Stochastic Analysis of Ash Handling Unit in a Process Industry

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ABSTRACT

The paper discusses decision support system for ash handling unit of a thermal power plant. The model developed helps in the operations and quantitative management of various maintenance decisions and actions. The results of this paper are therefore beneficial in deciding the relative repair priorities of various subsystems of ash handling unit.

Keywords: Decision Support System, Transition diagram, Probabilistic approach, Availability matrices, Quantitative Management

1. INTRODUCTION

Manufacturing processes involve a continuous flow of raw materials through a series of sequential operations, which transform the raw materials into the final products. Industries producing products like paper, chemical and sugar etc. during manufacturing have such continuous operations. The mechanical systems have attracted the attention of several researchers in the area of reliability theory. Kumar et.al. [1, 2] discussed about feeding systems in the sugar industry and paper industry. Kumar and Singh [3] analyzed the Availability of a washing system in paper industry. Singh and Pandey [4, 5] reported reliability analysis of mechanical systems in Fertilizer and Sugar industry. Kiureghian and Ditlevson [6] analyzed the availability, reliability and downtime of system with repairable components. Rajiv Khanduja et. al [7] reported the availability analysis of the bleaching system of a paper plant. Kumar et.al.[8] discussed the performance evaluation and availability analysis of ammonia synthesis unit of a fertilizer plant using probabilistic approach. Tewari et.al. [9] analyzed the performance evaluation and optimization for urea crystallization system in a fertilizer plant using Genetic Algorithm. Khanduja et.al. [10] developed the decision support system and performance model of a digesting system of a paper plant using a probabilistic approach. Deepika Garg et.al. [11] developed the mathematical model of a cattle feed plant using a birth-death Markov Process. The differential equations have been solved for the steady-state. The system performance has also been studied. Sanjeev et al. [12] discussed about simulation and modeling of urea decomposition system in a fertilizer plant. Gupta et al. [13] discussed reliability and availability analysis of ash handling unit of a steam thermal power plant. Jorn Vatn et al. [14] discussed the optimization of maintenance interval using classical cost benefit analysis approach in Norwegian railways.

2. SYSTEM DESCRIPTION

2.1 The Ash Handling System consists of five sub-systems:

1. Economiser ash hopper, denoted by E, having two units, failure of which results in to reduced capacity of system.
2. Electrostatic Precipitator (E.S.P), denoted by F, having single unit, failure of which results into system failure.
3. Air heater hopper, denoted by G, having two units, failure of which results into reduced capacity of system.
4. Slurry pump denoted by H, having three units in series, failure of which results into system failure.
5. Lower pressure pump, denoted by I, having two units (one working and one stand by at a time), failure of one results into system at reduced capacity.

The notations associated with the transition diagram (Figure 2) are as follows:

1. E, F, G, H, I: Subsystems in good operating state
2. E_1, G_1, I_1 : Indicates that E,G,I are working in reduced capacity respectively.
3. f, h, i : Indicates the failed state of F,H,I.
4. λ_i : Mean constant failure rates from states E,F,G,H,I,I_1 to the states E_1,f,G_1,h,I_1,i
5. μ_i : Mean constant repair rates from states E_1,f,G_1,h,I_1,i to the States E,F,G,H,I,I_1.
6. $P_i(t)$: Probability that at time 't' all units are good and the system is in ith state.
7. ' : Derivatives w.r.t. 't'

2.3 Mathematical Analysis of the System

Probability consideration gives following differential equations (Eq. 1 – Eq. 21) associated with the Transition Diagram (Figure 2).

