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A Markov Model for Performance Evaluation of Coal Handling Unit of a Thermal Power Plant

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ABSTRACT

The present paper discusses the development of a Markov model for performance evaluation of coal handling unit of a thermal power plant using probabilistic approach. Coal handling unit ensures proper supply of coal for sound functioning of thermal Power Plant. In present paper, the coal handling unit consists of two subsystems with two possible states i.e. working and failed. Failure and repair rates of both subsystems are taken to be constant. After drawing transition diagram, differential equations have been generated. After that, steady state probabilities are determined. Besides, some decision matrices are also developed, which provide various performance levels for different combinations of failure and repair rates of all subsystems. Based upon various performance values obtained in decision matrices and plots of failure rates/ repair rates of various subsystems, performance of each subsystem is analyzed and then maintenance decisions are made for all subsystems. The developed model helps in comparative evaluation of alternative maintenance strategies.

Keywords: Probabilistic approach, Steady state probabilities, Decision matrices.

1. INTRODUCTION

Any production system should be kept failure free (as far as possible) under the given operative conditions to achieve the set goals of economical production and long run performance. A highly reliable system tends of increase the efficiency of production. Many utility systems in the world have power plants operating with fossil fuel. In the thermal power plants, there is maximum requirement of coal as a fuel. The handling of this fuel is a great job. To handle the fuel i.e. coal, each power station is equipped with a coal handling plant. Maintenance of critical equipments for coal handling plants (CHP) of thermal power stations is typical job. For regular and economical

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generation of steam in a thermal plant, it is necessary to maintain each subsystem of coal handling unit.

According to Kumar and Pandey (1993), the failure rate of each subsystem in a particular system depends upon the operating conditions and repair policies used. From economic and operational point of view, it is desirable to ensure an optimum level of system availability. Barabady and Kumar (2007) states that the most important performance measures for repairable system designers and operators are system reliability and availability. Samrout et al. (2005) describes the availability and reliability as good evaluations of a system's performance. Their values depend on the system structure as well as the component availability and reliability. These values decrease as the component ages increase; i.e. their serving times are influenced by their interactions with each other, the applied maintenance policy and their environments. For the prediction of availability, several mathematical models have been discussed by Balaguruswamy (1984) and Dhillon (1983), which handle wide degree of complexities. Most of these models are based on the Markovian approach, wherein the times to failure and the times to repair follow exponential distribution. In other words, the failure and the repair rates are assumed to be constant. Some of the Markov analysis tools are 'SURE' given by Butler (1986), 'HARP' proposed by Smotherman et al. (1986), 'SAVE' given by Goyal et al. (1986), 'EHARP' described by Somani et al. (1992 and 1994), 'SHARPE' discussed by Sahner and Trivedi (1987), 'TANGRAM' proposed by Bernson et al. (1991), 'HIMAP' given by Krishnamurthi et al. (1996) and 'SURF-2' suggested by Beounes et al. (1993). Advantages of Markov chains are the capability of modeling systems with shared repair. Lim and Chang (2000) studied a repairable system modeled by a Markov chain with two repair modes. A text of general interest for studying reliability systems and performance measures is that of Høyland and Rausand (1994). Misra (1992) gives the three state systems using the Markovian approach and derives the formulae for steady state availability, the frequency of failure, mean time to failure and mean duration of down.

During the past decade a lot of study has been done by Butler (1986A), Ciardo et al. (1989), Koren and Gaertner (1987) and Sanders et al. (1993) on analysis tools for reliability, availability, performance and performability modeling. The considerable efforts have been made by the researchers providing general methods for prediction of system reliability designing equipments with specified reliability figures, demonstration of reliability values issues of maintenance, inspection, repair and replacement and notion of maintainability as design parameter, as stated by Sharma (1994). To maintain an efficiently operating system and avoid failure of critical equipment, it is necessary to maintain the critical parts of that equipment. There are varieties of critical equipment components in coal handling plants. These components require routine inspection to ensure their integrity. The purpose of the inspection is to identify any degradation in the integrity of the systems during their service life and to provide an early warning in order that remedial action can be taken before failure occurs.

