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RELIABILITY-BASED RISK ASSESSMENT OF AUXILIARY MACHINERY IN OPEN-PIT MINES: CASE STUDY OF A HYDRAULIC EXCAVATOR

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Abstract: Risk based approach has been proven in generating utility in the mining industry by multiple authors. However, most of the previous research has focused on heavy machinery, neglecting the impact that auxiliary machines have in overall risk management. The following study aims to propose a risk assessment methodology for auxiliary machinery in open-pit mines based on the analysis of a hydraulic excavator maintenance data. The overall risk was defined in accordance with the FMEA method, as a product of three partial indicators: severity, occurrence and detection of failures. Failure type distribution and distinction were illustrated via Pareto chart with the goal to rate the detection indicator. The chi-square tests of downtime and time between failure data were following and enabled analytical determination of the system's reliability and mean downtime, which led to evaluating the severity and occurrence of failures. Accordingly, framework for evaluation was proposed with a three dimensional risk assessment matrix as a result and proved on collected data.
Key words: risk, reliability, mining, hydraulic excavator

INTRODUCTION

Every basic technological system places the most emphasis on the machines that perform the fundamental tasks of a system as a whole. As systems get more complex, the role of auxiliary equipment gets more important. That being said, most modern lignite open-pit mines are equipped with large machinery (rotor excavators and dredges, conveyors with rubber belts and dumpers), which perform basic technological processes (excavation, transport and disposal of overburden, i.e. excavation, transport, crushing or loading of useful substance). However, in order to even be able to engage with the fundamental process, there is a wide variety of auxiliary tasks that need to be done. In mining technology, the machines which are specialized for those kind of assignments are called auxiliary machinery. Adding to that, high-quality execution of auxiliary tasks is one of the most important preconditions for satisfactory time and capacity utilization in the open-pit mine. [1]
Although it may not be immediately apparent from a wide perspective, the effects of the auxiliary activities have a substantial impact on the end result. Among numerous of them, the following should be particularly highlighted: site plan development work, cleaning works, slope shaping, moving, extending, shortening, or transferring conveyors, construction and maintenance of access roads, plateaus, ramps, various embankments and cuttings, canals and water reservoirs for mine drainage, shaping of disposal areas at the technical phase of land recultivation, works in the domain of routine and investment maintenance of equipment, etc. [1].
The majority of auxiliary mechanization machines represent tools for digging and carrying dug material, which they do simultaneously. In other words, the movement of the working instrument is achieved by movement of the entire machine. Auxiliary machinery is contained of machines such as: dozers, loaders, pipelayers, rippers, hydraulic excavators, graders, scrapers, dragline excavators, rollers, cranes, trucks, tankers, off-road vehicles, etc. Some of the mentioned machines possess a wide range of application, i.e. they have a more universal character (dozers), while others are narrowly specialized for performing only certain types of work (cranes, drills) [1]. Dozers, pipelayers, and hydraulic excavators are the most significant and prevalent auxiliary machines in open-pit mines, excluding transport vehicles [2].

Maximum output in a mining system can only be achieved through maximum equipment utilization, as it operates 24 hours a day. Therefore, adequate reliability, maintainability characteristics and maintenance strategy are fundamental factors in unexpected breakdown and failure prevention. Not only that unexpected problems limit the machine’s performance and effectiveness, but can also result in huge economic losses [3].
Having that in mind, the idea of managing risk in with the goal to minimize overall costs has arisen. In attempt to formulate a methodology that will tackle the problem properly, similar previous research has been reviewed at first. Eventually, the results will be discussed.