$$P_0^{'}(t)+(\lambda_1+\lambda_2+\lambda_3+\lambda_4)P_0(t)=\mu_3P_1(t)+\mu_1P_5(t)+\mu_2P_6(t)+\mu_4P_{20}(t) \quad (1)$$

$$P_1^{'}(t)+(\lambda_2+\lambda_4+\lambda_5+\mu_3)P_1(t)=\lambda_3P_0(t)+\mu_5P_2(t)+\mu_2P_7(t)+\mu_4P_8(t) \quad (2)$$

$$P_2^{'}(t)+(\lambda_1+\lambda_2+\lambda_4+\lambda_5+\mu_5)P_2(t)=\lambda_5P_1(t)+\mu_1P_3(t)+\mu_2P_9(t)+\mu_4P_{10}(t)+\mu_5P_{11}(t) \quad (3)$$

$$P_3^{'}(t)+(\lambda_2+\lambda_4+\lambda_5+\mu_1+\mu_3)P_3(t)=\lambda_1P_2(t)+\lambda_3P_4(t)+\mu_4P_{12}(t)+\mu_2P_{13}(t)+\mu_5P_{14}(t) \quad (4)$$

$$P_4^{'}(t)+(\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_5)P_4(t)=\mu_3P_3(t)+\lambda_5P_5(t)+\mu_5P_{15}(t)+\mu_2P_{16}(t)+\mu_4P_{17}(t) \quad (5)$$

$$P_5^{'}(t)+(\lambda_2+\lambda_4+\lambda_5+\mu_1)P_5(t)=\lambda_1P_0(t)+\mu_5P_4(t)+\mu_4P_{18}(t)+\mu_2P_{19}(t) \quad (6)$$

$$P_6^{'}(t)+\mu_2P_6(t)=\lambda_2P_0(t) \quad (7)$$

$$P_7^{'}(t)+\mu_2P_7(t)=\lambda_2P_1(t) \quad (8)$$

$$P_8^{'}(t)+\mu_4P_8(t)=\lambda_4P_1(t) \quad (9)$$

$$P_9^{'}(t)+\mu_2P_9(t)=\lambda_2P_2(t) \quad (10)$$

$$P_{10}^{'}(t)+\mu_4P_{10}(t)=\lambda_4P_2(t) \quad (11)$$

$$P_{11}^{'}(t)+\mu_5P_{11}(t)=\lambda_5P_2(t) \quad (12)$$

$$P_{12}^{'}(t)+\mu_4P_{12}(t)=\lambda_4P_3(t) \quad (13)$$

$$P_{13}^{'}(t)+\mu_2P_{13}(t)=\lambda_2P_3(t) \quad (14)$$

$$P_{14}^{'}(t)+\mu_5P_{14}(t)=\lambda_5P_3(t) \quad (15)$$

$$P_{15}^{'}(t)+\mu_5P_{15}(t)=\lambda_5P_4(t) \quad (16)$$

$$P_{16}^{'}(t)+\mu_2P_{16}(t)=\lambda_2P_4(t) \quad (17)$$

$$P_{17}^{'}(t)+\mu_4P_{17}(t)=\lambda_4P_4(t) \quad (18)$$

$$P_{18}^{'}(t)+\mu_4P_{18}(t)=\lambda_4P_5(t) \quad (19)$$

$$P_{19}^{'}(t)+\mu_2P_{19}(t)=\lambda_2P_5(t) \quad (20)$$

$$P_{20}^{'}(t)+\mu_4P_{20}(t)=\lambda_4P_0(t) \quad (21)$$

Initial conditions at time t = 0 are $P_i(t)=1$ for i = 0, otherwise $P_i(t)=0$

2.4 Steady State Availability

The steady state availability of the system can be analyzed by setting t→ ∞ and d/dt→ 0.The limiting probabilities from equations (1) – (21) are:

$$(\lambda_1+\lambda_2+\lambda_3+\lambda_4)P_0=\mu_3P_1+\mu_1P_5+\mu_2P_6+\mu_4P_{20} \quad (22)$$

$$(\lambda_2+\lambda_4+\lambda_5+\mu_3)P_1=\lambda_3P_0+\mu_5P_2+\mu_2P_7+\mu_4P_8 \quad (23)$$

