RELIABILITY AND AVAILABILITY ANALYSIS OF THE ASH HANDLING UNIT OF A STEAM THERMAL POWER PLANT

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ABSTRACT

The paper aims at assessing the reliability and availability of a critical ash handling unit of a steam thermal power plant by making a performance analysis and modeling, using probability theory and the Markov Birth-Death process. After drawing a transition diagram, differential equations are generated. After that, steady state probabilities are determined. Certain decision matrices are developed, which provide various availability levels. The behaviour analysis of the reliability module reveals that the availability decreases with increasing failure rates, while operational availability improves with initial increases in repair rates for different subsystems. Based upon various availability values, the performance of each subsystem is analyzed and used to make maintenance decisions for all subsystems.

OPSOMMING

Hierdie artikel poog om die betroubaarheid en beskikbaarheid van 'n kritiese ashanteringseenheid van 'n termiese stoomkragaanleg te beoordeel deur 'n werkverrigtingsanalise en modellering te doen aan die hand van waarskynlikheidsteorie en die Markovgeboorte-sterfteproses. Nadat die oorgangsdiagram opgestel is, is differensiaalvergelykings gegenereer. Vervolgens is die gestadigde-toestandwaarskynlikhede bepaal. Sekere besluitmatrikse is ontwikkel waar verskillende beskikbaarheidsvlakke verskaf is. Die analise van die gedrag van die betroubaarheidsmodule toon dat beskikbaarheid afneem met toenemende falingstempo's, terwyl operasionele beskikbaarheid verbeter met aanvanklike toenames en hersteltempo's vir die onderskeie subsisteme. Gebaseer op die verskillende beskikbaarheidswaardes, word die werkverrigting van elke subsisteem ontleed en aangewend om instandhoudingsbesluite vir alle subsisteme te neem.

1. INTRODUCTION

The process industry is becoming increasingly complex, with huge capital investment being made in process automation to enhance the reliability of systems. Invariably, the proper maintenance of such systems and the frequency of maintenance are some of the issues that are gaining importance in the industry. Maintenance is not only performed on the process instruments but also on the equipment from utilities, playing a major role in the smooth running of the process [1]. Amongst others, ash handling units constitute an essential part of the power generation system of a thermal plant. An ash handling unit – whatever the operational intentions may be, whether continuous or intermittent – is expected to furnish excellent performance. The high performance of an ash handling unit can be achieved with a highly reliable power plant and perfect maintenance. One of the widely used measures of such performance is 'availability', which is a function of both reliability and maintainability. In principle, it is the proportion of the uptime of the total time the unit is in service. For the prediction of availability, several mathematical models in the literature handle wide degrees of complexity [2, 3, 4, and 5]. Most of these models are based on the Markovian approach, where the failure and repair rates are assumed to be constant. In other words, the times to failure and the times to repair follow exponential distribution.

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) [4]. For example, Zervick [5] pointed out in the context of pressure vessels that a systematic strategy based on RAM principles helps to evaluate changes in inspection frequency, maintenance actions, or condition monitoring strategies, leading to a decrease in the frequency of planned shutdowns, increases in the time between statutory inspections, and a reduction in maintenance costs. Kurien [6] developed a simulation model for analyzing the reliability and availability of an aircraft training facility. The model was useful for evaluating various maintenance alternatives.

According to Barabady et al. [7], the most important performance measures for repairable system designers and operators are system reliability and availability. The improvement of system availability has been the subject of a large volume of research and articles in the area of reliability. Availability and reliability are good measures of a system's performance. Their values depend on the system structure as well as on component availability and reliability. These values decrease as component age increases – i.e. their service times are influenced by their mutual interactions, the applied maintenance policy, and their environments [8].

According to Ebling [9], factors that affect the RAM of a repairable system include machinery (type, number of machines, age, arrangement of machines in relation to one another, arrangement of components in the machine, inherent defects in components), operating conditions (level of skill and number of operating personnel, working habits, inter-personnel relationships, absenteeism, safety measures, environmental conditions, severity of tasks assigned, and shock loading – accidental or otherwise), maintenance conditions (competence and strength of maintenance personnel, attendance, working habits, safety measures, inter-personnel relationships, defects introduced by previous maintenance actions, effectiveness of maintenance planning and control), and infra-structural facilities (spare-parts, consumables, common and special tools).

