Reliability Characteristics Based Maintenance Scheduling: A Case Study of a Crushing Plant

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Abstract: The cost of maintenance is too high in mining industry to ignore. This is mainly due to poor understanding of the maintenance process which is greatly influenced by the reliability characteristics of the operating system. The paper introduces an approach for maintenance scheduling of a mining system based on reliability analysis which is divided into two parts. The first part introduces a methodology for optimal maintenance scheduling based on analysis of maintenance data in the form of time-between-failure and time-to-repair distributions. In the second part, we present a case study from Jajarm Bauxite Mine in Iran to illustrate the applicability of the maintenance scheduling model.

Key words: maintenance, reliability characteristics, maintainability, mines, availability importance measures.

1. Introduction

Maintenance is an important activity for the safe and efficient operation of any industrial plant or system. Keeping a system in a normal operating condition and maintaining the expected performance require the proper maintenance to be carried out during the whole life cycle of the system [1]. The probability of equipment failure is influenced by the engineering design, the operating conditions and how the equipment is maintained. There is a need for a method to measure the effectiveness and the weaknesses of maintenance operation in order to focus the development of maintenance activities towards the enhancement of system availability. The downtime costs of mining equipment are high and over the years many researchers from academia and industry have investigated ways and means of ensuring better equipment design and better maintenance procedures in the mining industry in an effort to reduce equipment downtime and enhance the availability and reliability of equipment [2 - 7]. Traditionally, mining companies have focused on the key measures of plant availability and utilization to measure equipment performance. It has been demonstrated that these measures alone are insufficient for assessing equipment performance. In practice, there is one factor which is often overlooked and which has a significant impact on equipment performance, namely equipment reliability. A focus on reliability is critical for the improvement of equipment performance and ensuring that equipment is available for production as per production schedules [8]. The main objectives of this study are i) to develop a maintenance strategy based on reliability characteristics of the operating system; and ii) to study and analyse the reliability, availability, and maintainability characteristics of the crushing plant at Jajarm Bauxite Mine of Iran to develop a cost effective maintenance schedules.

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2. Reliability Based Maintenance Scheduling

Maintenance costs are a major part of the total operating costs for many industries. For instance, maintenance-related costs account for approximately 30 to 50 percent of direct mining costs [9]. The experiences from other industries, such as the airline and chemical processing industries indicate that optimization of this function could lead to decrease in equipment downtime leading to reduction in production cost and increase in income. Maintenance activity must be guided by a maintenance strategy, which may be divided into design-out maintenance, preventive maintenance and corrective maintenance. Design-out maintenance aims at changing the design of the product or system, in order to eliminate, or reduce, the need for maintenance during the life cycle [10]. According to the time when the maintenance is executed, maintenance is usually classified into two major categories, corrective maintenance (CM) and preventive maintenance (PM). The former corresponds to the actions that occur after the system has broken down. The latter corresponds to the actions that are performed when the system is operating. The advantage of PM is that the system can always be in an operation state in an available condition when needed and the serious loss incurred by unplanned stoppages can be avoided [1].

Preventive maintenance can be divided into time-based maintenance (TBM) and condition-based maintenance (CBM). CBM involves regular inspection being carried out by humans or machines, and in the event of a fault, it involves the maintenance being applied preventively. In other words, CBM is the method used to detect faults or the symptoms of failure by inspection, and to perform the maintenance preventively if any fault is detected. It is necessary to present the optimal inspection interval in a preventive maintenance policy to improve the reliability of facilities by utilizing the mean time between failures (MTBF) based on reliability characteristics.

Two requirements must be met for the preventive maintenance of a component to be appropriate [11]. First, preventive maintenance makes sense when the component deteriorates with time. In other words, as the component ages, it becomes more susceptible to failure or is subject to wear-out. In reliability terms, this means that the component has an increasing failure rate. The second requirement is that the cost of preventive maintenance must be less than the cost of corrective maintenance [12].

