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MAINTENANCE PLAN FOR A FLEET OF ROTARY DRILL RIGS

HARMONOGRAM UTRZYMANIA I KONSERWACJI FLOTY OBROTOWYCH URZĄDZEŃ WIERTNICZYCH

In this paper a basic methodology was used for the reliability modeling and developing a maintenance program for a fleet of four drilling rigs. Failure and performance data was collected from Sarcheshmeh Copper Mine in Iran for a two-year period. Then the available data was classified and analyzed and reliability of all subsystems and whole rigs were modeled and studied. The failure data showed that, in all rigs, electrical, hydraulic and drilling systems are the most frequent failing subsystems of the machine. The reliability analysis showed that transmission system is the most reliable subsystem in all studied rigs. In order to calculate the reliability of whole fleet, it was assumed that operation of at least two drilling rigs is essential for satisfying the production goals. Therefore, probabilistic possibility of all fleet's states were calculated. In this paper, 80% is selected as the desired level of reliability for developing of preventive maintenance program for each subsystem of the drilling rigs. Finally, the practical approaches were suggested for improving the maintenance operation and productivity of the studied fleet.

Keywords: drilling, reliability, maintenance program, mine

W pracy omówiono metodologię wykorzystaną przy modelowaniu niezawodności i opracowywaniu harmonogramu utrzymania i konserwacji czterech obrotowych urządzeń wiertniczych. Dane o ich funkcjonowaniu i awariach w okresie dwuletnim zebrane zostały z kopalni miedzi Sarchesmeh w Iranie. Otrzymane dane zostały poddane analizie, opracowano modele niezawodności działania wszystkich podsystemów oraz urządzeń w całości. Dane o awariach wykazały, iż układy hydrauliczne i elektryczne we wszystkich urządzeniach wiertniczych wykazywały największa awaryjność. Analizy wykazały, że najbardziej niezawodnym podsystemem we wszystkich urządzeniach okazał się układ przenośnikowy. W obliczeniach całościowej niezawodności dla floty urządzeń przyjęto założenie, iż dla wykonania założonego poziomu produkcji niezbędna jest praca co najmniej dwóch urządzeń wiertniczych. Następnie obliczono prawdopodobieństwo zaistnienia wszystkich możliwych stanów poszczególnych urządzeń. W niniejszej pracy założono niezbędny poziom niezawodności jako 80% przy przygotowywaniu harmono-

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gramu konserwacji i działań zapobiegawczych wykonywanych w odniesieniu do wszystkich podsystemów urządzeń wiertniczych. W końcowej części pracy zaproponowano rozwiązania praktyczne mające na celu usprawnienie programów konserwacji i podniesienie produktywności grupy urządzeń.

Słowa kluczowe: wiertnictwo, niezawodność, konserwacja, kopalnia

1. Introduction

Drilling is the first stage in routine mining operation and its accuracy affects the productivity and efficiency of the rest of the operation. Therefore, having a comprehensive knowledge about the involved machineries especially their reliability behavior and maintenance needs, are essential.

From the brief literature review presented by Hoseinie et al. (2012), it can be concluded that that the reliability of mining machineries and systems have been studied since almost 45 years ago but very few researches have been done on drilling machines. Recently, Rahimdel et al., (2013) has published an article in the field of reliability of drilling operation in Sarcheshmeh Copper Mine using Markov method. In their research, all of possible stages for the fleet of four drilling machines have been considered and the reliability of drilling operation has been analyzed. Furthermore, researches on reliability of these machines had been based on field experiences and engineering judgments. Therefore, in current research for the first time, it has been aimed to study on the operational structure of rotary drilling machines and to define the main manageable subsystems of this important mining machine. Then, a fleet of four rotary drilling machines in Sarcheshmeh Copper Mine in Iran was selected to reliability modeling and analyzing. Regarding to the results of reliability modeling, the preventive maintenance plan has been suggested and finally, the effects of this plan on improvement of the fleet reliability have been discussed.

