Chapter – 7

Preventive maintenance of critical subsystem of dragline

7.1 Introduction

This chapter details about the preventive maintenance of components. An imperfect preventive maintenance model has been developed for the repairable critical components of the dragline. For non-repairable critical components, interval-based reliability centered preventive replacement model is presented. These models are suggested to be followed in the maintenance of dragline.

7.2 Maintenance Model

Maintenance models are developed based on the repair characteristic of the components. This work has investigated two types of maintenance models: (i) imperfect preventive maintenance and (ii) interval-based reliability centered preventive replacement

7.2.1 Imperfect Preventive Maintenance Model

Maintenance is a crucial part for ensuring smooth operation of the equipment. Equipment performance can be increased while maintenance expenses decrease using appropriate maintenance techniques. Corrective maintenance (CM) and preventative maintenance (PM) are the two popular maintenance approaches [6, 7] practiced in mining industry. PM stands for periodic maintenance, which includes checking the equipment for flaws. Depending on maintenance cycles, PM can be grouped as fixed cycle PM and variable cycle PM. PM implementation is more practical, but getting the optimal preventive result in actual production system is challenging. After each PM, the equipment will not return to a brand new state i.e. as good as new and the failure rate will not drop to zero. This is commonly known as perfect PM. Even, after PM a system cannot be in a state just before the failure i.e. as bad as old and this is known as the minimal repair PM [8]. Therefore, The imperfect PM model, a more inclusive and grounded strategy, has thus been suggested for the critical components of the dragline. It assumes that after PM, the system is in a condition that is neither "as good as new" nor "as bad as old," i.e., "repair does not return to its initial state. This approach can lessen equipment failure, but sometimes it may lengthen downtime or may lead to over- or under-repair.

A variety of maintenance optimization models are available in the literature [8–16]. Research on imperfect PM has developed different models like, a sequential imperfect preventive maintenance model [24], age reduction model [5, 18], model for repairable or non-repairable failure modes assuming a failure rate increasing factor[6,18] [21]. These models have helped researchers to recommend maintenance strategies [19-22] for enhancing system performance. For optimization of imperfect preventive maintenance strategies, this research has used the total excepted cost as the goal function to establish the ideal preventive maintenance interval using the multi-criteria decision-making technique [7]. Projected failure time distribution has been used to build the cost function and to determine the preventive maintenance interval [17]. It has used the minimal long-term expected cost rate as the objective of optimization.

7.2.2 Preventive replacement model of components

There are two approaches to manage preventive replacement decisions in maintenance policies: replacement of capital equipment and replacement of the specific component. Following discussion will focus on determining replacement intervals of critical components.

7.3 Methodology of developing maintenance strategy

This section explains the methodology followed to develop a maintenance strategy to address the issues in dragline maintenance. An imperfect preventive maintenance model with the introduction of the age reduction factor and failure rate rising factor has been presented here. The failure rate function, age reduction factor, and failure rate rising factor form the foundation of the proposed model. Most of the research work cited above, solely includes total cost in the objective function. This study modifies the objective function and establishes a cost rate function after careful consideration of various cost elements and time factors of the maintenance process. For the non-repairable critical components, an interval-based reliability- centered preventive replacement maintenance model has been suggested. Interval based reliability-centered preventive replacement strategy for non-repairable critical components has been developed as detailed in the following section. Figure 7.1 represents the developed methodology for the maintenance of dragline's subsystems or components. The above two methods have explained in the next sections.

