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Reliability and Risk Assessment of Electric Cable Shovel at Chadormalu Iron Ore Mine in Iran

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ABSTRACT

Nowadays, shovels play an important role in production of open pit mines and their failures result in significant production loss and considerable increase in maintenance costs. Therefore, reliability and risk analysis can help to improve production, productivity and reduce production costs. In this study, reliability of electric cable shovel of Chadormalu iron ore mine in Iran was investigated. Failure distribution function of the subsystems whose failure information is available was provided by statistical analysis using EasyFit 5.5, Minitab 18 and the subsystems with low or unavailable failure information which was generated by experts using normal distribution function. Criticality of subsystems was determined using Birnbaum and Fussell–Vesely importance measures reliability. Results showed that reliability of cable shovel has reached to zero after 40 hours and subsystems of crowd gearbox, swing gearbox, lubrication and bucket door are the most critical subsystems.

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1. INTRODUCTION

According to the growth of technology, complexity of systems and emphasis on product quality and efficiency of systems to gain more profit, reliability and maintainability becomes one of the main principles. Transport fleet performance in open pit mines effects mine production system and mining contractors have focused on not only amount of specified production but also performance of their machine transportation system for continuous production. The study of reliability and maintainability strategy plays an important role in operational process of system. This requires an effort to study, specify, measure and analyze the behavior of systems by reducing the failure probability which consequently increases life time and availability. Reliability analysis of different mining machines was investigated by many researchers. In recent decades, Roy et al. [1] studied reliability and maintainability of four electric rope shovels. Graphical method was applied for independent and identically distributed failure and repair data. Chi-squared test and Kolmogorov-Smirnov (K-V) method was implemented to find the best distribution function. Samantha et al. [2] examined reliability of three shovels machines using Fault Tree Analysis. They divided the shovel into six subsystems, including hydraulic, engine, transmission, track, bucket and others. Samantha et al. [3] studied reliability, maintainability and availability of Load-Haul-Dump (LHD) machine using repair and failure data by Markov modelling method. They divide the LHD machine into six major subsystems such as a power generating unit/drive unit, transmission, hydraulic, tire, brake and others, and a bucket connected in series. Hall and Daneshmand [4] considered different methods for analyzing and collecting failure and repair data in open pit mine machines. First, they described collecting sources related to mining machine in order to analyze reliability. Then, they examined statistical method to find distribution function of failure time and machine maintainability. Finally, reliability and maintainability of five hydraulic shovels was investigated using this method. Gupta et al. [5] studied the reliability of shearer in one of India's coal mine using Fault Tree Analysis. Failure distribution of 55 basic events were investigated by two-parameter Weibul distribution and these factors were ranked by Birnbaum

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factor. It was suggested that maintenances with higher rank failures should be prioritized. Gupta and Bhattacharya [6] considered a reliability of an armoured flexible conveyor (AFC) for an underground longwall mine. They used Birnbaum/Fussell-Vesely indicator to prioritize main failures. Barabady and Kumar [7] evaluated reliability of crushing plants at Jajarm Bauxite Mine in Iran. They presented a new modeling method for reliability analysis of maintainable systems which was considered by other researchers.

Elevli et al. [8] evaluated the maintainability of 7 electric cable shovels in an open cast mine in Turkey using statistical methods. Pratama et al. [9] conducted their studies on the fleet of open pit mining which includes 12 excavators. They divided excavator machine into 7 subsystems: hydraulic, optional accessories, electrical, engine, attachment/work equipment, undercarriage and other. Statistical analysis method was applied to obtain total reliability of the system and was considered reliability of undercarriage and other systems equal 1. Uzgören et al. [10] studied the reliability of two draglines in Turkey coal mine. Autocorrelation Function Plot (AFC) was implemented for trend and correlation test of failure data. Esmaeili et al. [11] investigated the reliability of three loaders in Sangan iron ore mine for a twelve-month period (2006-2007). They considered 9 subsystems for loader: Engine, electrical, Hydraulic, preventive maintenance, bucket, braking, structural, transmission and tire.