2. Rotary drilling machine

All the rotary drilling machines are composed of similar operational components and are made by putting together many assemblies. These assemblies are very costly and have many small parts (Gokhale, 2011). Various available machines (manufactured by different companies) have differences only in their technical and operational characteristics, e.g. rod length, motor power, maximum rotation speed etc. The general structure of rotary drilling rigs consists of: drive and feed unit, transmission, electric system block, compressor and pneumatic system, drilling assembles, hydraulic pumps and motors, oil tank and hydraulic system.

In this paper, according to the operation manuals of the existent drilling machines in case study mine, maintenance reports and field observations, five main subsystems were defined for this machine. These are connected in series configuration and are; hydraulic system, electrical system, pneumatic system, drilling assembles (will be called drilling system) and crawler assembles (will be called transmission system). The block diagram of a typical drilling machine can be seen in Figure 1.

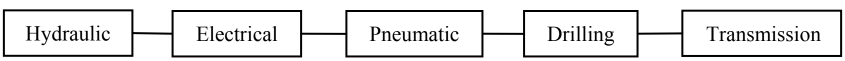

Fig. 1. Block diagram of rotary drilling machine

3. Reliability Modeling

Reliability is the probability of equipment or processes to function without failure when operated correctly for a given interval of time under stated conditions (Dhillon, 2008).

The reliability characteristic of equipment can be determined by analyzing of the time between failures (TBF) data. Failures occurring in repairable systems are the result of discrete events occurring over time. These processes are often called stochastic point processes (Modarres, 2006). The analysis includes the homogeneous Poisson process (HPP), the renewal process (RP), and the nonhomogeneous Poisson process (NHPP). A renewal process is a counting process where the inter-occurrence times are independent and identically distributed with an arbitrary life distribution (Rausand & Høyland, 2004). Upon failure, the component is thus replaced or restored to an as-good-as-new condition. The NHPP is often used to model repairable systems that are subject to minimal repair. Typically, the number of discrete events may increase or decrease over time due to trends in the observed data. An essential condition of any homogeneous Poisson process (HPP) is that the probability of events occurring in any period is independent of what has occurred in the preceding periods. Therefore, an HPP describes a sequence of independent and identically distributed (iid) exponential random variables.

Conversely, an NHPP describes a sequence of random variables that are neither independent nor identically distributed. To determine whether a process is an HPP or NHPP, one must perform a trend analysis and serial correlation test to determine whether an iid situation exists (Klefsj¨o & Kumar, 1992).

The data sets can be analyzed for the presence of trends by using the test suggested in military hand book-189 by calculating the test statistic as follows (MIL-HDBK-189).

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

where, the data are failure-truncated at the n^{th} failure at time T_n.

Under the null hypothesis of a homogeneous Poisson process, the test statistic U is chi-squared distributed with a $2(n-1)$ degree of freedom.

The presence of serial correlation can be tested by plotting the i^{th} TBF against $(i-1)^{\text{th}}$ TBF. If the plotted points are randomly scattered without any pattern, it can be interpreted that the TBFs are free from serial correlation.

4. Case Study; Sarcheshmeh Copper Mine

Sarcheshmeh Copper Mine is located in south-east of Iran and is the largest open pit mine of Iran. The annual production of the mine is 14 million tons. A fleet of four electrical-hydraulic rotary drilling machines (named as A, B, C and D) are used in this mine. Technical characteristics of the two newest machines (C and D) are given in Table 1.

TABLE 1

Technical characteristics of drilling machine

Parameters		Value
Technical properties	Drill rod rotation speed (RPM) (Maximum)	200
	Tramming speed (Level grade) (Km/h)	1.6
	Tramming speed (30 % grade) (Km/h)	1.6
	Maximum grade (%)	30
Hydraulic pumps	Number of hydraulic pumps	5
	Feed-gull-gown (Psi) (maximum)	3000
	Line pressure (Psi) (maximum)	400
	Speed of dust collection blower motor (RPM)	3000-3200
	Water injection pressure (Psi)	40-50
Main electrical motor	Voltage (V)	6600±%10
	Frequency (Hz)	150±%5
	Phase number	3
	Pole number	4
	Service factor	1.15
	Power (HP)	600
	Speed (RPM)	1500
	Gear box coupling (Ft.lbs)	16
	Maximum altitude (Ft)	900
	Ambient temperature range (°C)	–16 to 56

