AN AVAILABILITY SIMULATION MODEL AND PERFORMANCE ANALYSIS OF A COAL HANDLING UNIT OF A TYPICAL THERMAL PLANT

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ABSTRACT

The present paper describes the development of an availability simulation model for Coal handling unit of a thermal plant by making the performance analysis using probabiltic approach. In the present paper, the Coal handling unit consists of five subsystems. Assuming constant failure and repair rates for all the subsystems, the mathematical formulation is based on Markov birth-death process. After drawing the transition diagram, differential equations are generated. After that, steady state probabilities are determined. One availability matrix is also developed, which provides various performance/availability levels for different combinations of failure and repair rates of all subsystems. Based upon various availability values obtained in the availability matrix and graphs of failure/repair rates of different subsystems, performance and optimum values of failure/repair rates for maximum availability of each subsystem are analyzed. Subsequently maintenance priorities are decided for all subsystems.

OPSOMMING

Die artikel beskryf die ontwikkeling van 'n beskikbaarheidsimulasiemodel vir 'n steenkoolhanteringseenheid van 'n termiese aanleg deur gebruik te maak van werkverrigtingsanalise met 'n waarskynlikheidsbenadering. In die geval bestaan die hanteringseenheid uit vyf subsisteme. Onder die aanname van konstante faling- en hersteltempo's vir al die subsisteme word die wiskundige formulering gebaseer op die Markov geboorte-sterfte-proses. Nadat die oorgangsdiagram ontwikkel is, word differensiaalvergelykings gegenereer en waarna die gestadigde toestandwaarksynlikhede vasgestel word. Een beskikbaarheidsmatriks is verder ontwikkel wat toelaat vir verskillende werkverrigting-/beskikbaarheidsvlakke teen verskillende kombinasies van faling- en hersteltempo's van alle subsisteme. Gebaseer op verskillende beskikbaarheidswaardes verkry van die beskikbaarheidsmatriks en grafieke van die falings-/hersteltempo's van die onderskeie subsisteme, word werkverrigting en optimum waardes vir faling- en hersteltempo's vir maksimum beskikbaarheid van elke subsisteem ontleed. Vervolgens word instandhoudingsprioriteite vir elke subsisteem voorgehou.

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NOTATIONS

○ : Indicates the unit is in working state.
□ : Indicates the unit is in failed state.

A_i, i=1-3 : Represent full working states of Screener, Feeder and Hopper respectively.
B, C : Represent full working states of Wagon tippler and Conveyor respectively.
B_1, C_1 : Represent standby states of Wagon tippler and Conveyor respectively.
a_i, i=1-3 : Represent failed states of Screener, Feeder and Hopper respectively.
b ,c : Represent failed states of Wagon tippler and Conveyor respectively.
$P_0(t)$: Probability of the unit working at full capacity at time't'.
$P_4(t)$,$P_5(t)$,$P_{10}(t)$: Probabilities of the unit in cold standby(working) state.
$P_1(t)$-$P_3(t)$,$P_6(t)$-$P_9(t)$,$P_{11}(t)$-$P_{19}(t)$: Probabilities of the unit in failed state.
ϕ_i, i =1-5 : Mean rate of failures of Screener, Feeder, Hopper, Wagon tippler and Conveyor respectively.
λ_i, i =1- 5 : Mean rate of repairs of Screener, Feeder, Hopper, Wagon tippler and Conveyor respectively.
d/dt : Represents derivative w.r.t. time (t).

1. INTRODUCTION

Complex repairable systems present scenarios where operating and maintenance activities take place and multiple entities (persons, machines and environments) interact in a complex manner. Dynamic changes usually occur in the entities themselves. The behaviour of such systems can be studied in terms of their reliability, availability and maintainability (RAM) [1]. For example, Kurien [2] developed a simulation model for analyzing the reliability and availability of an aircraft training facility. The model was useful for evaluating various maintenance alternatives.

