Availability Optimization for Coal Handling System using Genetic Algorithm

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Abstract: The paper deals with the availability optimization for Coal Handling System of a National Thermal Power Corporation (N.T.P.C.) Plant, using Genetic Algorithm (G.A.). Mathematical formulation is carried out using probabilistic approach and Markov birth–death process is used to develop the Chapman-Kolmogorov difference differential equations. These equations are further solved recursively in order to derive the Steady State Availability expression. The optimal values of availability of coal handling system have been evaluated using Matlab G.A. tool. The steady state availability obtained from Markov analysis is also compared with the optimal availability calculated through G.A.

Keywords: Availability optimization, Genetic Algorithm, Coal handling system, Markov process, Chapman-Kolmogorov differential equations

1.0 Introduction

Availability is one of the measures of system performance besides reliability under the specified conditions of use. A complex plant may have systems and the subsystems connected functionally in series, parallel or a combination of these. In the literature, some researchers [1-9] have carried out system reliability optimization and cost analysis. A stochastic model has been developed in [1] to analyze performance of a cell operating with multistate including degraded states. The applications of model to determine reliability and productivity of the cell, as well as the utilization of its components under various operational conditions have been discussed.

The availability and MTTF expressions of washing system of a paper industry have been derived in [2] using simple probability considerations. A mathematical model of a complex bubble gum production system has been developed in [3] using Markov modeling. The reliability characteristics have been evaluated and analyzed in the paper. An optimization model [4] for the grid service allocation has been developed using Genetic Algorithm. A reliability model of a block-board manufacturing system in the plywood industry has been developed in [5] using time dependent and steady state availability under idealized and faulty preventive maintenance conditions. A Genetic Algorithm based optimization model [6] has been proposed to optimize availability for a series parallel system.

A maintenance optimization model of an engineering system assembled in a series configuration has been proposed in paper [7]. The various optimization techniques and their implementation have been discussed in [8] for some engineering problems. A systematic study for G.A. mechanism and identification of three basic operators: reproduction, crossover and mutation for obtaining near optimal solutions has been carried out in [9]. After going through comprehensive literature review, it has been felt that G.A., which has been successfully applied in various complex industries comprising series, parallel and hybrid systems, however has not been considered for availability optimization.

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of a thermal plant so far. In addition, as the plant management is always interested in maintaining maximum availability with optimal parameters, hence, the author has made an attempt to optimize the availability of the system concerned using G.A.

2.0 System Description

The plant is divided into many sections like Ash handling system, Water treatment system, Coal handling system, Condensate and feed water system and Air distribution system. The coal handling system comprises of various subsystems working in series and parallel configuration. The schematic diagram of Coal handling system as shown in figure 1 is as follows:

Coal from railway track hopper

- Wagon tipplers
  - Two conveyor belts in parallel
  - Crusher house
    - Two conveyor belts in parallel
      - Transfer point
        - Two conveyor belts in parallel
          - Raw coal bunker 1
          - Raw coal bunker 2
            - Coal pulverizing mill 1
            - Coal pulverizing mill 2
              - Pulverizing coal bunker 1
              - Pulverizing coal bunker 2
                - Furnace

Figure 1: Schematic Diagram of Coal Handling System

The Coal handling system consists of the following four critical subsystems:

i. **Wagon Tippler (C₁)**: These are the motorized operated machines. This subsystem consists of two units of wagon tipplers. Failure of any one forces to start with standby unit. Complete failure of the system occurs when standby unit of the wagon tippler also fails.

ii. **Conveyor Belts (C₂)**: These are the synthetic rubber belts, which move on metallic rollers and idlers, which are used for shifting of coal from one place to other place. There are two units of conveyors working in parallel. Failure of any one reduces the capacity of belt to transport the coal from one location to other. Complete failure of the system occurs when both the units fail.

iii. **Crusher House (C₃)**: The coal is received in the form of odd shaped lumps. These lumps are to be crushed to required size. These lumps are crushed by coal crushers whose failure causes complete failure of the system.
iv. **Coal Pulverizing Mills (C4):** The function of these mills is to make the fine powder of the coal for effective burning in the boiler. There are two units of Mills working in parallel. Failure of anyone reduces the capacity of the system and hence loss in production. Complete failure of the system occurs when both the mills fail.

### 2.1 Assumptions and Notation

i. Repair rates and failure rates are negative exponential and independent of each other.

ii. Simultaneous failures are not allowed among the subsystems.

iii. A repaired unit is, performance wise, as good as new.

iv. The Switch-over devices are perfect and repair facilities are always available.

v. The failure rates of other subsystems like coal bunkers and transfer point in coal handling system are almost insignificant.

