

ANALIZA NIEZAWODNOŚCIOWA MECHANICZNYCH USZKODZEŃ KOPAREK ZGARNIAKOWYCH

RELIABILITY ANALYSIS OF DRAGLINES' MECHANICAL FAILURES

W nowoczesnych kopalniach, w których wykorzystuje się różnego typu wysokiej klasy maszyny/sprzęt o wysokiej zdolności produkcyjnej i inwestycyjnej, takie jak koparki zgarniakowe, ważne jest aby maszyny te były obsługiwane w sposób niezawodny, zapewniający maksymalizację zysku. Dlatego też, zastosowanie analizy niezawodnościowej, która jest niezbędna do oceny niezawodności użytkowania i częstotliwości uszkodzeń, pozwala na planowanie czynności serwisowych pomagając utrzymać maszyny w stanie gotowości do pracy. W niniejszym artykule zamodelowano, na podstawie Procesu Odnowy (Renewal Process, RP), uszkodzenia mechaniczne dwóch koparek zgarniakowych. Podstawowe założenia RP o niezależność i identyczności rozkładu danych sprawdzono za pomocą wykresów funkcji autokorelacji. Oceny niezawodności dla różnych przedziałów czasowych dokonano według rozkładu najbardziej odpowiadającego danym, którym okazał się rozkład Weibulla. Dodatkowo, rozkładu tego użyto także do określenia przerw konserwacyjnych dla badanych maszyn. Na koniec analizowane koparki zgarniakowe porównano pod względem niezawodności.

Słowa kluczowe: niezawodność, koparka zgarniakowa, uszkodzenia.

In modern mines that use different types of sophisticated machine/equipment with high production capacity and investment such as draglines, it is important that the machine should be operated in a reliable way in order to maximize profits. In this manner, the reliability analysis is essential to assess mission reliability and frequency of failure so that this information can be used to plan maintenance activities to help for keeping the machines at operational state. In this paper, mechanical failures of the two draglines have been modeled on the basis of Renewal Process (RP). Whether or not the data is independent and identically distributed which is the basic assumption of RP has been checked by use of Autocorrelation Function Plots. Reliability estimates for different time intervals have been made according to best-fit distribution which was found as Weibull. Additionally, the distribution has been also used for estimating the maintenance intervals of the machines. Finally, the draglines have been compared in terms of reliability.

Keywords: reliability, dragline, failures.

1. Introduction

A system is a collection of two or more parts which is designed to perform one or more function. Systems subject to failures can be categorized into two groups: the non-repairable and the repairable ones. Any system that can be restored to operating condition in the event of failure is defined as a repairable system. On the other hand, any system that can not be brought back to working condition after experiencing a failure is defined as non-repairable system. Mining equipment such as shovels, trucks, draglines etc are repaired when they fail. Thus they are good examples of repairable system.

When dealing with repairable systems, reliability is commonly modeled by using the five main stochastic process models which are The Renewal Process (RP), The Homogenous Poisson Process, The Branching Poisson Process, The Superposed Renewal Process and The Non-Homogenous Poisson Process (NHPP). The RP and NHPP are well-known models used to study the reliability of mining machines by analyzing the failure data collected over a period of time (Table 1). If a system in service can be repaired to "good as new" condition following each failure, then the failure process is called as a renewal process[20]. A renewal process is stationary. Any non-stationary model which permits the modeling of trend in the number of

failures to be found in an interval in relation to total age of the system through the intensity function is called as a NHPP.

Some reasons to accomplish reliability analysis of mining machines as well the other repairable systems are to detect an oncoming failure, to determine maintenance time interval and to compare the similar machines in terms of failure characteristics and maintenance needs. In this scope, this study deals with the reliability analysis of mechanical subsystems of two draglines used in a state-owned coal company. The methodology followed in this study is given in Figure 1 which is a detailed flowchart of reliability modeling for repairable systems such as mining machines.

2. Reliability

Reliability is defined as the probability that a system, component, or device will perform its intended function satisfactorily without failure for a specified time period under a given condition. Thus, reliability is related to the probability of successful performance of any system.

