Simulation Model for Coal Crushing System of a Typical Thermal Power Plant

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Abstract—**The aim of this study is to develop an availability simulation model that can be used for evaluating the performance of coal crushing system of a thermal power plant using probability theory and Markov birth-death process. The present system under study consists of five subsystems with three possible states i.e. full capacity working, reduced capacity working and failed. Failure and repair rates of all subsystems are assumed to be constant. After drawing transition diagram, differential equations have been generated and solved using recursive approach. Then, steady state availability is determined, which is the developed availability simulation model. Besides, some availability matrices are also developed, which provide various performance or availability levels for different combinations of failure and repair rates of all subsystems. Hence, performance of coal crushing system is analyzed and evaluated. The developed model helps the plant management in getting the information about maximum availability of each of the five subsystems with optimum values of failure/repair rates and in comparative evaluation of alternative maintenance strategies.**

Index Terms— **Availability, Maintenance decisions, Steady state probabilities and Transition diagram.**

Symbols and Notations

The symbols and notations used in the present paper are as follows:

○ : Indicate the subsystems in full capacity working state.
⬭ : Indicate the subsystems in reduced working state.
▭ : Indicate the subsystems in failed state.
A, B, C, D, E : Denotes the full capacity working states of subsystems A, B, C, D and E respectively.
B_1, B_2: Denotes that the subsystem B is working with standby units.
C^1: Denotes that the subsystem C is working in reduced capacity.
a, b, c, d, e : Denotes the failed states of subsystems A, B, C, D and E respectively.
P_0 (t) : Indicate the probability that at time 't' the subsystems are working in full capacity without stand by unit.
P_i(t) i=2, 22 : Indicate the probabilities that at time 't' the subsystems are working in full capacity with standby units.
P_i(t) i=3, 7 and 12: Indicate the probabilities that at time 't' the subsystems are working in reduced capacity.
P_i(t) i=1, 4-6, 8-11, 13-21 and 23-28: Indicate the probabilities that at time 't' the subsystems are in failed states.
f_i and l_i , i=1-5: Indicate the mean failure rates and repair rates of subsystems A, B, C, D and E respectively.
d/dt : Indicate the derivative w.r.t. time (t).
Av. : Steady state availability of the system.

I. INTRODUCTION

Over the years, as engineering systems have become more complex and sophisticated, the reliability prediction of engineering systems is becoming increasingly important because of factors such as cost, risk of hazard, competition, public demand and usage of new technology. High reliability level is desirable to reduce overall cost of production and risk of hazards for larger, more complex and sophisticated systems, such as thermal power plant. It is necessary to maintain the steam thermal power plant to provide reliable and uninterrupted electrical supply for long time. In order to obtain regular and economical generation of electrical power, plant should be maintained at sufficiently high availability level corresponding to minimum overall cost [1].

Performance modelling is an activity in which the performance of a system is characterized by a set of performance parameters, whose quantitative values are used for evaluating the system’s availability. Performance modelling has a very important role in the coal crushing system of a thermal power plant. According to Barabady *et al.* [2], the most important performance measures for repairable system designers and operators are system reliability and availability. Availability and reliability are good evaluations of a system’s performance. Their values depend on the system structure as well as the component availability and reliability. These values decreases, as the component ages increases; i.e. their serving times are influenced by their interactions with each other, the applied maintenance policy and their environment [3]. For the prediction of availability, several mathematical models [4 to 8] have been discussed in literature, which handle wide degree of complexities. Most of these models are based on the Markovian approach, wherein the failure and the repair rates are assumed to be constant. In other words, the times to failure and the times to repair follow exponential distribution. The considerable efforts have been made by the researchers [9 to 11] providing general methods for the prediction of system reliability, designing equipments with specified reliability figures, demonstration of reliability values [12], issues of maintenance, inspection, repair and replacement and notion of maintainability as design parameter [11]. Kurien [13] developed a simulation model for analyzing the availability i.e. measure of performance of an aircraft training facility. The model was useful for evaluating various maintenance alternatives. Consideration of systems with randomly failing repairable components is of interest in many engineering fields [14 to 18]. The work under study presents a ‘reliability and performance evaluation model’ to predict the operational availability of coal crushing system of a steam thermal power plant, situated in north India. Further, simulation has also become an important tool for assessing the availability of complex process plants. The advantage with the simulation model is that the non-Markovian failure and the repair processes can be modeled easily [19].