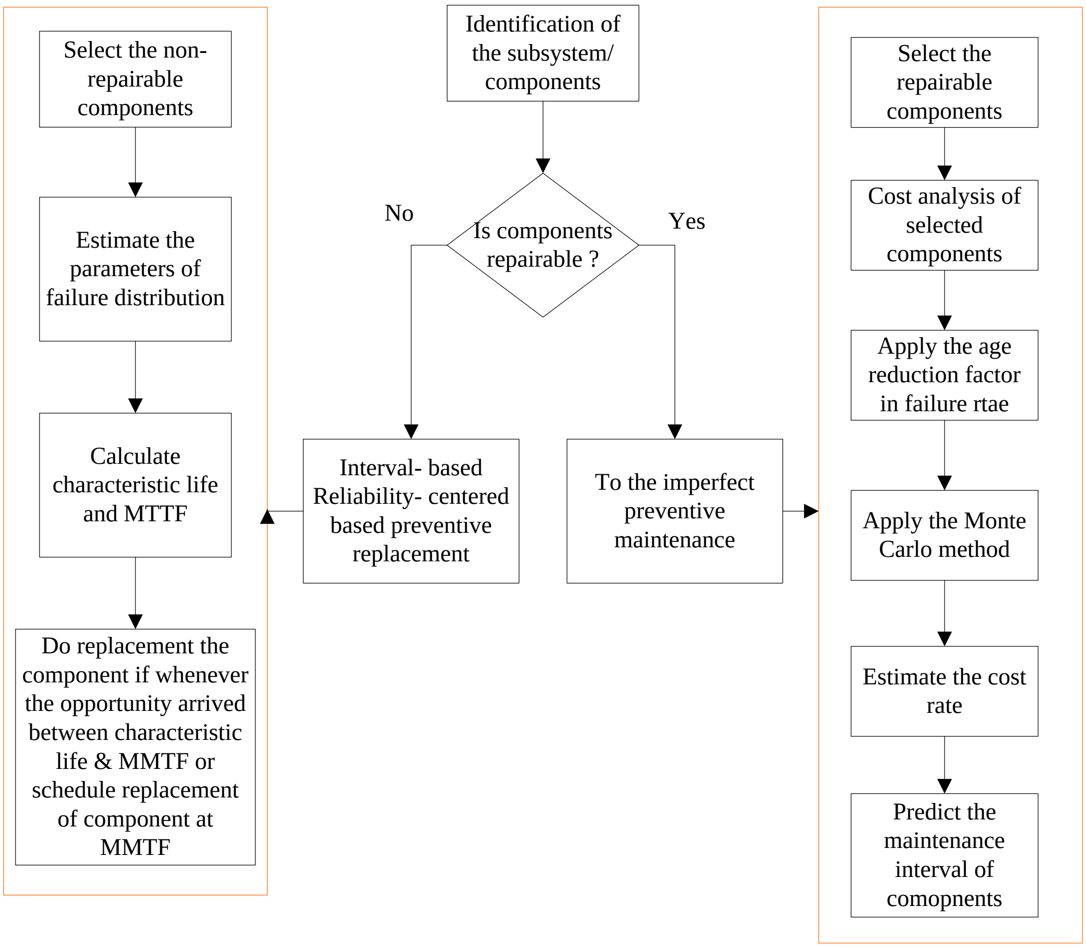

Figure 7. 1 flowcharts for the preventive maintenance of the dragline’s subsystem/components

7.3.1 Imperfect PM model of repairable critical components of dragging subsystem

This maintenance model incorporates the age reduction factor [5] and the failure rate increasing factor [6] for practical implementation of theoretical models into the real-world situation. The age decrease is a true reflection of maintenance. The failure rate of a component will revert to the level it was at just before maintenance following each periodic maintenance. After one maintenance, even though it is "repaired as new," the failure rate will still not be zero. However, following maintenance, there won't be a "repair as old" phenomenon and the failure rate will alter. The failure rate of the parts after imperfect PM falls between "repaired as new" and "repaired as old". The phenomenon that the failure rate of a part has escalated after maintenance as shown by the rising failure rate in figure 7.2. The disassembly, repair, and reinstall of the parts during maintenance process may result in some parts performing worse than they did before, and concealed risks of components' potential defect may be surfaced after maintenance. Here, an imperfect PM model for a repairable critical component within limited use time, is created by combining the age reduction factor and the increasing failure rate and depicted in figure 7.2.