$$(\lambda_1+\lambda_2+\lambda_4+\lambda_5+\mu_5)P_2=\lambda_5P_1+\mu_1P_3+\mu_2P_9+\mu_4P_{10}+\mu_5P_{11} \quad (24)$$

$$(\lambda_2+\lambda_4+\lambda_5+\mu_1+\mu_3)P_3=\lambda_1P_2+\lambda_3P_4+\mu_4P_{12}+\mu_2P_{13}+\mu_5P_{14} \quad (25)$$

$$(\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_5)P_4=\mu_3P_3+\lambda_5P_5+\mu_5P_{15}+\mu_2P_{16}+\mu_4P_{17} \quad (26)$$

$$(\lambda_2+\lambda_4+\lambda_5+\mu_1)P_5=\lambda_1P_0+\mu_5P_4+\mu_4P_{18}+\mu_2P_{19} \quad (27)$$

$$\mu_2P_6=\lambda_2P_0 \quad (28)$$

$$\mu_2 P_7 = \lambda_2 P_1 \tag{29}$$

$$\mu_4 P_8 = \lambda_4 P_1 \tag{30}$$

$$\mu_2 P_9 = \lambda_2 P_2 \tag{31}$$

$$\mu_4 P_{10} = \lambda_4 P_2 \tag{32}$$

$$\mu_5 P_{11} = \lambda_5 P_2 \tag{33}$$

$$\mu_4 P_{12} = \lambda_4 P_3 \tag{34}$$

$$\mu_2 P_{13} = \lambda_2 P_3 \tag{35}$$

$$\mu_5 P_{14} = \lambda_5 P_3 \tag{36}$$

$$\mu_5 P_{15} = \lambda_5 P_4 \tag{37}$$

$$\mu_2 P_{16} = \lambda_2 P_4 \tag{38}$$

$$\mu_4 P_{17} = \lambda_4 P_4 \tag{39}$$

$$\mu_4 P_{18} = \lambda_4 P_5 \tag{40}$$

$$\mu_2 P_{19} = \lambda_2 P_5 \tag{41}$$

$$\mu_4 P_{20} = \lambda_4 P_0 \tag{42}$$

Solving the above equations, we get:

Let us assume,

$P_1 = L_1 P_0$, $P_2 = L_2 P_0$, $P_3 = L_3 P_0$, $P_4 = L_4 P_0$, $P_5 = L_5 P_0$,, $P_6 = k_2 P_0$, $P_7 = k_2 L_1 P_0$,

$P_8 = k_4 L_1 P_0$, $P_9 = k_2 L_2 P_0$, $P_{10} = k_4 L_2 P_0$, $P_{11} = k_5 L_2 P_0$, $P_{12} = k_4 L_3 P_0$, $P_{13} = k_2 L_3 P_0$, $P_{14} = k_5 L_3 P_0$

$P_{15} = k_5 L_4 P_0$, $P_{16} = k_2 L_4 P_0$, $P_{17} = k_4 L_4 P_0$, $P_{18} = k_4 L_5 P_0$, $P_{19} = k_2 L_5 P_0$, $P_{20} = k_4 P_0$

Where, $K_1 = \frac{\lambda_1}{\mu_1}$, $K_2 = \frac{\lambda_2}{\mu_2}$, $K_3 = \frac{\lambda_3}{\mu_3}$, $K_4 = \frac{\lambda_4}{\mu_4}$, $K_5 = \frac{\lambda_5}{\mu_5}$

Now using normalizing conditions i.e. sum of all the probabilities is equal to one, we get: $\sum_{i=0}^{20} p_i = 1$

$$P_0 = \begin{bmatrix} 1 + L_1 + L_2 + L_3 + L_4 + L_5 + K_2 + K_2 L_1 + K_4 L_1 + K_2 L_2 + K_4 L_2 + K_5 L_2 + K_4 L_3 \\ + K_2 L_3 + K_5 L_3 + K_5 L_4 + K_2 L_4 + K_4 L_4 + K_4 L_5 + K_2 L_5 + K_4 \end{bmatrix}^{-1}$$

$$[A_V] = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 = [1 + L_1 + L_2 + L_3 + L_4 + L_5] P_0$$