Some of the salient features of the developed availability model are as follows:

1) The model provides an integrated modelling and analysis framework for performance evaluation of the coal crushing system of a thermal power plant.

2) The model combines a strong mathematical foundation with an intuitive graphical representation.
3) The transition diagram (figure 1) represents the various possible states of the system.

A. *Organization of paper*

The section 2 presents and discusses the processing and description of coal crushing system used for developing the transition diagram. The assumptions used for development of model are also listed in this section. Section 3 describes the development of a availability simulation model. Section 4 describes the performance evaluation made in this study. Section 5 and 6 describes the results and conclusion respectively.

II. COAL CRUSHING SYSTEM

The need for having an efficient and reliable coal crushing system is well recognized in view of the large capacity power stations being installed in India. A thermal power plant is a complex engineering system comprising of various systems: coal handling, steam generation, cooling water, condensate, ash handling, power generation, feed water and coal crushing system. For regular and economical generation of power, it is necessary to maintain each subsystem of coal crushing system. Amongst the several utilities, coal crushing system constitutes an essential part of the power generation system of a thermal power plant. Coal crushing system, with whatever may be the operational intentions, i.e. continuous or intermittent, is expected to furnish excellent performance. The high performance of such coal crushing system can be achieved with highly reliable power plant and perfect maintenance. In this system, the coal from coal bunkers, after passing through connecting rods, then mill boxes and then through conveyors, enters in to the big size shell, where crushing of rough coal in to pieces less than 2 inches (50 mm) in size takes place. The crushing action takes place with the help of a large number of small size metallic balls present in the shell. The crushed coal then transferred in to the boiler for steam generation operation.

A. *Assumptions*

The following assumptions are made in developing the probabilistic simulation model;

1) Failure/repair rates are constant over time and statistically independent.
2) A repaired unit is as good as new, performance wise, for a specified duration [20].
3) Sufficient repair facilities are provided.There are no simultaneous failures [21].
4) Standby units are of the same nature as that of active units.
5) System time between failure and repair time follows an exponential distribution.
6) Service includes repair and/or replacement [22].
7) The system may work at reduced capacity.

The transition diagram [23] (as given in figure 1) of the coal crushing system, shows the various possible states and helps in developing the different differential equations. Based on the transition diagram and developed differential equations, an availability simulation model has been developed. The failures and repairs for this purpose have been modelled as a birth and death process. The failure and repair rates of all subsystems of coal crushing system can be obtained with the help of history cards and maintenance sheets of various subsystems of the coal crushing system available with maintenance personnel of the thermal plant.

B. *System Description*

The performance of the any system depends on arrangement, configuration and performance of its subsystems. A typical system consists of a number of subsystems connected to each other logically in series, in parallel or in combination of series and parallel in most of the cases. Before analyzing the failure data, it is better to describe the configuration of coal crushing system and classify it into various subsystems so that the failures can be categorized. The present system consists of following five subsystems:

1) The assembly of two conveyors (in series) constituting one subsystem, denoted by A and failure of any conveyor results in to system failure.
2) Four connecting rods, two working at a time and another two are in standby mode, constituting another subsystem and is denoted by B, failure of which leads to system failure.
3) Two coal bunkers (in parallel), constituting one subsystem and is denoted by C. Failure of any coal bunker reduces the capacity of plant and loss in production. Complete failure occurs when both bunkers fails.
4) Single shell is another subsystem, denoted by D, arranged in series with other subsystems. Failure of this subsystem causes the complete failure of the system.
5) Two mill boxes constituting one subsystem and is denoted by E. Failure of any mill box causes the complete failure of the system.