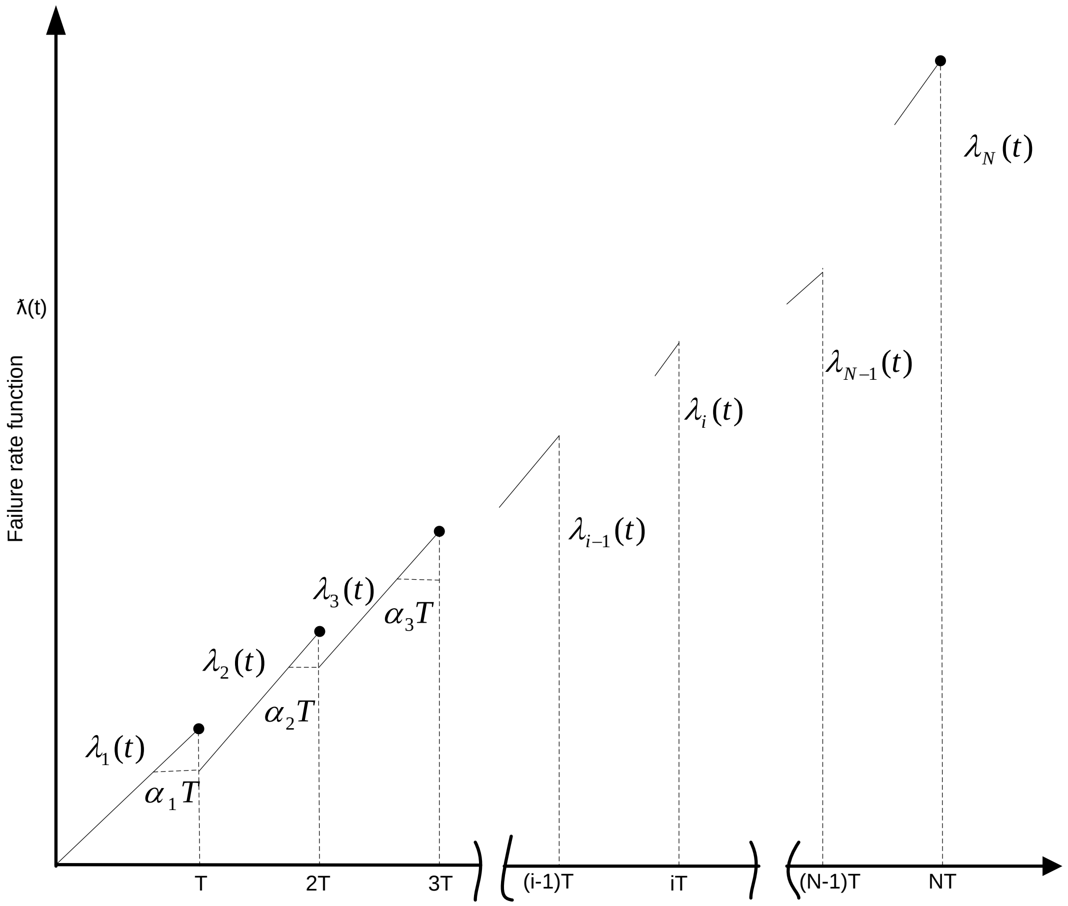

Figure 7. 2 Schematic diagram of the imperfect preventive maintenance model

Figure 7.2illustrates that after each maintenance, the age of the components decreases by $\alpha_i T$, when T is maintenance interval, and the components return to the state on time$(I-\alpha_i)T$ before the ith maintenance but the failure rate climbs faster after each maintenance cycle. The following is the recursive relationship of the components failure rate function expression over each maintenance cycle.