LITERATURE REVIEW

Hydraulic excavators certainly represent one of the most important and common parts of every open-pit mine system [2]. Therefore, it isn’t surprising that multiple studies have been done in order to to evaluate their reliability, availability and maintainability (RAM). A study by Kumar et al. [4] has shown the hydraulic excavator/shovel's failure rate and reliability, along with suggestions on how to improve overall capacity utilization by employing specifically timed preventive maintenance activities. It also illustrated the impact that the failure rate and reliability have on overall productivity of the mine. In order to determine of remaining useful life of an excavator, Ghomghaleh et al. [5] proposed a conceptual framework which relied on the reliability analysis in two classical and frailty models. Kumar et al. [6] analyzed failure and repair data, both graphically and statistically, with the goal to analytically determine RAM of shovel and dumper system at open-pit limestone mine. The Weibull distribution was chosen as the best fitting distribution using the K-S test. Liu et al. [7] have also done reliability analysis with the goal to identify the weakest component of a mechanical hydraulic system in excavators which will help in implementing appropriate maintenance strategies that are necessary for maintaining highly reliable systems. Numerous authors have suggested that failure risk assessment is a crucial extra prerequisite for developing an appropriate maintenance strategy, i.e. an effective plan for failure prevention. Spasojević Brkić et al. [8] analyzed results obtained in the excavator downtime analysis and proposed a risk assessment methodology. After the frequencies of downtime had been monitored by the defined categories of downtime, the consequences of the identified delays were evaluated and the risk was calculated. Velikanov et al. [9] sorted a variety of factors that can be the cause of a mining excavator to fail and calculated their frequencies. As they interpreted risk as the probability of failure, the most frequent factors were identified as those with the highest failure risk. Risk evaluation techniques that are more well-known have also been utilized, such as FMEA (Failure Mode and Effect Analysis) and FMECA (Failure Modes, Effects and Criticality Analysis) which were used in an attempt to develop an effective maintenance methodology of excavators in a study by Kumar & Kumar [10]. Despite the mentioned facts, literature review has shown a lack of work that has assessed failure risk based on RAM analysis. Therefore, the following study aims to evaluate failure risk in auxiliary machinery on an example of a hydraulic excavator (‘excavator’ in further text).

METHODOLOGY

The main concept of this study can be separated in four different stages. The root of the analysis lies in recorded downtimes and times between failures, which represent the primary sample of an excavator’s performance. Firstly, the gathered data must be analyzed and classified according to the type of downtime. Afterwards, downtimes and times between failures will be tested using a chi-square test in order to conclude which theoretical statistical distribution makes the best fit. The third stage of the study consists of establishing the reliability/unreliability functions. Depending the outcome of the statistical testing, the method of their determination shall be chosen. In other words, if the data can be approximated using an exponential theoretical distribution, mentioned functions can be determined analytically. Otherwise, other methods must be used, such as simulation, etc. Finally, three dimensional risk assessment model was proposed and overall excavator’s risk has been evaluated.

RESULTS AND DISCUSSION

Data analysis and classification

Delays in the observed auxiliary machines were classified according to the type of downtime: mechanical downtime, technological downtime, power/electricity downtime and downtime due to external influences. In order to represent a distribution of failure types and identify which ones are most significant, a Pareto chart has been constructed (Figure 1).

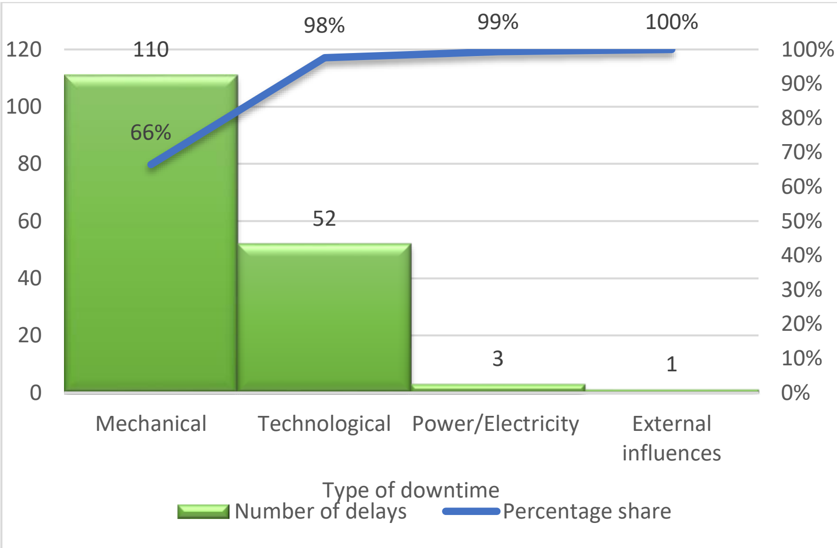

Fig. 1. *Pareto chart of downtime types*

As it can be seen in Figure 1, mechanical and technological delays represent an absolute majority with their 98% share in the whole sample. Therefore, from a maintenance and risk management perspective, the two types should the most significant factors.