If a component of each subsystem is allowed to run to failure, the expected cost of corrective maintenance (ECC) over a given time interval includes the cost of the consequence of failure (\(C_c\)) and the cost of repair (\(C_r\)) multiplied by the probability of the failure occurring \(P_f\):

\[
ECC = (C_c + C_r) \times P_f
\]  

(1)

If for a component of each subsystem the preventive maintenance strategy is applied, the expected cost of maintenance over a given time interval includes two mains categories:

i) Expected cost of corrective maintenance (ECC): It is not possible to remove all failures by use of preventive maintenance but the number of failure could be decreased. When regular inspections are conducted, the cost associated with the ECC is changed. Now, in addition to the equation 1, the probability of the failure being detected \((P_p)\) is incorporated. The expected cost of failure when the preventive maintenance \((ECF_i)\) strategy is applied could be calculated by:

\[
ECF_i = (C_c + C_r) \times P_f \times (1 - P_p)
\]  

(2)
In other words, $ECF_i = ECC \times (\text{the probability that inspection will not detect the potential failure})$.

ii) Expected cost of inspection and preventive maintenance: Other costs considered in the preventive maintenance strategy include the cost of the inspections and timely and untimely restoration of the equipment. The expected cost of inspection and preventive maintenance (ECI) could be given by equation 3.

\[
ECI = C_i + C_{p,m}P_f P_p + C_{p,m}(1 - P_f)P_e
\]

where:
- $C_i$ is the cost of an inspection,
- $C_{p,m}$ is the cost of restoration,
- $P_e$ is the probability that inspection will falsely indicate the potential failure.

The expected cost of preventive maintenance (ECP) is the sum of the equations 2 and 3.

\[
ECP = ECF_i + C_i + C_{p,m}P_f P_p + C_{p,m}(1 - P_f)P_e
\]

If the ECP is greater than the ECC, then corrective maintenance is required for the component; otherwise preventive maintenance is considered. Then based on the answer of question “is it possible to use a suitable condition monitoring that is cost effective to implement and operate?”, condition-based maintenance or time-based maintenance could be selected as a preventive maintenance strategy.

A detailed decision diagram for maintenance strategy and optimization of availability for a system is proposed in Figure 1 which shows the maintenance selection method for a component or subsystem based on the reliability characteristics (e.g. failure rate) and expected cost of maintenance. The first step in the selection of a better maintenance plan for each component or subsystem is to find the component’s or subsystem’s failure rate based on the available data from the maintenance reports, failure observations, daily reports, etc., because the judgment for each type of maintenance strategy depends on the situation of the component in the bathtub curve.

In order to optimize the availability of a system by the use of parameters such as MTBF and MTTR, the concept of importance measures could be applied. Availability is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided [13]. Operational availability can be calculated by equation 5.

\[
A = \frac{MTBF}{MTBF + MeanDownTime}
\]

Two availability importance measures are defined in Barabady [14] that can serve as a guideline for decision making in developing an availability improvement strategy. The first availability importance measure is based on the MTBF and shows the effect of the MTBF of component $i$ on the availability of the whole system. The MTBF of the component with the largest value of availability importance measure has the greatest effect on the availability of the whole system. This can be calculated by equation 6.

\[
I_{A,MTBF}^i = \frac{\partial A_i}{\partial MTBF_i}
\]
The second availability importance measure is based on the MTTR and shows the effect of the MTTR of component \( i \) on the availability of the whole system. The MTTR of the component with the largest value has the greatest effect on the availability of the whole system. This can be calculated by equation 7.

\[
I'_{A,MTTR} = -\frac{\partial A_s}{\partial MTTR_i}
\]  

(7)

A comparison of these two importance measures shows which one of these two availability parameters of component \( i \) namely MTBF or MTTR has more influence on the availability of the system. The parameter with more value has more effect on the availability of the system. This comparison will provide basis for decision making, whether the availability improvement should be based on reducing the MTTR or increasing the MTBF of critical components or subsystems. If there are some restrictions, the effort can be spent on both increasing the MTBF and decreasing the MTTR.

**Fig. 1: Conceptual Model for Maintenance Strategy using Reliability Characteristics**

3. Case Study

A crushing plant is used to reduce the size of ore in a mineral processing plant. The ore is hauled to the crushing plant by trucks from the mine. In the first step the ore is moved to a primary screen with two levels and is divided into three parts: i) pieces smaller than 20 mm, ii) pieces between 20 mm and 10 cm, and iii) pieces larger than 10 cm. The ore pieces with a size larger than 10 cm go to the primary crushing subsystem, which consists of two jaw crushers. The output of this phase and part ii (pieces between 20 mm and 10 cm) is divided into two parts by a secondary screen: a) pieces smaller than 20 mm and b) pieces larger than 20 mm. In this stage the pieces with a size larger than 20 mm are moved to the secondary crusher (cone crusher), which works in a closed circuit with a secondary screen. The ore pieces with a size smaller than 20 mm go to the end of the process from both the primary and the secondary screens.

