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Simulation modelling of condensate and feed water system in national thermal power plant

Sanjay Kajal
KurukshetraUniversity, Kurukshetra (Haryana)
Sanjay_kajal@rediffmail.com

P.C Tewari
KurukshetraUniversity, Kurukshetra (Haryana)
pctewari1@rediffmail.com

Abstract
The objective of the present paper is to develop availability simulation model for condensate and feed water system taken from National Thermal Power Plant (N.T.P.C.), Faridabad (India) using probabilistic approach and Markov birth-death process. The selected plant has been divided into many sections like Ash handling system, Feed water system, Water treatment system, Coal handling system, Condensate and feed water system, Steam generating system and Air distribution system. Using transition diagram, the difference differential equations are derived which are then solved recursively. The failure and repair rates of various subsystems are assumed to follow exponential distribution. A real time steady state availability simulation model has been developed to measure the performance of the system concerned using normalizing conditions. Availability matrices and contour plots are used to show the various availability levels of various subsystems. Further, the maintenance priorities are also set based upon the criticality of various subsystems. The analysis is done by making use of software package Matlab 7.0.4. The finding of this paper might be helpful to the plant management for improving the existing maintenance schedule.

Keywords: Simulation Modelling, Markov Birth-Death Process, Transition Diagram, Availability Matrices.

1. Introduction

In a process plant, the raw material is processed through various machines to achieve the final product. The production suffers due to failure of any intermediate system even for a small interval of time. The cause of failure may be due to poor design, system complexity, poor maintenance, lack of communication and coordination, inappropriate planning, lack of expertise and scarcity of inventories. Thus for the smooth running of a process plant, highly skilled manpower is required. System reliability is a measure of the performance of the system under the specified conditions. In most of the complex plants, it has been observed that these consist of systems and subsystems connected in series, parallel or a combination of these. A National Thermal Power Plant is a complex engineering system which provides electric power for domestic, commercial, industrial and agricultural use. For maximizing the productivity, availability and reliability of systems/subsystems in operation must be maintained at highest order. The purpose of the paper is to target the critical components of plant concerned so that the framework of appropriate maintenance strategies can be made. This will help the plant management to achieve the maximum availability by reducing the malfunctioning of various systems.

Since late 1960's, there had been a considerable development in the field of plant reliability, availability and its life cycle costs and maintainability [1,2]. Asha and Nair [3] examined the relationship between Mean Time To System Failure (M.T.S.F.) in an age replacement model with hazard rate and mean (reversed mean) residual life functions. Garg et. al. [4] developed a reliability model for a block- board manufacturing system in a plywood industry. The model discussed here helps in determining both time dependent and steady state availability under idealized as well as faulty Preventive Maintenance (PM). Gupta et. al. [5] computed the reliability, availability, and mean time before failure of the process of a plastic-pipe manufacturing plant consisting of a (K, N) system for various choices of failure and repair rates of sub-systems. Khanduja et. al. [6] carried out the availability analysis of bleaching system of a paper plant. Kiureghian and Ditlevson[7] analyzed the availability, reliability and downtime of system with repairable components. Mange Ram and Singh [8] discussed the availability of a complex system consisting of two independent repairable subsystems. The model is analyzed under “preemptive-repeat repair discipline” where A is a priority and B is non-priority. Ming-Yi et. al. [9] developed two component- level Preventive Maintenance policies for systems subjected to joint effect of partial recovery and variable operational conditions. Kumar et.al.[10]discussed about simulation and modelling of urea decomposition system in a fertilizer plant. Vatn and Aven[11] optimized the maintenance interval using classical cost benefit analysis approach in Norwegian railways. Vander Weide et. al. [12] presented a conceptually clear and comprehensive derivation of formulas for computing the discounted cost associated with a maintenance policy combining both condition-based and age-based criteria for Preventive Maintenance.

Design/Methodology/Approach:

- Understanding the selected industrial process or system through survey.
- Physically observing the system, its subsystems and their functioning.
- Mathematical formulation using transition diagram and development of simulation Model for Condensate and feed water system.
- Development of various availability matrices to depict the various availability levels.