4.1. Failure Data Collection and Analysis

In this research, the failure data of all drilling machines (A, B, C and D) in Sarcheshmeh Copper Mine have been collected over a period of 2 years. For identification of critical subsystem of any machines, Pareto analysis (failure frequency analysis) was done on the available data. The result of this analysis is shown in Figure 2. Regarding to this figure, electrical system of machines A and C as well the hydraulic subsystem of machines B and D, have the highest percent of failures. Also, drilling system of machines A and B respectively with 7% and 5% of all of failures are the best subsystems. Similarly, transmission system with 8% and pneumatics system with only 3% of total failures have the lowest failure in machines C and D. According to these results, it is obvious that any improvements or comprehensive maintenance plan should place a high level of attention on the electrical and hydraulic systems of the studied machines.

After Pareto analysis, the time between failures (TBF) of all subsystems was calculated. The data set was also analyzed for the presence of trend by using the MIL-HDBK-189 test. The computed value of the test statistic (Equation (2)) and Chi squared test for available TBF data are given in Table 2.

Regarding to the results of analytical analysis shown in Table 4, the assumption that the failure data of subsystems are trend free is valid for all machines except Transmission system of machine D. Also, the serial correlation test showed that the data are correlation free. As a result, the reliability of this subsystem should be analyzed by non-stationary model such as the NHPP. In this study, power law process (PLP) model as one of the most applied processes was used for reliability modeling of transmission subsystem of machine D.

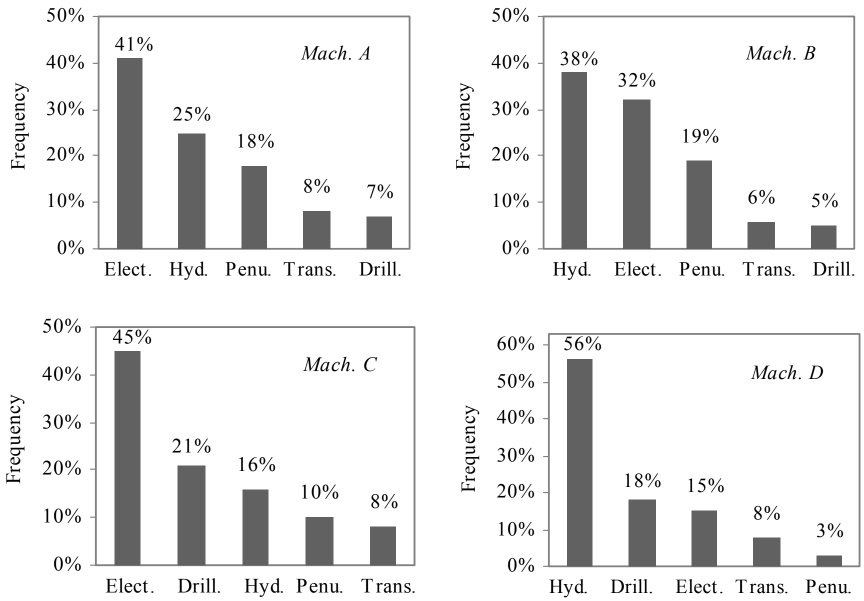

Fig. 2. Pareto analysis of drilling machines' subsystems in Sarcheshmeh Copper Mine