3. Performance Analysis

The failure and repair rates of various subsystems of Ash handling system are taken from the maintenance history sheet of thermal power plant. 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 system. The decision matrices are developed to determine the various availability levels for different combinations of failures and repair rates. Table 1, 2, 3, 4, 5 represent the decision matrices for various subsystems of Ash handling system. Accordingly, maintenance decisions can be made for various subsystems keeping in view the repair criticality and we may select the best possible combinations of failure and repair rates.

4. Results and Discussion

Tables 1 to 5 show the effect of failure and repair rates of Economiser ash hoppers, Electrostatic precipitator, Air heater hoppers, Slurry pumps & Lower pressure pumps on the steady state availability of the Ash handling system. Table 1 reveals the effect of failure and repair rates of Economiser ash hoppers subsystem on the availability of the system. It is observed that for some known values of failure / repair rates of Electrostatic precipitator, Air heater hoppers, Slurry pumps & Lower pressure pumps (λ_2=0.001, λ_3= 0.005, λ_4=0.02, λ_5=0.025, μ_2=0.1, μ_3=0.2, μ_4=0.1, μ_5=0.25), as the failure rates of Economiser ash hoppers increases from 0.0025 to 0.04 the availability decreases by about 0.36%. Similarly as repair rates of Economiser ash hoppers increases from 0.0125 to 0.2, the availability increases by about 0.10%.

Table 2 reveals the effect of failure and repair rates of Electrostatic precipitator on the availability of the System. It is observed that for some known values of failure / repair rates of Economiser ash hoppers, Air heater hoppers, Slurry pumps & Lower pressure pumps (λ_1=0.0025, λ_3= 0.005, λ_4=0.02, λ_5=0.025, μ_1=0.0125, μ_3=0.2, μ_4=0.1, μ_5=0.25), as the failure rates of Electrostatic precipitator increases from 0.001 to 0.002, the availability decreases by about 0.67%. Similarly as repair rates of Electrostatic precipitator increases from 0.1 to 0.5, the availability increases by about 0.54%.

Table 3 reveals the effect of failure and repair rates of Air heater hoppers on the availability of the System. It is observed that for some known values of failure / repair rates of Economiser ash hoppers, Electrostatic precipitator, Slurry pumps & Lower pressure pumps (λ_1=0.0025, λ_2= 0.001, λ_4=0.02, λ_5=0.025, μ_1=0.0125, μ_2=0.1, μ_4=0.1, μ_5=0.25), as the failure rates of Air heater hoppers increases from 0.005 to 0.00985, the availability decreases by about 0.01%. Similarly as repair rates of Air heater hoppers increases from 0.2 to 0.5, the availability increases by about 0.008%.

Table 4 reveals the effect of failure and repair rates of Slurry pumps on the availability of the System. It is observed that for some known values of failure /

repair rates of Economiser ash hoppers, Electrostatic precipitator, Air heater hoppers & Lower pressure pumps (λ_1=0.0025, λ_2= 0.001, λ_3=0.005, λ_5=0.025, μ_1=0.0125, μ_2=0.1, μ_3=0.2, μ_5=0.25), as the failure rates of Slurry pumps increases from 0.02 to 0.05, the availability decreases by about 16.37%. Similarly as repair rates of Slurry pumps increases from 0.1 to 0.5, the availability increases by about 12.55%.

Table 5 reveals the effect of failure and repair rates of Lower pressure pumps on the availability of the System. It is observed that for some known values of failure / repair rates of Economiser ash hoppers, Electrostatic precipitator, Air heater hoppers & Slurry pumps (λ_1=0.0025, λ_2= 0.001, λ_4=0.02, λ_3=0.005, μ_1=0.0125, μ_2=0.1, μ_4=0.1, μ_3=0.2), as the failure rates of Lower pressure pumps increases from 0.025 to 0.0625, the availability decreases by about 0.63%. Similarly as repair rates of Lower pressure pumps increases from 0.25 to 0.66, the availability increases by about 0.10%.

