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# RAM ANALYSIS OF ROTARY DRILLING MACHINES

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**Abstract:** Rotary drilling machines are the most common machines used for drilling the blast holes in mining and constructions activities. The vital role of drilling operation in mining activities reveals that, the performance analysis of drilling machines and their failure and repair behaviors are essential. Therefore, the present study focuses on the reliability, availability and maintainability (RAM) of drilling machines. In this paper, four rotary drilling machines at Sarcheshmeh Copper Mine in Iran are considered for repair and failure data collection. RAM analysis of drilling machines is done using Markov Approach. Results show that the reliability of drilling fleet is decreased by 0.67% in per hour drilling. The hydraulic system is the main unavailability reason of all machines. Moreover, the most failures of the two newest machines are completely repaired in 25 hours.

***Keywords***: *rotary drilling machine; Markov approach; reliability; maintainability; availability*.

## INTRODUCTION

Recently, rotary drilling is the most common drilling method used in surface mines for drilling the various rock qualities. A rotary drilling machine assemblies could be categorize as different parts including; undercarriage, main frame, leveling jacks, prime mover, air compressor, operator cab, driver cab, mast, auxiliary winch, rotary head, pipe rack, hydraulic system, dust control equipment and machinery house (Bhalchandra, 2011; Jimeno et al., 1995). In the recent researches (Rahimdel et al., 2013a,b,c), five main systems were defined for rotary drilling machines. These systems are the hydraulic, electrical, pneumatic, drilling assembles (is called drilling system) and crawler assembles (is called as transmission system) connected together in series configuration.

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Nowadays, reliability and performance analysis of LHD (Samanta et al., 2004; Vayenas et al., 2009), crushing plant (Barabady and Kumar, 2008), main conveyor (Simon et al., 2014), shovel (Samanta et al., 2001; Dubey et al., 2015) and dump truck (Allahkarami et al., 2016) were done using statistical modeling. Reviewing the literature shows that the reliability of mining machineries and equipment have already been studied, comprehensively. But, few researches have focused on drilling machines. Rahimdel et al., 2013a published an article in the field of reliability of drilling operation in Sarcheshmeh Copper Mine. In this research, 16 possible operation states were defined for the fleet of drilling machines and the probability of each states was calculated using Markov theory. The results show that, the probability of state in which all machines were active, was 77.20%. In the other research, reliability and maintainability of the pneumatic and hydraulic systems of above mentioned drilling machines were analyzed using statistical modeling (Rahimdel et al., 2013b,c). In the statistical reliability modeling, three methods are used for reliability analysis of the repairable systems including; renewal process (RP), homogeneous Poisson process (HPP), and non-homogeneous Poisson process (NHPP). In PR method, analysis is usually based on the assumption that the times between failures (TBF) are independent and identically distributed (iid) at the time domain. Trend and serial correlation tests are used for validation of this assumption. If there is trend in failure data, NHPP is used for modeling. If there is no trend and also serial correlation in data, the failure data are iid and classical statistical methods is used for modeling (Kumar, 1990; Hall et al., 2003; Barabady, 2007; Hoseinie et al., 2012; Rahimdel et al., 2016).

In the present study, Markov process as a stochastic modelling used for RAM analysis a fleet of rotary drilling machines. This methodology is useful for performance analyzing of system which their subsystems are independent, strongly. Describing the failure of system and also its subsequent repair are the advantages of the Markov process. In this process, the probability of a system being in a given state as a function of the sequence through which the system has traveled, is considered (Fuqua, 2003). Markov considers consequence of event and analysis the tendency of one event to be followed by another. With results of this paper, the safety operational probability of stationary states for fleet of drilling machines is illustrated. The most available system of each drilling machines is determined and also, maintainability of each machine system is calculated.

The rest of paper is organized as follows. In section 2, Markov process as the methodology of paper is explained. Then, application of mentioned methodology for RAM analysis of rotary drilling machines is illustrated. The failure and repair data are obtained in section 3. Finally, in section 4, reliability, availability and maintainability of drilling machines and their fleet are analyzed and discussed.

## METHODOLOGY; MARKOV PROCESS

The Markov approach can be used to study systems with random behavior which changes through time and space. In the basic Markov application, behavior of system must be characterized as a lack of memory (Billinton and Allan, 1992). On the other hand, future states of system are independent from all past states, except the immediately preceding one. Also, the probability of transition from one state to another states is stationary at all times (Billinton and Allan, 1992). For example, the state transition diagram of single repairable system when failure rate ($\lambda$) and repair rate ($\mu$) are constant is shown in Fig. 1 (Dhillon, 2008).