<table>
<thead>
<tr>
<th>State Description</th>
<th>Sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Capacity State (without standby)</td>
<td>C1, C2, C3, C4</td>
</tr>
<tr>
<td>One unit of sub-system C1 is in failed state and the system is working with standby unit</td>
<td>C1'</td>
</tr>
<tr>
<td>Failed State</td>
<td>c1, c2, c3, c4</td>
</tr>
<tr>
<td>Reduced capacity</td>
<td>C2 and C4</td>
</tr>
<tr>
<td>Failure rates</td>
<td>( \lambda_i; i = 14 ) to ( 17 )</td>
</tr>
<tr>
<td>Repair rates</td>
<td>( \mu_i; i = 14 ) to ( 17 )</td>
</tr>
<tr>
<td>Probability of full capacity working State</td>
<td>( P_0 ) and ( P_1 )</td>
</tr>
<tr>
<td>Probability of reduced capacity working state</td>
<td>( P_2, P_3, P_4, P_5, P_6, P_7 )</td>
</tr>
<tr>
<td>Probability of failed state</td>
<td>( P_8 ) to ( P_{27} )</td>
</tr>
</tbody>
</table>

### 2.2 Mathematical Modeling and Steady State Availability for Coal Handling System

The mathematical modeling for Coal handling System starts with the development of Chapman-Kolmogorov difference differential using transition diagram. The coal handling system is required to be available for long duration of time. So, the long run or steady state availability of the coal handling system is obtained by putting \( P_i(t) = 0 \) as \( t \to \infty \) in differential eqns. (1) to (12) (Appendix) and solving these equations recursively, we get:

\[
P_1 = \frac{N_{14}}{N_{13}} P_0 = M_4 P_0
\]

\[
P_2 = \frac{N_{15}}{N_{13}} P_0 + \frac{N_{14}}{N_{12}} P_0 + M_4 P_0
\]

\[
P_3 = \frac{N_{16}}{N_{15}} P_0 + \frac{N_{14}}{K_1} P_1 + \frac{N_{11}}{K_1} P_2 = \frac{N_{16}}{K_1} P_0 + \frac{N_{14}}{K_1} M_4 P_0 + \frac{N_{11}}{K_1} M_2 P_0 = M_5 P_0
\]

\[
P_4 = N_3 P_0 + N_4 P_3 + N_5 P_2 = N_3 P_0 + N_4 M_3 P_0 + N_5 M_2 P_0 + N_6 M_2 P_0 = M_6 P_0
\]

\[
P_5 = \frac{\lambda_{14}}{K_1} P_1 + \frac{\lambda_{15}}{K_4} P_2 + \frac{\lambda_{15N1}}{K_1} P_3 + \frac{\lambda_{15N2}}{K_1} P_3 + \frac{\lambda_{15N3}}{K_3} P_2 + \frac{\lambda_{15N4}}{K_3} P_1 = \frac{\lambda_{17}}{K_5} M_4 P_0 + \frac{\lambda_{14}}{K_5} M_4 P_0 + \frac{\lambda_{15N1}}{K_5} M_4 P_0 + \frac{\lambda_{15N2}}{K_5} M_4 P_0 + \frac{\lambda_{15N3}}{K_5} M_4 P_0 + \frac{\lambda_{15N4}}{K_5} M_4 P_0 +
\]

\[
P_6 = N_1 P_3 + N_3 P_1 + N_4 P_4 = N_1 M_2 P_0 + N_3 M_3 P_0 + N_4 M_4 P_0 + N_5 M_4 P_0 + N_6 M_4 P_0 = M_8 P_0
\]

\[
P_7 = N_1 M_2 P_0 + N_3 M_3 P_0 + N_4 M_4 P_0 + N_5 M_4 P_0 = \frac{\lambda_{14} M_2 P_0 + \lambda_{15} M_2 P_0}{T_7} = M_8 P_0
\]
where

\[ T_1 = \lambda_{15} + \mu_{14} \quad T_2 = \lambda_{16} + \lambda_{17} + \mu_{15} \quad T_3 = \lambda_{14} + \mu_{17} + \mu_4 \quad T_4 = \lambda_{14} + \lambda_{15} + \mu_{17} \]

\[ T_5 = \lambda_{45} + \mu_{14} + \mu_7 \quad T_6 = \mu_4 + \mu_5 + \mu_{17} \quad T_7 = \lambda_7 + \mu_{44} + \mu_{15} \]