Hosseini et al. [12] considered shearer reliability in Tabas longwall mine in Iran. They divided the shearer into six subsystems (water, haulage, hydraulic, electrical, cable and cutting arms) with serial structure. they presented reliability of each drum shearer subsystem separately. Jain et al [13] discussed reliability characteristics based on coverage factors and fuzzy logic using a developed Markov model for repairable systems. Kumar and Ram [14] analyzed availability, reliability, MTTF, sensitivity analysis and cost-effectiveness of a coal handling unit of a thermal power plant using Laplace transforms and differential equations. Rahimdel et al. [15] studied reliability of four rotary drilling machines in Sarcheshmeh Copper Mine in Iran. They divided this machine into five subsystems as follows: hydraulic, electrical, pneumatic, drilling and transmission. Since hydraulic system plays an important role in drilling machines and a failure in this system leads to major problems in power machines, reliability of hydraulic subsystem was studied using statistical method. Deka and Chattopadhaya [16] studied reliability of two bulldozers in which failure data is low. The number of failures in these two machines were ten and weibull distribution was used to calculate reliability and failure rate of two bulldozers. Furuly et al. [17] analyzed the reliability and maintainability the main conveyor in the Svea Coal Mine in Norway. In this study, six conveyors were nominated for analyzing. El-Damcese et al. [18] used triangular fuzzy failure rates to consider uncertainty of data failures and evaluated reliability analysis for series and parallel systems. Nuri et al. [19] considered failure probability in crushing plant and mixing bed hall at Khoy cement factory in Iran, using fault tree analysis. Morshedlu et al. [20] presented preventive maintenance time of power supports in Tabas coal mine, using statistical methods and suggested preventive maintenance time intervals based on 80 percent reliability. Dindarlu [21] forcasted time between failures of LHD machine using Support Vector Regression (SVR) method. Moniri et al. [22] studied reliability-based maintenance in order to improve the performance of copper mine truck in Sungun in Iran. The trucks include six major subsystems: engine, transmission, hydraulics, electrical, body and frame and tires. They were also divided into 24 minor subsystems and a statistical method was used to analyze reliability and repair of all subsystems. Truck availability was calculated using Monte-Carlo simulation approach. Allahkarami et al. [23] studied reliability engine system of dump trucks in Miduk copper mine in Iran. Optimal maintenance intervals were assumed 21 hours according to confidence level of 90 percent reliability. Nuri et al. [24] evaluated reliability of crusher system in in Khoy cement factory, using statistical method. They considered confidence level of 90 percent reliability for preventive maintenance purpose. In 2017, they [25] also calculated the reliability of loader system in Songun copper mine in Iran, using regression model which was introduced as Proportional Hazards Model (PHM). This model consisted two functions according to time-dependent data and risk factors.

In this paper, reliability of cable shovel of Chadormalu mine in Iran was evaluated. This machine was divided into 7 major subsystems and 27 minor subsystems in a serial structure and failure distribution function of the subsystems with available failure data was determined, using statistical method. The subsystems with unavailable failure data was analyzed according to experts' opinion and Weibull distribution. Moreover, criticality of each subsystem was calculated by importance measures Birnbaum and Fussell–Vesely.

2. RESEARCH METHODOLOGY

In this section, modelling approach for reliability is described and evaluating failure risk by Birnbaum and Fussell–Vesely importance measures is defined.

2. 1. Reliability Modelling Time between failure (TBF) and time to repair (TTR) distribution function are considered as important contributions to calculate reliability. Thus, finding the best probability density function is the first step for this purpose. The proposed algorithm is presented in Figure 1 in order to analyze reliability and maintainability [2,7,12]. According to this figure, two evaluation stages are carried out to recognize data type and select the best modelling method. In the first stage, data are evaluated for the trend test. Nonhomogeneous Poisson process is used to analyze reliability and maintainability where there is no trend. Otherwise, correlation test is applied. According to the existence of data correlation, methods of homogenous Poisson process, such as Poisson branching process are chosen for modeling. If there is not any trend or correlation, data are identically and independently distributed and the proposed method is classic statistic and renewable process. In this case, in order to find the best distribution function among different distribution functions, Kolmogorov–Smirnov test and Anderson-Darling test are utilized. U statistical test is used for trend test by Equation (1) [15]:

$$U = 2\sum_{i=1}^{n-1} ln(T_n / T_i) \tag{1}$$

where, n is total number of failures, T_n is time of the nth failure and T_i is time of the ith failure. In this method, null hypothesis is that data do not follow any trend. According to this hypothesis, U indicator has a Chi-Square Distribution and the degree of freedom is 2(n-1). If U is greater than the critical number in the standard table, the null hypothesis will be accepted at 95 percent confidence level.