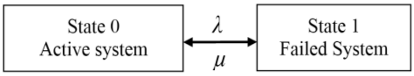


Fig. 1. Transmission diagram for a repairable system (Dhillon, 2008)

The following assumptions are associated with the Markov method (Dhillon, 2006, 2008):

- All of the transition rates of system are constant.
- The transitional probability from one state to another, in the finite time interval $\Delta t$ is given by $\lambda.\Delta t$, where $\lambda$ is the constant transition rate from one system state to another.
- All of occurrences are independent and,
- The occurrence probability of more than one transition in finite time interval, from one state to another, is negligible.

The assumptions mentioned above mean that the failure and repair rates of system are obey from exponential distribution. Therefore, the reliability and maintainability of system are obtained as follows:

$$R(t) = \exp(-\lambda.t) , \tag{1}$$

$$M(t) = 1 - \exp(-\mu.t) , \tag{2}$$

where, $R(t)$ is the reliability function, $M(t)$ is the maintainability function, $\lambda$ is the failure rate and $\mu$ is the repair rate and $t$ is time. It is noted that in the exponential distribution, the main time to failure (MTTF) and main time to repair (MTTR) are equal to $1/\lambda$ and $1/\mu$, respectively. According to state transmission process, described in Fig. 1, the probability of system being in state $i$ at time ($t+\lambda.t$), for $i$ = 0 (operating normally) and $i$ = 1 (failed) are calculated as the follow (Billinton and Allan, 1992; Dhillon, 2006, 2008, 2010):

$$P_0(t + \Delta t) = P_0(t)(1 - \lambda.\Delta t) + P_1(t)\mu.\Delta t , \tag{3}$$

$$P_1(t+\Delta t) = P_0(t)(1-\mu.\Delta t) + P_1(t)\lambda.\Delta t\ , \tag{4}$$

On the other hand, $P_0$ ($t$+Δ$t$) is equal to {probability of system being in the operating state at time $t$ (or $P_0$ ($t$)) AND probability of state in which the system not failed between $t$ and $t$+Δ$t$ (or $1 - \mu\Delta t$)} plus {probability of being failed states at time $t$ (or $P_1$ ($t$)) AND probability of being repaired between $t$ and $t$+Δ$t$ (or $\lambda.\Delta t$)}.

With solving equations (3) and (4) for large time ($t \to \infty$), $P_0$ (availability of system steady state) and $P_1$ (unavailability of system steady state) are calculated as follow (Billinton and Allan, 1992; Dhillon, 2006, 2008, 2010):

$$P_0(t) = \frac{\mu}{\lambda+\mu}, \tag{5}$$

$$P_1(t) = \frac{\lambda}{\lambda+\mu}, \tag{6}$$

On the other hand, the probability of state in which system is failed ($P_0$ ($t$)) or repaired ($P_1$ ($t$)) at time $t$ are calculated from the above equations.

## APPLICATION OF MARKOV PROCESS FOR RAM ANALYSIS OF DRILLING MACHINES

In this section, the reliability, availability and maintainability of the fleet of drilling machines are modeled and discussed using the methodology described in the before section. To achieve this aim, first, the transmission diagram of drilling machine is constructed as Fig. 2.

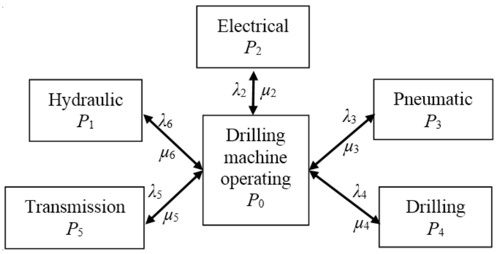


Fig. 2. Transmission diagram of drilling machine

In Fig. 2, the operation state of system is shown by 0 and the failure state of system is shown by $i$ (is equal to 1 to 5). Also, the failure and repair rates of each system, respectively, are shown by $\lambda_i$ and $\mu_i$. At the first state, drilling machine is active (with the probability $P_0$). If each system is failed (with failure rate $\lambda_i$), machine will be failed. If the failed system is repaired (with repair rate $\mu_i$), machine will be returned to the active state. It should be noted that the transmission states occur between the failed and operated states and also the systems reside in a discrete state, are continuous in time, therefore, this is a Markov chain. On the other hand, the mentioned methodology is usable for RAM analysis. To reach this aim, equations (3) and (4) could be generalized for solving this problem as follow (Billinton and Allan 1992; Samanta et al., 2004):

$$P_0(t) = 1/(1+\sum_{i=1}^{5}\frac{\lambda_i}{\mu_i})\,, \tag{7}$$

$$P_i = (\lambda_i\,/\,\mu_i)\,/(1+\sum_{i=1}^{5}\frac{\lambda_i}{\mu_i})\,, \tag{8}$$

Therefore, the probability that drilling fleet is being in the failure state and repair state, in the stationary state, could be calculated using above equations.