TABLE 2

Computed value of the test statistic U for TBF

Machines	Subsystem	Degree of freedom	Calculated statistic U	Lower Chi^2 value (2.5% level of significance)	Upper Chi^2 value (97.5% level of significance)	Null hypothesis	Modeling method
1	2	3	4	5	6	7	8
A	Hydraulic	94	96.78	69.07	122.72	accepted	RP
	Electrical	160	202.78	126.87	196.92	rejected	NHPP
	Pneumatic	76	110.55	53.78	102.00	rejected	NHPP
	Drilling	22	38.51	10.98	36.78	rejected	NHPP
	Transmission	26	28.86	13.84	41.92	accepted	RP
B	Hydraulic	198	143.2	160.92	238.86	rejected	NHPP
	Electrical	162	152.45	128.65	199.13	accepted	RP
	Pneumatic	98	196.62	72.5	127.28	rejected	NHPP
	Drilling	22	45.5	10.98	36.78	rejected	NHPP
	Transmission	26	38.42	13.84	41.92	accepted	RP
C	Hydraulic	200	270.22	162.73	241.06	rejected	NHPP
	Electrical	66	55.19	45.43	90.35	accepted	RP
	Pneumatic	46	66.51	29.16	66.62	accepted	RP
	Drilling	90	67.72	65.65	118.14	accepted	RP
	Transmission	30	27	16.79	46.98	accepted	RP

TABLE 2. Continued

1	2	3	4	5	6	7	8
D	Hydraulic	304	296.56	257.59	354.19	accepted	RP
	Electrical	78	85.48	55.47	104.32	accepted	RP
	Pneumatic	14	22.29	5.63	26.12	accepted	RP
	Drilling	96	78.19	70.78	125.00	accepted	RP
	Transmission	40	16.41	24.43	59.34	rejected	NHPP

After doing the iid tests, the parameters of reliability functions should be estimated. In this paper, the Easy*fi*t and MS Excel softwares were used for data analyzing and finding the best-fit distributions and parameters. The Kolmogorov-Smirnov (K-S) test has been used for selecting the best distributions. The results of data analysis, best-fitted distributions and estimated parameters for all data sets are illustrated in Table 3. Also, the related reliability curves were plotted as shown in Figure 3. Regarding to this figure, transmission subsystem is the most reliable subsystem in four machines. Electrical subsystem of machines A, similar to hydraulic subsystem of machines C and D and pneumatic subsystem of machine B have the lowest reliability level at all of time operation of machines.

TABLE 3

The results of data analysis and best-fit distributions

Machine	Subsystem	Best-fit distribution	Estimated parameters
A	Hydraulic	Weibull (3P)	$\alpha = 0.671$; $\beta = 79.98$; $\gamma = 0.625$
	Electrical	NHPP	$\beta = 0.693$; $\eta = 12.592$
	Pneumatic	NHPP	$\beta = 0.687$; $\eta = 35.951$
	Drilling	NHPP	$\beta = 0.550$; $\eta = 78.149$
	Transmission	Gamma	$\alpha = 1.683$; $\beta = 193.0$
B	Hydraulic	NHPP	$\beta = 0.906$; $\eta = 62.693$
	Electrical	Weibull (3P)	$\alpha = 0.698$; $\beta = 66.66$; $\gamma = 0.125$
	Pneumatic	NHPP	$\beta = 0.498$; $\eta = 4.097$
	Drilling	NHPP	$\beta = 0.431$; $\eta = 31.522$
	Transmission	Lognormal	$\sigma = 0.827$; $\mu = 6.187$
C	Hydraulic	NHPP	$\beta = 0.855$; $\eta = 51.227$
	Electrical	Gamma	$\alpha = 0.775$; $\beta = 396.47$
	Pneumatic	Lognormal	$\sigma = 0.965$; $\mu = 5.448$
	Drilling	Lognormal	$\sigma = 1.175$; $\mu = 4.278$
	Transmission	Exponential	$\lambda = 0.0025$; $\gamma = 18.5$
D	Hydraulic	Lognormal	$\sigma = 1.309$; $\mu = 3.42$
	Electrical	Exponential	$\lambda = 0.0045$; $\gamma = 11.125$
	Pneumatic	Gen. Gamma	$k = 0.832$; $\alpha = 0.797$; $\beta = 509.5$
	Drilling	Weibull (2P)	$\alpha = 0.7978$; $\beta = 182.4$
	Transmission	NHPP	$\eta = 1680.31$; $\beta = 2.33$