Serial correlation test of data is carried out graphically by plotting the ith TBF against (i-1)th TBF. If the plotted points do not follow a special trend and randomly scattered without any clear pattern it can be inferred that the data are free from serial correlation or independent [11,23].

In some systems and subsystems, maximum number of failure is one in the considered time interval. In order to find distribution function of these subsystems, their failure data must be collected within minimum 5 to 6 years. To cope with this problem, opinions of experts in maintenance section are used [6, 26, 27]. Gupta and Bhattacharya [6] used Weibull distribution function (shape and scale parameters are 1 and mean time between failure (MTBF) is based on experts' opinion) to evaluate reliability of AFC conveyor for the subsystems whose data are unavailable or not existed. This function is equivalent to an exponential function with a failure rate of 1/MTBF [28].

Another approach for failure distribution function is using experts' opinions according to average TBF in a time interval with 75 percent confidence level. For example, suppose that expert opinion on TBF is 4500 ± 700 for system A. Failure distribution function for system A is a normal distribution with mean 4500 and standard deviation 608.7. Standard deviation is calculated as follows:

$$Z_{\frac{\alpha}{2}} \frac{\delta}{\sqrt{n}} = 700 \qquad (Z_{\frac{\alpha}{2}} = 1.15, n = 1) \qquad \rightarrow \delta = 608.7$$

Figure 2 illustrates system reliability according to the mentioned approach. At the minimum acceptable confidence level of 0.8, the optimal maintenance intervals for weibull and normal distribution are 1000 and 4000 hours, respectively. According to the experts' opinions, normal distribution is used to describe failure distribution of system A.

2. 2. Evaluating Failure Risks

In reliability analyzing, importance measure is applied to recognize and rank the most critical subsystems. In this paper, two importance measures e.g., Birnbaum and Fussell–Vesely were selected. Birnbaum measure is obtained by the following Equation (2) [29]:

$$I^B(i|t) = \frac{\partial R(t)}{\partial R_i(t)} \tag{2}$$

where R (t) is the total reliability of the system and Ri (t) is reliability of ith system at time t. This measure shows the increase in total reliability of system by increasing reliability of ith system. In other words, this measure depends on both subsystem reliability and position of system.

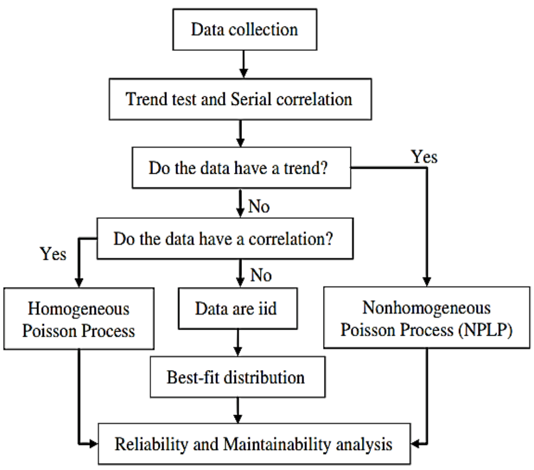

Figure 1. Process of reliability analysis in maintainable systems [7, 12]

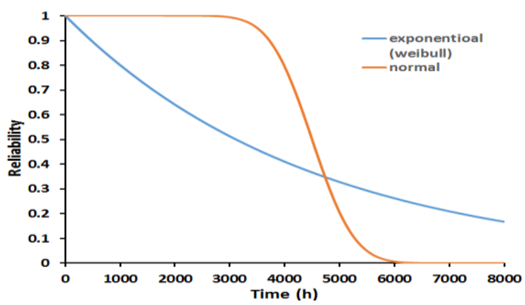

Figure 2. Reliability of system A with normal, Weibull and exponential distribution functions

Fussell–Vesely importance measure shows the probability of minimum failure in a minimal cut set in which ith piece is corrupted at time t (Equation (3)) [28].

$$I^{FV}(i|t) = \frac{Pr(D_i(t))}{Pr(C(t))} \quad (3)$$

$Pr(C(t))$ is the probability of failure at time t and $Pr(D_i(t))$ is the probability of minimal cut set which contains ith piece at time t. A minimal cut set fails when all the pieces of this set fail. Thus, Fussell-Vesely's importance measure indicates that a special piece can fail without a critical failure for the system.