5. Conclusions

Therefore, on the basis of repair rates, the maintenance priority should be given as per following order:

1. Slurry pumps
2. Electrostatic precipitator
3. Lower pressure pumps
4. Economiser ash hoppers
5. Air heater hoppers

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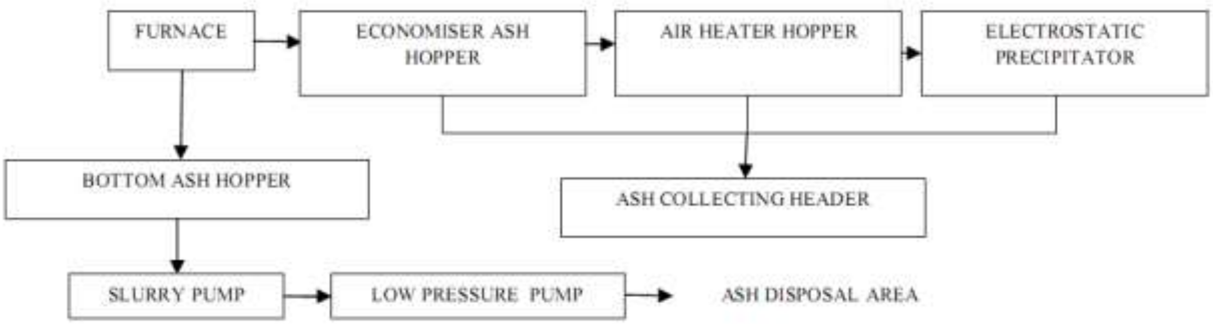

Figure 1: Schematic diagram of Ash handling system

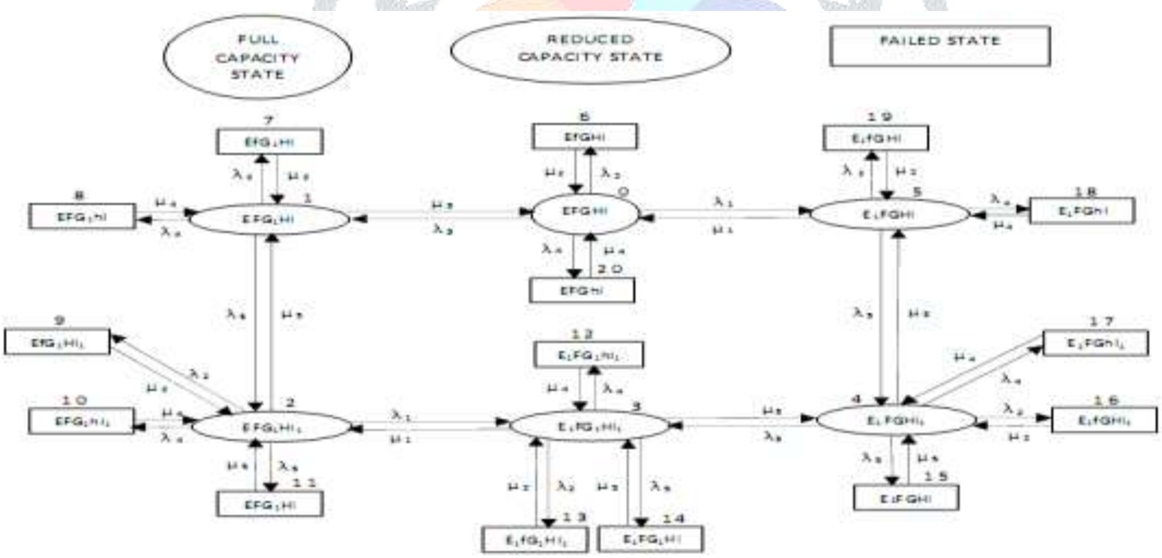

Figure 2: Transition diagram of Ash handling system

Table 1: Effect of Failure and Repair Rates of Economizer ash hopper on Availability