During the past decade much study has been done on analysis tools [3-11] for reliability, availability, performance and performability modeling. Considerable efforts have been made by researchers providing general methods for the prediction of system reliability [12, 13] designing equipment with specified reliability figures, demonstration of reliability values 1[4] issues of maintenance, inspection, repair and replacement and the notion of maintainability as a design parameter [13]. For the prediction of availability, several mathematical models have been discussed in the literature, which deal with a wide degree of complexities [15, 16]. Most of these models are based on the Markovian approach, where the failure and the repair rates are assumed to be constant. In other words, the times to failure and the times to repair follow the exponential distribution. The steady state availability continues to be applicable as long as the components of the system are statistically independent [17, 18]. Some of the Markov analysis tools are Sharpe [19], Surf-2 [20], Himap [21], Save [9], Harp [6], Eharp [22, 23], Sure [7] and Tangram [24]. Advantages of Markov chains are the capability of modeling systems with shared repair. The disadvantages of Markov chains are the state-space explosion and the assumption of exponential distribution (in time homogeneous Markov chains) for the failure and repair event times (25). Extensions of the theory of Markov chains to model non-exponential distributions such as Markov regenerative stochastic processes have also been recently proposed [26].

Misra [27] gives the three state systems. Using the Markovian approach, Misra [27] derives the formulae for steady state availability, the frequency of failure, mean time to failure and mean duration of down. Kołowrocki [28] presents multi-state series, parallel and series-parallel and parallel-series systems with regular reliability structures, considering the components that have exponential reliability functions with different transition rates between subsets of their states. Pham et al. [29] also present expressions for reliability and mean time to failure of k-out-of-n systems.

The thermal industry is becoming quite complex with a significant capital investment being incurred on process automation to enhance the reliability of system. Invariably, the proper maintenance of such systems and the frequency of maintenance are some of the issues that are gaining importance in industry. Production suffers due to failure of any intermediate system even for small interval of time. The cause of failure may be due to poor design, system complexity, poor maintenance, lack of communication and coordination, defective planning, lack of expertise/experience and scarcity of inventories. Thus, to run a process plant highly skilled/ experienced maintenance personnel are required. For efficient functioning, it is essential that various systems of the plant remain in upstate as far as possible. However, during operation they are liable to fail in a random fashion. The failed subsystem can however be placed back into service after repair/replacements. The rate of failure of the subsystems in the particular system depends upon the operating conditions and repair policies used [30]. According to Barabady et al. [31], 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 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 [32]. For regular and economical generation of steam, it is necessary to maintain each subsystem of a coal handling unit. From an economic and operational point of view, it is desirable to ensure an optimum level of system availability. The goal of maximum steam generation may be achieved under the given operating conditions, making the coal handling unit failure free, by examining the behaviour of the system and making the maintenance decision a top priority for most critical subsystem.

In addition simulation has also become an important tool for assessing the availability of complex process plants. The advantage of a simulation model is that non-Markovian failure and the repair processes can be modeled easily. Such modeling techniques help to investigate more complex operations, failure and repair patterns [33]. The operational states, which the system takes up as a result of each failure or repair can be logged and used for computing the overall system availability [34].

2. COAL HANDLING UNIT (CHU)

A thermal power plant is a complex engineering system consisting of various systems: Coal handling, Steam Generation, Cooling Water, Crushing, Ash handling, Power Generation and Feed water system. In a coal handling unit, the coal is unloaded at various unloading stations and transported by conveyors to crushing and screening plant via the transfer house. After crushing the required quantity of coal is transported to a bunker via a transfer house and the remaining coal is stored in a stockyard. This coal is reclaimed as per requirement. From the bunker the coal flows through coal mills to the boiler furnace. The main aim of the CHU is to maintain the level of coal in the bunkers for a smooth coal supply to the boiler. There are varieties of critical equipment components in a coal handling unit. 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.

2.1 Coal Handling Unit Description

The Coal handling unit consists of the following five subsystems:

1. The Screener 'A_1' subsystem is a single unit, failure of which leads to unit failure.
2. The Feeder 'A_2' subsystem is a single unit, failure of which leads to unit failure.
3. The Hopper 'A_3' subsystem is a single unit, failure of which leads to unit failure.
4. The wagon tippler 'B' consists of two units. Failure of any one forces one to start a stand-by unit. Complete failure of the system occurs when the stand-by unit of the wagon tippler also fails.

5. The conveyor 'C' consists of two units, failure of the first force the stand-by unit to run.

Complete failure of the system occurs when the stand-by unit of the conveyor also fails.