$$\lambda_i(t) = \lambda(t), t \in [0,T) \tag{7.4}$$

$$\lambda_2(t) = \psi_1 \lambda_1(t + T - \alpha_1 T), t \in [T,2T] \tag{7.5}$$

$$\lambda_3(t) = \psi_2 \lambda_2(t + 2T - \alpha_2 T), t \in [T,3T] \tag{7.6}$$

$$\vdots$$

$$\lambda_i(t) = \psi_{j-1} \lambda_{j-1}(t + (j-1)T - \alpha_{j-1} T) = \prod_{i=1}^{j-1} \psi_i \lambda \left(t + \sum_{i=1}^{j-1} (1-\alpha_i) T \right), t \in [(j-1)T, jT] \tag{7.7}$$

$\vdots$

$$\lambda_N(t) = \psi_{N-1}\lambda_{N-1}(t+(N-1)T-\alpha_{N-1}T) = \prod_{i=1}^{N-1}\psi_i\lambda\left(t+\sum_{i=1}^{N-1}(1-\alpha_i)T\right), t\in[(N-1)T, NT) \qquad (7.8)$$

Where, $1 \le i \le N$, the components are subject to N preventive maintenance within a limited use time, α_i is the age reduction factor, ψ_i is the failure rate increasing factor.

Age reduction factor can be expressed as [22], $\alpha_i = \dfrac{3i}{6i+7}$

Where i represents the number of maintenance.

Failure rate increasing factor (ψ) has been estimated by taking the average of the difference of the failure rates at two successive failures.

7.3.2 Calculation of optimum interval for PM

Modern design challenges are becoming more complicated, which frequently leads to conflicting aims. Engineering design exhibits such crucial but incompatible goals by attempting to minimize cost, minimize weight, maximize reliability, maximize performance, etc. [8]. Therefore, an optimization method that methodically and concurrently optimizes a group of objective functions has been used here.

The cost factors for maintenance of dragline subsystems/components consider the following three aspects: the cost of preventive maintenance C_p, the average cost of repair C_r and the cost of downtime C_d.

(i) Preventive maintenance cost

The preventive maintenance cost C_p can be divided into two parts: labor cost C_l, and material cost C_m:

$$C_p = C_l + C_m \qquad (7.9)$$

The total preventive maintenance cost within a limited use time is expressed as:

$$C_{p_{Total}} = \sum_{i=1}^{N} C_p \tag{7.10}$$

(ii) Repair costs

Following figure 7.1, the number of failures of the component during the jth maintenance cycle $[(j-1)T, jT]$ can be expressed as:

$$F_j = \int_0^T \prod_{i=1}^{j-1} \psi_i \lambda(t + \sum_{i=1}^{n}(1-\alpha_i)T)dt \tag{7.11}$$

The total number of failures within a limited use time can be expressed as:

$$F_{Total} = \sum_{j=1}^{N} \int_0^T \prod_{i=1}^{j-1} \psi_i \lambda(t + \sum_{i=1}^{n}(1-\alpha_i)T)dt \tag{7.12}$$

The total repair cost within the limited use time can be expressed as:

$$C_r = c_r F_{Total} \tag{7.13}$$

Where, c_r is the average repair cost.

(iii) Downtime Cost (C$_d$)

The downtime contained the preventive maintenance time and the repair time. If the preventive maintenance time is t_p, the average repair time is t_r, and the downtime loss per unit time is c_d,

The total preventive maintenance time can be expressed as follows:

$$T_p = \sum_{i=1}^{N} t_p(i) \tag{7.14}$$

The total repair time of failures can be

$$T_r = t_r \sum_{j=1}^{N} \int_0^T \prod_{i=1}^{j-1} \psi_i \lambda(t + \sum_{i=1}^{n}(1-\alpha_i)T)dt \tag{7.15}$$