## THE CASE STUDY; DRILLING MACHINES OF SARCHESHMEH COPPER MINE IN IRAN

In this paper, drilling machines at Sarcheshmeh Copper Mine of Iran is used for all data collection. Sarcheshmeh Copper Mine with coordinates 55° 52' 20" east longitude and 29° 56' 40" north latitude and altitude 2620 meters, on average, is one of the ten biggest copper mines of world. This mine located at 65 kilometers in south-west of Rafsenjan City from Kerman province, Iran. A fleet of four rotary drilling machines at this mine (named as A, B, C and D) are used for data collection. Technical characteristics of the two newest machines (C and D) are given in Tab. 1. Fig. shows two of studied drilling machines.

Fig. 3. The two of studied drilling machines (Rahimdel et al., 2013a)

Tab. 1. Technical characteristics of drilling machine

| Model: DMH, 1800 XL, Ingersoll-Rand | | | |
|---|---|---|---|
| Technical properties | | Main electrical motor | |
| Drill rod rotation speed (RPM) (Maximum) | 200 | Voltage (V) | 6600±%10 |
| Tramming speed (Level grade) (Km/h) | 1.6 | Frequency (Hz) | 150±%5 |
| Tramming speed (30 % grade) (Km/h) | 1.6 | Phase number | 3 |
| Maximum grade (%) | 30 | Pole number | 4 |
| Hydraulic pumps | | Service factor | 1.15 |
| Number of hydraulic pumps | 5 | Power (HP) | 600 |
| Feed-gull-gown (Psi) (maximum) | 3000 | Speed (RPM) | 1500 |
| Line pressure (Psi) (maximum) | 400 | Gear box coupling (Ft.lbs) | 16 |
| Rotation speed of dust collection blower motor (RPM) | 3000-3200 | Maximum altitude (Ft) | 900 |
| Water injection pressure (Psi) | 40-50 | Ambient temperature range (°C) | -16 to 56 |

The failure and repair data of drilling machines are collected in the period of two years from the field observations and drilling and blasting office of mine. Then, the failure and repair rate of each system of machines are calculated and given in Tab. 2. Data analysis shows that, the electrical system of machine A and hydraulic system of machines B, C and D have the most failure rate. Therefore, the inspections and checking services should be focused on these systems.

Tab. 2. The failure and repair rate of the drilling machines

| System | Machine A | | Machine B | | Machine C | | Machine D | |
|---|---|---|---|---|---|---|---|---|
| | F-R | R-R | F-R | R-R | F-R | R-R | F-R | R-R |
| Hydraulic | 0.0092 | 0.0412 | 0.0146 | 0.0349 | 0.0139 | 0.0735 | 0.0157 | 0.0694 |
| Electrical | 0.0138 | 0.0849 | 0.0118 | 0.2132 | 0.0033 | 0.1117 | 0.0043 | 0.2865 |
| Pneumatic | 0.0057 | 0.0415 | 0.0092 | 0.0269 | 0.0026 | 0.1920 | 0.0022 | 0.1412 |
| Drilling | 0.0021 | 0.1809 | 0.0019 | 0.0882 | 0.0071 | 0.1843 | 0.0047 | 0.1698 |
| Transmission | 0.0031 | 0.0611 | 0.0020 | 0.0935 | 0.0024 | 0.2004 | 0.0020 | 0.0961 |

Note: F-R is failure rate and R-R is repair rate

## RAM ANALYSIS OF DRILLING MACHINES

In this section, reliability of machine systems is calculated using the methodology described in the previous section. Then, the availability and maintainability of each system are calculated and discussed. It should be noted that, the relationship between systems of machines is series. Therefore, the reliability of drilling machine ($R_m$) is calculated as:

$$R_m = \prod_{i=1}^{n} R_i \, , \tag{8}$$

where, $R_i$ is the reliability of system $i$ and $n$ is the number of system.