Let T be the time-to-failure random variable. Then reliability at time t , $R(t)$, is the probability that the system will not fail by time t ,

$$R(t) = P(T > t) = 1 - P(T \leq t) = 1 - F(t) = 1 - \int_0^t f(t)dt \quad (1)$$

Tab. 1. Some Reliability Studies of Mining Machines Using the RP and NHPP

Year	Author (s)	Machine	RP	NHPP
1989[2]	Kumar, U.	LHD ¹	*	
1992[3]	Kumar, U. and Klefsjö, B.	LHD		*
1993[4]	Kumar, D. and Vagenas, N.	LHD	*	
1994[5]	Paraszczak, J. and Perreault, J.F.	LHD	*	
1995[6]	Majumdar S.K.	Hydraulic Excavator		*
1997[7]	Vagenas, N. et al	LHD	*	*
2001[8]	Pulcini G.	Rear Dump Truck, LHD		*
2001[9]	Rao K.R.M. and Prasad P.V.N.	LHD		*
2001[10]	Samanta, B. et al	Hydraulic Shovel	*	*
2003[11]	Hall, R.A. and Daneshmend, L.K.	Hydraulic Shovel	*	
2003[12]	Hall, R.A. and Daneshmend, L.K.	Scoops and Trucks	*	
2004[13]	Lhorente B. et al	Electric Haul Truck	*	
2005[14]	Barabady J. and Kumar U.	Crushing Plant	*	*
2007[15]	Barabady J. and Kumar U.	Crushing Plant	*	
2008[16]	Elevli S. et al	Electric Shovel	*	
2008[17]	Barabady J. and Kumar U.	Crushing Plant	*	*
2009[18]	Gupta S. et al	Armoured Flexible Conveyor	*	
2009[19]	Louit D.M. et al	Backhoe		*
2009[20]	Vayenas N. and Wu X.	LHD	*	

¹ Load Haul Dump Machine

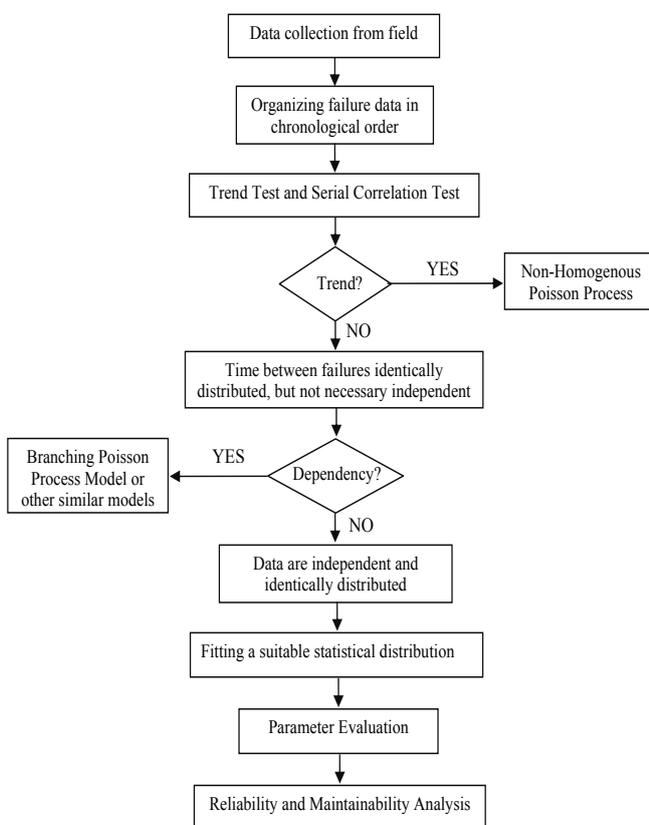


Fig. 1. Basic Methodology of Reliability Modeling. [Adapted from Samanta et al[10] and Barabady and Kumar [17]]

Where $f(t)$ and $F(t)$ are the probability density function and cumulative distribution function, respectively.

The Mean Time between Failures (MTBF) is a key reliability metric for systems that can be repaired or restored. It is defined as the mean time that a system works without failure. MTBF may be calculated either by the average of operation time before a failure occurred or by taking the mean of the failure distribution. Then, from the definition of a mean or expected value,

$$MTBF = \int_0^{\infty} tf(t)dt = \int_0^{\infty} [1 - F(t)]dt = \int_0^{\infty} R(t)dt \quad (2)$$

Distributions that describe the time-to-failure, the time it takes for a component to fail, are called as failure distributions or lifetime distributions. Commonly used failure distributions which are Exponential, Lognormal, Normal and Weibull are briefly presented in table 2.