Chi-square testing

The data was preprocessed into two samples – downtime and time between failures. Affiliation of the samples to the exponential theoretic distribution was established by applying chi-square test. Testing results showed that the time between failure could be described with the exponential distribution characterised by parameter $\lambda = 0.0001138530$ with the relevance threshold of $\alpha = 0{,}01$ (Figure 2). Exponential distribution parameter (λ) will be equal to failure intensity $\lambda_e = 0.0001138530\ 1/\text{min} = 0.00683118\ 1/\text{h}$.

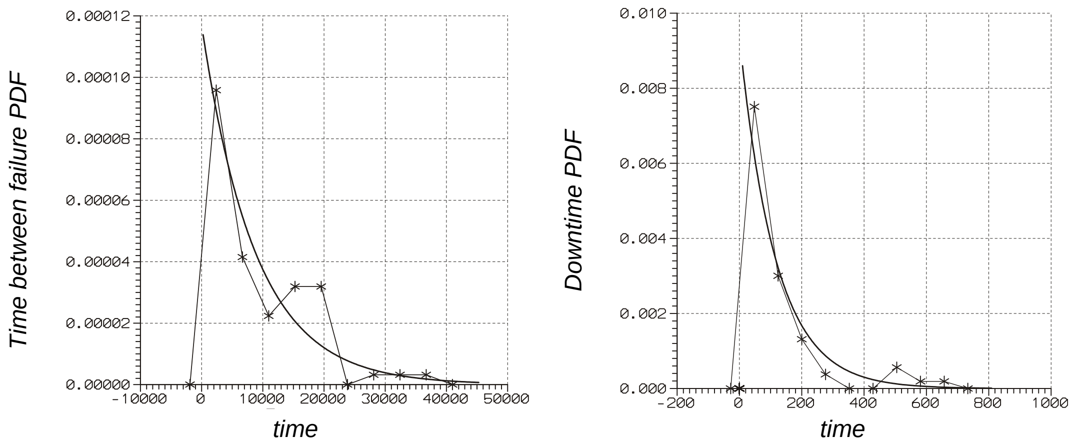

Fig. 2. *Time between failure and downtime distribution*

When it comes to downtime (repair time) sample, the results showed that the sample can be described with the exponential distribution characterised by parameter $\lambda = 0.0085975507$ with the relevance threshold of $\alpha = 0.01$ (Figure 2). Parameter of the distribution (λ) will be equal to repair intensity $\mu e = 0.0085975507\ 1/\mathrm{min} = 0.515853042\ 1/\mathrm{h}$.

Reliability analysis

Based on the testing of time between failure sample, the reliability of an excavator (probability that it will perform its specified function for a given time) can be shown by the exponential distribution forms, i.e. equation (1) can be used:

$$R(t) = e^{-\lambda_e \mathrm{t}} = e^{-0.00683118 \cdot \mathrm{t}} , \quad (1)$$

where λ_e $[1/\mathrm{h}]$ is the failure rate of the excavator.

On the contrary, the probability that the system will fail in a period of given time is framed inside the definition of unreliability and it can be determined by following Equation 2.

$$F(t) = 1 - e^{-\lambda_e \mathrm{t}} = 1 - e^{-0.00683118 \cdot \mathrm{t}} \quad (2)$$

Figure 3 provides a graphical representation of the change in excavator's reliability and unreliability in a period of one month, approximately 30 days (720 h).

The average operating time between the failures ($MTBF_e$) of excavators is equal to:

$$MTBF = \frac{1}{\lambda_e} = \frac{1}{0.00683118} = 146.39\ \mathrm{h} \quad (3)$$

The average delay time due to the failures (MDT_e) of excavators is equal to:

$$MDT = \frac{1}{\mu_e} = \frac{1}{0.515853042} = 1.94\ \mathrm{h} , \quad (4)$$

where μ_e [1/h] is the repair rate of the excavator.