The assumptions for the calculation of reliability, maintainability, and availability in this case study are:

1. The system is repairable.
2. The system is subjected to repair and maintenance.
3. The Weibull distribution is used for analysis of the time between failures data and the time to repair data.
4. The studied function is assumed to be independent.
5. The time to repair also includes all waiting and logistics time.
6. The repaired components are as good as new.

We have divided the crushing plant into some subsystems, e.g. the primary screen, primary crusher, conveyer, secondary crusher and secondary screen, etc. Earlier, a preliminary study of the reliability characteristics of a crushing plant at Jajarm Bauxite Mine showed that the conveyer subsystem and secondary screen subsystem are the two most critical subsystems [15]. In this part of the present paper, we have selected the conveyer subsystem and secondary screen subsystem for improvement maintenance by using reliability analysis. The discussion and the results are based on the analysis of the time between failure and the time to repair of both subsystems for a period of one year. Based on the analysis, maintenance policies are also suggested. The results obtained using the model to evaluate the data collected in this case study are discussed with respect to the following quantitative measures for both subsystems: i) the reliability, ii) the maintainability, iii) the availability, and iv) the maintenance strategy.

The data collected in this study were mostly based on maintenance reports and daily operational reports. The data concerning the time between failure and the time to repair for a period of one year were sorted and analyzed. For the determination of the probability density function of failure and repair data in this study, the 2-parameter Weibull distribution was chosen, due to its flexibility in representing components with constant, increasing and decreasing failure rates.

3.1. The Reliability of both Subsystems

Table 1 shows the results of the reliability assessment, which estimated the parameter of failure time distribution by using ReliaSoft’s Weibull++ 6 software. Table 1 includes failure occurrence trends for the conveyer and the screen subsystem of the crushing plant.
In the Weibull analysis, the failure rates for both the screen and the conveyer subsystem of the crushing plant give a shape parameter greater than one, indicating an increasing failure rate due to an aging process (See also Figure 2). The MTBF of the secondary screen subsystem is longer than that of the conveyer subsystem.

### Table 1: Parameters of the Weibull distribution for TTF

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Weibull Parameters</th>
<th>MTBF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta$</td>
<td>$\eta$</td>
</tr>
<tr>
<td>Conveyer</td>
<td>1.19</td>
<td>16.17</td>
</tr>
<tr>
<td>Screen</td>
<td>1.54</td>
<td>23.83</td>
</tr>
</tbody>
</table>

Figure 3 shows the reliability of the conveyer subsystem and the secondary screen subsystem against time. Continuous lines are the best fit line for TBF data set of the conveyer subsystem and the screen subsystem. The reliability of the secondary screen subsystem is greater than that of the conveyer subsystem for different operation times.

**Fig. 2: Failure Rate of the Screen and the Conveyer Subsystems**
3.2. The Maintainability of both Subsystems

Table 2 shows the results of the maintainability analysis based on the Weibull distribution for the TTR. In the case study, as mentioned before, the repair time is the time from the point of failure to the start of the system again, which means that MTTR is the same with mean down time. From Table 2, it is found that the MTTR of the conveyer subsystem is longer than the MTTR of the screen subsystem.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Weibull Parameters</th>
<th>MTTR</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converyer</td>
<td>1.2458 1.5238</td>
<td>1.42</td>
<td>0.915</td>
</tr>
<tr>
<td>Screen</td>
<td>1.3783 1.1178</td>
<td>1.02</td>
<td>0.958</td>
</tr>
</tbody>
</table>

The maintainability of both subsystems is shown in Figure 5. With a repair time of 1 hour, the maintainability of the secondary screen subsystem and the conveyer subsystem is 58% and 45% respectively, which means that there is a 45% probability that the conveyer subsystem and a 58% probability that the screen subsystem will be repaired within 1 hour. Based on Figure 7, the maintainability of the secondary screen subsystem for all levels of time to repair is greater than that of the conveyer subsystem. The repair time depends not only on the technical systems but also on the maintenance crew.
3.3. The Availability of both Subsystems