2.2 Assumptions for the Availability Simulation Model

The assumptions used in developing the simulation model are

1. System failure/repair follows the exponential distribution.
2. There is no simultaneous failure. [35, 36]
3. Sufficient repair facilities are provided. [37]
4. Service includes repair and/or replacement. [38]
5. Failure/repair rates are constant over time and statistically independent [39]
6. Standby units are of the same nature as that of active systems. [38]
7. A repaired unit is as good as new, performance wise, for a specified duration.[40]

The transition diagram [41] (figure 1) of Coal handling unit shows the various possible states, that the unit can acquire. Based on the transition diagram, an availability simulation model has been developed. The failures and repairs have for this purpose been modeled as birth and death processes.

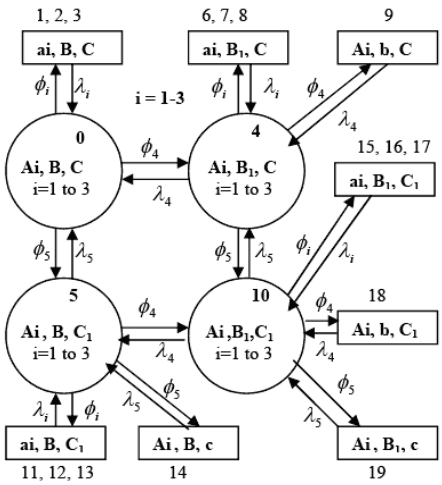

Figure: 1 Transition Diagram of Coal Handling Unit (i=1 to 3)

3. AVAILABILITY SIMULATION MODEL

The system starts from a particular state at time't' and reaches another state (failed) or remains in the same state (operative) during the time interval Δt, this transition depends upon the preceding state of the system. The mathematical modeling is done using simple probabilistic considerations and differential equations are developed using the birth-death process. Various probability considerations give the following differential equations associated with the Coal handling unit. [42] These equations are solved for determining the steady state availability of the Coal handling unit.

$$(\frac{d}{dt}+\sum_{i=1}^{5}\phi_i)P_0(t)=\sum_{i=1}^{5}\lambda_i P_i(t) \quad (1)$$

$$(\frac{d}{dt}+\sum_{i=1}^{5}\phi_i+\lambda_4)P_4(t)=\sum_{i=1}^{5}\lambda_i P_{i+5}+P_0(t)\phi_4 \quad (2)$$

$$(\frac{d}{dt}+\sum_{i=1}^{5}\phi_i+\lambda_5)P_5(t)=\sum_{i=1}^{3}\lambda_i P_{i+10}+P_0(t)\phi_5+P_{14}(t)\lambda_5+P_{10}\lambda_4 \quad (3)$$

$$(\frac{d}{dt}+\sum_{i=1}^{5}\phi_i+\lambda_4+\lambda_5)P_{10}(t)=\sum_{i=1}^{5}\lambda_i P_{i+14}+P_4\phi_5+P_5\phi_4 \quad (4)$$

$$(\frac{d}{dt}+\lambda_m)Pi(t)=\phi_m P_i(t) \quad (5)$$

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

A thermal plant is a process where raw material is processed through various subsystems continuously until the final product is obtained. Thus, putting derivative of probability equal to zero as attains the long run availability of the system of a thermal plant: therefore by putting $d/dt=0\ at\ t\rightarrow\infty$ [43] into differential equations one gets

$$P_i=\left(\frac{\phi_m}{\lambda_m}\right)P_j \quad (6)$$

Where in equation (6) for

$m=1, then\ \mathrm{i}=1, \mathrm{j}=0; \mathrm{i}=6, \mathrm{j}=4, \mathrm{i}=11, \mathrm{j}=5; \mathrm{i}=15, \mathrm{j}=10$
$m=2, then\ \mathrm{i}=2, \mathrm{j}=0; \mathrm{i}=7, \mathrm{j}=4, \mathrm{i}=12, \mathrm{j}=5; \mathrm{i}=16, \mathrm{j}=10$
$m=3, then\ \mathrm{i}=3, \mathrm{j}=0; \mathrm{i}=8, \mathrm{j}=4; \mathrm{i}=13, \mathrm{j}=5; \mathrm{i}=17, \mathrm{j}=10$
$m=4, then\ \mathrm{i}=9, \mathrm{j}=4; \mathrm{i}=18, \mathrm{j}=10$
$m=5, then\ \mathrm{i}=14, \mathrm{j}=5; i=19, \mathrm{j}=10$