Over the years, as engineering systems have become more complex and sophisticated, the reliability prediction of engineering systems has become increasingly important as factors such as cost, risk of hazard, competition, public demand, and usage of new technology have changed. A high reliability level is desirable to reduce the overall costs of production and the risk of hazards in larger, more complex and sophisticated systems such as a thermal power plant. It is necessary to maintain the steam thermal power plant to provide reliable and uninterrupted electrical supply for lengthy periods of time.

Considerable efforts have been made by researchers to provide general methods for the prediction of system reliability [10-12], designing equipment with specified reliability values, demonstrating reliability values [13], focusing on issues of maintenance, inspection, repair, and replacement, and on the notion of maintainability as a design parameter [12]. To obtain regular and economical generation of electrical power, a plant should be maintained at a sufficiently high availability level corresponding with minimum overall cost. To this end, this research presents a 'reliability and economic evaluation model' for a steam thermal power plant, to predict its operational availability.

An interest in the consideration of systems with randomly failing repairable components is found in many engineering fields [14-18]. A computer network consisting of servers, hubs, routers, and workstations; a power distribution system consisting of generation plants, transmission lines, substations, and local distribution lines; and a highway transportation network consisting of roadways, tunnels, and bridges are examples of such systems. The interest lies not only in the availability of the system for operation at any given time, or in the reliability of operation during a specified interval of time, but also in measuring how rapidly the system can be put back into service after each failure. Furthermore, one is often interested in identifying critical components within a system, particularly in the context of upgrading the system's availability or reliability, or reducing the duration of downtimes [19].

The need for an efficient and reliable ash handling 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 comprised of various units: coal handling, steam generation, cooling water, crushing, ash handling, power generation, and feed water. For the regular and economical generation of power, it is necessary to maintain each ash handling subsystem. The failure of each item of equipment or subsystem depends upon the operating conditions and maintenance policies used. From the economic and operational points of view, it is desirable to ensure an optimum level of system availability. The goal of maximum power generation may be achieved under the given operating conditions, making the ash handling unit failure free, by examining the behavior of the system and making the maintenance decision a top priority for the most critical subsystem. In this paper, the maintenance aspects of an ash handling unit – an important part of the power generation function of a thermal power plant – is discussed.

2. NOMENCLATURE

These are the symbols and notations associated with the transition diagram:

1. ○ indicates the system in the operating condition.
2. □ indicates the system in the breakdown condition.
3. ⬭ indicates the system in the reduced capacity state.
4. A, B, C, D indicate that the subsystems are working at full capacity.
5. D_1 indicates that stand-by unit of subsystem D is in an operating state.
6. B' indicates that subsystem B is working at a reduced capacity.
7. a, b, c, d indicate that all subsystems are in a failed state due to the failure of a standby unit as well.
8. ϕ_1 Failure rate of subsystem A (electrostatic precipitator).
9. ϕ_2 Failure rate of subsystem B (hopper).
10. ϕ_3 Failure rate of subsystem C (slurry pump).
11. ϕ_4 Failure rate of subsystem D (low pressure pump).
12. λ_1 Repair rate of subsystem A.
13. λ_2 Repair rate of subsystem B.
14. λ_3 Repair rate of subsystem C.
15. λ_4 Repair rate of subsystem D.
16. $\partial / \partial t$ indicates derivative w.r.t. time 't'.
17. $P_0(t)$ denotes the probability that at time 't' all units are working.

18. $P_1(t)$ denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem A.
19. P_2 (t) denotes the probability that at time ‘t’ the system is a reduced capacity state due to the failure of subsystem B.
20. P_3 (t) denotes the probability that at time ‘t’ the system is in a failed state due to failure of subsystem C.
21. $P_4(t)$ denotes the probability that at time ‘t’ the system is working at full capacity with standby unit D.
22. P_5 (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem A, and subsystem D is working with a standby unit.
23. $P_6(t)$ denotes the probability that at time ‘t’ the system is in a reduced capacity state due to the failure of subsystem B, and subsystem D is working with a standby unit.
24. P_7 (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem C, and subsystem D is working with a standby unit.
25. P_8 (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem D.
26. P_9 (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem A, and subsystem B working at reduced capacity.
27. P_{10} (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem B when operating at reduced capacity.
28. P_{11} (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem C, and subsystem B working at reduced capacity.
29. P_{12} (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem A, subsystem B is working at reduced capacity, and subsystem D is working with a standby unit.
30. P_{13} (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem B, and subsystem D is working with a standby unit.
31. P_{14} (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem C, subsystem B is working at reduced capacity, and subsystem D is working with a standby unit.
32. P_{15} (t) denotes the probability that at time ‘t’ the system is in a failed state due to the failure of subsystem D (working with a standby unit), when subsystem B was working at reduced capacity.