Reliability of drilling machines and their systems are calculated and illustrated in Fig. 4. Regarding to Fig. 4. The drilling and transmission systems are the most reliable system in machines A and B. While, the transmission and pneumatic systems of machines B and C have the highest reliability level. The hydraulic system has the lowest reliability in all drilling machines. The reliability of all drilling machines will be reached to zero after about 150 h operation. On the other hand, after each hour, the machine reliability is decreased by 0.67%.

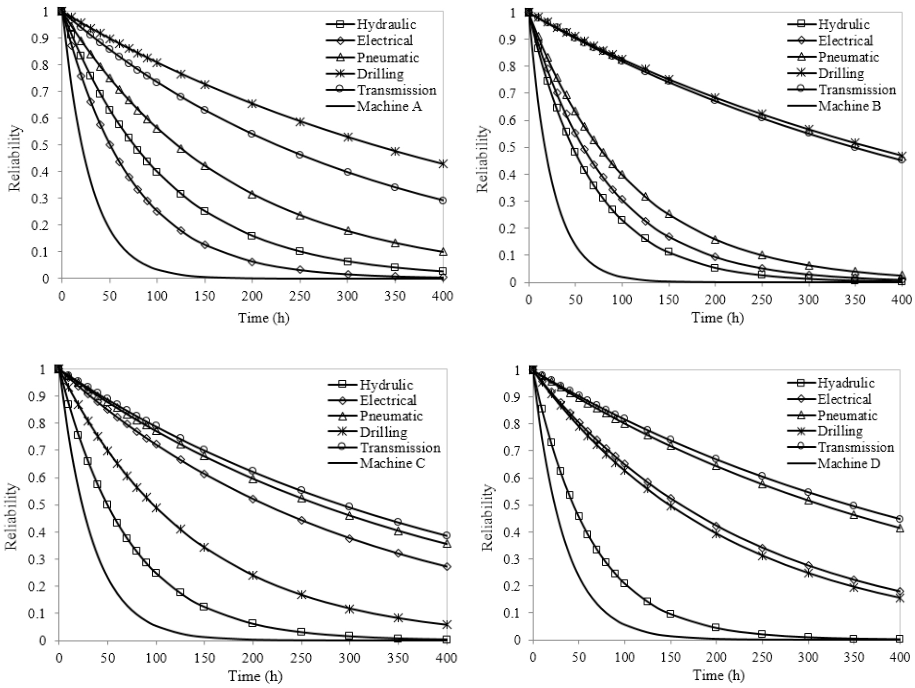


Fig. 4. Reliability plots of each drilling machines and their systems

Regarding to mine management and drilling and basting office of Sarcheshmeh Mine, to have a desirable drilling operation, activation of at least two drilling machines is sufficient. To achieve this aim, there are three different stages for the fleet of drilling machines including; operation of four, three or two drilling machines. Also, there are two conditions for each stage; active and fail. All of the mentioned stages are given in Tab. 3. In the first stage, all drilling machines are active. In the second stage there are three active machines. Finally, in the third stage there are only two active machine.

Tab. 3. All of the possible states for activation of at least two drilling machines

| Stage no. | State no. | Active drilling machines |
|---|---|---|
| 1 | 1 | A, B, C, D |
| 2 | 1<br>2<br>3 | A, B, C<br>A, B, D<br>B, C, D |
| 3 | 1<br>2<br>3<br>4<br>5<br>6 | A, B<br>A, C<br>A, D<br>B, C<br>B, D<br>C, D |

With considering activation of at least two drilling machines, reliability of drilling fleet in each time intervals can be calculated. For example, at time 20 hours, reliability of machines A, B, C and D is 0.507, 0.454, 0.557 and 0.562, respectively. Reliability of the drilling fleet in condition with four active drilling machines is calculated as:

$$0.507\times0.454\times0.557\times0.562= 0.072.$$

Reliability of drilling fleet when there are only three active drilling machines is calculated as:

$$[0.507\times0.454\times0.557\times(1-0.562)] + [0.507\times0.454\times(1-0.557)\times0.562] \\ + [0.507\times(1-0.454)\times0.557\times 0.562] + [(1-0.507)\times0.454\times 0.557\times 0.562] = 0.271.$$

Accordingly, reliability of drilling fleet in condition with only two active drilling machines, calculated as:

$$[0.507\times0.454\times(1-0.557)\times(1-0.562)] + [0.507\times(1-0.454)\times0.557\times(1-0.562)] \\ + [(1-0.507)\times0.454\times0.557\times(1-0.562)] + [0.507\times(1-0.454)\times(1-0.557)\times0.562] \\ + [(1-0.507)\times0.454\times(1-0.557)\times0.562] + [(1-0.507)\times(1-0.454)\times0.557\times0.562] \\ = 0.376.$$

With considering the above calculations, the reliability of drilling fleet at time 20 hours is calculated as:

$$0.072 + 0.271 + 0.376 = 0.719.$$

On the other hand, after 20 hours operation, there are at least two active drilling machines with 71.90% probability. The reliability of drilling fleet at all times is calculated using the above mentioned procedure and shown in Fig. 5.