Putting the values of probabilities from equation 6 in equations 1-5, and solving these equations recursively, the following are the values of all state probabilities in terms of full working state probability i.e P_0:

$P_1=\frac{\phi_1}{\lambda_1}P_0$
$P_2=\frac{\phi_2}{\lambda_2}P_0$
$P_3=\frac{\phi_3}{\lambda_3}P_0$
$P_4=C_7P_0$
$P_5=C_6P_0$
$P_6=\frac{\phi_1}{\lambda_1}P_4$
$P_7=\frac{\phi_2}{\lambda_2}P_4$
$P_8=\frac{\phi_3}{\lambda_3}P_4$
$P_9=\frac{\phi_4}{\lambda_4}P_4$
$P_{10}=C_5P_0$
$P_{11}=\frac{\phi_1}{\lambda_1}P_5$
$P_{12}=\frac{\phi_2}{\lambda_2}P_5$
$P_{13}=\frac{\phi_3}{\lambda_3}P_5$
$P_{14}=\frac{\phi_5}{\lambda_5}P_5$
$P_{15}=\frac{\phi_1}{\lambda_1}P_{10}$
$P_{16}=\frac{\phi_2}{\lambda_2}P_{10}$
$P_{17}=\frac{\phi_3}{\lambda_3}P_{10}$
$P_{18}=\frac{\phi_4}{\lambda_4}P_{10}$
$P_{19}=\frac{\phi_5}{\lambda_5}P_{10}$

3.1 Steady state availability

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

i.e $\sum_{i=0}^{19}P_i=1$, therefore

$$P_0 = \frac{1}{\left[(1 + C_5 + C_6 + C_7)(1 + \frac{\phi_1}{\lambda_1} + \frac{\phi_2}{\lambda_2} + \frac{\phi_3}{\lambda_3}) + \frac{\phi_4}{\lambda_4}(C_7 + C_5) + \frac{\phi_5}{\lambda_5}(C_5 + C_6)\right]}$$

The steady state availability of Coal handling unit may be obtained as summation of all working state probabilities i.e:

A_V=Summation of all working states

Or $A_V = P_0 + P_4 + P_5 + P_{10}$ or

$$A_V = P_0(1 + C_7 + C_6 + C_5) \quad (7)$$

where

$C_1 = \phi_4 + \phi_5$, $C_2 = \phi_5 + \lambda_4$, $C_3 = \phi_4 + \lambda_5$, $C_4 = \lambda_4 + \lambda_5$

$C_5 = \frac{C_1C_2C_3 - \lambda_4\phi_4C_3 - C_2\lambda_5\phi_5}{\lambda_4\lambda_5(C_3 + C_2)}$, $C_6 = \frac{\phi_5 + \lambda_4C_5}{C_3}$, $C_7 = \frac{\lambda_5C_5 + \phi_4}{C_2}$

4. PERFORMANCE ANALYSIS

Performance analysis forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation and evaluation)[44]. The performance of Coal handling unit of a thermal plant is mainly affected by the failure and repair rates of each subsystem. These unit parameters ensure a high availability of the Coal handling unit. From the maintenance history of the coal handling unit of thermal power plant and through discussions with the plant personnel, appropriate failure and repair rates of all five subsystems are taken and the availability matrix i.e availability values (as in table 1) is prepared accordingly by putting these failure and repair rates values in expression for availability $A_{V.}$ (eq. 7). These availability values are then plotted. Figures 2-6 represent the plots for various subsystems of coal handling unit, depicting the effect of failure /repair rates of various subsystems on coal handling unit availability. The model includes all possible states of nature, that is, failure events (ϕ) and the identification of all the courses of action, i.e, repair priorities (λ). This model is used to implement the maintenance policies for a coal handling unit in a thermal plant. The various availability levels may be computed for different combinations of failure and repair rates / priorities. On the basis of analysis, the best possible combination (ϕ, λ) that is, optimal maintenance strategy may be selected.

5. RESULTS AND DISCUSSION

The following observations are made from table 1 and figures no. 2-6, which reveal the effect of failure and repair rates of various subsystems on the availability of the coal handling unit.