1.1 Organization of the Paper

- The section 2 presents and discusses the processing and description of coal handling unit, along with the preparation of transition diagram. The unit description, symbols and nomenclature along with required assumptions used for development of model are also listed in this section.
- Section 3 describes the development of Markov mathematical model.
- Section 4 describes the performance evaluation made in this study.

- Section 5 and 6 presents the results and conclusions respectively of study made in this paper.

2. COAL HANDLING UNIT

A thermal power plant is a complex engineering system comprising of various systems: Coal handling, Steam Generation, Cooling Water, Crushing, Ash handling, Power Generation and Feed water system. In a coal fired thermal power plant the chemical energy stored in coal, is converted successively into thermal energy, then in mechanical energy and, finally in electrical energy for continuous use and distribution across a wide geographic area. The coal from railway bogies is unloaded by the wagon tippler, which is collected in two underground hoppers. From the hoppers the coal is transferred to either of the two conveyors by means of vibrating feeders. Dust suspension equipment is provided to suppress the coal dust created during the unloading of coal. From the conveyors the coal is again transferred to the next conveyor unit. Again failure of one leads convey on other, which supplies the coal to the crusher house. In crusher house the size of coal pieces is reduced. If a situation arises where coal bunkers are full, then coal is crushed and stacked with the help of stacker reclaimers. At a particular moment when coal bunkers are empty, the coal can be reclaimed with the help of stacker. The aim of layout of coal handling unit, as described in figure 1, is to provide maximum flexibility and to ensure for high reliability of the plant. Thus coal handling unit is the main and most important part of a thermal plant.

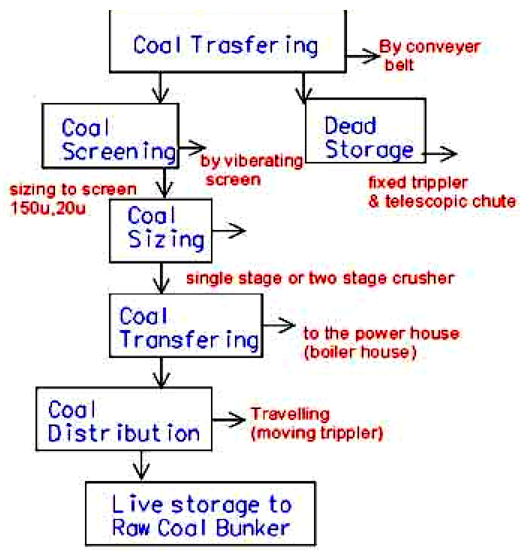

Figure 1 Coal handling unit

2.1. Unit Description

A typical system consists of a number of components or subsystems connected to each other logically either in series or in parallel in most cases. The performance of the system depends on the performance of its subsystems and on the configuration of the system. The coal handling unit consists of following subsystems;

(1) The wagon tippler 'W' is having two units in parallel. Failure of any one forces to start stand-by unit. Complete failure of the unit occurs when stand-by unit of the wagon tippler also fails.

(2) The conveyor 'C' consists of two units, failure of first forces the stand-by unit to run. Complete failure of the unit occurs when the stand-by unit of conveyor also fails.

2.2. Symbols and Nomenclature

The symbols and notations associated with the transition diagram are as follows;

○ Indicates the subsystems in operating condition.

□ Indicates the subsystems in breakdown condition.

W, C Indicates that the subsystems are working at full capacity.

W^1C^1 Indicates that stand-by units of the subsystems are in operating state.

W C Indicates that both subsystems are in failed state due to failure of stand-by unit also.

ϕ_1, ϕ_2 Indicates the failure rate of subsystems W and C.

ϕ_3 Failure rate of both subsystems (W and C) simultaneously.

λ_1, λ_2 Indicates repair rate of subsystems W and C.

λ_3 Repair rate of both subsystems (W and C) simultaneously.

$P'_i(t)$ Indicates derivative with respect to 't'.

$P_0(t)$ Probabilities that at time 't' the subsystems are working without stand by unit.

$P_1(t)$ to $P_3(t)$ Probabilities that at time 't' the subsystems are working with stand by units.

$P_4(t)$ to $P_7(t)$ Probabilities that at time 't' the subsystems are in failed state.