As discussed previously, the drilling rig was taken to comprise five clearly identifiable subsystems which are functionally arranged in a series configuration as shown in the reliability block diagram in Figure 1. This means that the drilling machine is in working condition only

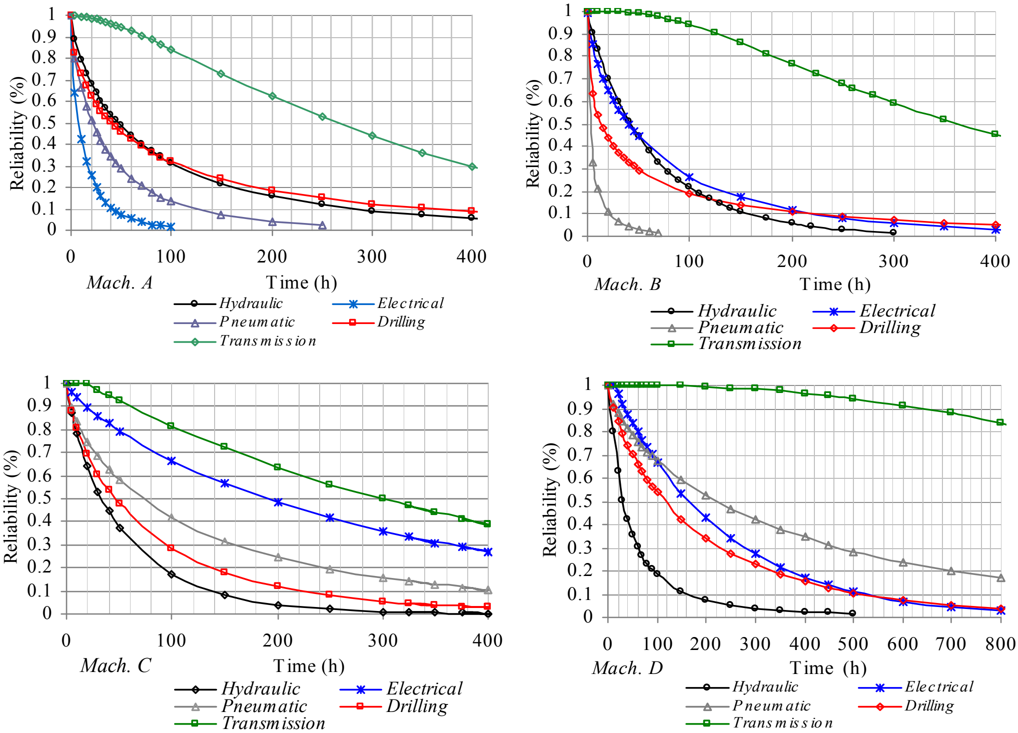

Fig. 3. Reliability plots of subsystem of drilling machines

when all subsystems are working satisfactorily. The reliability of such machines can be calculated by multiplication of reliability of all subsystems.

Referring to data analysis and reliability plots presented in Figure 3, final calculated reliability plots of studied drilling rigs are shown in Figure 4. As can be seen in this figure, machine C has the highest reliability and the lowest one is rig A. It should be noticed that, rigs A and B are older than C and D. since, their reliability in lower than the new machines in all the studied period of time. Also, machines A and B have been bought in the same year and their working hours are very similar. Therefore, their plots are very similar. The calculation shows that the reliability of all drilling rigs reaches to zero after almost 90 h of operation.

Regarding to managerial decision and production plan of Sarcheshmeh Copper Mine, operation of at least two drilling rigs is essential for having a desirable drilling operation and satisfy the production goals. Therefore, to calculate the reliability of drilling fleet, all of possible states for machines should be considered. There were three different stages for drilling machines and for each of stages, two condition of active and failure exists. In the first stage all of machines were active. In the second stage there were three active machines: A, B and C, or A, B and D, or B, C and D. At last, in the third stage there were only two active machines: A and B, or A and C, or A and D, or B and C, or B and D and also C and D. Reliability of drilling fleet in each time interval can be calculated with summation of probability of all states which mentioned above. Using this technique, reliability of drilling fleet was calculated and plotted in Figure 5. To illustrate the