1. It is observed from table 1 and figures no. 2 that for some known constant values of failure/repair rates of other four subsystems, as failure rate of screener (ϕ_1) increases from 0.001 (once in 1000 hrs) to 0.005(once in 200 hrs) the unit availability decreases by almost 1 %. Similarly as repair rate of screener (λ_1) increases from 0.30 (once in 3.33 hrs) to 0.50 (once in 2 hrs) there is slight increase in unit availability.

→ Availability (Av) → A_0

Subsytem 1 : Screener						
λ_1 / Φ_1	**.3**	**.35**	**.4**	**.45**	**.5**	**Constant Values**
0.001	.9191	.9195	.9198	.9201	.9203	$\phi_2 = .0035, \lambda_2 = .3$
0.002	.9163	.9171	.9177	.9182	.9186	$\phi_3 = .0125, \lambda_3 = .35$
0.003	.9135	.9147	.9157	.9163	.9169	$\phi_4 = .0225, \lambda_4 = .35$
0.004	.9108	.9123	.9135	.9145	.9152	$\phi_5 = .06, \lambda_5 = .3$
0.005	.9080	.9100	.9115	.9126	.9135	

Subsytem 2 : Feeder						
λ_2 / Φ_2	**.2**	**.25**	**.30**	**.35**	**.40**	**Constant Values**
0.002	.9170	.9187	.9198	.9206	.9212	$\phi_1 = ..003, \lambda_1 = .4$
0.00275	.9139	.9162	.9177	.9188	.9197	$\phi_3 = .0125, \lambda_3 = .35$
0.0035	.9108	.9137	.9156	.9170	.9181	$\phi_4 = .0225, \lambda_4 = .35$
0.00425	.9077	.9112	.9135	.9152	.9165	$\phi_5 = .06, \lambda_5 = .3$
0.005	.9046	.9087	.9114	.9134	.9149	

Subsytem 3 : Hopper						
λ_3 / Φ_3	**.2**	**.275**	**.350**	**.425**	**.5**	**Constant Values**
0.005	.9247	.9306	.9339	.9362	.9377	$\phi_1 = ..003, \lambda_1 = .4$
0.00875	.9089	.9189	.9247	.9285	.9312	$\phi_2 = .0035, \lambda_2 = .3$
0.0125	.8937	.9075	.9156	.9209	.9247	$\phi_4 = .0225, \lambda_4 = .35$
0.01625	.8790	.8964	.9068	.9135	.9183	$\phi_5 = .06, \lambda_5 = .3$
0.02	.8647	.8856	.8980	.9062	.9120	

Subsytem 4: Wagon Tippler						
λ_4 / Φ_4	**.1**	**.225**	**.35**	**.475**	**.6**	**Constant Values**
0.005	.9169	.9185	.9187	.9188	.9189	$\phi_1 = ..003, \lambda_1 = .4$
0.01375	.9051	.9159	.9176	.9182	.9185	$\phi_2 = .0035, \lambda_2 = .3$
0.0225	.8853	.9113	.9156	.9171	.9178	$\phi_3 = .0125, \lambda_3 = .35$
0.03125	.8601	.9048	.9127	.9152	.9168	$\phi_5 = .06, \lambda_5 = .3$
0.04	.8316	.8968	.9091	.9134	.9154	

Subsytem 5: Conveyor						
λ_5 / Φ_5	**.1**	**.2**	**.3**	**.4**	**.5**	**Constant Values**
0.02	.9156	.9364	.9407	.9424	.9431	$\phi_1 = ..003, \lambda_1 = .4$
0.04	.8524	.9156	.9307	.9364	.9392	$\phi_2 = .0035, \lambda_2 = .3$
0.06	.7789	.8865	.9157	.9273	.9332	$\phi_3 = .0125, \lambda_3 = .35$
0.08	.7070	.8524	.8969	.9157	.9252	$\phi_4 = .0225, \lambda_4 = .35$
0.1	.6415	.8160	.8756	.9019	.9157	