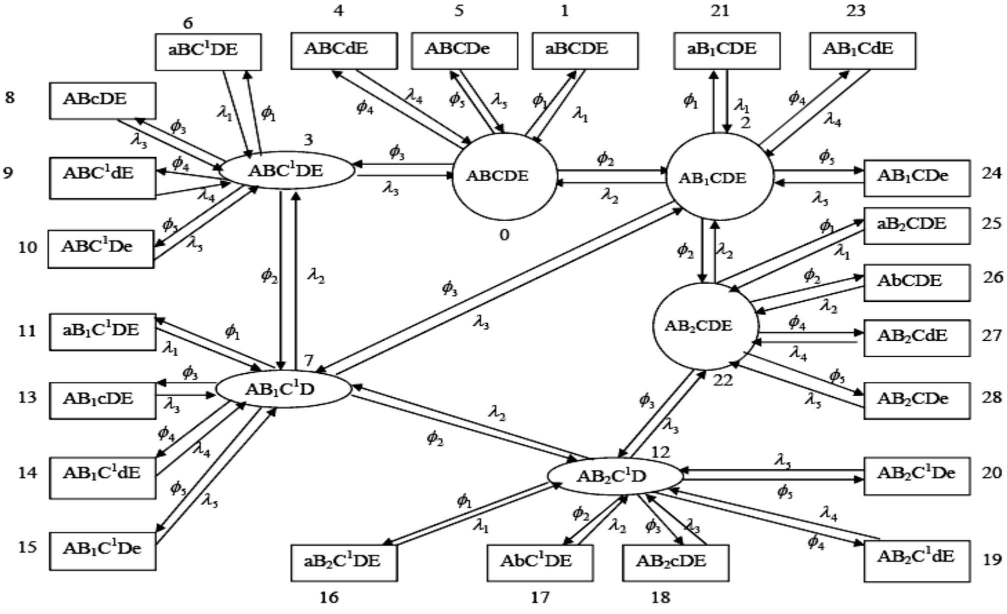

Figure 1: Transition diagram of coal crushing system

III. DEVELOPMENT OF SIMULATION MODEL

Markov state transition diagram is helpful in analyzing reliability and availability of a repairable system. All possible flow of states for the present system under consideration has been described in a transition diagram, which is logical representation of all possible state's probabilities encountered during the availability analysis of coal crushing system [24]. The failure and repair rates of the different subsystems are used as standard input information to the model. Formulation is carried out using the joint probability functions based on the transition diagram.

A. *Markov Approach*

According to Markov if $P_0(t)$ represent the probability of zero occurrences in time t. The probability of zero occurrences in time (t + Δt) is given by Equation (eq.) 1;

i.e $P_0(t+\Delta t) = (1 - l\,t).P_0(t)$ (1)

Similarly $P_1(t+\Delta t) = (f.\Delta t).P_0(t) + (1 - l.\Delta t).P_1(t)$ (2)

Where f is the failure rate and l is the repair rate respectively.

The eq. 2 shows the probability of one occurrence in time (t + Δt) 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, as stated by Srinath [23].

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

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

The performance modelling is an activity in which the performance of a system is characterized by a set of performance parameters (repair and failure rates) whose quantitative values are used to assess the system's availability [25]. The system starts from a particular state at time 't' and reaches another state (failed) or remain in the same state (operative) during the time interval Δt. The state of the system defines the condition at any instant of time and the information is useful in analyzing the current state and in the prediction of the failure state of the system. Modelling is done using a simple probabilistic consideration and differential equations are developed using a Markov birth-death process [26]. Using the concept used in eq. 3 and various probability considerations, the following differential equations associated with the transition diagram of coal crushing system are formed [26].

$$\left(\frac{d}{dt} + \sum_{i=1}^{5} f_i\right)P_0(t) = \sum_{i=1}^{5} l_i P_i(t) \tag{4}$$

$$\left(\frac{d}{dt} + \sum_{i=1}^{5} f_i + l_2\right)P_2(t) = l_1 P_{21}(t) + l_2 P_{22}(t) + l_3 P_7(t) + l_4 P_{23}(t) + l_5 P_{24}(t) + f_2 P_0(t) \tag{5}$$

$$\left(\frac{d}{dt} + \sum_{i=1}^{5} f_i + l_2\right)P_{22}(t) = l_1 P_{25}(t) + l_2 P_{26}(t) + l_3 P_{12}(t) + l_4 P_{27}(t) + l_5 P_{28}(t) + f_2 P_2(t) \tag{6}$$

$$\left(\frac{d}{dt} + \sum_{i=1}^{5} f_i + l_3\right)P_3(t) = \sum_{i=1}^{5} l_i P_{i+5}(t) + f_3.P_0(t) \tag{7}$$

$$\left(\frac{d}{dt}+\sum_{i=1}^{5} f_i + l_2 + l_3\right)P_7(t) = \sum_{i=1}^{5} l_i P_{i+10}(t) + f_2.P_3(t) + f_3.P_2(t) \qquad (8)$$

$$\left(\frac{d}{dt}+\sum_{i=1}^{5} f_i + l_2 + l_3\right)P_{12}(t) = \sum_{i=1}^{5} l_i P_{i+15}(t) + f_2.P_7(t) + f_3.P_{22}(t) \qquad (9)$$

$$\left(\frac{d}{dt}+ l_m\right)P_i(t) = f_m P_j(t) \qquad (10)$$

With the initial condition P_0 (0) =1; 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, putting derivative of all probabilities equal to zero, yields the long run availability of the thermal plant system.