\[ N_i = \frac{\lambda_{14}}{T_i} \quad N_2 = \frac{\lambda_{13}}{T_5} \quad N_3 = \frac{\lambda_{14} + \lambda_{12}}{T_6 T_7} \quad N_4 = \frac{\lambda_{13} \lambda_{17}}{T_8 T_9} \]

\[ N_5 = \frac{\lambda_{17}}{K_4} \quad N_6 = \frac{\mu_{15} (1 + \mu_{14} N_1)}{K_5} \quad N_7 = \frac{\mu_{14} \left( \frac{\lambda_{17}}{K_4} \right)}{K_5} \quad N_8 = \frac{\mu_{14} \mu_{13} N_3}{K_4 K_5} \]

\[ N_9 = \lambda_{13} N_4 + \frac{\mu_{14} N_2 N_3 \lambda_{14}}{K_5} \quad N_{10} = \lambda_{15} N_3 + \lambda_{14} N_4 + \mu_{14} N_2 N_3 \lambda_{14} + \mu_{14} N_2 \lambda_{14} N_3 + \frac{\mu_{14} N_2 \lambda_{14} N_3}{K_5} \]

\[ N_{11} = \lambda_{17} + \lambda_{15} N_9 + \mu_{14} N_3 + \frac{\mu_{14} N_2 N_3 \lambda_{14} + \mu_{14} N_3 \lambda_{14} N_3}{K_5} \]

\[ N_{12} = \lambda_{17} N_{11} + \frac{\mu_{17} N_{11}}{K_3} \quad N_{13} = \lambda_{17} \lambda_{15} + \mu_{14} N_{13} \frac{\lambda_{14} N_{13}}{T_5 N_{12}} \quad N_{14} = \frac{\mu_{17} N_{11} + \mu_{17} N_{11}}{K_3} \]

\[ N_{15} = \frac{\mu_{14} \mu_{13} N_3}{K_4} \quad N_{16} = \frac{\mu_{14} \mu_{13} N_1}{T_7} \quad N_{17} = \frac{\mu_{14} \mu_{13} N_1}{T_7} \]

\[ K_5 = \frac{\mu_{14} \lambda_{14} N_{14}}{T_5 N_{12}} \quad K_3 = \frac{\mu_{14} \lambda_{14} N_{14}}{T_5 N_{12}} \quad K_3 = T_3 - \lambda_{15} N_6 - \mu_{14} N_1 - \frac{\mu_{14} N_2 N_{14} \lambda_{14} N_3}{K_5} \]

Now using normalizing conditions *i.e.*, sum of all the probabilities is equal to one, we get:

\[ \sum_{i=0}^{27} p_i = 1 \]

\[ p_i = \begin{bmatrix} 1 + M_1 + M_2 + M_3 + M_4 + M_5 + M_7 + M_{16} + M_{14} + M_{13} + M_{12} + M_{11} + M_{10} + M_9 + M_8 + M_7 + M_6 + M_5 + M_4 + M_3 + M_2 + M_1 + M_0 + \lambda_{17} M_1 + \lambda_{15} M_1 + \lambda_{14} M_1 + \lambda_{13} M_1 + \lambda_{12} M_1 + \lambda_{11} M_1 + \lambda_{10} M_1 + \lambda_{09} M_1 + \lambda_{08} M_1 + \lambda_{07} M_1 + \lambda_{06} M_1 + \lambda_{05} M_1 + \lambda_{04} M_1 + \lambda_{03} M_1 + \lambda_{02} M_1 + \lambda_{01} M_1 + \lambda_{00} M_1 \end{bmatrix} \]

Steady state availability of Coal handling system (\( A_p \)) may be obtained as summation of probabilities of all working and reduced capacity states, *i.e.,*

\[ A_p = \sum_{i=0}^{27} P_i = 96.20\% \quad (13) \]

Taking \( \lambda_{14}=0.005, \mu_{14}=0.10, \lambda_{17}=0.02, \lambda_{15}=0.15, \lambda_{16}=0.005, \mu_{15}=0.60, \lambda_{17}=0.01, \mu_{17}=0.08 \) (Data taken from Maintenance History sheets)

The availability (\( A_p \)) as given by eqn. (13) includes all possible states of nature, that is, failure events (\( A_f \)) and the identification of all the courses of action *i.e.*, repair priorities (\( \mu_i \)). The various availability levels may be computed for different combinations of failure and repair rates. This model can be used to make strategic maintenance policies for Coal handling system.