Table 1: Availability matrix of various subsystems of Coal handling unit

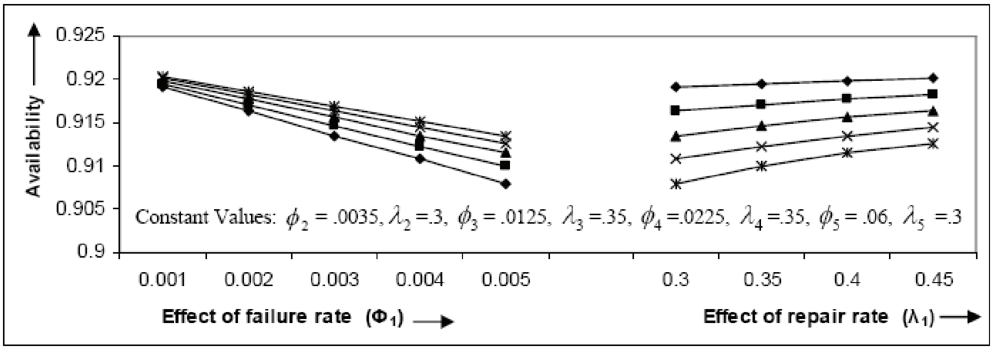

Figure 2: Effect of Screener's failure & repair rates on unit availability

2. It is observed from table 1 and figures no. 3 that for some known constant values of failure/repair rates of other four subsystems as failure rate of feeder (ϕ_2) increases from 0.002 (once in 500 hrs) to 0.005(once in 200 hrs) the unit availability decreases by almost 1 %. Similarly as the repair rate of feeder (λ_2) increases from 0.2 (once in 5 hrs) to 0.40 (once in 2.5 hrs), unit availability increases by approximately 1%.

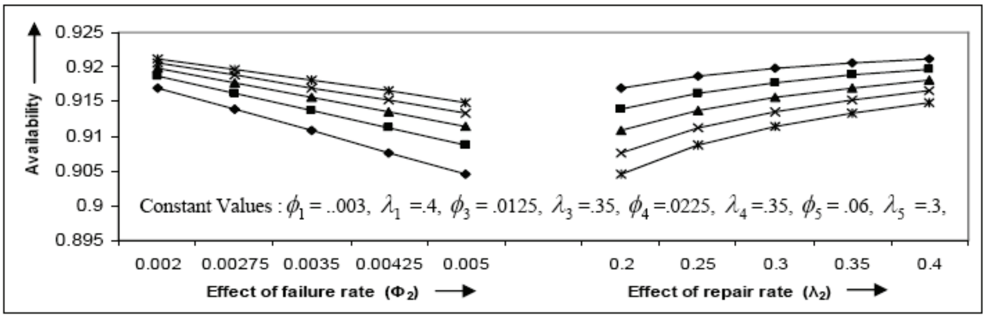

Figure 3: Effect of Feeder's failure & repair rate on unit availability

3. It is observed from table 1 and figure no. 4 that for some known constant values of failure/repair rates of other four subsystems as failure rate of hopper (ϕ_3) increases from 0.005 (once in 200 hrs) to 0.02(once in 50 hrs) the unit availability decreases by almost 6 %. Similarly as repair rate of hopper (λ_3) increases from 0.2 (once in 5 hrs) to 0.5 (once in 2 hrs), there is approximately a 2% increase in unit availability.

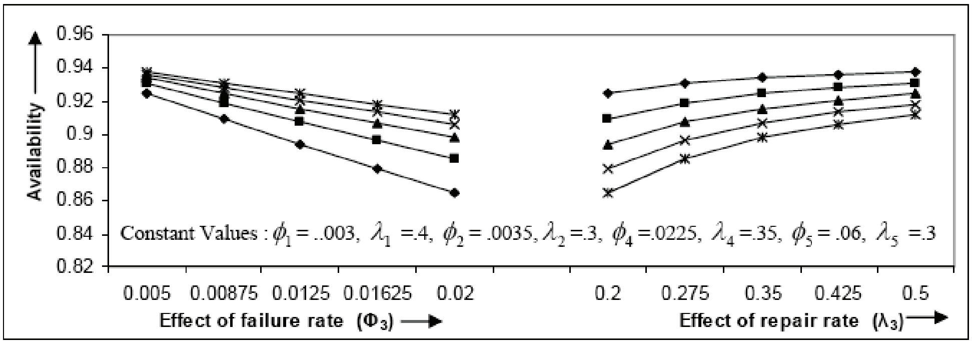

Figure 4: Effect of Hopper's failure & repair rates on unit availability

4. It is observed from table 1 and figures no. 5 that for some known constant values of failure/repair rates of other four subsystems, as failure rate of wagon tippler (ϕ_4) increases from 0.005 (once in 200 hrs) to 0.04(once in 25 hrs), the unit availability decreases by almost 8.5 %. Similarly as repair rate of wagon tippler (λ_4) increases from 0.1 (once in 10 hrs) to 0.6 (once in 1.67 hrs), the unit availability increases slightly.

