655.28	High	4

The second partial indicator is the probability of occurrence (O). It presents a quantified parameter that shows the level of uncertainty or likelihood that an unforeseen delay or failure could happen. Table 4 depicts the evaluation procedure based on the system's unreliability. Table 5 examines the failure function in four distinct scenarios, highlighting the increasing significance of this indicator over time.

Table 4. 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 5. 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	$F(8) = 0.2103$	2
II	1 day = 24 h	$F(24) = 0.5075$	3
III	2 days = 48 h	$F(48) = 0.7574$	4
IV	3 days = 72 h	$F(72) = 0.8805$	5

The third partial indicator, detection rate (D), quantifies the impact of a failure type based on the simplicity of determining its cause when a failure occurs. Additionally, it weighs the potential problems with discovering a specific failure mode through controls and inspections (Wang et al., 2012). Table 6 provides the ranking of the event detection rate based on the type of failure.

Table 6. Detection rate indicator evaluation

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

Table 7 presents a thorough risk classification and recommended actions based on a study by Spasojević Brkić et al. (2023) that has already outlined the guidelines. The individual risks of each failure type are given in the following equations, considering the worst-case scenario when it comes to the probability of occurrence.

$$RPN_M = S \cdot O \cdot D = 3 \cdot 5 \cdot 2 = 30 \quad (7)$$
$$RPN_E = S \cdot O \cdot D = 4 \cdot 5 \cdot 4 = 80 \quad (8)$$
$$RPN_O = S \cdot O \cdot D = 4 \cdot 5 \cdot 3 = 60 \quad (9)$$

Table 7. 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.

In summary, the evaluated risks for mechanical and other types of failure are evaluated as “Low” and “Medium”, whereas electrical failures can potentially cause the most problems, being in the category of “High” risk, which indicates that cost analysis should be done every month. Figure 5 displays a graphic representation of the conveyor's highlighted RPNs in a three-dimensional risk assessment matrix. Risk analysis enables perceiving the “critical spots” of the system and reconsidering the current maintenance strategy. In other words, if the system is generating costs beyond defined boundaries, a change in the maintenance approach is advised. Proper maintenance strategy with adequate diagnostic tools allows the engineer to make a decision on when the moment of preventive belt replacement will be, which drastically reduces the probability of unplanned downtime and potential replacement of the belt with a new one in emergency mode (Błażej et al., 2022).

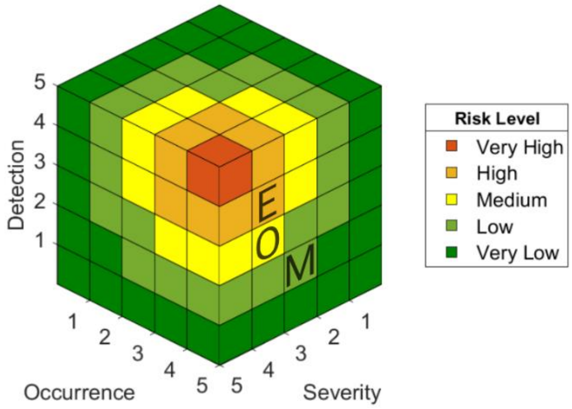

Figure 6. RPNs of a belt conveyor system in a 3D Risk Assessment Matrix
(M – Mechanical, E – Electrical and O – Other type of failure)

5. CONCLUSION

Although years of exploitation increase the overall system's risk level and slowly drag its reliability down, an adequate maintenance strategy can minimize the consequences and generate annual savings of several million euros. That being said, a risk assessment approach can help companies map the spots in the system that represent a barrier to their development by losing them huge amounts of revenue annually. High RPN scores indicate that failure prevention isn't managed properly and that something different must be done from a strategic management point of view. This research's primary limitations are the initial small sample size and the absence of reference risk scores for other heavy machines. Additionally, the financial data, which was the root of the severity indicator formation, could be taken as outdated. Inflation and volatility in the energy market certainly had a significant impact on prices during the previous years. Therefore, besides expanding the present sample, the focus of further research efforts should be on applying the established methodology to the rest of heavy equipment and revising the costs of delays per hour based on the latest financial reports in the mining industry.

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 Innovations 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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