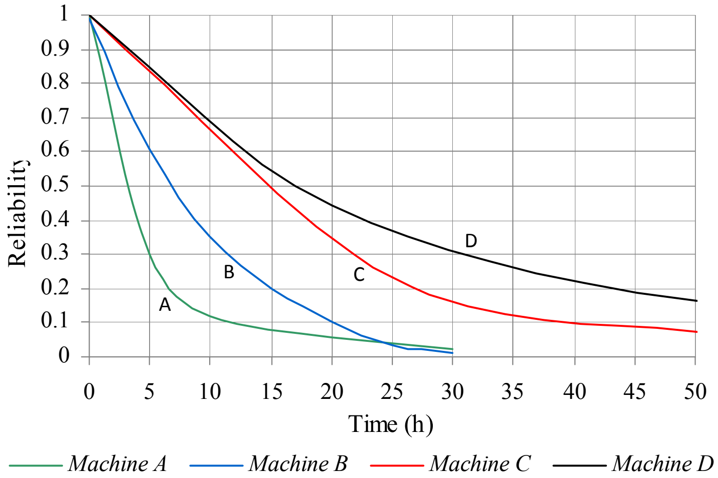

Fig. 4. Reliability plots of drilling machines in Sarcheshmeh Coper Mine

calculations, as an example, the reliability of drilling fleet at time 10 is calculated and shown in Table 4. Reliability (and failure probability) of machines A, B, C and D at this time was 0.160 (and 1-0.160), 0.073 (and 1-0.073), 0.488 (and 1-0.488) and 0.664 (and 1-0.664). Based on the calculation and as can be seen in Figure 5, reliability of drilling fleet reaches to zero after almost 50 hours of drilling operation.

TABLE 4

Calculation of reliability of drilling fleet after 10 h operation

Stage	Number of active machine	Active machines	Safety probability	Reliability of drilling fleet
First	4	A, B, C, D	0.160 × 0.073 × 0.488 × 0.664 = 0.004	0.004 + 0.002 + 0.004 + 0.020 + 0.048 + 0.002 + 0.024 + 0.050 + 0.010 + 0.021 + 0.252 = 0.437
Second	3	A, B, C	0.160 × 0.073 × 0.488 × (1 – 0.664) = 0.002	
		A, B, D	0.160 × 0.073 × (1 – 0.488) × 0.664 = 0.004	
		B, C, D	(1 – 0.160) × 0.073 × 0.488 × 0.664 = 0.020	
		C, D, A	0.488 × (1 – 0.073) × 0.664 × 0.160 = 0.048	
Third	2	A, B	0.160 × 0.073 × (1 – 0.488) × (1 – 0.664) = 0.002	
		A, C	0.160 × (1 – 0.073) × 0.488 × (1 – 0.664) = 0.024	
		A, D	0.160 × (1 – 0.073) × (1 – 0.488) × 0.664 = 0.050	
		B, C	(1 – 0.160) × 0.073 × 0.488 × (1 – 0.664) = 0.010	
		B, D	(1 – 0.160) × 0.073 × (1 – 0.488) × 0.664 = 0.021	
		C, D	(1 – 0.160) × (1 – 0.073) × 0.488 × 0.664 = 0.252	

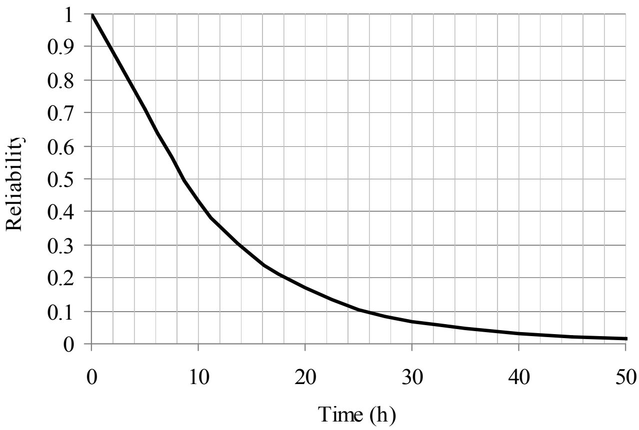

Fig. 5. Reliability of drilling fleet in Sarcheshmeh Copper Mine

5. Maintenance Scheduling and Reliability Improvement

Preventive maintenance (PM) regularly consists of scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment. PM schedules periodic inspections and maintenance at pre-defined intervals (time, operating hours, or cycles) and attempts to reduce equipment failures (NASA, 2008).