3. MODEL DESCRIPTION AND FORMULATION

The ash handling system consists of four subsystems:

1. Electrostatic precipitator (ESP), denoted by A, having a single unit, failure of which results in plant failure.
2. Hopper, denoted by B, having a single unit, failure of which results in reduced capacity of the plant.
3. Slurry pump, denoted by C, having a single unit, failure of which results in plant failure.
4. Lower pressure pump, denoted by D, having two units (one working and one on standby at any given time), the failure of one resulting in the other starting.

4. RELIABILITY AND AVAILIBILITY MODELLING

A reliability prediction module for a thermal power plant has been developed to predict operational system availability. The failure and repair rates of the different subsystems are used as standard input information to the module. The flow of states for the system under consideration has been described in the state transition diagram shown in Figure 1, which is a logical representation of all possible state probabilities encountered during the failure analysis of a steam thermal power plant. Formulation is carried out using the joint probability functions based on the transition diagram. These probabilities are mutually exclusive, and provide reason to implement a Markovian approach for an availability analysis of power generation process [11-14, 20]. The following assumptions are made:

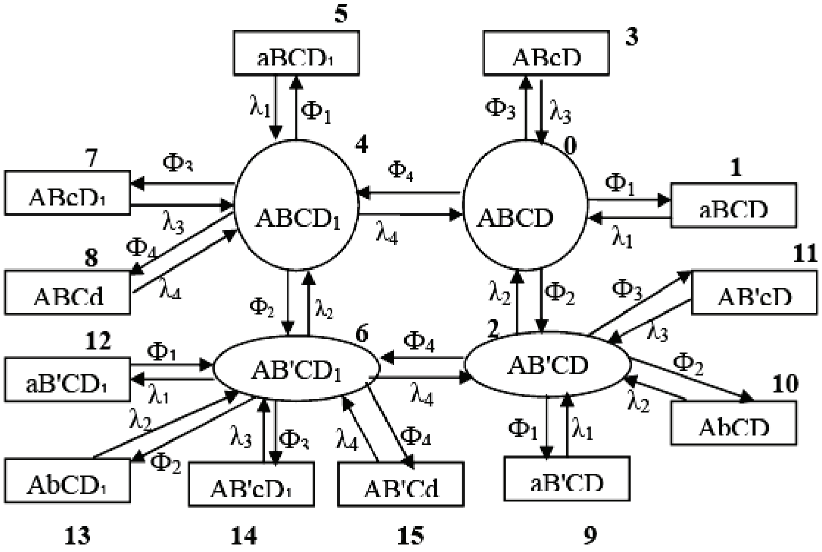

Figure 1: Transition diagram of ash handling unit

a) At any given time the system is either in the operating state or in a failed state.
b) Failure and repair rates are constant and statistically independent.
c) A repaired subsystem is as good as new.
d) Standby subsystems are of the same nature and capacity as the active subsystems.
e) Repair facilities are readily available.

Mathematical modeling is done using simple probabilistic considerations, while differential equations are developed using the Markov birth-death process. If the state of the system is probability-based, then the model is a Markov probability model. The present reliability analysis is concerned with a discrete-state continuous-time model, also called a Markov process. The Markov model is defined by a set of probabilities p_{ij}, where p_{ij} is the probability of transition from any state i to any state j. For example, the equipment transits from operating state (i) to failed state (j) with probability P_{ij}. One of the most important features of the Markov process is that the transition probability p_{ij} depends only on states i and j, and is completely independent of all past states except the last one, state i.

The objective is to obtain an expression for the probability of n occurrences in time t. The probability of n occurrences in time t is denoted by $P_n(t)$, i.e.:

Probability(X = n, t) = $P_n(t)$ (n = 0, 1, 2, . . .)

Then $P_0(t)$ represents the probability of zero occurrences in time t. The probability of zero occurrences in time (t + Δt) is given by

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

The probability of zero occurrences in time $(t+\Delta t)$ is equal to the probability of zero occurrences in time t multiplied by the probability of no occurrences in time Δt. The probability of no occurrences in time Δt is given by $(1-\lambda\Delta t)$. The probability of one occurrence in time $(t+\Delta t)$ is composed of two parts, namely (a) the 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. Thus,

$P_1(t+\Delta t) = (\phi\,\Delta t)\,P_0(t) + (1-\lambda\Delta t)\,P_1(t)$

Or $P_1(t+\Delta t) = P_0(t)\,\phi\,\Delta t + P_1(t) - \lambda\,\Delta t\,P_1(t)$