3. CASE STUDY

Cable shovel P&H 2100 BL Chadormalu iron ore mine in Iran is the case study of this research, which produces 2100 iron ore per hour. Figure 3 shows a picture of cable shovel.

Cable shovel subsystems are introduced according to some researches [2,7-9,11] and experts' opinions in Chadormalu iron ore mine as follows:

Cable system: it consists of three different cables (suspension, trip and hoist cable). The suspension cable connects the boom to gantry. Trip cable opens the dipper door and hoist cable links the bucket of the shovel to the hoist drum.

Dipper system: Dipper (Bucket) consists of body, door, tooth, arc and clutch. hoist cable links to the bucket by its arc in order to lift it and the clutch links the door to the bottom of the bucket.

Stick system: Stick links the bucket from one side and boom the other side. At the bottom of the stick, there are racks that allow the origination of movements as forward and backward movements. The stick can also move upwards and downwards around the connecting axis which is done by changing the hoist cable length.

Undercarriage system: Chains or crawler shoes, rollers, idler, tumbler and frame are closed on the chassis of the wheel.

Engine and transmission system: This system consists of crowd, propel, trip, swing, main motor, magnetorque, and chain case. Main motor is the most important part of a shovel. It moves the magnetorque (magnetic induction) and rotates it so that the hoist gearbox moves and the bucket lifts. Also, it moves the chain case gearbox and makes the swing generator and crowd/propel generator to swing in order to supply the power for swing, crowd and propel engines. Crowd, propel and trip engines are located outside the mobile chassis and in a free space.

Pneumatic system: In the cable shovel, lubrication, brake and horn are carried out by wind forces. Thus, this system contains the subsystems of lubrication, brake, horn and wind transfer system.

Electrical system: This system includes sections such as electric current transfer path from the fixed chassis to the mobile chassis (slip rings), high voltage Alternating Current (AC), low voltage AC and Direct Current (DC) circuits.

In Figure 4 major and minor subsystems of cable shovel is illustrated. Since failure in any system or subsystem leads to machine breakdown, all seven systems and subsystems are considered serially. Figure 5 represents the reliability block diagram of major systems of cable shovel. Failure data of systems and subsystems are collcted for cable shovel within 15 months interval through reports of maintenance unit in Chadormelou mine.

Failure data of cable shovel subsystems have no trend and correlation. Thus, renewable process and classic statistics are applied using Minitab 18 and EasyFit 5.5 software. Table 1 shows trend test for hoist cable subsystem using U test. Figure 6 illustrates serial correlation of this subsystem graphically.

Table 2 indicates the best distribution function for TBFs of different cable shovel subsystems using Kolmogorov-Smirnov test and Anderson-Darling test. Easyfit software cannot detect distribution function with less than 5 failures. Thus, Minitab software is implemented to find the best distribution function. This software uses Anderson-Darling test for the proposed purpose.

Figure 3. Cable shovel P&H 2100 BL

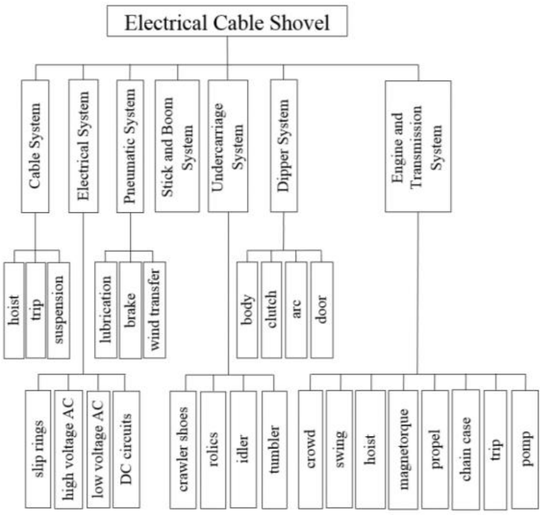

Figure 4. major and minor subsystems of cable shovel

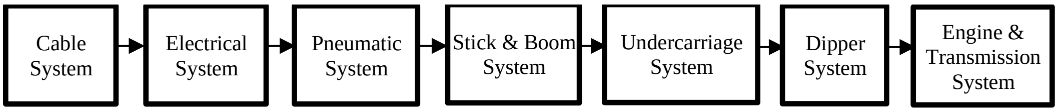

Figure 5. Reliability block diagram of cable shovel

TABLE 1. Trend test of hoist cable subsystem using U test

subsystem	Number of failure	Degree of freedom	Calculated statistic U	Rejection of null hypothesis at 5% level of significance	Modeling method
Cable hoist	17	32	20.21	20.07	Renewal process