Findings:

- Relationship between failure and repair rates among the various subsystems of Condensate and Feed Water System.
- Simulation modeling which originate the various steady state availability matrices for different combinations of failure and repair rates of each subsystem.
- Deriving the maintenance priorities based upon their respective repair rates, helping the plant management to have best maintenance schedule.

2. System Layout

2.1 System Description

The steam after doing useful work in the turbine is condensed to water in Condenser where the loss of water is compensated with the help of Makeup water. This hot water is collected in the Hot well which acts as reservoir. The hot water is pumped to the Deaerator from Hot well with the help of Condensate Extraction Pumps (C.E.P.) after being heated in the Low Pressure Heaters (L.P.H.). The function of Deaerator is to removes the dissolved oxygen, air and other gases from the feed water. From the Deaerator, water is stored in a feed water storage tank. The Boiler Feed Pump (B.F.P.) discharges feed water to the boiler at the Economizer after getting heated up in two High Pressure Heaters (H.P.H.). The feed water is further heated up in the Economizer by the hot flue gases leaving the boiler before entering the Boiler to which the water walls and super heaters of boiler are connected.

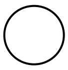
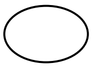
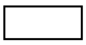
2.2 System Configuration

The Condensate and Feed Water System comprises of the following five critical subsystems:
Sub-system A (Condensate Extraction Pump): These are the motorized operated machines. This subsystem consists of two units of Condensate Extraction Pump having 100% capacity. Failure of any one forces to start the stand-by unit. Complete failure of the system occurs when stand-by unit also fails.
Sub-system B (Low Pressure Heater): This subsystem consists of three units of low pressure heaters arranged in series. Failure of any one unit causes the complete failure of the system.

Sub-system C (Boiler Feed Pump): The function of boiler feed pump is to discharges feed water to the boiler at the Economizer after getting heated up in the High Pressure Heater. This subsystem consists of two units having 100% capacity. Failure of any one forces to start the stand-by unit. Complete failure of the system occurs when stand-by unit also fails.
Sub-system D (High Pressure Heater): The function of this subsystem is to increase the temperature and pressure of water before feeding it to economizer. There are two units of high pressure heater working in series. Failure of any one unit causes complete failure of system.
Sub-system E (Economizer): The subsystem consists of one unit subjected to minor and major failure. In Economizer, heat carried in flue gases are used to increase the boiler feed water temperature from 231°c to 280°c. Partial failure of Economizer can set the system to reduced working capacity, while major failure can cause complete failure of system.

The failure rates of other subsystems are almost negligible and therefore are not considered for analysis.

2.3 Notations and Assumptions

A, B, C, D, E	: Indicate that the sub-systems are working in full capacity.
A_1, C_1	: Indicate that one unit of sub-systems A and C is in failed state and the other sub system having 100% capacity is working properly.
E^1	: Indicates the reduced state of the sub-system E.
b, d	: Indicate the failed state of the sub-systems B and D.
a_1, c_1, e^1	: Indicate the total failure of system due to failure of second standby unit of A and C and complete failure of sub-system E.
λ_i	: Failure rates of the sub-systems A, B, C, D, E.
ϕ, ψ, μ, σ, η	: Repair rates of A, B, C, D, E respectively.
$P_i(t)$	: The system is working in full capacity. For *i* = 0, 1, 2, 3.
	: Indicates the system is in full working state.
	: Indicates the system is in reduced capacity working state.
	: Indicates the system is in failed state.

The assumptions used in developing performance model are as follows (Figure 1):
1. Failure and repair rates are assumed to be constant over time.
2. A repaired unit as good as new, performance wise, for a specified duration.
3. Service includes repair and/or replacement and sufficient repair facilities are provided.
4. Standby subsystems are of same capacity as that of active systems and
5. System may work at reduced capacity.