Depending on the intervals set, PM can result in a significant increase in inspections and routine maintenance. PM also reduces the frequency and seriousness of unplanned machine failures for components with defined, age-related wear patterns.

Reliability approach is one of the best ways to schedule the maintenance operations which is used is this research. Based on this approach, PM interval is estimated based on the reliability model and the reliability level which we wish to have in our operation. In many engineering operations, 80% is selected as the best practical value for efficiency and performance evaluation. Therefore, this value is assumed as a desired reliability level for whole operation of drilling fleet. This level of reliability is achieved for drilling fleet after approximately 4 hour operation (see Figure 5). In this time, the reliability of machines A, B, C and D is reached to 0.72, 0.71, 0.92 and 0.91 respectively. Also, regarding to series configuration of machines' subsystems and assumption of that the reliability of each subsystem is equal; reliability of each subsystem of machines will be calculated as 0.94, 0.93, 0.98 and 0.98. Therefore, the times in which reliability of subsystems reach the mentioned values, were considered as the reliability-based preventive maintenance intervals. The calculated intervals in Sarcheshmeh Copper mine are shown in Table 5.

As can be seen in Table 5, the results of calculations show that the maintenance intervals for machine A and machine B are very short and it is impossible to do it in practice view point of high costs and very low availability. The investigations showed that these machines are very old and in their wear-out period of life cycle. The further studies and visits from the machines showed that, the electrical, pneumatic and drilling subsystems are not in good condition and many replacements should be done in their parts which will cause high costs. Therefore, as a critical decision, it is suggested that these two machines should be replaced totally with new ones. In the time period before buying and replacement of these rigs, the mine drilling should go ahead with machine C and D and the machine A and B should be only as standby machines. However, they might be unreliable even for operating as a standby machine.

TABLE 5

Reliability-based maintenance intervals

Subsystem	Machine A	Machine B	Machine C	Machine D
Hydraulic	1.58	2.41	1.58	3.55
Electrical	~ 0	1.07	7.61	22.48
Pneumatic	0.48	~ 0	1.64	5.07
Drilling	0.36	~ 0	1.51	4.41
Transmission	45.61	93.55	39.21	469.64

The other result of the analysis which should be considered is that the machine C and D have problems and weaknesses in their electrical, pneumatic and drilling subsystems too, but in better level than A and B. Therefore, as our back analysis shows in Sarcheshmeh mine, the goal reliability of 80% for whole drilling operation is a little bit costly decision which can affect the total exploitation cost of the ore. Therefore, a new reliability goal and strategy should be taken by mine managers.

In total, revised assumptions for maintenance planning of this fleet are as follow;

- machine A and B are standby rigs and only will operate in short and urgent cases
- machine C and B are operative rigs of mine
- machine A and B should be replaced as soon as possible
- machine C and D can be future standby rigs when new rigs will be bought

Regarding the above discussion, the aim of our analysis will be to present a maintenance program for machines C and D. For optimizing the maintenance schedule, the tasks which have the similar intervals are done in one interval that is acceptable for all related subsystems. Using this method, the combined and improved preventive maintenance intervals for subsystems of all studied drilling machines were calculated and are presented in Table 6.

TABLE 6

Improved PM intervals for subsystems of studied drilling machines

Machine	Subsystem (machine)	Combined and improved PM intervals
C & D	Hydraulic + Pneumatic + Drilling	2.5
	Electrical (C)	7.5
	Transmission + Electrical (D)	30

Regarding to reliability analysis of machines C and D after the first PM operation (on time 2.5), the reliability of these machines increase quickly. After 2.5 h of operation, all of subsystems of these machines except of transmission and electrical system are repaired and the reliability of machines increases more than the first PM operation. After 7.5 h operation, electrical subsystem of machine C is under repaired and reliability of this machine will increase rather that before. On time 30 all of subsystem of these machines serviced and maintained.