2.3. Assumptions for Model Development

1. Failure/repair rates are constant over time and statistically independent, as stated by Gupta et al. (2009).
2. At any given time, the system is either in operating state or in the failed state, as assumed by Gupta et al. (2009A).
3. Sufficient repair facilities are available, as given by Srinath (1994).
4. Standby units are of the same nature and capacity as that of active systems.
5. Service includes repair and/or replacement, as given by Khanduja et al. (2008).
6. A repaired unit is as good as new, performance wise, for a specified duration, as used by S. Gupta et al. (2008).

7. System failure/repair follows the exponential distribution, as stated by Gupta et al. (2009B).

The transition diagram of coal handling unit is as shown below in figure 2;

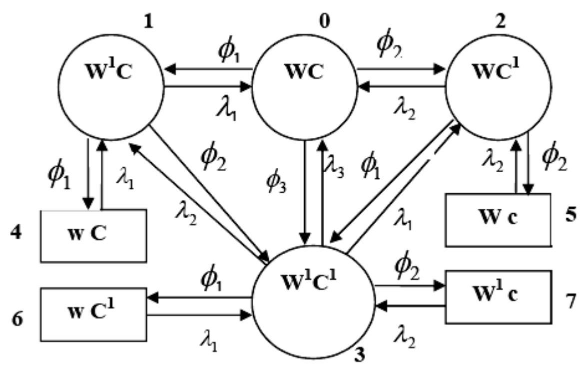

Figure 2 Transition diagram of coal handling unit

3. MARKOV MODEL OF COAL HANDLING UNIT

The mathematical model has been developed for making the performance evaluation of the coal handling unit using simple probabilistic considerations. Formulation is carried out using the joint probability functions based on the transition diagram. These probabilities are mutually exclusive and provide the scope to implement Markovian approach. The failure and repair rates of the different subsystems are used as standard input information to the model. The flow of states for the system under consideration, as described by Kumar et al. (1999), in a transition diagram as shown in figure 2, which is logical representation of all possible state's probabilities encountered during the failure analysis of coal handling unit of a thermal power plant. The present performance evaluation is concerned with a discrete-state continuous-time model, is called a Markov process. Let the probability of n occurrences in time t be denoted by $P_n(t)$, i.e.,

$$\text{Probability}(X = n, t) = P_n(t) \qquad (n = 0, 1, 2 \ldots).$$

Then, $P_0(t)$ represent the probability of zero occurrences in time t. The probability of zero occurrences in time $(t + \Delta t)$ is given by equation 1; i.e.

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

Similarly $P_1(t + \Delta t) = (\phi.\Delta t).P_0(t) + (1 - \lambda.\Delta t).P_1(t)$ (2)

The equation (2) shows the probability of one occurrence in time $(t + \Delta t)$ and is composed of two parts, namely, (a) probability of zero occurrences in time t multiplied by the probability of one occurrence in the interval Δt and (b) the probability of one occurrence in time t multiplied by the probability of no occurrences in the interval Δt.

Then simplifying and putting $\Delta t \to 0$, one gets

$$(\frac{d}{dt}+\phi)P_1(t)=\lambda.P_0(t) \tag{3}$$

Using the concept used in equation (3) and various probability considerations, the following differential equations associated with the transition diagram of the coal handling unit are formed, as described by Kumar et al. (2007).

$$P'_i(t)+\sum_{i=1}^{i=3}(\phi_i P_0)(t)=\sum \lambda_j P_k(t) \text{ Where for } i\text{=1-3, the values are } j\text{=1-3, } k\text{=1-3} \tag{4}$$

$$P'_i(t)+\sum_{r=1}^{r=2}(\phi_r+\lambda_m)P_i(t)=\sum \lambda_j P_k(t)+\phi_i P_{i-1}(t) \tag{5}$$

For i=1, m=1; j=2, k=3; j=1, k=4 respectively.

$$P'_i(t)+\sum_{r=1}^{r=2}(\phi_r+\lambda_m)P_i(t)=\sum \lambda_j P_k(t)+\phi_i P_{i-2}(t) \tag{6}$$

For i=2, m=2; j=2, k=5; j=1, k=3 respectively.