3. Simulation Modelling of Condensate and Feed Water System

$$[\frac{d}{dt} + \sum_{i=1}^{5} \lambda_i]P_0(t) = \phi P_1(t) + \mu P_3(t) + \eta P_4(t) + \psi P_8(t) + \sigma P_{10}(t) \quad (1)$$

$$[\frac{d}{dt} + \sum_{i=1}^{5} \lambda_i + \phi]P_1(t) = \psi P_9(t) + \sigma P_{11}(t) + \phi P_{12}(t) + \eta P_5(t) + \mu P_2(t) + \lambda_1 P_0(t) \quad (2)$$

$$[\frac{d}{dt} + \sum_{i=1}^{5} \lambda_i + \phi + \mu]P_2(t) = \phi P_{16}(t) + \psi P_{15}(t) + \mu P_{14}(t) + \sigma P_{13}(t) + \lambda_3 P_1(t) + \lambda_1 P_3(t) + \eta P_6(t) \quad (3)$$

$$[\frac{d}{dt} + \sum_{i=1}^{5} \lambda_i + \mu]P_3(t) = \phi P_2(t) + \psi P_{17}(t) + \mu P_{19}(t) + \sigma P_{18}(t) + \eta P_7(t) + \lambda_3 P_0(t) \quad (4)$$

$$\frac{d}{dt} + \sum_{i=1}^{5} \lambda_i + \eta]P_4(t) = \lambda_5 P_0(t) + \phi P_5(t) + \mu P_7(t) + \psi P_{20}(t) + \sigma P_{21}(t) + \eta P_{22}(t) \quad (5)$$

$$\frac{d}{dt} + \sum_{i=1}^{5} \lambda_i + \phi + \eta]P_5(t) = \lambda_5 P_1(t) + \lambda_1 P_4(t) + \mu P_6(t) + \eta P_{32}(t) + \phi P_{33}(t) + \sigma P_{34}(t) + \psi P_{35}(t) \quad (6)$$

$$[\frac{d}{dt} + \sum_{i=1}^{5} \lambda_i + \phi + \mu + \eta]P_6(t) = \lambda_5 P_2(t) + \lambda_3 P_5(t) + \lambda_1 P_7(t) + \eta P_{27}(t) + \psi P_{28}(t) + \phi P_{29}(t) + \mu P_{30}(t) + \sigma P_{31}(t) \quad (7)$$

$$[\sum_{i=1}^{5} \lambda_i + \mu + \eta]P_7(t) = \lambda_5 P_3(t) + \lambda_3 P_4(t) + \phi P_6(t) + \psi P_{23}(t) + \mu P_{24}(t) + \sigma P_{25}(t) + \eta P_{26}(t) \quad (8)$$

$$\left[\frac{\mathrm{d}}{\mathrm{dt}} + \psi\right] P_j(t) = \lambda_2 P_k(t)$$ *for j=8,k=0;j=9,k=1; j=15,k=2; j=17,k =3; j=20,k =4; j=23, k =7; j=28,k =6; j=35,k =5* (9)