The total downtime loss cost within the limited use time is

$$C_d = c_d (T_p + T_r) \tag{7.16}$$

The total cost is given as

$$C_{Total} = C_{p_{Total}} + C_r + C_d \tag{7.17}$$

Thus the total cost rate (per unit time) can be expressed as

$$E(N) = \frac{C_{Total}}{T_{Total}} \tag{7.18}$$

The optimization model calculates the maintenance interval of the component for the lowest cost rate, within the constrained usage time of the component. Therefore the objective function is:

$$Mininize\ E(N) = \frac{C_{Total}}{T_{Total}} \tag{7.19}$$

Where N, number of maintenance is the decision variable

The Monte Carlo simulation method has been used to determine the optimum maintenance interval of the component. In order to reduce the number of simulations and for determining the relationship between the maintenance frequency and the cost rate, the Monte Carlo simulation was performed with continuously change values of the maximum maintenance frequency. The optimal maintenance frequency and the best maintenance interval for the component are chosen based on the lowest cost rate. Figure 7.3 depicts the precise steps of the Monte Carlo simulation.

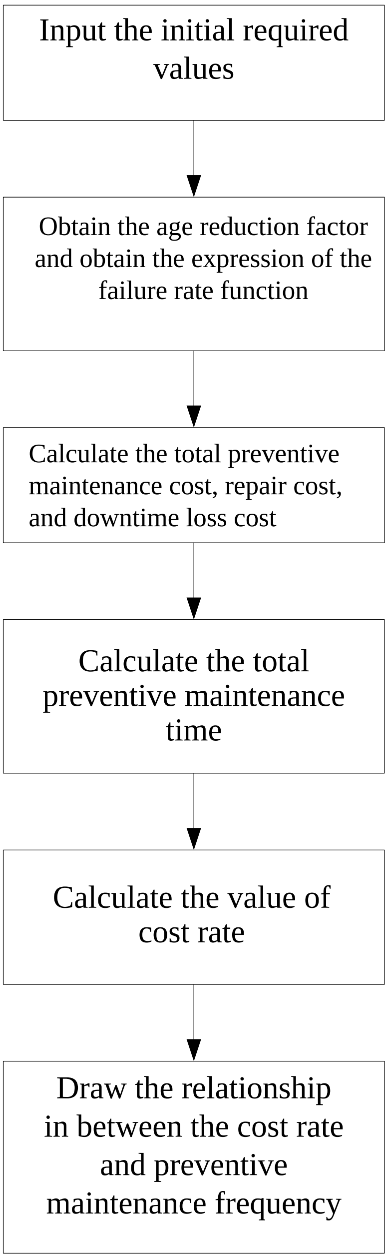

Figure 7. 3 Flow chart of the cost rate optimization method

7.3.3 Interval-based preventive replacement of non-repairable components of dragging mechanism

Replacement issues with deteriorating systems have been thoroughly researched. Typically, a lifetime distribution with parameters derived from historical data describes the interval between failures. Discussions with the maintenance practitioner during the field study culminated in the recommendation of interval-based preventive replacement of non-repairable components instead of run-to-failure replacement, to reduce the cost of downtime. This work suggests interval-based opportunistic preventive replacement and preventive replacement of non-repairable components. Application of intervals including the estimation of a window of opportunity for the lowest downtime cost, and scheduling replacement work whenever an opportunity arises is advocated. The interval of characteristic life and mean life of a component is a favourable time for opportunistic preventive replacement and scheduled preventive replacement thereafter. Figure 7.1 details various steps of the methodology.

7.4 Result & Discussion

For this study, failure data and financial data related to the maintenance from January 2013 to April 2015 for drag motor are collected. The parameters of failure distribution were obtained as given in table. To calculate the maintenance period of the drag motor, imperfect maintenance model and optimization model method has been used.

Optimization model has been used to calculate the PM maintenance and cost rate of the drag motor and imperfect maintenance model has been applied. Failure rate increasing factor (ψ) has been estimated by taking the average of the difference of the failure rates. To estimate the cost rate model, Monte Carlo simulation method has been used as per shown in figure 7.3.