$$P'_i(t)+\sum_{r=1}^{r=2}(\phi_r+\lambda_m)P_i(t)=\sum \lambda_j P_k(t)+\sum \phi_a P_b(t) \tag{7}$$

For i=3, m=1-3 ; and j=1, k=6; j=2, k=7, also when b=0, a=3; b=1, a=2; b=2, a=1 respectively.

$$P'_i(t)+\lambda_{i-3}P_i(t)=\phi_{i-3}P_k(t) \quad \text{For } i\text{=4, } k\text{=1; } i\text{=5, } k\text{=2 respectively} \tag{8}$$

$$P'_i(t)+\lambda_{i-5}P_i(t)=\phi_{i-5}P_k(t) \quad \text{For } i\text{=6-7; } k\text{=3} \tag{9}$$

With the initial condition P_0 (0) =1 and zero otherwise.

Since any thermal plant is a process industry, where raw material is processed through various subsystems continuously till the final product is obtained. Thus, as stated by Arora and Kumar (1997), putting derivative of all probability equal to zero, so as to attain the long run availability of the system of a thermal plant i.e. $P'_i(t)=0 \; as \quad t\to\infty$ into differential equations (4-9) and solving these equations (4-9) recursively, following are the values of all state probabilities in terms of full working state probability i.e. P_0.

$$P_1=C_7P_0 \tag{10}$$

$$P_2=C_6P_0 \tag{11}$$

$$P_3 = C_5 P_0 \tag{12}$$

$$P_4 = (\phi_1 / \lambda_1) P_1 \tag{13}$$

$$P_5 = (\phi_2 / \lambda_2) P_2 \tag{14}$$

$$P_6 = (\phi_1 / \lambda_1) P_3 \tag{15}$$

$$P_7 = (\phi_2 / \lambda_2) P_3 \tag{16}$$

Where

$$C_7 = (\phi_1 + C_5 \lambda_2)/C_2 \tag{17}$$

$$C_6 = (\phi_2 + C_5 \lambda_1)/C_3 \tag{18}$$

$$C_5 = \frac{(C_1 C_2 C_3 - \phi_1 \lambda_1 C_3 - \phi_2 \lambda_2 C_2)}{(\lambda_1 \lambda_2 C_3 + \lambda_1 \lambda_2 C_2 + \lambda_3 C_2 C_3)} \tag{19}$$

$$C_4 = \lambda_1 + \lambda_2 + \lambda_3 \tag{20}$$

$$C_3 = \phi_1 + \lambda_2 \tag{21}$$

$$C_2 = \phi_2 + \lambda_1 \tag{22}$$

$$C_1 = \phi_1 + \phi_2 + \phi_3 \tag{23}$$

3.1 Steady state availability using normalizing condition

The probability of full working capacity, namely, P_0 determined by using normalizing condition; i.e sum of the probabilities of all working states and failed states is equal to 1.

i.e $\sum_{i=0}^{7} P_i = 1$, therefore, using all the above values of P_1 to P_7 (equation 10-16), one gets;

$$P_0 = 1/[(1 + C_5 + C_6 + C_7) + (\phi_1/\lambda_1)(C_5 + C_7) + (\phi_2/\lambda_2)(C_5 + C_6)] \tag{24}$$

Now, the steady state availability of coal handling unit may be obtained as summation of all working states probabilities i.e A_v = Summation of all working states Or $A_v = P_0 + P_1 + P_2 + P_3$ or

$$A_{V.} = P_0 \, [1 + C_7 + C_6 + C_5] \tag{25}$$

4. PERFORMANCE EVALUATION

Joseph and Douglas (2006) states that performance evaluation forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation and evaluation). According to Deming (1982), it is not possible to determine the value of an intervention without having analysis data that would allow one to show improvement over a baseline level of performance, thereby highlighting the importance of sound performance evaluation practices.