TABLE 2. Best distribution function for TBFs of different cable shovel subsystems

Systems	Subsystems	Kolmogorov-Smirnov (K-S) test						Best-fitted distribution	Parameters
		Exponential	Gamma	Lognormal	Normal	Weibul-2P	Weibul-3P		
Cable	trip	0.139	0.130	0.137	0.231	0.135	0.169	Gamma	α =0.93574 β=197.53
	hoist	0.182	0.162	0.120	0.310	0.144	0.148	Lognormal	μ=4.5393 σ=1.0846
Electric	slip rings	0.253	0.171	0.228	0.270	0.297	0.317	Gamma	α =0.84985 β =401.6
	high voltage AC	0.468	0.126	0.133	0.158	0.170	0.213	Gamma	α =8.7238 β =44.297
	low voltage AC	0.366	0.039	0.038	0.078	0.067	0.034	Weibul-3P	α =24.586 β =1.81 θ =15.086
	DC circuits	0.394	0.064	0.052	0.097	0.092	0.060	Lognormal	μ=3.5515 σ=0.32852
Pneumatic	lubrication	0.102	0.106	0.080	0.183	0.090	0.074	Weibul-2P	α =71.603 β =1.2162
	brake	0.140	0.163	0.155	0.272	0.156	0.148	Exponential	λ =0.00585
	wind transfer	0.166	0.162	0.148	0.166	0.138	0.264	Weibul-2P	α =279.7 β =1.398
Stick & Boom		0.289	0.299	0.302	0.465	0.191	0.266	Weibul-2P	α =517.2 β =1.671
Undercarriage	crawler shoes*	0.213	0.254	0.190	0.269	0.255	0.349	Lognormal	μ=6.105 σ=1.081
Engine and Transmission	crowd*	0.262	0.271	0.252	0.206	0.286	0.325	Normal	μ=834 σ=864.3
	swing*	1.715	0.221	0.180	0.631	0.196	0.471	Weibul-2P	α =327.4 β =0.5003
	hoist	0.212	0.235	0.235	0.260	0.220	0.276	Exponential	λ =0.00357
	magnetorque	0.373	0.263	0.225	0.340	0.251	0.203	Weibul-3P	α=99.126 β=0.61258 θ =21
Dipper	door	0.236	0.148	0.118	0.289	0.117	0.109	Weibul-3P	α=145.13 β=0.60552 θ =7
	clutch	0.183	0.170	0.197	0.166	0.213	0.145	Weibul-3P	α=0.83035 β=185.34 θ =23.0
	arc*	0.293	0.359	0.250	0.250	0.365	0.285	Lognormal	μ=4.721 σ=0.9834

* Since failure number is low (less than 5 numbers of TBF), Anderson-Darling test is applied.

In some minor subsystems, there is no failure in the proposed time interval or there is maximum one failure. According to this approach, failure distribution function for these subsystems were evaluated using experts' opinions and normal distribution function which is summarized in Table 3.

Since systems and subsystems are serial, total reliability is calculated through the multiplication of each subsystem reliability (Equation (4)) [28]:

$$R_{system}(t) = \prod_{i=1}^{n} R(t)_i \tag{4}$$

According to Figure 7, stick and undercarriage system has the highest reliability value. Reliability of electrical system reaches to zero after 50 hours and cable reliability has medium values. Engine and transmission, pneumatic and dipper systems have the same reliability value. Also, reliability of shovel cable becomes zero after 40 hours (Figure 8).