Or $P_1(t+\Delta t) - P_1(t) = \Delta t[\phi.P_0(t) - \lambda P_1(t)]$

Or $P_1(t+\Delta t) - P_1(t)/\Delta t = \phi P_0(t) - \lambda P_1(t)$

$Lt\,\Delta t \to 0$

$\partial/\partial t\,P_1(t) = \phi\,P_0(t) - \lambda\,P_1(t)$ or $\partial/\partial t\;P_1(t) + \lambda\,P_1(t) = \phi\,P_0(t)$

Or $[\partial/\partial t + \lambda]\,P_1(t) = \phi\,P_0(t)$ (Z)

Using the concept in equation (Z), and considering constant failures and repair rates, the mathematical formulation is done using the probabilistic Markov birth-death approach. The various probability considerations give the following differential equations associated with the ash handling unit; and these equations are solved for determining the steady state performance of the coal handling system.

$P_0(t)(\partial/\partial t + \phi_1 + \phi_2 + \phi_3 + \phi_4) = P_1(t).\lambda_1 + P_2(t).\lambda_2 + P_3(t).\lambda_3 + P_4(t).\lambda_4$ (1)

$P_1(t)[\partial/\partial t + \lambda_1] = P_0(t)\,\phi_1$ (2)

$P_2(t)(\partial/\partial t + \lambda_2 + \phi_4 + \phi_1 + \phi_2 + \phi_3) = P_0(t)\phi_2 + P_6(t)\lambda_4 + P_9(t)\lambda_1 + P_{10}(t)\lambda_2 + P_{11}(t)\lambda_3$ (3)

$P_3(t)[\partial/\partial t + \lambda_3] = P_0(t).\phi_3$ (4)

$P_4(t)(\partial/\partial t + \phi_1 + \phi_2 + \phi_3 + \phi_4 + \lambda_4) = P_0(t).\phi_4 + P_5(t).\lambda_1 + P_6(t).\lambda_2 + P_7(t).\lambda_3 + P_8(t).\lambda_4$ (5)

$P_5(t)[\partial/\partial t + \lambda_1] = P_4(t).\phi_1$ (6)

$P_6(t)(\partial/\partial t + \lambda_2 + \phi_1 + \phi_2 + \phi_3 + \phi_4 + \lambda_4) = P_4(t).\phi_2 + P_{12}(t).\lambda_1 +$
$P_{13}(t).\lambda_2 + P_{14}(t).\lambda_3 + P_{15}(t).\lambda_4 + P_2(t)\phi_4$ (7)

$P_7(t)[\partial/\partial t + \lambda_3] = P_4(t).\phi_3$ (8)

$P_8(t)[\partial/\partial t + \lambda_4] = P_4(t).\phi_4$ (9)

$P_9(t)[\partial/\partial t + \lambda_1] = P_2(t).\phi_1$ (10)

$P_{10}(t)[\partial/\partial t + \lambda_2] = P_2(t)\,\phi_2$ (11)

$P_{11}(t)[\partial/\partial t + \lambda_3] = P_2(t).\phi_3$ (12)

$P_{12}(t)[\partial/\partial t + \lambda_1] = P_6(t)\,\phi_1$ (13)

$P_{13}(t)[\partial/\partial t + \lambda_2] = P_6(t).\phi_2$ (14)

$P_{14}(t)[\partial/\partial t + \lambda_3] = P_6(t).\phi_3$ (15)

$P_{15}(t)[\partial/\partial t + \lambda_4] = P_6(t).\phi_4$ (16)

With initial conditions at time t = 0
$P_i(t) = 1$ for $i = 0$ and $= 0$ for $i \neq 0$

4.1 Solution of equations

The steady state behavior of the system can be analyzed by letting t→∞ and d/dt→ 0; the limiting probabilities from equations (1) – (16) are:

$P_0(\phi_1 + \phi_2 + \phi_3 + \phi_4) = P_1.\lambda_1 + P_2\lambda_2 + P_3.\lambda_3 + P_4\lambda_4$ (17)

$P_1\lambda_1 = P_0\,\phi_1$ (18)

$P_2(\lambda_2 + \phi_4 + \phi_1 + \phi_2 + \phi_3) = P_0\phi_2 + P_6\lambda_4 + P_9\lambda_1 + P_{10}\lambda_2 + P_{11}\lambda_3$ (19)

$P_3\lambda_3 = P_0\,\phi_3$ (20)