From maintenance history sheet of coal handling unit of thermal power plant and through the discussions with the plant personnel, appropriate failure and repair rates of both subsystems are taken and availability matrices (performance values) are prepared accordingly (Table 1 and 2) by putting these failure and repair rates values in expression (25) for availability (Av.). The Performance evaluation deals with the quantitative analysis of all the factors viz. courses of action (λ_i) and states of nature (ϕ_i), which influence the maintenance decisions associated with the coal handling unit of thermal power plant. This model is developed under the real decision making environment i.e. decision making under risk (probabilistic model) and used to implement the proper maintenance decisions for the coal handling unit. The availability matrices simply reveal the various performance levels for different combinations of failure and repair rates/priorities. These performance values obtained in availability matrices for both subsystems are then plotted. Figures 3 to 6 represent the plots for the various subsystems of coal handling unit, depicting the effect of failure and repair rate of both subsystems on coal handling unit performance. On the basis of analysis made, the best possible combinations (ϕ, λ) may be selected.

5. RESULTS AND DISCUSSION

On the basis of availability values as given in Table 1 and table 2, the performance evaluation is done using the developed model (using Markov approach). The following observations are made from Table 1 and 2, which reveals the effect of failure and repair rates of various subsystems on the availability of coal handling unit.

Table 1 Availability matrix of wagon tippler subsystem of coal handling unit

Availability ⟶

λ_1 / ϕ_1	0.1	0.225	0.35	0.475	0.6	Constant values
0.005	0.9651	0.9669	0.9671	0.9672	0.9673	ϕ_2 = .06, λ_2 =.3, ϕ_3 = .001, λ_3 =.05
0.01375	0.9527	0.9642	0.9660	0.9666	0.9669	
0.0225	0.9320	0.9593	0.6939	0.9655	0.9662	
0.03125	0.9055	0.9523	0.9608	0.9637	0.9651	
0.04	0.8753	0.9437	0.9569	0.9615	0.9637	

Table 1 along with plot in Figure 3 reveal the effect of failure rates and Table 1 along with plot in Figure 4 reveal the effect of repair rates of wagon tippler subsystem on the performance/availability of coal handling unit. It is observed that for some known values of failure / repair rates of conveyor and values of failure / repair rates of both subsystems simultaneously, as failure rate of wagon tippler (ϕ_1) increases from 0.005 (5 times in 1000 hrs) to 0.04 (4 times in 100 hrs), the unit availability decreases by approximately 9%. Similarly as repair rate of wagon tippler (λ_1) increases from 0.1 (once in 10 hrs) to 0.6 (6 times in 10 hrs), the unit availability increases slightly.

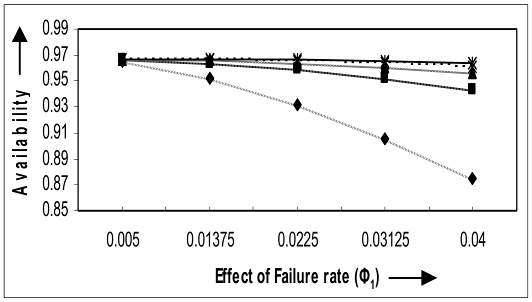

Figure 3 Effect of failure rate on availability

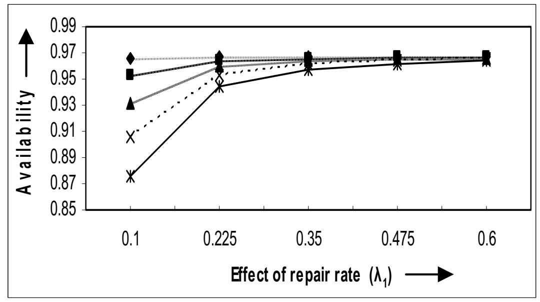

Figure 4 Effect of repair rate on availability

Table 2 Availability matrix of conveyor Subsystem of coal handling unit

Availability ⟶

ϕ_2 \ λ_2	.1	.2	.3	.4	.5	Constant values
.02	.9636	.9668	.9917	.9935	.9944	$\phi_1 = .0225, \lambda_1 = .35$ $\phi_3 = .001, \lambda_3 = .05$
.04	.8947	.9638	.9805	.9869	.9900	
.06	.8150	.9318	.9639	.9769	.9833	
.08	.7374	.8945	.9433	.9637	.9745	
.1	.6670	.8547	.9198	.9487	.9639	