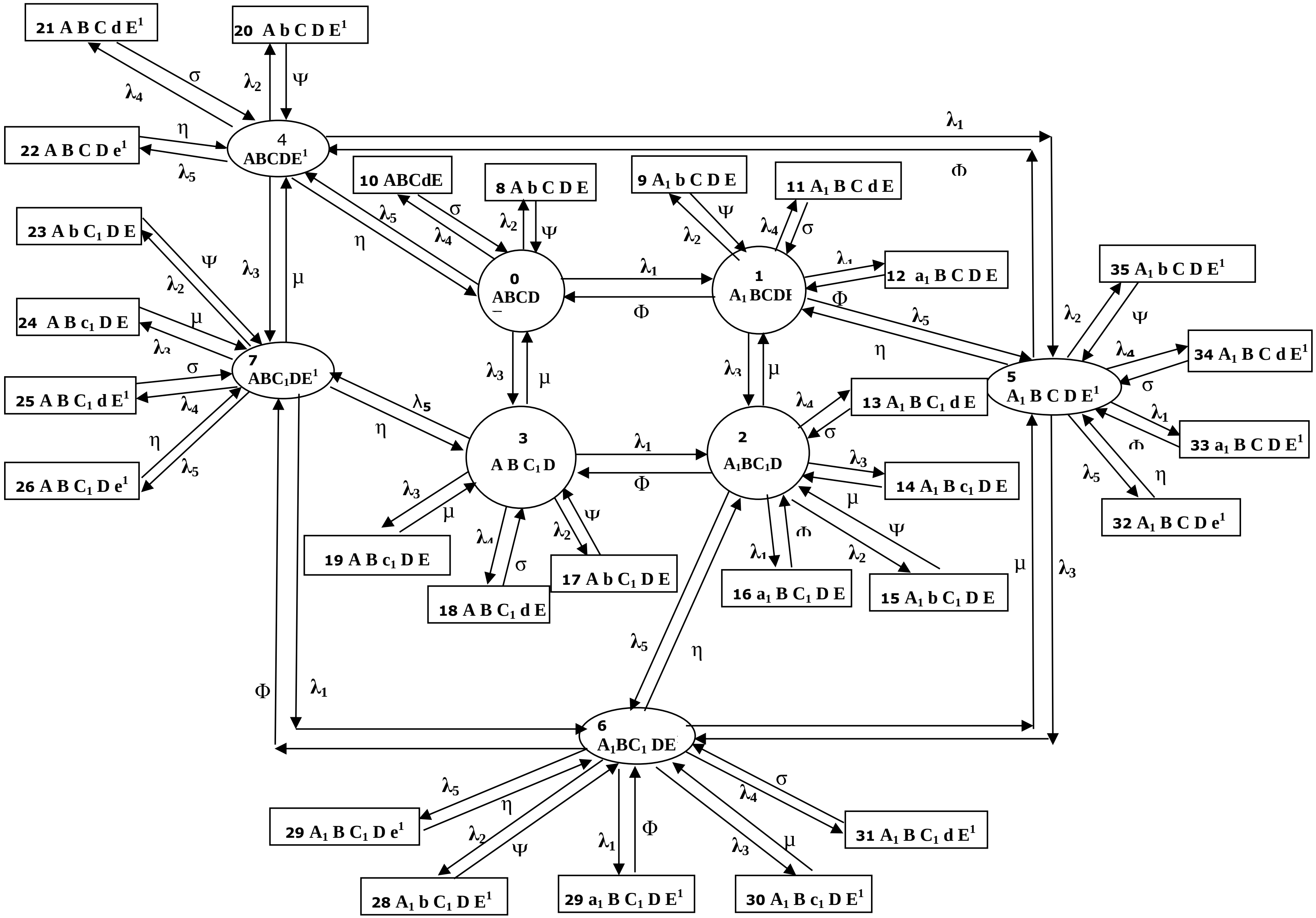


Figure 1: Transition Diagram of Condensate and Feed Water System

$[\frac{\mathrm{d}}{\mathrm{dt}}+\sigma]P_j(t)=\lambda_4 P_k(t)$ *for j=10,k=0;j=11,k=1; j=13,k=2; j=18,k =3; j=21,k =4; j=25,k =7; j=31,k =6; j=34,k =5* (10)

$\left[\frac{\mathrm{d}}{\mathrm{dt}}+\phi\right]P_j(t)=\lambda_1 P_k(t)$ *for j=12,k=1;j=16,k=2; j=29,k=6; j=33,k =5* (11)

$\left[\frac{\mathrm{d}}{\mathrm{dt}}+\mu\right]P_j(t)=\lambda_3 P_k(t)$ *for j=14,k=2;j=19,k=3; j=24,k=7; j=30,k =6* (12)

$\left[\frac{\mathrm{d}}{\mathrm{dt}}+\eta\right]P_{22}(t)=\lambda_5 P_4(t)$ *for j=22,k=4;j=26,k=7; j=27,k=7; j=32,k =5* (13)

In a process industry, as the system is required to run for a long time, so the simulation modelling is done in terms of long run availability *Av*. The availability simulation model expression is derived by taking $\frac{d}{dt}$=0, i.e. doing the probabilities independent of "t", we get:

$\sum_{i=1}^{5}\lambda_i\,]P_0=\phi P_1+\mu P_3+\eta P_4+\psi P_8+\sigma P_{10}$

$\sum_{i=1}^{5}\lambda_i\,+\phi]P_1=\psi P_9+\sigma P_{11}+\phi P_{12}+\eta P_5+\mu P_2+\lambda_1 P_0$

$\sum_{i=1}^{5}\lambda_i\,+\phi+\mu]P_2=\phi P_{16}+\psi P_{15}+\mu P_{14}+\sigma P_{13}+\lambda_3 P_1+\lambda_1 P_3+\eta P_6$