$P_4(\phi_1 + \phi_2 + \phi_3 + \phi_4 + \lambda_4) = P_0.\phi_4 + P_5.\lambda_1 + P_6.\lambda_2 + P_7.\lambda_3 + P_8.\lambda_4$ (21)

$P_5\lambda_1 = P_4\,\phi_1$ (22)

$P_6(\lambda_2 + \phi_1 + \phi_2 + \phi_3 + \phi_4 + \lambda_4) = P_4\phi_2 + P_{12}\lambda_1 + p_{13}.\lambda_2 + P_{14}.\lambda_3 + P_{15}.\lambda_4 + p_2\phi_4$ (23)

$P_7\lambda_3 = P_4\phi_3$ (24)

$P_8\lambda_4 = P_4\,\phi_4$ (25)

$P_9\lambda_1 = P_2\,\phi_1$ (26)

$$P_{10}\lambda_2 = P_2.\phi_2 \tag{27}$$
$$P_{11}\lambda_3 = P_2.\phi_3 \tag{28}$$
$$P_{12}\lambda_1 = P_6.\phi_1 \tag{29}$$
$$P_{13}\lambda_2 = P_6.\phi_2 \tag{30}$$
$$P_{14}\lambda_3 = P_6.\phi_3 \tag{31}$$
$$P_{15}\lambda_4 = P_6.\phi_4 \tag{32}$$

Solving these equations recursively, we get

$$P_6 = P_0\phi_4\phi_2[(\phi_4+\lambda_2)+(\phi_2+\lambda_4)]/$$
$$[(\lambda_2+\lambda_4)(\phi_2+\lambda_4)(\phi_4+\lambda_2)-\phi_2\lambda_4(\phi_4+\lambda_2)-\phi_4\lambda_4((\phi_2+\lambda_4)]$$
$$\text{Or } P_6 = P_0.a \tag{A}$$

where a = $\phi_4\phi_2[(\phi_4+\lambda_2)+(\phi_2+\lambda_4)]/[(\lambda_2+\lambda_4)(\phi_2+\lambda_4)(\phi_4+\lambda_2)-\phi_2\lambda_2(\phi_4+\lambda_2)-\phi_4\lambda_4((\phi_2+\lambda_4)]$

Also $P_2 = P_0[\phi_2 + a\lambda_4]/(\phi_4+\lambda_2)$

$$\text{Or } P_2 = P_0.b \tag{B}$$

where $b = (\phi_2 + a\lambda_4)/(\phi_4+\lambda_2)$

Similarly $P_4 = P_0(\phi_4 + a\lambda_2)/(\phi_2+\lambda_4)$

$$\text{Or } P_4 = P_0\ .c \tag{C}$$

where $c = (\phi_4 + a\lambda_2)/(\phi_2+\lambda_4)$

$$P_1 = (\phi_1/\lambda_1)P_0 \tag{D}$$
$$P_3 = (\phi_3/\lambda_3)P_0 \tag{E}$$
$$P_5 = c.(\phi_1/\lambda_1)P_0 \tag{F}$$
$$P_7 = c.(\phi_3/\lambda_3)P_0 \tag{G}$$
$$P_8 = c.(\phi_4/\lambda_4)P_0 \tag{H}$$
$$P_9 = b.(\phi_1/\lambda_1)P_0 \tag{I}$$
$$P_{10} = b.(\phi_2/\lambda_2)P_0 \tag{J}$$
$$P_{11} = b.(\phi_3/\lambda_3)P_0 \tag{K}$$
$$P_{12} = a(\phi_1/\lambda_1)P_0 \tag{L}$$
$$P_{13} = a.(\phi_2/\lambda_2)P_0 \tag{M}$$
$$P_{14} = a.(\phi_3/\lambda_3)P_0 \tag{N}$$
$$P_{15} = a.(\phi_4/\lambda_4)P_0 \tag{O}$$

