Decision Support System and Performance Evaluation of The Digesting System of A Paper Plant

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INTRODUCTION

Due to automation in the process industries, maintenance is considered as an integral part of the production process. It is done by optimal utilization of maintenance resources and by maintaining high availability level. For increasing the productivity, availability of systems/subsystems in operation must be maintained at highest order. To achieve high production goals, the systems should remain operative (run failure free) for maximum possible duration.However, practically, these systems are subjected to random failures due to poor design, wrong manufacturing techniques, lack of operative skills, poor maintenance, overload, delay in starting maintenance and human error etc. These causes lead to non-availability of an industrial system resulting into improper utilization of resources (man, machine, material, money and time). Therefore, to achieve high production and good quality, there should be highest system availability (long run system availability). The paper plants are complex and repairable engineering systems, comprising of various units namely chipping, digesting, washing, bleaching, screening, stock preparation and paper production etc. These units are arranged in hybrid configurations. The important process of a paper industry, upon which the quality of paper depends, is the digesting process. In the process of paper formation, the chips from storage are fed in to a digester. A chemical compound, Sodium Hydroxide (NaOH) is added to the digester and the steam is forced from the bottom. The wooden chips are cooked for about 8 to 10 hrs so that lignin and other fibers present in the wooden chips get dissolved. After that, these cooked chips are flown to a blow tank in which black liquid is added for dilution. Then these cooked chips are passed through various systems like washing, bleaching, screening, stock preparation and paper making etc.to convert into paper.

DIGESTING SYSTEM DESCRIPTION

The Digesting system of a paper plant consists of four subsystem viz. screw feeder, belt conveyor, shuttle conveyor, digester that are arranged in series and parallel configuration.

I. Screw Feeder (A): It consists of two units out of which one is standby. The function of the screw feeder is to extract the wooden chips from storage silos and transfer it to the belt conveyor. When both screw feeders fail, it causes complete failure of the system.

II. Belt Conveyor (B): It consists of one unit to carry the chips. When a belt conveyor fails, it causes complete failure of the system.

III. Shuttle Conveyor(C): It consists of one unit to feed wooden chips from belt conveyor to the digester. When the shuttle conveyor fails, it causes complete failure of the system.

IV. Digester (D): It consists of three units in parallel to cook the wooden chips. If one digester fails, the system is subjected to reduced capacity. When all the three digesters fail at a time, it causes complete failure of the system.

ASSUMPTIONS AND NOTATIONS

The following assumptions and notations are addressed for the purpose of mathematical analysis of the Digesting system:

I. Failure/repair rates are constant over time and statistically independent.
II. A repaired unit is as good as a new one far as performance is concerned.
III. The standby units/subsystems are of the same nature.
IV. The system failure/repair follows exponential distribution.
V. System may work at reduced capacity.
VI. There is no simultaneous failure among the subsystems.

A, B, C D: Represent good working states of respective Screw Feeder, Belt Conveyor, Shuttle Conveyor, Digester.
a,b,c,d : Represent failed states of respective Screw Feeder , Belt Conveyor, Shuttle Conveyor , Digester.
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$: Respective mean constant failure rates of A,B,C,D .
$\mu_1, \mu_2, \mu_3, \mu_4$: Respective mean constant repair rates of a,b,c,d .
d/dt : Represents derivative w.r.t ‘t’.
$P_i(t)$: Represents the state probability that the system is in ith state at time t .

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PERFORMANCE MODELING

The mathematical modeling is done by using simple probabilistic considerations and differential equations are developed with the help of a transition diagram. These equations are solved for determining the steady state availability of the Digesting system. Various probability considerations give the following differential equations associated with the Digesting system :

$$\left(d/dt+\sum_{i=1}^{4}\lambda i\right)P_0(t)=\mu_1P_1(t)+\sum_{i=2}^{3}\mu i\, P_{i+4}(t)+\mu_4P_2(t) \quad (1)$$

$$\left(d/dt+\sum_{i=1}^{4}\lambda i+\mu_1\right)P_1(t)=\sum_{i=1}^{3}\mu i\, P_{i+7}(t)+\mu_4P_3(t)+\lambda_1P_0(t) \quad (2)$$

$$\left(d/dt+\sum_{i=1}^{4}\lambda i+\mu_4\right)P_2(t)=\sum_{i=2}^{3}\mu i\, P_{i+9}(t)+\lambda_4P_0(t)+\mu_1P_3(t)+\mu_4P_4(t) \quad (3)$$