3. Data analysis

3.1. Data collection

The raw maintenance data of two draglines (defined as D1 and D2) which operate on different coal panels have been obtained from the operational and maintenance records of Tuncbilek Coal Mine, Turkey. Since obtaining reliable and accurate results depend on the existence of quality failure data, mechanical failures have been decided to deal with after examining raw data. The primary problem with the data covering the period of 5 years (2004-2008) was the lack of information concerning time between failures (TBF). For overcoming of this problem, tables have been designed to compute the TBF by using the available data which are failure type, failure date and time, repair duration and shift hours.

Tab. 2. Failure Distributions

Distribution	Exponential	Lognormal	Normal	Weibull
Probability Density Function	$f(t) = \lambda e^{-\lambda t}$	$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\ln t - \mu)^2}{2\sigma^2}}$	$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}$	$f(t) = \beta\alpha^{-\beta} t^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^\beta}$
Parameters of Distribution	$\lambda = \text{Failure Rate}$	$\mu = \text{Mean (Log scale)}$ $\sigma = \text{Std.Dev. (Log scale)}$	$\mu = \text{Mean}$ $\sigma = \text{Std. Deviation}$	$\alpha = \text{Scale Parameter}$ $\beta = \text{Shape Parameter}$
MTBF	$MTBF = 1/\lambda$	$MTBF = e^{(\mu + \sigma^2/2)}$	$MTBF = \mu$	$MTBF = \alpha\Gamma(1 + 1/\beta)$
Standard Deviation	$\sigma = 1/\lambda$	$\sigma = \sqrt{e^{2\mu + \sigma^2}(e^{\sigma^2} - 1)}$	$\sigma = \sqrt{\frac{(t-\mu)^2}{N}}$	$\sigma = \alpha\sqrt{\Gamma(1 + 2/\beta) + \Gamma^2(1 + 1/\beta)}$
Reliability	$R(t) = e^{-\lambda t}$	$R(t) = 1 - \Phi\left(\frac{\ln t - \mu}{\sigma}\right)$	$R(t) = 1 - \Phi\left(\frac{t - \mu}{\sigma}\right)^{**}$	$R(t) = e^{-(t/\alpha)^\beta}$

* $\Gamma = \text{Gamma Function}$

** $\Phi(z)$ is the cumulative distribution function for the standard normal variable (z).

3.2. Assessing the presence of trend and serial correlation

The next step after the sorting and classification of the data is the validation of the independent and identically distributed (iid) nature of the data of each dragline. The methods available to determine whether or not data is independent and identically distributed mentioned in reliability literature can be divided into two groups: Graphical Methods (Cumulative Failures vs. Time Plot, Scatter plot of Successive Service Lives, Nelson- Aalen Plot, Total Time on Test Plot) and Analytical Methods (The Mann Test, The Laplace Test, The Lewis- Robinson Test, The Military Handbook Test) [19]. In addition to these methods, Autocorrelation Function Plot (ACF Plot) which is not common in reliability literature can be used for this aim. In this study, ACF plot has been used to assess the presence of trend and serial correlation.

In the case that the value of a particular variable is dependent on previous values of this variable, autocorrelation is present in data. Autocorrelation is also sometimes called “lagged correlation” or “serial correlation”. The set of autocorrelation coefficients arranged as a function of separation in time is the Autocorrelation Function (ACF). The quantity r_k is called the autocorrelation coefficient at lag k. In order to visually assess the autocorrelation in a set of time-ordered data, ACF plots that show non-zero or significant autocorrelations are usually used.

The plot of the autocorrelation function as a function of lag is also called the correlogram. The lag-1 coefficient observed in ACF plot is often (but not always) adequate for giving a rough indication of the amount of serial correlation in a series.

Figure 2 and 3 shows the ACF plots of the D1 and D2 respectively. The straight lines on the graphs which are useful in detecting nonzero correlations are two standard deviation limits. If the probability limits at a particular lag do not contain the estimated coefficient, there is a statistically significant correlation at that lag at the 95% confidence level. However, any given r_k has a 5% chance of being outside the 95% confidence limits, so that one value outside the limits might be expected in a correlogram plotted out to lag 20 even if the time series is drawn from a random (not autocorrelated) population. Thus, Figure 2 and 3 revealed that there is no indication for the presence of correlation and trend. That means, Time between Failures (TBF) data of the two draglines are independent and identically distributed.