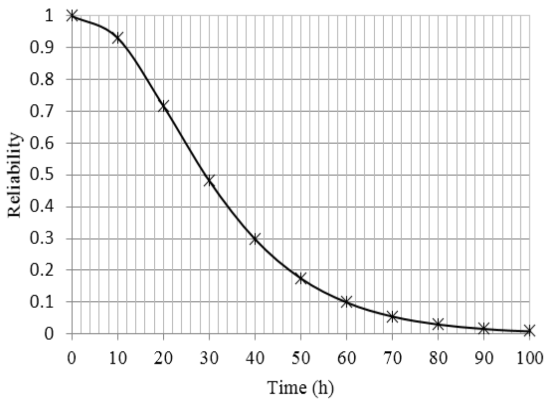


Fig. 5. Reliability plot of drilling machines and the fleet of machines

Regarding to Fig. 5, the reliability of drilling fleet is reduced to about 90% after 12 hours operation. The drilling machines of Sarcheshmeh Copper Mine work in two shift per day and 6 hours per shift. On the other hand, if no maintenance action is performed until starting the second shift, the failure probability of drilling fleet is increased to 10%. Therefore, the maintenance scheduling should be considered to improve the drilling fleet operation. To achieve this goal, considering preventive maintenance (PM) schedule based on reliability analysis is essential. In many engineering activates, 80% is considered as the target reliability level to propose the PM intervals. Drilling machines have vital role in open pit mining operation. Therefore, in this study, 90% is considered as the target reliability for the PM intervals suggestion. Reliability-based maintenance intervals for all systems are given in Tab. 4. To optimize this maintenance scheduling, it should be better that, the PM tasks which have the similar intervals are done in one interval. Therefore, the manageable time intervals for maintenance are given in Tab. 5.

Tab. 4. Reliability-based maintenance interval for 90 % reliability level (hour)

| Machine | Hydraulic | Electrical | Pneumatic | Drilling | Transmission |
|---|---|---|---|---|---|
| A | 11.46 | 7.65 | 18.34 | 49.72 | 34.22 |
| B | 7.19 | 8.90 | 11.50 | 55.67 | 53.14 |
| C | 7.55 | 32.37 | 40.82 | 14.76 | 44.44 |
| D | 6.72 | 24.50 | 48.00 | 22.60 | 52.34 |

Regarding to the classic shift-based maintenance scheduling, the hydraulic system of all machines and the electrical system of machines A and B can be maintained about at the end of each operational shift. The electrical system of machines C and D should be maintained almost every five shifts. PM schedule of the other systems should be done regarding to Tab. 5.

Tab. 5. Integrated time intervals for the drilling machines systems (hour)

| Machine | Hydraulic | Electrical | Pneumatic | Drilling | Transmission |
|---|---|---|---|---|---|
| A | 8 | 8 | 15 | 53 | 40 |
| B | 8 | 8 | 15 | 53 | 53 |
| C | 8 | 28 | 44 | 18 | 40 |
| D | 8 | 28 | 44 | 18 | 53 |

Investigation of the satisfactorily function of each machine system at the specific time is one of the most helpful aspects of equipment performance analysis. Therefore, the following of this section studies the availability of each system of drilling machine. The availability of drilling machines is calculated using the methodology described at the pervious section and results are given in Tab. 6. Regarding to Tab. 6, the availability of machines A, B, C and D, respectively, is 63%, 54%, 78% and 77%. Availability of drilling fleet, while there are at least two active machines, is calculated as 68%. Machines C and D are the most available machines. The hydraulic system is the most unavailable system in all drilling machines and it is the main reason of drilling machines unavailability. Moreover, the hydraulic system has the lowest PM interval. Therefore, it is clear that the hydraulic is the critical system in all drilling machines. Therefore, this system should be under the serious inspection activities.