$$\left(d/dt+\sum_{i=1}^{4}\lambda i+\mu_1+\mu_4\right)P_3(t)=\sum_{i=1}^{3}\mu i\, P_{i+12}(t)+\lambda_1P_2(t)+\lambda_4P_1(t)+\mu_4P_5(t) \quad (4)$$

$$\left(d/dt+\sum_{i=1}^{4}\lambda i+\mu_4\right)P_4(t)=\sum_{i=2}^{4}\mu i\, P_{i+14}(t)+\lambda_4P_2(t)+\mu_1P_5(t) \quad (5)$$

$$\left(d/dt+\sum_{i=1}^{4}\lambda i+\mu_1+\mu_4\right)P_5(t)=\sum_{i=1}^{4}\mu i\, P_{i+18}(t)+\lambda_1P_4(t)+\lambda_4P_3(t) \quad (6)$$

$$(d/dt+\mu_1)P_i(t)=\lambda_1P_j(t) \quad \text{where } i=8,13,19 \quad j=1,3,5 \quad (7)$$

$$(d/dt+\mu_2)P_i(t)=\lambda_2P_j(t) \quad \text{where } i=6,8,11,14,16,20 \quad j=0,1,2,3,4,5 \quad (8)$$

$$(d/dt+\mu_3)P_i(t)=\lambda_3P_j(t) \quad \text{where } i=7,10,12,15,17,21 \quad j=0,1,2,3,4,5 \quad (9)$$

$$(d/dt+\mu_4)P_i(t)=\lambda_4P_j(t) \quad \text{wherei}=18,22 \quad j=4,5 \quad (10)$$

With initial conditions at time t = 0

$P_i(t) = 1$ for $i = 0$

$= 0$ for $i \neq 0$

The paper plant is a process industry where the raw material is processed through various subsystems continuously till the final product is obtained. Thus, the long run availability of the Digesting system of a paper plant is attained by putting derivative of all probability equal to zero as $\rightarrow\infty$ and $d/dt\rightarrow 0$ into differential equations. After doing so, one gets:

$P_1=T_{13}P_0$ $\quad$ $P_2= T_{14}P_0$ $\quad$ $P_3= T_{12}P_0$ $\quad$ $P_4= T_{15}P_0$ $\quad$ $P_5= T_{16}P_0$

$P_6=B_2P_0$ $\quad$ $P_7=B_3P_0$ $\quad$ $P_8=B_1T_{13}P_0$ $\quad$ $P_9= B_2T_{13}P_0$ $\quad$ $P_{10}= B_3T_{13}P_0$

$P_{11}= B_2T_{14}P_0$ $\quad$ $P_{12}= B_3T_{14}P_0$ $\quad$ $P_{13}= B_1T_{12}P_0$ $\quad$ $P_{14}= B_2T_{12}P_0$ $\quad$ $P_{15}= B_3T_{12}P_0$

$P_{16}= B_2T_{15}P_0$ $\quad$ $P_{17}= B_3T_{15}P_0$ $\quad$ $P_{18}= B_4T_{15}P_0$ $\quad$ $P_{19}= B_1T_{16}P_0$ $\quad$ $P_{20}= B_2T_{16}P_0$

$P_{21}= B_3T_{16}P_0$ $\quad$ $P_{22}= B_4T_{16}P_0$

Where $B_i = \lambda i/\mu i$ $\quad$ $i= 1,2,3,4$

$T= \lambda_1 + \lambda_4,$ $\quad$ $T_1= \lambda_4 + \mu_1,$ $\quad$ $T_2= \lambda_1 + \lambda_4+ \mu_4,$ $\quad$ $T_3= \lambda_4 + \mu_1+ \mu_4,$ $\quad$ $T_4= \lambda_1 + \mu_4,$

$T_5= \mu_1 + \mu_4,$ $\quad$ $T_7= =[(T/\mu_4)-\{(\lambda_1*\mu_1)/(T_1*\mu_4)\}],$ $\quad$ $T_8= \mu_1/T_1,$

$T_9=[(T_2* T_4)/(\mu_1*\mu_4)-\{(\lambda_1* T_2)/(T_5*\mu_4)\}-(\lambda_4/\mu_1)],$ $\quad$ $T_{10}=[(\lambda_4* T_4)/(\mu_4*\mu_1)+\{(\lambda_1* \lambda_4/ T_5*\mu_4)\}],$