Therefore by putting $d/dt = 0\ at\ \ t \to \infty$ [8] into differential equations, one gets;

$$P_i = (f_m / l_m)P_j \qquad (11)$$

Where in eq. (11)

$$when\, m=1,\ then\, i=1, j=0;\ i=6, j=3;\ i=11, j=7;\ i=16, j=12;\ i=21, j=2;\ i=25, j=22$$

$$m=2,\ then\, i=17, j=12;\ i=26, j=22$$

$$m=3,\ then\ i=8, j=3;\ i=13, j=7;\ i=18, j=12$$

$$m=4,\ then\, i=4, j=0;\ i=9, j=3;\ i=14, j=7;\ i=19, j=12;\ i=23, j=2;\ i=27, j=22$$

Now putting the values of probabilities from equation (11) in equations 4 to 9, and solving these equations recursively, yields the values of all state probabilities in terms of full working state probability i.e. P_0.

$$P_1 = \frac{f_1}{l_1}P_0,\ P_2 = C_{13}P_0,\ P_3 = C_{12}P_0,\ P_4 = \frac{f_4}{l_4}P_0,$$

$$P_5 = \frac{f_5}{l_5}P_0,\ P_6 = \frac{f_1}{l_1}P_3,\ P_7 = C_{11}P_0,\ P_8 = \frac{f_3}{l_3}P_3,$$

$$P_9 = \frac{f_4}{l_4}P_3,\ P_{10} = \frac{f_5}{l_5}P_3,\ P_{11} = \frac{f_1}{l_1}P_7,\ P_{12} = C_{15}P_0,$$

$$P_{13} = \frac{f_3}{l_3}P_7\ ,\quad P_{14} = \frac{f_4}{l_4}P_7\ ,\quad P_{15} = \frac{f_5}{l_5}P_7\ ,$$

$$P_{16} = \frac{f_1}{l_1}P_{12}\ ,\quad P_{17} = \frac{f_2}{l_2}P_{12}\ ,\quad P_{18} = \frac{f_3}{l_3}P_{12}\ ,$$

$$P_{19} = \frac{f_4}{l_4}P_{12}\quad P_{20} = \frac{f_5}{l_5}P_{12},\ P_{21} = \frac{f_1}{l_1}P_2,\ P_{22} = C_{14}P_0,$$

$$P_{23} = \frac{f_4}{l_4}P_2,\ P_{24} = \frac{f_5}{l_5}P_2,\ P_{25} = \frac{f_1}{l_1}P_{22},\ P_{26} = \frac{f_2}{l_2}P_{22},$$

$$P_{27} = \frac{f_4}{l_4}P_{22},\ P_{28} = \frac{f_5}{l_5}P_{22}$$

Where C_{11} to C_{15} are constants.

B. *Normalizing Condition*

The probability of full working capacity (without standby units), namely P_0 is determined by using normalizing condition: (i.e. sum of the probabilities of all working states, reduced capacity and failed states is equal to 1) [22].

i.e $\sum_{i=0}^{28} P_i = 1$, therefore

$$P_0 = \frac{1}{\left[\begin{array}{l}(1+\frac{f_1}{l_1}+\frac{f_4}{l_4}+\frac{f_5}{l_5})(1+C_{12}+C_{13}+C_{14}+C_{15}+C_{16})+ \\ \frac{f_3}{l_3}(C_{11}+C_{12}+C_{15})+\frac{f_2}{l_2}(C_{14}+C_{15})\end{array}\right]} \qquad (11)$$

C. *Steady State Availability (Av.)*

The steady state availability of coal crushing system may be obtained as summation of all full working and reduced capacity working state probabilities. Hence

$$Av. = P_0 + P_2 + P_3 + P_7 + P_{22} + P_{12}$$

Or $Av. = P_0(1 + C_{11} + C_{12} + C_{13} + C_{14} + C_{15})$ (12)

Equation 12 represents the availability simulation model of the coal crushing system.