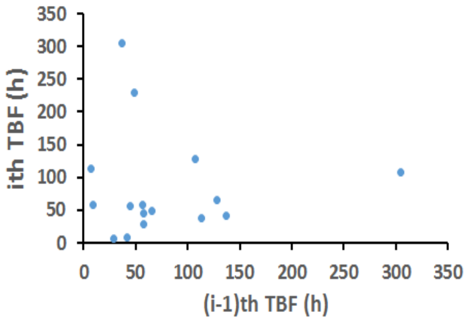

Figure 6. Serial correlation of hoist cable subsystem

TABLE 3. Failure distribution function of the subsystems without historical data

System	Subsystem	Experts' Opinions	Normal Distribution
Cable	Suspension	4500±700	μ=4500 σ=608.7
	Rollers	15000±3000	μ=15000 σ=2068.7
Undercarriage	Idler	2000±500	μ=2000 σ=434.78
	Tumbler	5000±1500	μ=5000 σ=1304.35
	Chain Case	2000±700	μ=2000 σ=608.7
Engine and Transmission	Propel	6000±1500	μ=6000 σ=1304.35
	Trip	3000±500	μ=3000 σ=434.78
	Pomp	5000±1000	μ=5000 σ=869.56
Dipper	Body	3500±500	μ=3500 σ=434.78

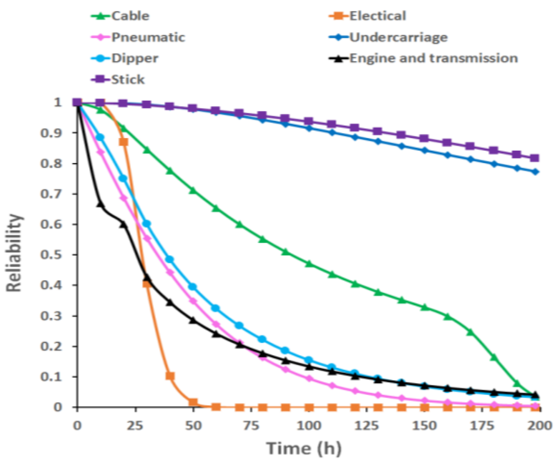

Figure 7. Reliability of shovel cable subsystems

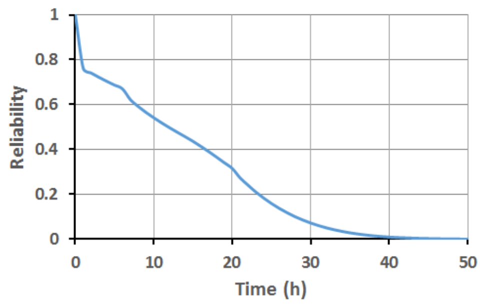

Figure 8. Total reliability of shovel cable

At the following, criticality of shovel cable subsystems is determined using importance measures Birnbaum and Fussell–Vesely. Table 4 illustrates the criticality of subsystems without 10 hours.

TABLE 4. Ranking shovel cable subsystems using Birnbaum and Fussell–Vesely measures in 10 hours

System-subsystem	Reliability	Birnbaum factor	F–V factor	rank by Birnbaum/F–V
C-trip	1.0000	0.4832	-	22
C-hoist	0.9758	0.4951	0.0468	7
C-suspension	1.0000	0.4832	1.59E-13	20
E-slip rings	1.0000	0.4832	-	22
E-high voltage AC	1.0000	0.4832	-	22
E-low voltage AC	1.0000	0.4832	-	22
E-DC circuits	0.9998	0.4833	0.0004	14
P-lubrication	0.9892	0.5353	0.1884	4
P-brake	0.9026	0.5153	0.1206	5
P-wind transfer	0.9377	0.4884	0.0209	9
Stick and Boom	0.9984	0.4840	0.0031	11
U-crawler shoes	1.0000	0.4833	0.0006	13
U-rollers	0.9997	0.4832	8.85E-09	19
U-idler	1.0000	0.4832	4.61E-06	16
U-tumbler	1.0000	0.4832	0.0001	15
D-door	0.9909	0.5413	0.2079	3
D-body	0.8926	0.4832	1.93E-15	21
D-clutch	0.9999	0.4832	-	22
D-arc	0.8327	0.4876	0.0176	10
E&T-crowd	0.9615	0.5705	0.2963	2
E&T-swing	1.0000	0.5803	0.3238	1
E&T-hoist	1.0000	0.5025	0.0745	6
E&T-magnetorque	0.9995	0.4832	-	22
E&T-propel	0.8469	0.4832	4.26E-06	17
E&T-chain case	1.0000	0.4834	0.0010	12
E&T-trip	1.0000	0.4832	6.01E-12	18
E&T-pomp	0.9889	0.4886	0.0215	8

Figure 9 shows the criticality of critical subsystems within [0, 40] interval. Crowd and swing gearbox are the most critical subsystems within 5 hours and lubrication and dipper door subsystems become critical after 15 hours.