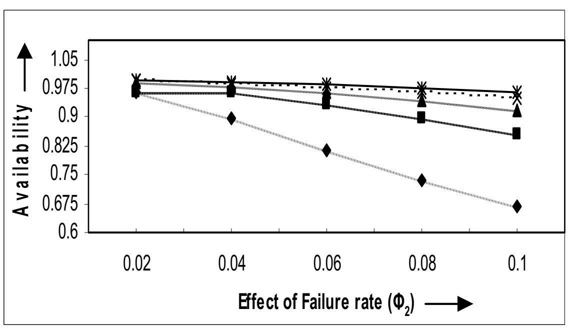

Figure 5 Effect of failure rate on availability

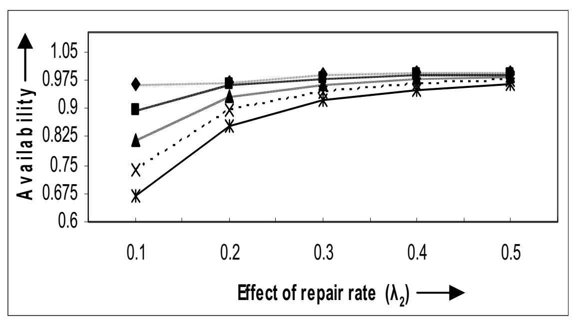

Figure 6 Effect of repair rate on availability

Similarly, Table 2 along with plot in figure 5 highlight the effect of failure rates and Table 2 along with plot in Figure 6 highlight the effect of repair rates of conveyor subsystem on the performance/availability of coal handling unit. It is observed that for some known values of failure / repair rates of wagon tippler and values of failure / repair rates of both subsystems simultaneously, as failure rate of conveyor (ϕ_2) increases from 0.02 (twice in 100 hrs) to 0.1(once in 10 hrs), the unit availability decreases by about 29%, which is more than for wagon tippler subsystem. Similarly as repair rate of conveyor (λ_2) increases from 0.10 (once in 10 hrs) to 0.5 (twice in 10 hrs), the unit availability increases by about 3 %.

Table 3 depicts the optimum values of failure and repair rates of both subsystems. Also, value of maximum availability along with the respective failure/repair rates is shown in Table 3.

Table 3 Optimum values of failure and repair rates of subsystems of coal handling unit

S.No.	Subsystem	Failure Rates (ϕ_i)	Repair Rates (λ_i)	Maximum Availability Level
1.	Wagon Tippler	$\phi_1 = 0.005$	$\lambda_1 = 0.6$	96 %
2.	Conveyor	$\phi_2 = 0.02$	$\lambda_2 = 0.5$	99 %

6. CONCLUSIONS

A large no. of failures occurs due to improper design and overstressing of components, which can be avoided by introducing the properly designed components of higher inbuilt performance. The unit performance can be also being improved using redundancy technique. Here, it may concluded that performance improves by increasing repair and reducing failure rates for various sub-systems, therefore, failure and repair rates of coal handling unit should be optimized well to accomplish the goal of sufficiently high performance.

The unit availability has been excellent, mainly because of the low failure rate, supported by the state of the art repair facilities A Markov model for is presented to predict operational availability of coal handling unit of thermal plant. The expression for availability (Av.) as given in equation 25 depicts the availability probabilistic model (Markov model), which further helps in performance evaluation of coal handling unit. The availability matrices are also developed. It also shows the relationship among various failure and repair rates (ϕ_i, λ_i) for each subsystem. It also provides the various availability levels (Av.) for different combinations of failure and repair rates for each subsystem. One may select the best possible combination of failure events and repair priorities for each subsystem. Availability matrices as given in table 2 and figure 5 and 6, clearly shows that the conveyor subsystem is most critical subsystem as far as maintenance is concerned, as the effect of its failure rates on the system availability is much higher than another subsystem. The analysis also helps in analyzing the performance of the system concerned, which will ensure the maximum overall availability of coal handling unit of a thermal plant. The optimum values of failure and repair rates for maximum availability level for each subsystem are given in table 3. Table 3 shows that conveyor subsystem is having maximum availability (99%). So findings of this paper will be highly beneficial to the plant management for the corrective and orderly execution of proper maintenance decisions and hence to enhance the performance of coal handling unit of a thermal power plant.

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