These costs are estimated based on the data collected from the mines.

- $C_m =$ material cost = INR80000 $C_r = Repair\ cost = c_r$= INR75000
- $C_l = labour\ cost$ = INR 5000
- $C_d = Downtime\ cost$= INR 200000
- Repair time, t_r=2.5hr
- Total time(T)=2000hr
- Motor failure data follow the Weibull distribution. Estimated parameters are:

- η=51.45720898;
- β=1.238635027

The preventive maintenance frequency vs cost rate plot obtained from the model discussed in section 7.2.1 is shown in figure 7.3. The results attribute the minimum cost rate (min E (N)) and PM frequency.

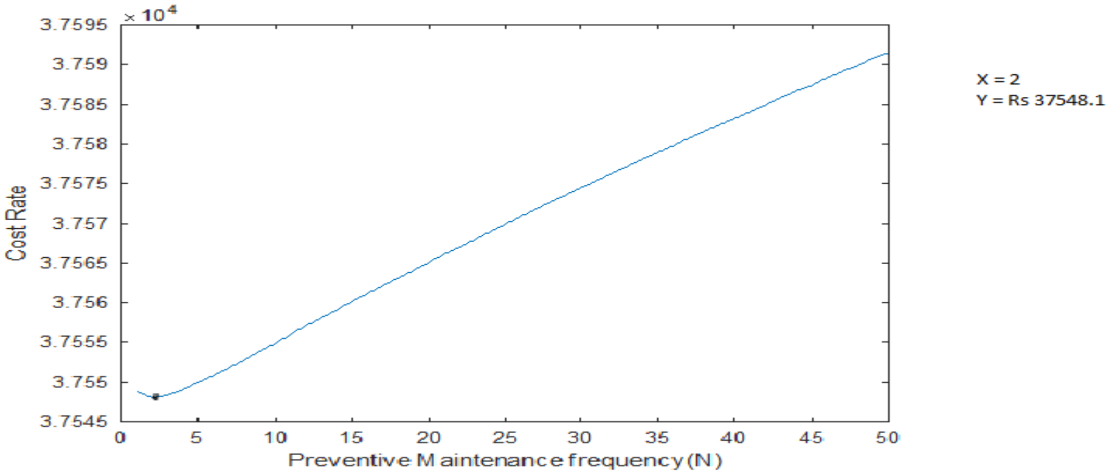

Figure 7.4 The relationship between the number of drag motor maintenance N and cost rate

It is observed from figure 7.4 that at N=2, the cost rate E (N) reaches a minimum, which is Rs. 37548/ h. Therefore the optimum interval for PM maintenance is 4000 hours.

Drag rope and drag chain are two critical replaceable components of the drag mechanism. From table 4.2 it is obvious that the failure times of drag rope and drag chain follows the weibull distribution and Weibull parameters are:

- Drag rope, β = 0.8459, η= 751.4251
- Drag chain, β = 0.8558, η= 433.3874

The characteristic life of the drag rope and chain has been estimated using the parameters of the best fit Weibull distribution and are 751.4251 hrs and 433.3874 hrs respectively, while the MTTF value of the drag rope and chain are 4508.55 hrs and 2600.25 hrs, respectively. This study suggests an opportunistic preventive replacement of the drag rope between 751hrs. – 4508 hrs. and this interval is 433 hrs. – 2600 hrs. for drag chain. Otherwise, replace drag ropes after 4508 hrs. and drag chain 2600 hrs. of use to avoid undue downtime. These results are useful information for inventory management.

7.5 Summary

Two maintenance strategies are developed for the repairable and non-repairable components of the most critical subsystem of the dragline. This research prescribed imperfect PM at the optimum interval, based on the lowest cost rate, to be followed for the maintenance of repairable components. The non-repairable components may be replaced once they complete their characteristic life. As and when opportunity arises replace the non-repairable components and follow a mandatory replacement policy after MTTF.