Now $P_0+P_1+P_2+P_3+P_4+P_5+P_6+P_7+P_8+P_9+P_{10}+P_{11}+P_{12}+P_{13}+P_{14}+P_{15}=1$

$$\text{Or } P_0 = 1/[1+a+b+c+(\phi_1/\lambda_1)(1+a+b+c)+(\phi_2/\lambda_2)(a+b)+(\phi_3/\lambda_3)(1+a+b+c) + (\phi_4/\lambda_4)(a+c)] \tag{P}$$

$$\text{Therefore } A_0 = P_0+P_2+P_4+P_6 = P_0\,[1+b+c+a] \tag{R}$$

5. RELIABILITY AND AVAILABILITY ANALYSIS

Using the maintenance history sheet of the ash handling unit of the thermal power plant, and discussions with the plant personnel, appropriate failure and repair rates of all four subsystems are chosen and decision matrices (availability values) are prepared accordingly with the failure and repair rate values in expression (R) for A_0. The decision support system deals with the quantitative analysis of all the factors, viz. courses of action and states of nature, which influence the maintenance decisions associated with the ash handling unit of the thermal power plant. The decision models are developed in the real decision-making environment – i.e. decision-making under risk (probabilistic model) – and are used to implement the proper maintenance decisions for the ash handling unit. Tables 1, 2, 3, and

4 represent the decision matrices for various subsystems of the ash handling unit. These matrices give the various availability levels for different combinations of failure and repair rates/priorities. The availability values obtained in decision matrices for all four subsystems are plotted. Figures 2, 3, 4, and 5 represent the plots for various subsystems of the ash handling unit, depicting the effect of the failure/repair rate of the various subsystems on the ash handling unit's availability. On the basis of the analysis, the best possible combinations (ϕ , λ) may be selected.

6. RESULTS AND DISCUSSION

Availability (Av) $\rightarrow A_0$

ϕ_1 \ λ_1	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**Constant values**
0.001	0.881012	0.884910	0.886217	0.886872	0.887265	ϕ_2 = 0.00125
0.00125	0.879075	0.883932	0.885563	0.886380	0.886872	ϕ_3 = 0.035
0.0015	0.877148	0.882956	0.884910	0.885890	0.886479	ϕ_4 = 0.0436 λ_2 = 0.35
0.00175	0.875229	0.887983	0.884258	0.885399	0.886086	λ_3 = 0.3
0.002	0.873318	0.881012	0.883607	0.884910	0.885694	λ_4 = 0.455

Table 1: Decision matrix of the electrostatic precipitator subsystem of the ash handling system

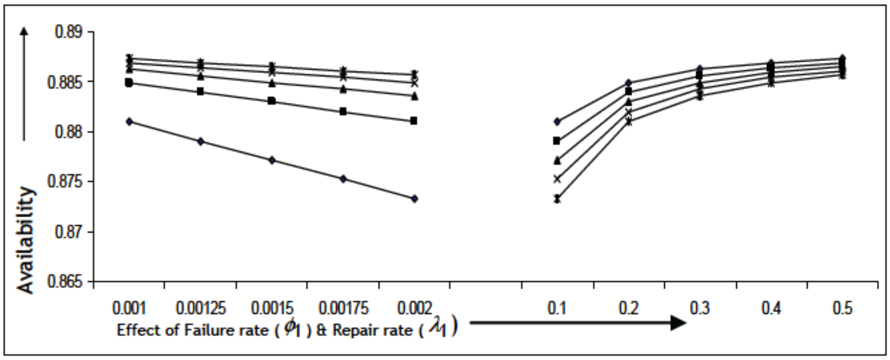

Figure 2: The effect of the failure and repair rate of the electrostatic precipitator subsystem on the ash handling unit's availability

Table 1 and Figure 2 show the effect of failure and repair rates of the electrostatic precipitator subsystem on the availability of the ash handling system. It is observed that, for some known values of failure / repair rates of hopper, slurry pump, and low pressure pump (ϕ_2 =.00125, ϕ_3 =0.035, ϕ_4 =0.0436, λ_2 =0.35, λ_3 =0.3, λ_4 =0.455), as the failure rate of the electrostatic precipitator increases from 0.001 (once in 1,000 hrs) to 0.002 (once in 500 hrs), the unit availability decreases by approximately 1%. Similarly, as the repair rate of the electrostatic precipitator increases from 0.1 (once in 10 hrs) to 0.5 (once in 2 hrs), the unit availability increases to approximately 1%.

→ Availability (Av) → A_0

λ_2 \ ϕ_2	***0.2***	***0.275***	***0.35***	***0.425***	***0.5***	***Constant values***
0.005	0.884972	0.884979	0.88498	0.884993	0.885139	ϕ_1= 0.0015
0.00875	0.884946	0.884952	0.884953	0.884962	0.8849684	ϕ_3 = 0.035 ϕ_4 = 0.0436
0.00125	0.884889	0.884904	0.884910	0.8854913	0.884915	λ_1 = 0.3
0.001625	0.884868	0.884893	0.884906	0.884908	0.884912	λ_3 = 0.3
0.02	0.877858	0.881075	0.882508	0.883267	0.883717	λ_4 = 0.455