IV. PERFORMANCE EVALUATION

The developed model is used to predict the availability, hence to evaluate the performance of coal crushing system of thermal power plant for known input values of failure and repair rates of its subsystems. The performance of the system is mainly affected by the failure and repair rates of its subsystem. From maintenance history sheet of coal crushing system and through the discussions with the plant personnel, appropriate failure and repair rates of all subsystems are taken and availability matrices are prepared accordingly by putting these failure and repair rates values in eq. 12, the availability simulation model (Av.). This model forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation and analysis). These unit parameters ensure the high availability or performance of the coal crushing system. This model includes all possible states of nature, that is, failure events (f_i) and the identification courses of action, i.e. repair priorities (l_i). Tables 1 to 5 represent the availability matrices for various subsystems of the coal crushing system. These matrices simply reveal the various availability levels for different combinations of failure and repair rates. On the basis of analysis made, the best possible combination (f , l) may be selected. These availability values in availability matrices further helps in (i) obtaining the optimum values of failure and repair rates of various subsystems of the crushing system for maximum availability (ii) identifying the subsystem which ensures the maximum availability, as shown in table 6.

V. RESULTS AND DISCUSSION

The performance of coal crushing system is analyzed with the developed availability simulation model. On the basis of availability values, as given in availability matrices indicated in table 1 to 5 and plots in figure 2 to 6, the following observations are made, which reveals the effect of failure and repair rates of various subsystems on the availability of coal crushing system.

A. Subsystem A: Conveyors

The effect of failure and repair rates of conveyor subsystem on the availability of coal crushing system is shown in table 1 and figure 2. It is observed that for some known values of failure / repair rates of other four subsystems (as given in table 1), as failure rate of conveyor increases from 0.02 (once in 50 hrs) to 0.1 (once in 10 hrs), the system availability decreases by about 25 %. Similarly as repair rate of conveyor increases from 0.1 (once in 10 hrs) to 0.5 (once in 02 hrs), the system availability increases by about 9 %.

TABLE 1: AVAILABILITY MATRIX OF CONVEYOR SUBSYSTEM OF COAL CRUSHING SYSTEM

Availability (Av) →

λ_1 / f_1	0.1	0.2	0.3	0.4	0.5	Constant values
0.02	0.6987	0.7512	0.7705	0.7805	0.7886	$f_2 = 0.0525$, $l_2 = 0.18$ $f_3 = 0.0059$, $l_3 = 0.06$ $f_4 = 0.0057$, $l_4 = 0.133$ $f_5 = 0.0150$, $l_5 = 0.291$
0.04	0.6130	0.6987	0.7328	0.7512	0.7626	
0.06	0.5460	0.6530	0.6987	0.7240	0.7400	
0.08	0.4923	0.6130	0.6676	0.6987	0.7188	
0.10	0.4481	0.5776	0.6391	0.6751	0.6987	

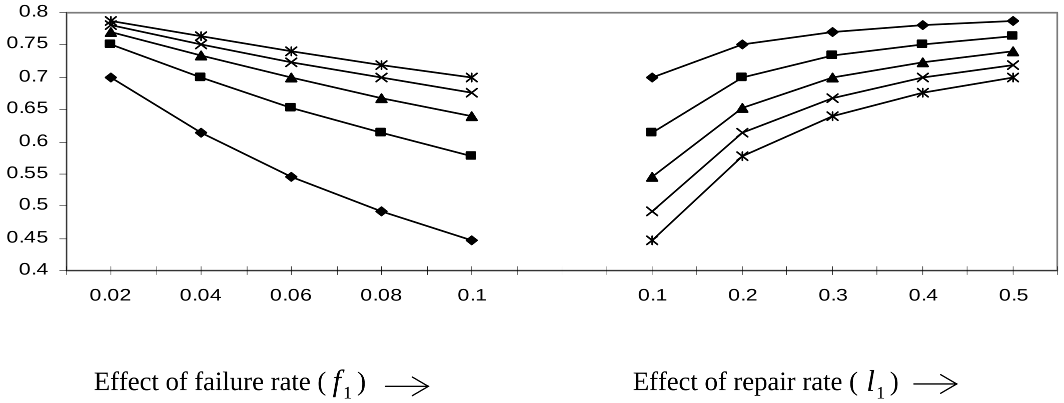

Figure 2: Effect of failure and repair rates of conveyor subsystem on system availability