3.3. Determining best-fit theoretical probability distribution

As no trend and correlation was identified in data, the renewal approach is valid for modeling the failure data (see figure 1). Therefore, we can continue the reliability analysis fitting

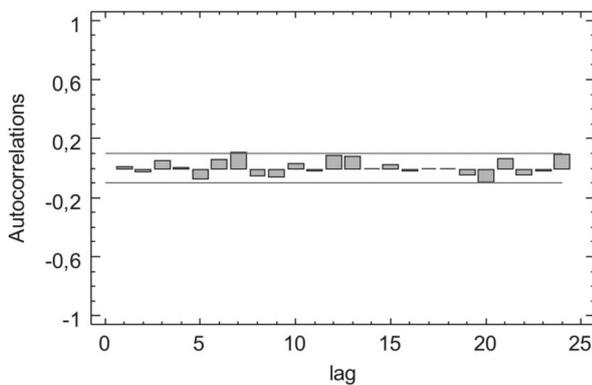


Fig. 2. ACF Plot for D1

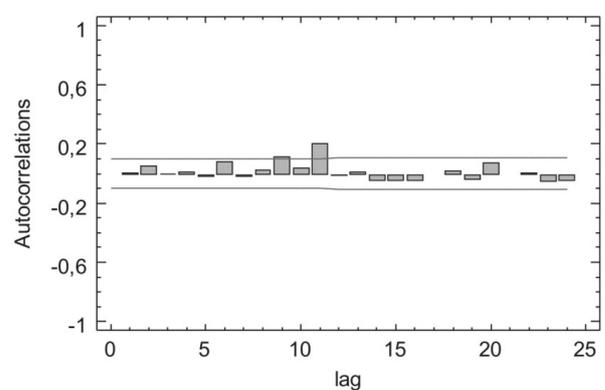


Fig. 3. ACF Plot for D2

Tab. 3. Best-Fit Theoretical Distribution for D1

Distribution	Estimated Parameter	K-S Test [DN, (P-value)]*	MTBF (h)
Exponential	$\lambda = 0.0103$	0.0738 (0.0216)	97.2453
Lognormal	Log scale: mean=3.9385 Log scale: std. dev.=1.2354	0.0628 (0.0760)	110.1260
Normal	Mean=97.2453 Standard deviation=122.51	0.2160 (0.0000)	97.2453
Weibull**	Shape (β)=0.9140 Scale(α)=92.8228	0.0457 (0.3535)	97.0282

*P-values less than 0.05 would indicate that TBF does not come from the selected distribution with 95% confidence.
**The best distribution for D1 is Weibull distribution.

Tab. 4. Best-Fit Theoretical Distribution for D2

Distribution	Estimated Parameter	K-S Test [DN, (P-value)]*	MTBF (h)
Exponential	$\lambda = 0.0131$	0.0679 (0.0492)	76.1203
Lognormal	Log scale: mean=3.7157 Log scale: std. dev.=1.2124	0.0613 (0.0975)	85.6855
Normal	Mean=76.1203 Standard deviation=101.3860	0.2271 (0.0000)	76.1203
Weibull**	Shape (β)=0.9263 Scale(α)=73.1569	0.03867 (0.5847)	75.7989

*P-values less than 0.05 would indicate that TBF does not come from the selected distribution with 95% confidence.
**The best distribution for D2 is Weibull distribution.

a distribution given in table 2 to TBF data. The parameters of distributions estimated by using Statgraphics software were tabulated in table 3 and 4. The Kolmogorov-Smirnov test has been used to decide if the failure data comes from a population with a specific distribution. These tables reveals that the TBF data of draglines is best modeled using the Weibull Distribution.

3.4. Comparison of D1 and D2

Reliability estimates of the draglines have been made for different time intervals by taking their best-fit distribution (Table 5). It is clearly seen that reliability decreases as the time intervals increase. However, the decreasing rate of reliability of D2 is considerably higher than D1. For 10 hours of operation, the probability that the machine will not fail is 0.88 for D1 and 0.85 for D2. On the other hand for 140 hours the reliability estimates are 0.23 and 0.16 respectively. The difference between D1 and D2 is increasing as the mission time increases. The results are also shown graphically in figure 4.

Besides, MTBF or Expected Time to Next Failure for D1 and D2 were found to be 97.0282 and 75.7989 hours respectively as seen in table 4 and 5. Both MTBF and reliability values indicate that D2 is less reliable than D1. The reasons for that might be the different environmental conditions, working period without major revision, and capacity of draglines. The capacity of D2 is twice of D1 and it operates 500 hours more than D1 annually as seen in table 6. The working environment

of dragline D2 has a slope of about 5° with faults and cracks. The dragline D1 works on the flat surface and there is no fault on ground. The major revision was carried out about 6 years ago for the Dragline D1 and 14 years ago for D2.