λ_1 / μ_1	0.0025	0.005	0.01	0.02	0.04	Constant values
0.0125	0.825189	0.824427	0.823434	0.822392	0.821520	λ_2=0.001, μ_2=0.1, λ_3=0.005, μ_3=0.2, λ_4=0.02, μ_4=0.1. λ_5=0.025, μ_5=0.25
0.025	0.825681	0.825189	0.824427	0.823434	0.822392	
0.05	0.825965	0.825681	0.825189	0.824427	0.823434	
0.1	0.826118	0.825965	0.825681	0.825189	0.824427	
0.2	0.826198	0.826118	0.825965	0.825681	0.825189	

Table 2: Effect of Failure and Repair Rates of Electrostatic precipitator on Availability

λ_2 / μ_2	0.001	0.00125	0.0015	0.0175	0.002	Constant values
0.1	0.825189	0.823490	0.821798	0.820113	0.818435	λ_1=0.002, μ_1=0.0125, λ_3=0.005, μ_3=0.2, λ_4=0.02, μ_4=0.1, λ_5=0.025, μ_5=0.25
0.2	0.828608	0.827750	0.826895	0.826041	0.825189	
0.3	0.829754	0.829180	0.828608	0.828036	0.827465	
0.4	0.830328	0.829897	0.829467	0.829037	0.828608	
0.5	0.830673	0.830328	0.829983	0.829639	0.829295	

Table 3: Effect of Failure and Repair Rates of Air heater hopper on Availability

λ_3 / μ_3	0.005	0.00850	0.00902	0.00950	0.00985	Constant values
0.2	0.825189	0.825096	0.825082	0.825069	0.825060	λ_1=0.0025, μ_1=0.0125, λ_2=0.001, μ_2=0.1, λ_4=0.02, μ_4=0.1, λ_5=0.025, μ_5=0.25
0.275	0.825226	0.825157	0.825147	0.825138	0.825131	
0.35	0.825248	0.825193	0.825185	0.825177	0.825172	
0.425	0.825262	0.825216	0.825209	0.825203	0.825199	
0.5	0.825271	0.825233	0.825227	0.825222	0.825218	

Table 4: Effect of Failure and Repair Rates of Slurry pump on Availability

μ_4 \ λ_4	0.02	0.0275	0.035	0.0425	0.05	Constant values
0.1	0.825189	0.777095	0.734299	0.695970	0.661444	λ_1=0.0025, μ_1=0.0125, λ_2=0.001, μ_2=0.1, λ_3=0.005, μ3=0.2, λ_5=0.025, μ_5=0.25
0.2	0.899407	0.870062	0.842571	0.816764	0.792491	
0.3	0.927205	0.906199	0.886124	0.866919	0.848529	
0.4	0.941758	0.925417	0.909634	0.894380	0.879628	
0.5	0.950712	0.937345	0.924348	0.911707	0.899407	

Table 5: Effect of Failure and Repair Rates of Lower pressure pump on Availability

μ_5 \ λ_5	0.025	0.0343	0.0436	0.0529	0.0625	Constant values
0.25	0.825189	0.824099	0.822686	0.820960	0.818860	λ_1=0.0025, μ_1=0.0125, λ_2=0.001, μ_2=0.1, λ_3=0.005, μ_3=0.2, λ_4=0.02, μ_4=0.1
0.3525	0.825810	0.825255	0.824533	0.823646	0.822563	
0.455	0.826063	0.825728	0.825291	0.824753	0.824094	
0.5575	0.826190	0.825966	0.825674	0.825313	0.824870	
0.66	0.826263	0.826103	0.825893	0.825635	0.825317	