B. Subsystem B: Connecting rods

The effect of failure and repair rates of connecting rods subsystem on the availability of coal crushing system is depicted in table 2 and figure 3. It is observed that for some known values of failure / repair rates of other four subsystems (as given in table 2), as failure rate of connecting rods increases from 0.005 (five failures in 1000 hrs) to 0.1 (once in 10 hrs), the system availability decreases by about 46 %. Similarly as repair rate of connecting rod increases from 0.1 (once in 10 hrs) to 0.26 (once in 04 hrs), the system availability increases slightly, and shows increasing trend.

TABLE 2: AVAILABILITY MATRIX OF CONNECTING ROD SUBSYSTEM OF COAL CRUSHING SYSTEM

Availibility (Av) →

λ_2 f_2	0.10	0.14	0.18	0.22	0.26	Constant values
0.005	0.7668	0.7671	0.7672	0.7673	0.7674	$f_1 = 0.0600, l_1 = 0.3$ $f_3 = 0.0059, l_3 = 0.06$ $f_4 = 0.0057, l_4 = 0.133$ $f_5 = 0.0150, l_5 = 0.291$
0.0287	0.5924	0.7316	0.7556	0.7623	0.7648	
0.0525	0.3580	0.5897	0.6987	0.7371	0.7521	
0.0762	0.3280	0.4675	0.6082	0.6869	0.7244	
0.1	0.3096	0.4044	0.5265	0.6243	0.6840	

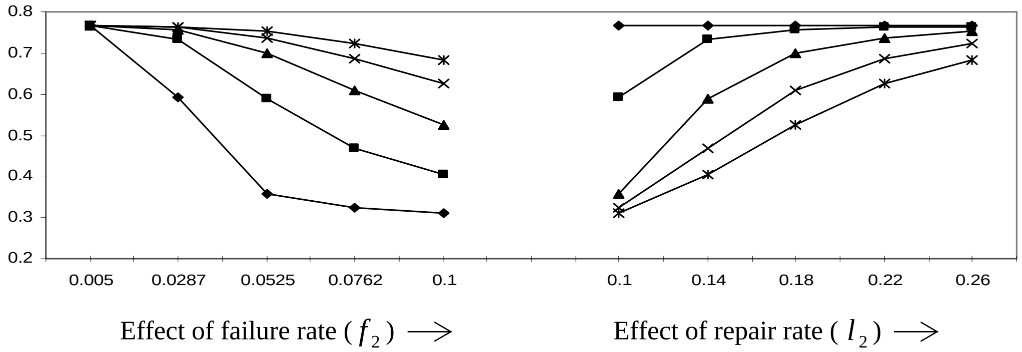

Figure 3: Effect of failure and repair rates of connecting rod subsystem on system availability

C. *Subsystem C: Coal bunkers*

The effect of failure and repair rates of coal bunkers subsystem on the availability of coal crushing system is depicted by table 3 and figure 4. It is observed that for some known values of failure / repair rates of other four subsystems (as given in table 3), as failure rate of coal bunker increases from 0.0013 (thirteen failures in 10000 hrs) to 0.01 (once in 100 hrs), the system availability decreases by about 5 %. Similarly as repair rate of coal bunker increases from 0.02 (once in 50 hrs) to 0.1 (once in 10 hrs), the system availability increases by about 5 %.

TABLE 3: AVAILABILITY MATRIX OF COAL BUNKER SUBSYSTEM OF COAL CRUSHING SYSTEM

Availability (Av) →

λ_3 f_3	0.02	0.04	0.06	0.08	0.1	Constant values
0.0013	0.6632	0.6851	0.6987	0.7087	0.7163	$f_1 = 0.0600, l_1 = 0.30$ $f_2 = 0.0525, l_2 = 0.18$ $f_4 = 0.0057, l_4 = 0.133$ $f_5 = 0.0150, l_5 = 0.291$
0.0036	0.6631	0.6841	0.6986	0.7085	0.7161	
0.0059	0.6542	0.6831	0.6974	0.7081	0.7159	
0.0082	0.6390	0.6806	0.6971	0.7075	0.7153	
0.0105	0.6198	0.6750	0.6950	0.7068	0.7151	