$T_{11}=[(T_4/\mu_4)+\{(\lambda_1*\mu_1/ T_5*\mu_4\}+(\lambda_4/ T_5)],$ $\quad$ $T_{12}=[\{(T_7* T_9)- T_{10}\}/\{ T_{11}+(T_8* T_9)\}]$

$T_{13}=[\{ \lambda_1+(T_{12}*\mu_4)\}/ T_1],$ $\quad$ $T_{14}=[\{ T-(\mu_1* T_{13})\}/ \mu_4]$

$T_{15}=[\{(T_2* T_{14})- \lambda_4-(\mu_1* T_{12})\}/ \mu_4],$ $\quad$ $T_{16}=[\{(\lambda_1* T_{15})+(\lambda_4* T_{12})\}/ T_5]$

Using normalizing condition i.e. sum of all the state probabilities equal to one i.e.

$$\sum_{i=1}^{22} Pi = 1, \text{ we get:}$$

$$T_{13}P_0+T_{14}P_0+T_{12}P_0+T_{15}P_0+T_{16}P_0+B_2P_0+B_3P_0+B_1T_{13}P_0+B_2T_{13}P_0+B_3T_{13}P_0+B_2T_{14}P_0+B_3T_{14}P_0+B_1T_{12}P_0+B_2T_{12}P_0+B_3T_{12}P_0+B_2T_{15}P_0+B_3T_{15}P_0+B_4T_{15}P_0+B_1T_{16}P_0+B_2T_{16}P_0+B_3T_{16}P_0 + B_4T_{16}P_0 =1$$

$$P_0[T_{13}+T_{14}+T_{12}+T_{15}+T_{16}+B_2+B_3+B_1T_{13}+B_2T_{13}+B_3T_{13}+B_2T_{14}+B_3T_{14}+B_1T_{12}+B_2T_{12}+B_3T_{12}+B_2T_{15}+B_3T_{15}+B_4T_{15}+B_1T_{16} +B_2T_{16}+B_3T_{16} + B_4T_{16}]=1$$

Now, the steady state availability of the Digesting system may be obtained as summation of all working and reduced capacity state probabilities as

$$\text{Hence Av.} = \sum_{i=0}^{5} Pi$$

$Av. = P_0 + P_1 + P_2 + P_3 + P_4 + P_5$

$Av = (1+T_{13}+T_{14}+T_{12}+T_{15}+T_{16})/[1+T_{13}+T_{14}+T_{12}+T_{15}+T_{16}(1+B_2+B_3)+B_1(T_{13}+T_{12}+T_{16})+ B_4(T_{15}+T_{16})]$

Therefore, Availability of the system (Av.) represents the performance model of the Digesting system. It can be used for performance evaluation and optimization of this operating system of the paper plant.

EVALUATION OF PERFORMANCE

This performance evaluating model includes all possible states of nature, that is, future events (λ_i) and the identification of all the courses of action, that is, repair priorities (μ_i). This model is simulated to find the availability levels at different values of failure and repair rates .On the basis of analysis, one may select the best possible combination (λ_i, μ_i), that is, optimal maintenance strategies and decide about the relative maintenance priorities for four subsystems of the Digesting system.

Table 1: Decision Matrix for the screw feeder subsystem of the Digesting system

Availability (Av.) ⟶

λ_1 \ μ_1	0.2	0.3	04	0.5	λ_2=0.002
0.002	0.98028	0.98033	0.98035	0.98036	λ_3=0.002
0.004	0.97999	0.98019	0.98026	0.9803	λ_4= 0.001
0.006	0.97952	0.97998	0.98013	0.98021	μ_2= 0.2 μ_3= 0.2
0.008	0.97888	0.97968	0.97996	0.98009	μ_4= 0.05

Table2: Decision Matrix for the belt conveyor subsystem of the Digesting system

Availability (Av.) ⟶

λ_2 \ μ_2	0.2	0.3	04	0.5	λ_1=0.002
0.002	0.98028	0.98349	0.98511	0.98608	λ_3=0.002
0.004	0.97076	0.97709	0.98028	0.9822	λ_4= 0.001
0.006	0.96143	0.97076	0.97555	0.97836	μ_1= 0.2 μ_3= 0.2
0.008	0.95227	0.96452	0.97076	0.97455	μ_4= 0.05

Table 3: Decision Matrix for the shuttle conveyor subsystem of the Digesting system