It is known fact that the reliability of a machine can be improved by means of Preventive Maintenance (PM). PM is

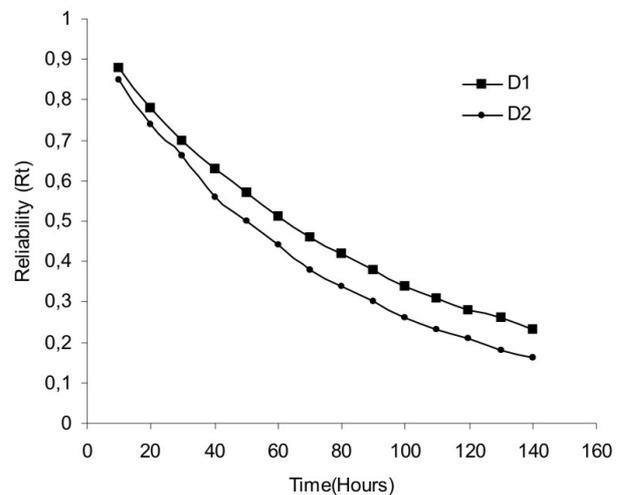


Fig. 4. Reliability of D1 and D2 for different time intervals

Tab. 5. Reliability R(t) of the Draglines D1 and D2 at the different time intervals

Dragline	Time (t) in Hours													
	10	20	30	40	50	60	70	80	90	100	110	120	130	140
D1	0.88	0.78	0.70	0.63	0.57	0.51	0.46	0.42	0.38	0.34	0.31	0.28	0.26	0.23
D2	0.85	0.74	0.66	0.56	0.50	0.44	0.38	0.34	0.30	0.26	0.23	0.21	0.18	0.16

Tab. 6. Parameters of draglines used in the mine

Dragline	Year	Bc (m ³)	Bl (m)	Ba (°)	Or (m)	MI (t)	Wm (t)	Dd (m)	Aw (h)
D1	1969	15.3	62.5	36	59	42	795	22	4500
D2	1977	30.6	72.0	33	70	86	1500	35	5000

Bc: Bucket capacity; Bl: Boom length; Ba :Boom angle; Or: Operating radius; MI: Maximum allowable load; Wm: Working mass; Dd: Digging depth; Aw: Annual working hours

carried out at preplanned time intervals to prevent future random failures of the machine. The inspections during PM help to identify faults requiring correction while they are still minor, before they give way to major failures. The PM time intervals for different levels of reliability are calculated and tabulated in table 7. Thus, to achieve 90% reliability, maintenance activities must be carried out before 7.91 hours for the D1 and 6.44 hours for the D2. For a reliability level of 90%, however, the estimated maintenance interval is too short for practical implemen-

tation. Therefore the maintenance interval for 75% and 70% reliability levels may be adopted initially, which is about 23.75 hours for D1 and 24.04 hours for D2 corresponding approximately to a one day operation.

4. Conclusion

Economic sustainability of the mining activities requires machines with high reliability. Therefore, reliability has become the main concern of mine managers. In this study, the data of two draglines have been analyzed for reliability purposes. Main motivation behind the selection of dragline is their effect in successfully meeting the production target of coal mine. This study showed that reliability analysis is very useful for understanding the failure characteristics of the machines and deciding an appropriate maintenance interval. Another conclusion drawn from this study is that the same type of machines might require different maintenance intervals due to their different working environmental conditions. Therefore the reliability of each machine should be evaluated separately for effective maintenance scheduling.

Tab. 7. Reliability-based preventive maintenance time Intervals for D1 and D2

Reliability Level	Maintenance Interval, hours	
	D1	D2
0.90	7.91	6.44
0.85	12.71	10.29
0.80	17.99	14.49
0.75	23.75	19.06
0.70	30.05	24.04

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Assoc. Prof. Dr. Nevin UZGÖREN

Dumlupınar University
Department of Business Administration
43270, Kütahya, Türkiye
e-mail: nuzgoren@dpu.edu.tr

Assoc. Prof. Dr. Önder UYSAL

Dumlupınar University
Mining Engineering Department,
43270, Kütahya, Türkiye
e-mail: uysal@dpu.edu.tr

Assoc. Prof. Dr. Sermin ELEVLI

Prof. Dr. Birol ELEVLI
Ondokuz Mayıs University
Industrial Engineering Department
55139, Samsun, Türkiye
e-mail: sermin.elevli@omu.edu.tr
e-mail: birol.elevli@omu.edu.tr