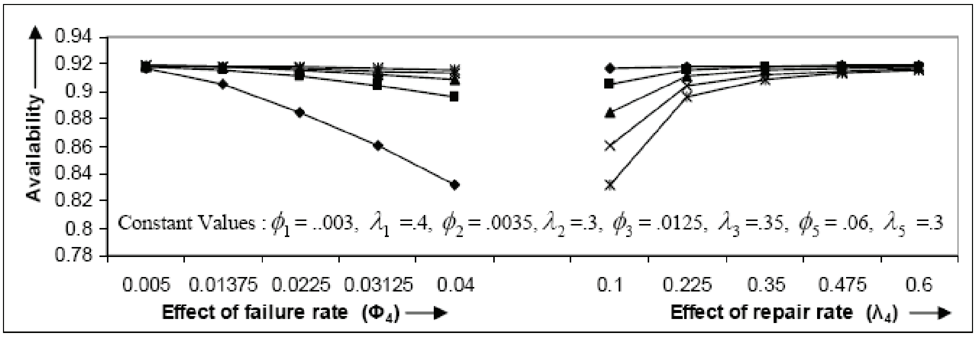

Figure 5: Effect of Wagon Tippler's failure & repair rates on unit availability

5. It is observed from table 1 and figures no. 6 that for some known values of failure/repair rates of other four subsystems as failure rate of conveyor (ϕ_5) increases from 0.02 (once in 50 hrs) to 0.1(once in 10 hrs), the unit availability decreases by about 27%. Similarly as repair rate of conveyor (λ_5) increases from 0.10 (once in 10 hrs) to 0.50 (once in 2 hrs), the unit availability increases by approximately 3%.

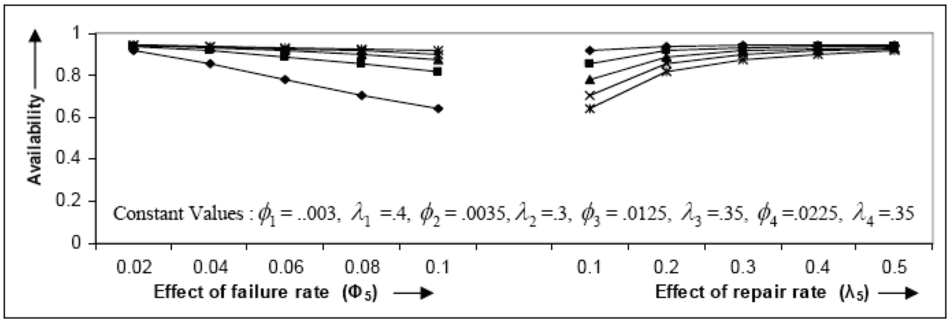

Figure 6: Effect of Conveyor's failure & repair rates on unit availability

6. CONCLUSIONS

The expression for the steady state availability (A_v) as given in equation 7 depicts the availability simulation model, which further helps in performance analysis of the coal handling unit. The availability matrix is also developed. It can thus be concluded that the model is effective for evaluation of performance of various sub-systems of a coal handling unit of a thermal plant. 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 (A_v) 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 helps in analyzing the performance of the system concerned, which will ensure the maximum overall availability of the 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 2 as shown below. The findings of this paper are discussed with the concerned thermal plant management. Such results are found highly beneficial to the plant management for the performance analysis of a coal handling unit of a thermal plant.

S.No.	**Subsytem**	**Failure Rates** (ϕ_i)	**Repair Rates** (λ_i)	**Maximum Availability Level**
1.	Screener	ϕ_1 = 0.001	λ_1 = 0.5	92 %
2.	Feeder	ϕ_2 = 0.002	λ_2 = 0.4	92 %
3.	Hopper	ϕ_3 = 0.005	λ_3 = 0.5	94 %
4.	Wagon tippler	ϕ_4 = 0.005	λ_4 = 0.6	92 %
5	Conveyor	ϕ_5 =.02	λ_5 = 0.5	94%

Table 2: Optimum values of failure and repair rates of subsystems of coal handling unit

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