The operational availability of the conveyer subsystem and the secondary screen subsystem could be calculated by using equation 5. The availability of the conveyer and the secondary screen subsystem is 0.915 and 0.958 respectively. The availability of each subsystem could be increased by reducing the MTTR or/and by increasing the MTBF. By using equations 6 and 7, the availability importance measure based on MTBF and the availability importance measure based on MTTR for an individual subsystem can be calculated by:

\[ I_{MTBF,i} = \frac{\partial A_i}{\partial MTBF} = \frac{MTTR}{MTBF(MTBF + MTTR)} A \]  
\[ (8) \]

\[ I_{MTTR,i} = \frac{\partial A_i}{\partial MTTR} = \frac{1}{MTBF(MTBF + MTTR)} A \]  
\[ (9) \]

Equation 8 and 9 show which of the two parameters, MTBF and MTTR, have a greater effect on the availability of each subsystem. For the secondary screen and the conveyer subsystems of the crushing plant MTBF>MTTR, therefore \( I_{MTTR,i} > I_{MTBF,i} \) indicating that a decrease in MTTR provides greater marginal benefit. However, the investment required to decrease the MTTR may be much greater than that required to increase the MTBF. A cost trade-off is essential for making the final decision, for more information see [15]

3.4. The Maintenance Strategy for both Subsystems

The failure rates for both the secondary screen and the conveyer subsystems of the crushing plant give a shape parameter greater than one, which means that the failure rate increases with time. For the control of the second condition for preventive maintenance strategy a cost trade-off is essential. If the ECP is greater than the ECC, then corrective maintenance is required for the component; otherwise preventive maintenance is considered. A numerical example of the concept of equations 1 to 4 can be illustrated with considering to a component of conveyer subsystem with following information:

\[ C_i = $10, C_c = $200, C_r = $50, C_{p.m} = $50, P_f = \%2, P_p = \%70, Pe = \%20 \]

By identifying associated cost with the inspections or failures and assigning probability to the event, one can canceled the value of preventive maintenance and corrective maintenance. The expected cost of corrective maintenance and preventive maintenance are calculated $50
and $40 respectively by equations 1 and 4. In this case it is more cost effective to do preventive maintenance.

We could define a critical level of reliability for both subsystems, which would mean that each subsystem would have to work with this level of reliability at least, and based on the critical level of reliability, the inspection interval could be identified. Table 3 shows the inspection time intervals for the conveyor and the screen subsystems. From Table 3, it can be seen, for example, that the conveyor subsystem will work with 70% reliability at least if the inspection for preventive maintenance is carried out after 6.8 hours. The inspection intervals for the different reliability levels listed in Table 3 may be used for inspection, repair, servicing, condition monitoring or replacement, depending on the safety implications, the cost–benefit considerations and the nature of the fault. For a reliability level of 90%, however, the maintenance interval estimated for both subsystems and some critical faults is too short for practical implementation. With this method it is possible to detect faults and the symptoms of failure by inspection, and to operate maintenance preventively if any fault is detected.

<table>
<thead>
<tr>
<th>Critical level of reliability</th>
<th>Time intervals of inspection (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conveyor</td>
</tr>
<tr>
<td>0.5</td>
<td>11.9</td>
</tr>
<tr>
<td>0.6</td>
<td>9.2</td>
</tr>
<tr>
<td>0.7</td>
<td>6.8</td>
</tr>
<tr>
<td>0.8</td>
<td>4.6</td>
</tr>
<tr>
<td>0.9</td>
<td>2.4</td>
</tr>
</tbody>
</table>

4. Conclusions

Appropriate maintenance task selection and performance at appropriate intervals of time are essential to an optimal maintenance program. We have suggested a decision diagram for maintenance strategies using reliability characteristics (Figure 2). Two availability importance measures are defined, which can serve as a guideline for decision making in developing an availability improvement strategy. In the case study, the failure rates for both subsystems increase, which means the subsystem works in a wear-out condition. For the secondary screen and the conveyor subsystems of the crushing plant $I_{MTTR,i} > I_{MTBF,i}$ indicating that a decreasing MTTR provides greater marginal benefit for optimization of availability. However, the investment required to decrease the MTTR may be much greater than that required to increase the MTBF. A cost trade-off is essential for making the final decision. It is recommended that the maintenance time interval calculated for 70% reliability should be adopted at first. This interval can then be adjusted after the benefits obtained in terms of cost, safety, and operational effectiveness of the machine have been observed.

References