Table 2: Decision matrix of the hopper subsystem of the ash handling system

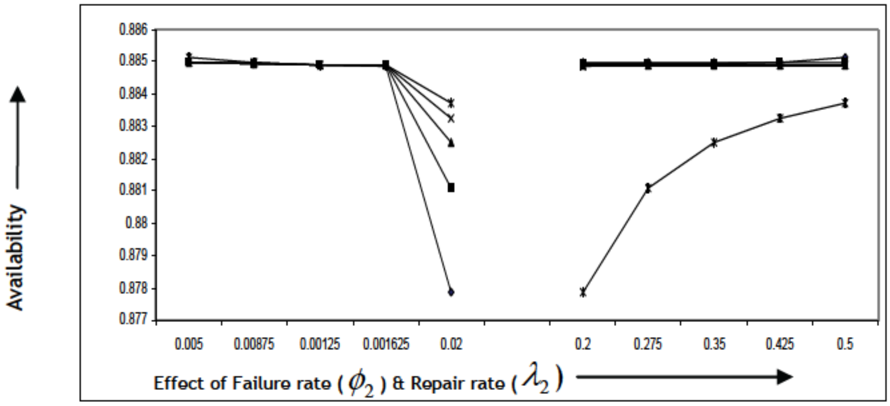

Figure 3: The effect of the failure and repair rate of the hopper subsystem on the ash handling unit's availability

Table 2 and Figure 3 depict the effect of failure and repair rates of the hopper subsystem on the availability of the ash handling system. It is observed that, for some known values of failure / repair rates of the electrostatic precipitator, slurry pump, and low pressure pump (ϕ_1=.0015, ϕ_3=0.035, ϕ_4=0.0436, λ_1=0.3, λ_3 =0.3, λ_4=0.455), as the failure rate of the hopper increases from 0.005 (once in 200 hrs) to 0.02 (once in 50 hrs), the unit's availability decreases by approximately 1%. Similarly, as the repair rate of the hopper increases from 0.2 (once in 5 hrs) to 0.5 (once in 2 hrs), the unit's availability increases to 1%.

Table 3 and Figure 4 reflect the effect of failure and repair rates of the slurry pump subsystem on the availability of the ash handling system. It is observed that, for some known values of failure / repair rates of the electrostatic precipitator, hopper, and low pressure pump (ϕ_1 =.0015, ϕ_2=0.00125, ϕ_2=0.0436, λ_1=0.3, λ_2 =0.35, λ_4=0.455), as the failure rate of the slurry pump increases from 0.02 (once in 50 hrs) to 0.05 (once in 20 hrs), the unit's availability decreases by approximately 16%. Similarly, as the repair rate of the slurry pump increases from 0.1 (once in 10 hrs) to 0.5 (once in 2 hrs), the unit's availability increases by approximately 12%.

→ **Availability (Av) → A_0**

λ_3 / ϕ_3	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***	Constant values
0.02	0.824136	0.898156	0.925876	0.940387	0.949314	ϕ_1 = 0.0015 ϕ_2 =0.00125 ϕ_4 = 0.0436 λ_1 = 0.3 λ_2 = 0.35 λ_4 = 0.455
0.0275	0.776161	0.868891	0.904929	0.924093	0.935986	
0.035	0.733465	0.841473	0.884910	0.908354	0.923027	
0.0425	0.695221	0.815732	0.865757	0.893143	0.910422	
0.05	0.660767	0.791520	0.847415	0.878432	0.898156	

Table 3: Decision matrix of the slurry pump subsystem of the ash handling system

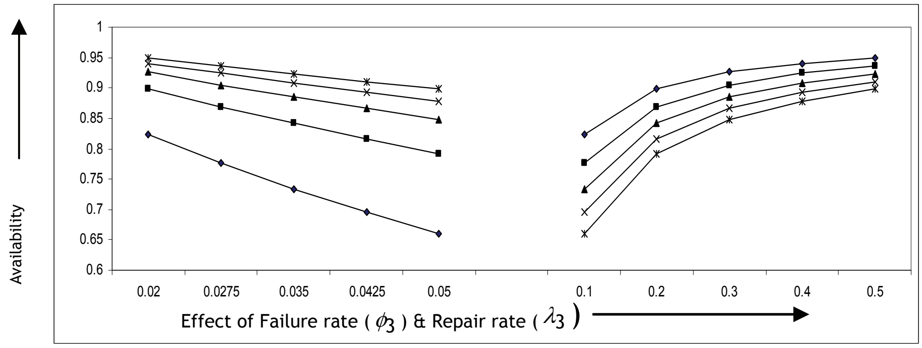

Figure 4: The effect of the failure and repair rate of the slurry pump subsystem on the ash handling unit's availability