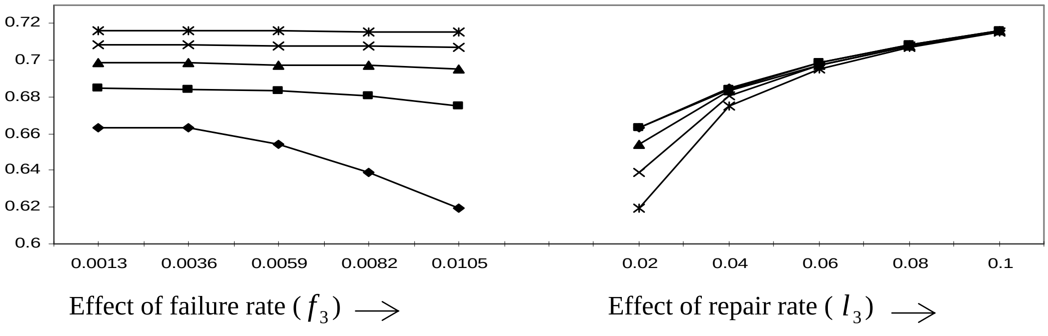

Figure 4: Effect of failure and repair rates of coal bunkers subsystem on system availability

D. *Subsystem D: Shell*

The effect of failure and repair rates of shell subsystem on the availability of coal crushing system is shown by table 4 and figure 5. It is observed that for some known values of failure / repair rates of other four subsystems (as given in table 4), as failure rate of shell increases from 0.00133 (133 failures in 100000 hrs) to 0.01 (once in 100 hrs), the system availability decreases by about 6 %. Similarly as repair rate of shell increases from 0.067 (once in 15 hrs) to 0.2 (once in 05 hrs), the system availability increases slightly and shows increasing trend.

TABLE 4: AVAILABILITY MATRIX OF SHELL SUBSYSTEM OF COAL CRUSHING SYSTEM

Availability (Av) →

λ_4 / f_4	0.067	0.1	0.133	0.166	0.2	Constant values
0.00133	0.7101	0.7134	0.7151	0.7161	0.7168	$f_1 = 0.0600$, $l_1 = 0.30$ $f_2 = 0.0525$, $l_2 = 0.18$ $f_3 = 0.0059$, $l_3 = 0.06$ $f_5 = 0.0150$, $l_5 = 0.291$
0.0035	0.6941	0.7025	0.7068	0.7095	0.7112	
0.0057	0.6787	0.6918	0.6987	0.7029	0.7057	
0.0078	0.6.645	0.6819	0.6910	0.6967	0.7005	
0.01	0.6503	0.6718	0.6832	0.6903	0.6951	

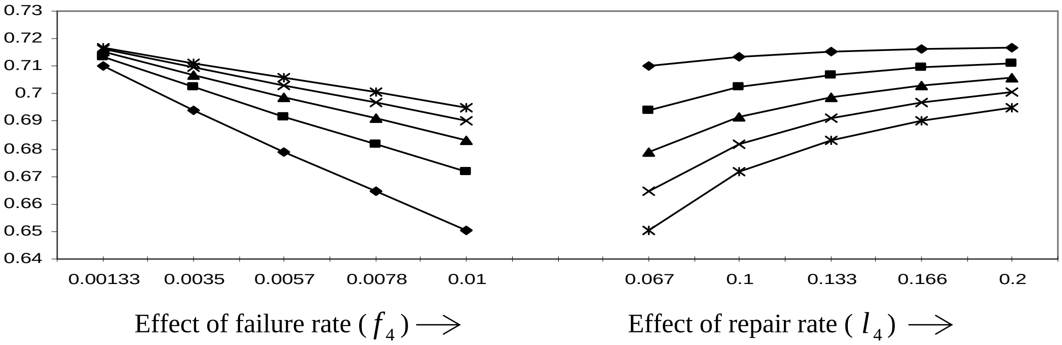

Figure 5: Effect of failure and repair rates of shell subsystem on system availability

E. *Subsystem E: Mill boxes*

The effect of failure and repair rates of mill box subsystem on the availability of coal crushing system is shown by table 5 and figure 6. It is observed that for some known values of failure / repair rates of other four subsystems (as given in table 5), as failure rate of mill box increases from 0.005 (five failures in 1000 hrs) to 0.025 (twenty five failures in 1000 hrs), the system availability decreases by about 5 %. Similarly as repair rate of mill box increases from 0.083 (once in 12 hrs) to 0.5 (once in 02 hrs), the system availability increases by about 1 %.