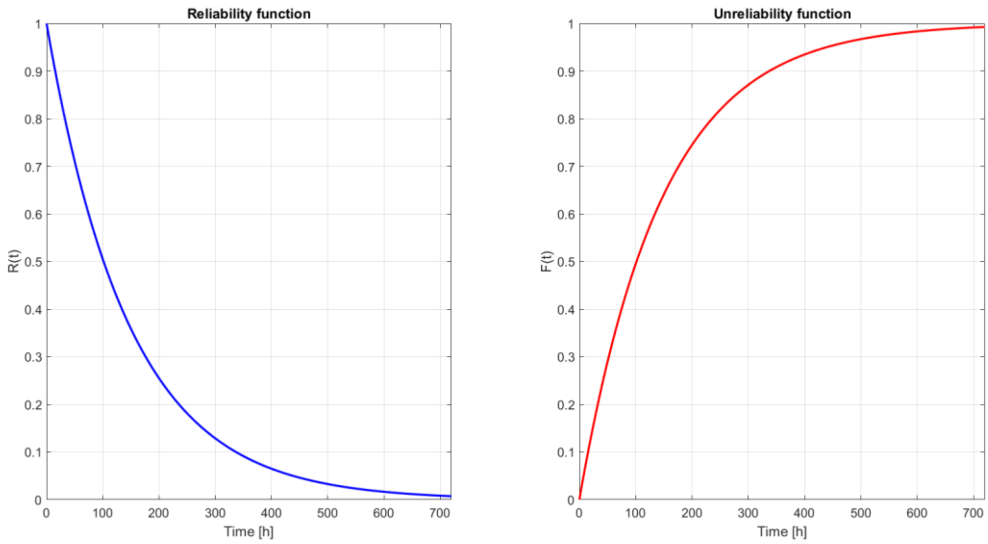

Fig. 3. *System's reliability and unreliability over time*

Risk assessment model

International standard ISO/IEC 31010 defined and described one of the most common tools for risk assessment and management for complex technical systems, the FMEA method (Failure Modes and Effects Analysis) [11]. According to the method, risk level is evaluated by calculating the risk performance number (RPN). Three partial indicators (each being evaluated from 1 to 5) are integrated into the risk performance, which directly describe risk as a comprehensive concept [12].
Finally, overall RPN for all failures that indicates the level of overall risk in hydraulic excavators is given Equation 8.

$$RPN = S \cdot O \cdot D \tag{5}$$

The first partial indicator is the severity of consequences (S). This indicator aims to quantify the effects of the incident so that the severity of it may be more precisely evaluated. The severity of the failure is measured by total costs (TC) which are generated as a consequence of excavator not working and include repair costs and lost revenue. According to [13], for every hour in which machine doesn't work, the company loses 66.6125 EUR, i.e. $\mathrm{ATC} = 66.6125\ [\mathrm{EUR/wh}]$. Having that in mind, ranking of event's severity is given in Table 1.

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

Overall severity rank is evaluated by calculating average total costs per failure:

$$ATC \cdot MDT = 66.6125 \cdot 1.94 = 129.23\ \mathrm{EUR} \tag{6}$$

Therefore, overall severity of consequences is evaluated as Low ($S = 2$).
Another partial indicator is is the probability of occurrence (O). It shows the level of uncertainty, i.e. indicates the probability that an unexpected event - failure will occur. Evaluation process based on system's unreliability is given in Table 2. As this indicator changes through time, in order to illustrate its impact, probability of failure is evaluated in four different scenarios shown in Table 3. After the tenth day operating time, the excavator enters a phase defined by "Very High" probability of occurrence, which means that from that on failure is inevitable.