→ **Availability (Av) → A_0**

λ_4 / ϕ_4	***0.25***	***0.3525***	***0.455***	***0.5575***	***0.66***	***Constant values***
0.025	0.884353	0.887803	0.889252	0.889993	0.890423	ϕ_1 = 0.0015 ϕ_2 = 0.00125 ϕ_3 = 0.035 λ_1 = 0.3 λ_2 = 0.35 λ_3 = 0.3
0.0343	0.878555	0.884715	0.887340	0.888695	0.889484	
0.0436	0.871400	0.880829	0.884910	0.887034	0.888279	
0.0529	0.863085	0.876223	0.881998	0.885032	0.886818	
0.0625	0.853476	0.870790	0.878527	0.882628	0.885057	

Table 4: Decision matrix of the low pressure pump subsystem of the ash handling system

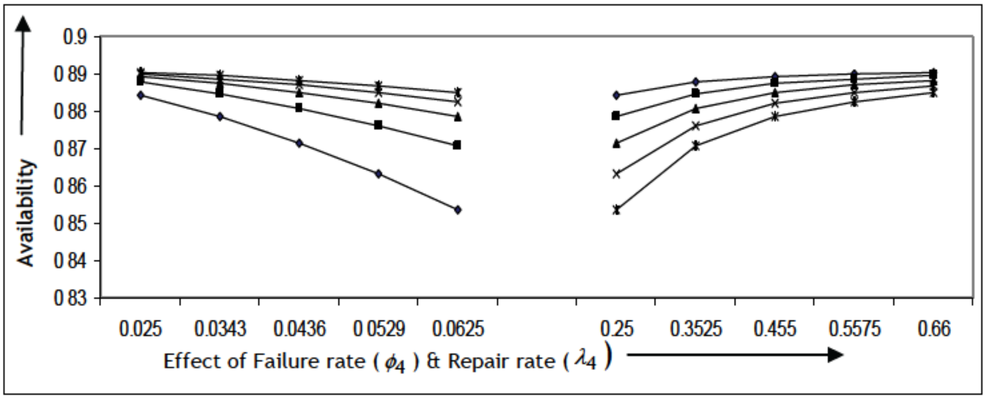

Figure 5: The effect of the failure and repair rate of the low pressure pump subsystem on the ash handling unit's availability

Table 4 and Figure 5 reveal the effect of failure and repair rates of the low pressure pump subsystem on the availability of the ash handling system. It is observed that, for some known values of failure / repair rates of the electrostatic precipitator, hopper, and slurry pump (ϕ_1=.0015, ϕ_2=0.00125, ϕ_3=0.035, λ_1=0.3, λ_2 =0.35, λ_3=0.3), as the failure rate of the low pressure pump increases from 0.025 (once in 40 hrs) to 0.0625 (once in 16 hrs), the unit's availability decreases by approximately 3%. Similarly, as the repair rate of the low pressure pump increases from 0.25 (once in 4 hrs) to 0.66 (once in 1.5 hrs), the unit's availability increases by approximately 2-3%.

7. CONCLUSION

The low failure rate, supported by state-of-the-art repair facilities, has resulted in excellent system availability. The availability model and decision support system for the ash handling system have been developed with the help of mathematical modeling using a probabilistic approach. The decision matrices are also developed. The matrices facilitate maintenance decisions at critical points where repair priority should be given to some particular subsystem of the ash handling system. The decision matrix given in Table 3 clearly shows that the slurry pump is the most critical subsystem as far as maintenance is concerned. So the slurry pump subsystem should be given top priority, as the effect of its repair rates on the unit's availability is much higher than that of the electrostatic precipitator, the induced draft fan, or the low pressure pump. Therefore, on the basis of repair rates, maintenance priority should be set as follows:

1. First priority should be given to the slurry pump.
2. Second priority should be given to the low pressure pump.
3. Third priority should be given to either the electrostatic precipitator or the hopper, since it is observed from Tables 1 and 2 that, with increases in their failure rates, the unit's availability is decreased by an equal amount - i.e. 1%.

In view of the possible increase in the ash handling failure rate, the model was found to be useful in assessing the system's performance vis-à-vis system availability. The model would certainly assist the maintenance team to decide the repair strategy for pumps so that the system operates with the utmost efficiency.

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