TABLE 5: AVAILABILITY MATRIX OF MILL BOX SUBSYSTEM OF COAL CRUSHING SYSTEM

Availability (Av) →

λ_5 / f_5	0.083	0.187	0.291	0.396	0.5	Constant values
0.005	0.7124	0.7165	0.7185	0.7198	0.7206	$f_1 = 0.0600$, $l_1 = 0.3$ $f_2 = 0.0525$, $l_2 = 0.18$ $f_3 = 0.0059$, $l_3 = 0.06$ $f_4 = 0.0057$, $l_4 = 0.133$
0.010	0.7004	0.7083	0.7124	0.7148	0.7165	
0.015	0.6888	0.7004	0.7063	0.7099	0.7124	
0.020	0.6776	0.6926	0.7004	0.7051	0.7083	
0.025	0.6667	0.6850	0.6945	0.7004	0.7043	

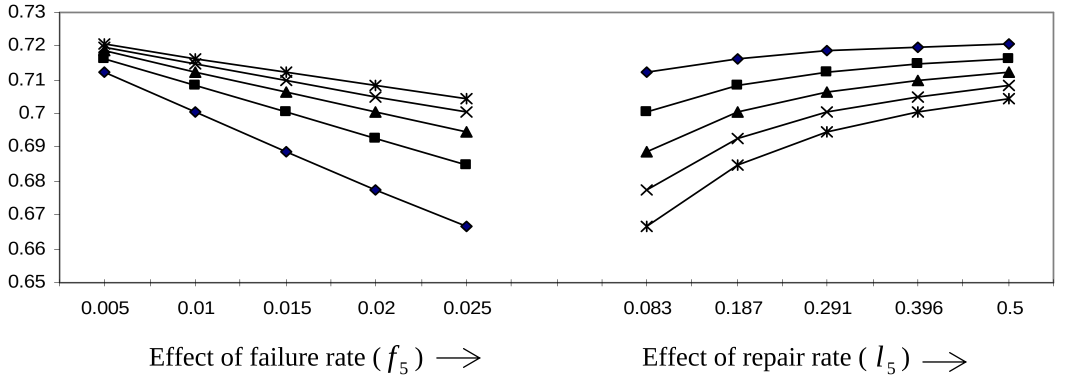

Figure 6: Effect of failure & repair rates of mill box subsystem on system availability.

F.

*T*he maximum availability level for each subsystem with their corresponding optimum values of failure and repair rates is given in table 6, which further helps in identifying the subsystem with maximum availability. It is observed that first subsystem, i.e. conveyor, is having maximum availability (78.86%).

TABLE 6: OPTIMUM VALUES OF FAILURE AND REPAIR RATES OF VARIOUS SUBSYSTEMS OF THE COAL CRUSHING SYSTEM

S. No.	Failure rates (f_i)	Repair rates (λ_i)	Maximum availability level
1.	f_1 = 0.02	λ_1= 0. 5	78.86%
2.	f_2 = 0.0013	λ_2 = 0.1	76.74%
3.	f_3 = 0.005	λ_3 = 0.4	71.63 %
4	f_4 = 0.00133	λ_4 = 0.2	71.68 %
5.	f_5 = 0.005	λ_5 = 0.5	72.06 %

VI. CONCLUSION

The system availability has been excellent, mainly because of the low failure rate, supported by the state of the art repair facilities. It can thus be concluded that this availability simulation model provides the various availability levels for different combinations of failure and repair rates for each and every subsystem. One may select the best possible combination of failure events and repair priorities for each subsystem. It can be concluded from tables 1 to 5 and figures 2 to 6 that, as failure rate increases, the availability decreases and as repair rate increases, the availability increases. The developed model helps in determining the optimal maintenance strategies, which will ensure the maximum overall availability of coal crushing system. It is also concluded that first subsystem (conveyors) is having maximum availability. The corresponding optimum values of failure and repair rates for maximum availability level for each subsystem are available. Such results are found highly beneficial to the plant management for the availability and performance analysis of coal crushing system of a thermal power plant. Further, these results help in making the decisions related to maintenance, to be performed in thermal plant.

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