Availability (Av.) ⟶

λ_3 \ μ_3	0.2	0.3	04	0.5	λ_1=0.002
0.002	0.98028	0.98349	0.98511	0.98608	λ_2=0.002
0.004	0.97076	0.97709	0.98028	0.9822	λ_4= 0.001
0.006	0.96143	0.97076	0.97555	0.97836	μ_1= 0.2 μ_2= 0.2
0.008	0.95227	0.96452	0.97076	0.97455	μ_4= 0.05

Table 4: Decision Matrix for the digester subsystem of the Digesting system

Availability (Av.) ⟶

λ_4 \ μ_4	0.05	0.075	0.10	0.125	λ_1=0.002
0.001	0.98028	0.98029	0.98030	0.98030	λ_2=0.002
0.003	0.98000	0.98021	0.98026	0.98028	λ_3= 0.002
0.005	0.97916	0.97996	0.98016	0.98023	μ_1= 0.2 μ_2= 0.2
0.007	0.97753	0.97945	0.97994	0.98011	μ_3= 0.2

DISCUSSION

Table 1 reveals the effect of failure and repair rates of screw feeder on the availability of Digesting system as failure rate of screw feeder (λ_1) increases from 0.002 (once in 500 hrs) to 0.008 (once in 125 hrs) ,the system availability decreases 0.15

%. Similarly, as the repair rate (μ_1) increases from 0.2(once in 5hrs) to 0.5(once in 2 hrs), the system availability increases negligibly to 0.008 %.

Table 2 shows the effect of failure and repair rates of belt conveyor on the availability of Digesting system as failure rate of belt conveyor (λ_2) increases from 0.002 (once in 500 hrs) to 0.008 (once in 125 hrs) ,the system availability decreases considerably by 3 %. Similarly, as the repair rate (μ_2) increases from 0.2 (once in 5 hrs) to 0.5 (once in 2 hrs), the system availability increases by 0.6 %.

Table 3 depicts the effect of failure and repair rates of shuttle conveyor on the availability of Digesting system, as failure rate of shuttle conveyor (λ_3) increases from 0.002 (once in 500 hrs) to 0.008 (once in 125 hrs), the system availability decreases considerably by 3 %. Similarly, as the repair rate (μ_3) increases from 0.2 (once in 5 hrs) to 0.5 (once in 2 hrs), system availability increases by 0.6 %.

Table 4 explains the effect of failure and repair rates of digester on the availability of Digesting system as failure rate of digester (λ_4) increases from 0.001 (once in 1000 hrs) to 0.007 (once in 142.85 hrs), the system availability decreases significantly by 0.28 %. Similarly, as the repair rate (μ_4) increases from 0.05(once in 20 hrs) to 0.125 (once in 8 hrs), the system availability increases by 0.002 %.

CONCLUSIONS

The Decision Support System for Digesting system has been developed with the help of performance modeling using probabilistic approach. The decision matrices (Table1-4) that have been developed to facilitate the maintenance decisions to be made at critical points where repair priority should be given to some particular subsystem of the Digesting system. Decision matrix, as given in Tables 2 and 3, clearly shows that the Belt Conveyor and Shuttle Conveyor are the most critical subsystems as far as maintenance is concerned. Therefore, Belt Conveyor and Shuttle Conveyor subsystems should be given top priority, as the effect of its failure / repair rates on the unit availability is much higher than that of screw feeder and digester subsystems. Based on the repair rates, the relative repair priorities from maintenance point of view should be done in this order:

I. Belt Conveyor & Shuttle Conveyor   II. Screw feeder   III. Digester

It also provides the various availability levels for different combinations of failure and repair rates for every subsystem. On the basis of this logical analysis, we may select the best possible combination of failure events and repair priorities for each subsystem. It helps in determining the optimal maintenance strategy, which will ensure the maximum availability of the Digesting system in a paper plant. The optimum values of failure and repair rates for each subsystem of the Digesting system are given below in Table 5. The findings of this paper are discussed with the concerned paper plant management. Such results are found to be highly beneficial to the plant management for the evaluation of performance and timely execution of maintenance decisions of the Digesting system in a paper plant.

Table 5: Optimum values of failure and repair rates

Sr.No.	Failure Rates (λ_i)	Repair Rates (μ_i)	Maximum Availability Level
1.	$\lambda_1 = 0.002$	$\mu_1 = 0.5$	0.98036
2.	$\lambda_2 = 0.002$	$\mu_2 = 0.5$	0.98608
3.	$\lambda_3 = 0.002$	$\mu_3 = 0.5$	0.98608
4	$\lambda_4 = 0.001$	$\mu_4 = 0.125$	0.98030

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