### 3.0 Availability Optimization for Coal Handling System Using Genetic Algorithm

In the present work, an attempt has been made to optimize the system availability using G.A. approach. G.A. is a powerful probabilistic approach for search and optimization. It uses different representations, mutations, crossovers and selection mechanisms. Table 1 shows the G.A. parameters taken for performance optimization.
**Table 1**: Genetic Algorithm Parameters for Coal Handling System

<table>
<thead>
<tr>
<th>Population Type: Double Vector</th>
<th>Reproduction (Elite Count): 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population Size: 20 to 160 in step size of 20</td>
<td>Reproduction (Crossover fraction): 0.80</td>
</tr>
<tr>
<td>Creation Function: Uniform</td>
<td>Mutation Probability: 0.015</td>
</tr>
<tr>
<td>Fitness Scaling: Rank</td>
<td>Crossover Probability: Heuristic-0.85</td>
</tr>
<tr>
<td>Selection: Stochastic</td>
<td>Migration: Direction-Forward</td>
</tr>
<tr>
<td>Stopping Criteria: Generation-50 to 450 in step size 50</td>
<td>Number of Variables: 8</td>
</tr>
</tbody>
</table>

The failure and repair parameters of each subsystem affect the performance optimization of Coal handling system. Genetic Algorithm is hereby proposed to synchronize the failure and repair parameters of each subsystem for getting optimal availability. To use Genetic Algorithm for solving the given problem, the chromosomes are coded in real structures. The system parameters are mapped in between the specific bound [lower, upper]. The system has four constraint parameters (four failure and four repair parameters). These parameters are optimized keeping in view the fitness function i.e., the maximum availability. The designed ranges of failure and repair rates are taken from the maintenance history sheets of the plant.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\lambda_{14}$</th>
<th>$\mu_{14}$</th>
<th>$\lambda_{15}$</th>
<th>$\mu_{15}$</th>
<th>$\lambda_{16}$</th>
<th>$\mu_{16}$</th>
<th>$\lambda_{17}$</th>
<th>$\mu_{17}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>0.005-0.025</td>
<td>0.75-1.5</td>
<td>0.02-0.10</td>
<td>0.55-0.65</td>
<td>0.05-0.12</td>
<td>0.01-0.08</td>
<td>0.08-0.40</td>
<td>0.3-0.60</td>
</tr>
</tbody>
</table>

4.0 Results and Discussion

Firstly, the availability optimization is carried out by varying the number of generations from 50 to 450 in step size of 50. It is observed that the optimum availability of Coal handling system of N.T.P.C plant comes out to be 98.86% at 250 number of generations. The corresponding values of failure and repair rates are $\lambda_{14} = 0.011$, $\mu_{14} = 0.475$, $\lambda_{15} = 0.0202$, $\mu_{15} = 0.5028$, $\lambda_{16} = 0.00503$, $\mu_{16} = 0.5614$, $\lambda_{17} = 0.01043$, $\mu_{17} = 0.3892$, which is the best possible combination of failure and repair rates of different subsystems. The effect of number of generations on availability of Coal handling system is shown by Figure 2.

Secondly, the optimization is carried out by varying the population size from 20 to 160 in step size of 20. It is evident that the best possible combination of failure and repair parameters are $\lambda_{14} = 0.00934$, $\mu_{14} = 0.4719$, $\lambda_{15} = 0.02135$, $\mu_{15} = 0.51857$, $\lambda_{16} = 0.005191$, $\mu_{16} = 0.5891$, $\lambda_{17} = 0.01065$, $\mu_{17} = 0.3702$, at which the optimum value of system availability is 98.87% with population size 120. The effect of population size on system availability is shown in Figure 3.
The availability optimization of the Coal handling system is discussed in this paper. The steady state availability is calculated as 96.20% by putting the values of failure and repair rates taken from maintenance history sheets. Genetic algorithm is hereby used to calculate optimal value of availability, which comes out to be 98.87% i.e., the increase of 2.67%. The comparison in steady state availability and optimized availability using genetic algorithm is shown by table 4.

The effect of number of generation and population size on system availability is also discussed in the paper. These optimized parameters will be useful to the plant management for the timely execution of proper maintenance decisions and hence to enhance the system performance of Coal handling system.

In order to achieve the optimum availability level, the corresponding repair and failure rates of the subsystems should be maintained. The failure rates can be maintained through good design, reliable machines, proper preventive maintenance schedule and providing standby components etc. The corresponding repair rates can be achieved by employing more trained workers and utilizing better repair facilities.