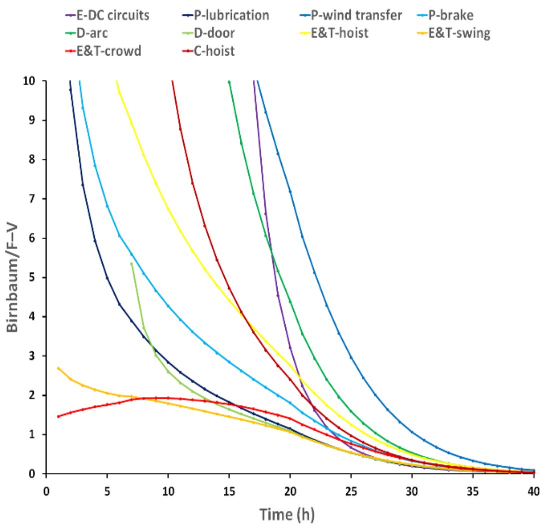

Figure 9. Fussell–Vesely/ Birnbaum measure for ten critical shovel cable subsystems within [0, 40] hour

4. CONCLUSION

In this paper, reliability of cable shovel of Chadormalu mine in Iran was studied and the most critical subsystems of shovel was ranked by their measure of importance. First, cable shovel was divided into 7 major subsystems and 27 minor subsystems serially. Then, failure data of shovel cable subsystems were collected within 15 months using Chadormalu Iron Mine reports. Failure distribution function of available subsystems (18 subsystems) are obtained using classic statistics and Minitab 18 and EasyFit 5.5 software. Failure fitness function of the subsystems with low failure data or without any failure (9 subsystems) was obtained by normal distribution function and experts' opinions. Reliability of cable shovel becomes zero after 40 hours. The most reliability values are major stick and chassis, cable, bucket, pneumatic, gearbox, motor and electrical subsystems, respectively. Criticality of subsystems were evaluated by two measures, Birnbaum and Fussell–Vesely and it was ranked using Birnbaum/F–V measure. The most critical subsystems are crowd gearbox, swing gearbox, lubrication and critical dipper door, respectively.

Compared to other studies on cable shovels, comprehensive research was done on systems and subsystems of shovel, for example pneumatic and electrical systems. Also in the field of mining equipment reliability analysis, the use of reliability importance measures is a new topic. Shovel plays important role in open pit mine production and its failure has a major impact on production. Therefore, determining its critical components through reliability importance measures can be used to make better decisions about maintenance performance, monitoring of sensitive item conditions, spare parts inventory and ultimately helping to improve equipment efficiency and reduce operating costs.

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Reliability and Risk Assessment of Electric Cable Shovel at Chadormalu Iron Ore Mine in Iran

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چکیده

امروزه شاول‌ها نقش مهم و حیاتی در تولید معادن روباز دارند و خرابی آن‌ها منجر به کاهش محسوس تولید و افزایش قابل توجه هزینه نت می‌شود. از این رو تحلیل قابلیت اطمینان و ارزیابی ریسک آن به افزایش تولید و بهره‌وری و کاهش هزینه‌های تولید کمک شایانی می‌کند. در این تحقیق قابلیت اطمینان شاول کابلی معدن سنگ آهن چادرملو در ایران مورد تجزیه و تحلیل قرار گرفت. تابع توزیع خرابی زیرسیستم هایی که اطلاعات خرابی آنها در دسترس بودند با استفاده از آمار کلاسیک و نرم‌افزارهای EasyFit 5.5 و Minitab 18 و برای زیرسیستم‌هایی که اطلاعات خرابی آنها اندک و یا ناموجود بوده با استفاده از نظر خبرگان و تابع توزیع نرمال بدست آمد. همچنین با استفاده از شاخص‌های اهمیت قابلیت اطمینان نظیر فاکتورهای Birnbaum و Fussell–Vesely میزان بحرانی بودن زیرسیستم‌ها تعیین شد. نتایج نشان می‌دهد که پس از ۴۰ ساعت قابلیت اطمینان کلی شاول کابلی به صفر رسیده و زیرسیستم‌های گیربکس کرود، گیربکس سوئینگ، گریسکاری و درب باکت بحرانی‌ترین زیرسیستم‌ها هستند.

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