$\sum_{i=1}^{5}\lambda_i\,+\mu]P_3=\phi P_2+\psi P_{17}+\mu P_{19}+\sigma P_{18}+\eta P_7+\lambda_3 P_0$

$\sum_{i=1}^{5}\lambda_i\,+\eta]P_4=\lambda_5 P_0+\phi P_5+\mu P_7+\psi P_{20}+\sigma P_{21}+\eta P_{22}$

$\sum_{i=1}^{5}\lambda_i\,+\phi+\eta]P_5=\lambda_5 P_1+\lambda_1 P_4+\mu P_6+\eta P_{32}+\phi P_{33}+\sigma P_{34}+\psi P_{35}$

$\sum_{i=1}^{5}\lambda_i\,+\phi+\mu+\eta]P_6=\lambda_5 P_2+\lambda_3 P_5+\lambda_1 P_7+\eta P_{27}+\psi P_{28}+\phi P_{29}+\mu P_{30}+\sigma P_{31}$

$\sum_{i=1}^{5}\lambda_i\,+\mu+\eta]P_7=\lambda_5 P_3+\lambda_3 P_4+\phi P_6+\psi P_{23}+\mu P_{24}+\sigma P_{25}+\eta P_{26}$

$\psi P_8=\lambda_2 P_0$ $\quad\psi P_9=\lambda_2 P_1$ $\quad\sigma P_{10}=\lambda_4 P_0$ $\quad\sigma P_{11}=\lambda_4 P_1$ $\quad\phi P_{12}=\lambda_1 P_1$

$\sigma P_{13}=\lambda_4 P_2$ $\quad\mu P_{14}=\lambda_3 P_2$ $\quad\psi P_{15}=\lambda_2 P_2$ $\quad\phi P_{16}=\lambda_1 P_2$ $\quad\psi P_{17}=\lambda_2 P_3$

$\sigma P_{18}=\lambda_4 P_3$ $\quad\mu P_{19}=\lambda_3 P_3$ $\quad\psi P_{20}=\lambda_2 P_4$ $\quad\sigma P_{21}=\lambda_4 P_4$ $\quad\eta P_{22}=\lambda_5 P_4$

$\psi P_{23}=\lambda_2 P_7$ $\quad\mu P_{24}=\lambda_3 P_7$ $\quad\sigma P_{25}=\lambda_4 P_7$ $\quad\eta P_{26}=\lambda_5 P_7$ $\quad\eta P_{27}=\lambda_5 P_7$

$\psi P_{28}=\lambda_2 P_6$ $\quad\phi P_{29}=\lambda_1 P_6$ $\quad\mu P_{30}=\lambda_3 P_6$ $\quad\sigma P_{31}=\lambda_4 P_6$ $\quad\eta P_{32}=\lambda_5 P_5$

$\phi P_{33}=\lambda_1 P_5$ $\quad\sigma P_{34}=\lambda_4 P_5$ $\quad\psi P_{35}=\lambda_2 P_5$

On solving these equations recursively, we get

$P_1=\frac{N_{27}}{N_{26}}P_0=M_1P_0$ $\qquad P_2=N_{25}P_0+\frac{\mathrm{N}_{24}\mathrm{N}_{27}}{\mathrm{N}_{26}}P_0=M_2P_0$

$P_3=N_{19}P_0+N_{20}P_1+N_{21}P_2=N_{19}P_0+N_{20}M_1\,P_0+N_{21}M_2P_0=M_3P_0$

$P_4=N_{12}P_1+N_{13}P_2+N_{14}P_3+N_{15}P_0=N_{15}P_0+N_{12}M_1P_0+N_{13}M_2P_0+N_{14}M_3P_0=M_4P_0$

$P_5=N_5P_1+N_6P_2+N_7P_3+N_8P_4=N_5M_1P_0+N_6M_2P_0+N_7M_3P_0+N_8M_4P_0=M_5P_0$

$P_6=N_1P_2+N_2P_5+N_3P_3+N_4P_4=N_1M_2P_0+N_2M_5P_0+N_3M_3P_0+N_4M_4P_0=M_6P_0$

$P_7=\frac{\lambda_5\mathrm{P}_3+\lambda_3\mathrm{P}_4+\phi\mathrm{P}_6}{\mathrm{T}_7}=\frac{\lambda_5\mathrm{M}_3\mathrm{P}_0+\lambda_3\mathrm{M}_4\mathrm{P}_0+\phi\mathrm{M}_6\mathrm{P}_0}{\mathrm{T}_7}=M_7P_0$