Table 2. *Probability of occurence evaluation*

Criterion	Probability of occurence	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 day = 24 h	$F(24) = 0.1512$	1
II	5 days = 120 h	$F(120) = 0.5595$	3
III	7 days = 168 h	$F(168) = 0.6826$	4
IV	10 days = 240 h	$F(240) = 0.8059$	5

Detection (D) presents the third partial indicator and it indicates the attitude of a failure mode that will be recognized by controls and inspections, i.e. when a failure occurs, how easily can the cause of the problem be detected [14]. Ranking of event's detection rate is done based on failure type and it is given in Table 4.

Table 4. *Detection 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

General detection rate of failures in excavators is estimated based on an expected value of ranks:

$$M(R_D) = \sum_{i=1}^{4} p_i \cdot R_{Di} = \frac{110}{165} \cdot 2 + \frac{52}{165} \cdot 3 + \frac{3}{165} \cdot 4 + \frac{1}{165} \cdot 3 = 2.37 \quad (7)$$

Having safety as a priority and respecting the previously defined methodology that requires evaluating every indicator with a whole number, final detection rate will be rounded up to a higher number, i.e. $D = 3$.
Following the suggestions defined in a cost-based model for monitoring the lifetime of the earth moving machines [13] and different RPN interpretations [12, 15], overall risk classification along with suggested actions is defined in Table 5.

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 primary factor determining the economic lifetime is whether the costs caused by the machine are lower than the cost of renting one at a market price of 70 EUR/wh [13]. Therefore, if the results of the cost analysis indicate that the machine isn't economically justified anymore, i.e. $\mathrm{ATC} \geq 70\ [\mathrm{EUR/wh}]$, machine replacement is suggested.
Finally, overall risk in excavators, with the worst case scenario when it comes probability of failure, is equal to:

$$RPN = S \cdot O \cdot D = 2 \cdot 5 \cdot 3 = 30 \quad (8)$$

According to Table 5, overall risk can be rated as "Low", which indicates that cost analysis should be done once in 6 months. Graphical representation of highlighted excavator's RPN in a three dimensional risk matrix is shown in Figure 4.

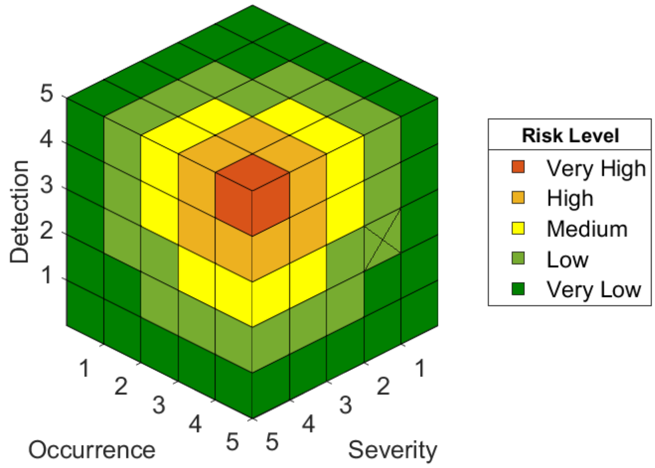

Fig. 4. *Excavator's RPN in a 3D Risk Assessment Matrix*

CONCLUSION

Failure risk assessment has been proposed by a number of authors as an essential additional requirement for creating an adequate maintenance strategy. Unexpected machine breakdowns can, along with other consequences, generate economic consequences that are substantial in the company's overall development. The results of the study showed that usage of the monitored excavator is currently economically justifiable, i.e. it generates more revenue than the total costs needed for its functioning, as it fulfills the lowest defined risk class. Higher risk classes inside the framework imply different suggestions in terms of more frequent cost analyses. As the machine climbs the risk latter through years of exploitation, the probability of it becoming loss-making grows. In order to become more attentive in recognising the possibility of replacing old machine with a new one, either via outsourcing or buying a new one, risk approach can be a practical solution. Therefore, the methodology for risk evaluation proposed in this study can be used as a tool in reducing maintenance costs of the company and improving overall efficiency. Besides that, the main limitations of this study are the initial sample size and lack of referent risk scores for other auxiliary machines. Therefore, further research should be focused on expanding the existing sample (or gathering a new, bigger one) and applying the defined methodology to the rest of the mentioned equipment so that its maximum utility can be generated.

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