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References


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Appendix

The difference differential equations are generated using Markov birth-death process and are as follows:

\[ P_0(t) + \left( \sum_{i=1}^{17} \lambda_i \right) P_0(t) = \sum_{i=1}^{15} \mu_i P_{i-1}(t) + \mu_{17} P_1(t) + \mu_{16} P_0(t) \]  
(1)

\[ P_1(t) + \left( \sum_{i=1}^{17} \lambda_i + \mu_{14} \right) P_1(t) = \lambda_{14} P_0(t) + \mu_{17} P_2(t) + \mu_{15} P_1(t) + \mu_{16} P_0(t) + \mu_{13} P_1(t) \]  
(2)

\[ P_2(t) + \left( \sum_{i=1}^{17} \lambda_i + \mu_{15} \right) P_2(t) = \lambda_{15} P_0(t) + \mu_{17} P_3(t) + \mu_{16} P_1(t) + \mu_{15} P_0(t) + \mu_{13} P_2(t) \]  
(3)

\[ P_3(t) + \left( \sum_{i=1}^{17} \lambda_i + \mu_{17} \right) P_3(t) = \lambda_{17} P_0(t) + \lambda_{15} P_4(t) + \mu_{14} P_0(t) + \mu_{17} P_5(t) + \mu_{16} P_1(t) + \sum_{i=17}^{15} \mu_i P_{i+1}(t) \]  
(4)

\[ P_4(t) + \left( \sum_{i=1}^{17} \lambda_i + \mu_{14} + \mu_{17} \right) P_4(t) = \lambda_{17} P_0(t) + \lambda_{15} P_4(t) + \mu_{14} P_1(t) + \mu_{17} P_5(t) + \mu_{15} P_2(t) + \mu_{14} P_0(t) + \mu_{17} P_3(t) + \mu_{16} P_1(t) + \sum_{i=17}^{15} \mu_i P_{i+1}(t) \]  
(5)

\[ P_5(t) + \left( \sum_{i=1}^{17} \lambda_i + \mu_{14} + \mu_{15} \right) P_5(t) = \lambda_{14} P_1(t) + \lambda_{14} P_4(t) + \mu_{14} P_0(t) + \mu_{15} P_6(t) + \mu_{16} P_1(t) + \mu_{15} P_3(t) + \mu_{16} P_1(t) + \sum_{i=17}^{15} \mu_i P_{i+1}(t) \]  
(6)

\[ P_6(t) + \left( \sum_{i=1}^{17} \lambda_i + \mu_{14} + \mu_{15} + \mu_{17} \right) P_6(t) = \lambda_{14} P_1(t) + \lambda_{15} P_3(t) + \lambda_{16} P_1(t) + \lambda_{17} P_5(t) + \mu_{16} P_1(t) + \mu_{16} P_2(t) + \mu_{15} P_6(t) + \mu_{17} P_3(t) \]  
(7)

\[ P_7(t) + \left( \sum_{i=1}^{17} \lambda_i + \mu_{14} + \mu_{15} + \mu_{17} \right) P_7(t) = \lambda_{14} P_2(t) + \lambda_{15} P_5(t) + \mu_{14} P_2(t) + \mu_{15} P_7(t) + \mu_{16} P_2(t) \]  
(8)

\[ P_i(t) + \mu_{16} P_i(t) + \mu_{17} P_i(t) \]  
(9)

For \( i = 12, j = 1; i = 15, j = 5; i = 21, j = 6; i = 27, j = 7. \)

\[ P_1(t) + \mu_{16} P_1(t) = \lambda_{16} P_1(t) \]  
(10)

For \( i = 9, j = 2; i = 16, j = 3; i = 22, j = 6; i = 26, j = 7. \)

\[ P_1(t) + \mu_{16} P_1(t) = \lambda_{16} P_1(t) \]  
(11)

For \( i = 8, j = 1; i = 10, j = 0; i = 11, j = 1; i = 13, j = 4; i = 14, j = 5; i = 17, j = 3; i = 24, j = 6; i = 25, j = 7. \)

\[ P_1(t) + \mu_{17} P_1(t) = \lambda_{17} P_1(t) \]  
(12)

For \( i = 18, j = 3; i = 19, j = 4; i = 20, j = 5; i = 23, j = 6. \)

Initial conditions at time \( t = 0 \) are

\[ P_i(t) = 1 \text{ for } i = 0 \text{ and } = 0 \text{ for } i \neq 0. \]