Tab. 6. The drilling machines availability and of the machines systems unavailability

| Machines availability | | System unavailability | | | | |
|---|---|---|---|---|---|---|
| | | Hydraulic | Electrical | Pneumatic | Drilling | Electrical |
| A | 0.63 | **0.14** | 0.10 | 0.09 | 0.01 | 0.03 |
| B | 0.54 | **0.23** | 0.03 | 0.18 | 0.01 | 0.01 |
| C | 0.78 | **0.16** | 0.02 | 0.01 | 0.03 | 0.01 |
| D | 0.77 | **0.18** | 0.01 | 0.02 | 0.02 | 0.2 |

The rest of this section is devoted to study maintainability of the drilling machines. The maintainability of machine systems is calculated and plotted in Fig. 6. Regarding to Fig. 6, machines C and D are the most maintainable machines. While, the hydraulic system of these machines is the lowest maintainable system among the others. Maintainability of machines C and D reaches to more than 90% at 25 hours. On the other hands, the most failures of machines C and D will be completely repaired in 25 hours. While, the 90% failures of machines A and B will be repaired at 40 and 50 hours, respectively. Regarding to the above discussion, it is proposed that machines A and B, especially their hydraulic system, should be under overhaul repair before starting to operate normally.

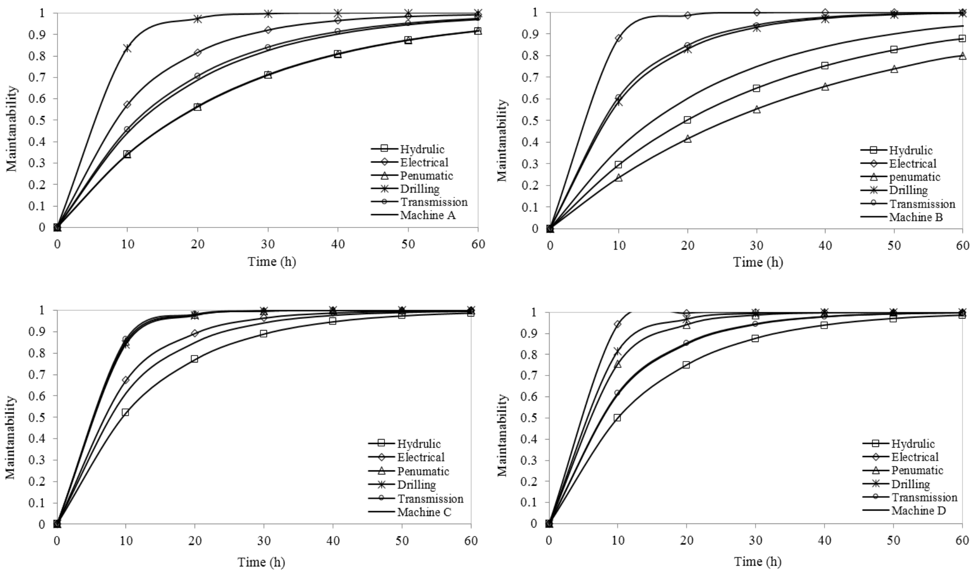


Fig. 6. The maintainability plot of the drilling machines systems

## CONCLUSIONS

The present study is in the field of performance analysis of four rotary drilling machines at Sarcheshmeh Copper Mine of Iran (named as A, B, C and D). At the first step, the Markov process for the performance analysis of rotary drilling machines are discussed. Then, the failure rate and repair rate of five manageable systems of the machines are calculated. Finally, the reliability, availability and maintainability of each system of machines are analyzed and discussed based on Markov process.

Results of this research can be summarized as follows:

- The electrical system of machine A and the hydraulic system of machines B, C and D, have the most failure rate.
- The drilling fleet reliability is reached to 90% only at the end of the second working shift.
- The availability of drilling fleet is calculated as 68%. Machines C and D are the most available machines. While, the hydraulic system is the main reason of machines unavailability.
- More than 90% failures of machines C and D are completely repaired at 24 hours. While, the most failures of machines A and B are repaired at 40 and 50

hours, respectively. The drilling system of machines A and C and the electrical system of machines B and D are the most maintainable systems.

- It is recommended that, the hydraulic system of drilling machines should be under overhaul repair before starting to operate normally.

Results of this study are helpful to manage the operational conditions of drilling fleet. Using the maintenance schedule proposed in this paper, servicing, checking and maintaining systems of drilling machines will improve the drilling performance. Studying the effects of proposed PM schedule on the operational cost reductions and also the improvement of drilling machines reliability and availability should be included in future studies.

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