Finally, using the above-suggested schedule, the reliability of the drilling machines is improved in sensible way. As shown in Figure 6, after each preventive maintenance operation, the reliability of machines increases related to the maintenance tasks and the number of the subsystems maintained. In all graphs, before the first PM, tow reliability plots, with PM and without PM, are overlapped, but, after the first PM reliability of machines are increased, quickly. This process will be occurred after any PM interval, frequently. The calculations show that, the reliability of studied machines C and D will be improved by 87.51% and 93.35% on average, respectively.

Also, as our main goal of this research, reliability of the drilling fleet is affected by PM operations. Regarding to mentioned maintenance strategy, number of machines and the operation configuration within the fleet, we will be able to the reliability of drilling fleet of Sarcheshmeh Copper Mine in the period of 63.21% to 100% (average: 81.62%).

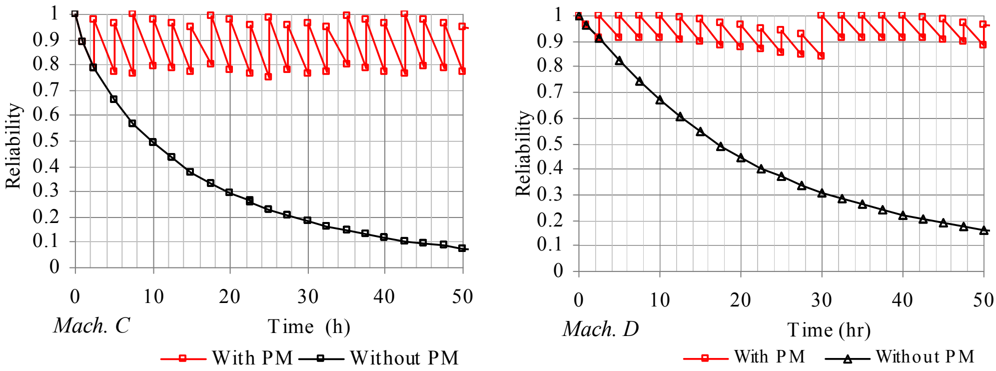

Fig. 6. Effects of the suggested PM schedule on reliability of machines C and D

7. Conclusions

In this paper the operational structure of rotary drilling machines was studied and five subsystems of the drilling machines including the hydraulic, electrical, pneumatic, drilling and transmission subsystems were defined for the first time.

Pareto analysis showed than the electrical subsystem of machines A and C similar to hydraulic subsystem of machines B and D, because having the most failures, are critical subsystems of mentioned machines.

The analysis shown that, NHPP modeling method were useable for reliability analysis of electrical, pneumatic and drilling subsystem of machine A, hydraulic, pneumatic and drilling subsystem of machine B, hydraulic subsystem of machine C and transmission subsystem of machine D. Other subsystems of the mentioned machines were iid and renewal process was used for reliability modeling of them.

According to series relationship between any subsystems of drilling machines, reliability of all of machines was calculated and plotted. Then considering there were at last two active machines, reliability of drilling fleet of mine was plotted. Results show that the reliability of machines A, B, C and D reached to zero after 40, 30, 100 and 150 h. On the other words, without consider any maintenance and services before mentioned times, drilling machines will be stopped at these times, surely. Also, reliability of the fleet of machines reached to 80% only after 4 h operation.

The results of calculations showed that the maintenance intervals for machines A and B were very short. These machines were very old and in their wear-out period of life cycle, so that, it was suggested that these two machines should be replaced totally with new ones.

To achieve a suitable manageable maintenance schedule for machines C and D, a task package was developed. With regarding to suggested maintenance schedule, reliability of machines C, D and drilling fleet will be improved by 87.51%, 93.35% and 81.62% in average, noticeably.

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