Where

$T_1=\lambda_2+\phi$

$T_2=\lambda_5+\phi+\mu-\lambda_1N_{21}-\eta N_1-\eta N_2N_6-\eta N_2N_7N_{21}-\eta N_2N_8N_{13}-\eta N_2N_8N_{14}N_{21}-\eta N_3N_{21}-\eta N_4N_{13}-\eta N_4N_{14}N_{21}$

$T_3=\lambda_1+\lambda_5+\mu-\frac{\eta\lambda_5}{T_7}-\frac{\eta\lambda_3N_{14}}{T_7}-\frac{\eta\phi N_2N_7}{T_7}-\frac{\eta\phi N_3}{T_7}-\frac{\eta\phi N_2N_8N_{14}}{T_7}-\frac{\eta\phi N_4N_{14}}{T_7}$

$T_4=\lambda_1+\lambda_3+\eta-\phi N_8-\frac{\mu\quad\lambda_3}{T_7}-\frac{\phi\mu\quad N_2N_8}{T_7}-\frac{\phi\mu\quad N_4}{T_7}$ $\qquad T_5=\lambda_3+\phi+\eta-\mu N_2$

$T_6=\phi+\mu+\eta-\frac{\lambda_1\phi}{T_7}$ $\qquad T_7=\lambda_1+\mu+\eta$

$N_1=\frac{\lambda_5}{T_6}$ $\quad N_2=\frac{\lambda_3}{T_6}$ $\quad N_3=\frac{\lambda_1\lambda_5}{T_6T_7}$ $\quad N_4=\frac{\lambda_1\,\lambda_3}{T_6T_7}$ $\quad N_5=\frac{\lambda_5}{T_5}$ $\quad N_6=\frac{\mu N_1}{T_5}$

$N_7=\frac{\mu N_3}{T_5}$ $\quad N_8=\frac{(\lambda_1+\mu N_4)}{T_5}$ $\quad N_9=\phi N_5+\frac{\mu\phi N_2N_5}{T_7}$ $\quad N_{10}=\phi N_6+\frac{\phi N_1\mu}{T_7}+\frac{\phi\mu\quad N_2N_6}{T_7}$

$N_{11}=\phi N_7+\frac{\mu\lambda_5}{T_7}+\frac{\phi N_2N_7\,\mu}{T_7}+\frac{\phi\mu\quad N_3}{T_7}$ $\quad N_{12}=\frac{N_9}{T_4}$ $\quad N_{13}=\frac{N_{10}}{T_4}$ $\quad N_{14}=\frac{N_{11}}{T_4}$ $\quad N_{15}=\frac{\lambda_5}{T_4}$

$N_{16}=\frac{\eta\lambda_3N_{15}}{T_7}+\frac{\eta\phi N_2N_8N_{15}}{T_7}+\frac{\eta\phi N_4N_{15}}{T_7}$

$N_{17}=\frac{\eta\lambda_3N_{12}}{T_7}+\frac{\eta\phi N_2N_5}{T_7}+\frac{\eta\phi N_2N_5}{T_7}+\frac{\eta\phi N_2N_8N_{12}}{T_7}+\frac{\eta\phi N_4N_{12}}{T_7}$

$N_{18}=\phi+\frac{\eta\lambda_3N_{13}}{T_7}+\frac{\eta\phi N_1}{T_7}+\frac{\eta\phi N_2N_6}{T_7}+\frac{\eta\phi N_2N_8N_{13}}{T_7}+\frac{\eta\phi N_4N_{13}}{T_7}$

$N_{19}=\frac{N_{16}}{T_3}$ $\qquad N_{20}=\frac{N_{17}}{T_3}$ $\qquad N_{21}=\frac{N_{18}}{T_3}$

$N_{22}=\lambda_3+\lambda_1N_{20}+\eta N_2N_5+\eta N_2N_7N_{20}+\eta N_2N_8N_{12}+\eta N_2N_8N_{14}N_{20}+\eta N_3N_{20}+\eta N_4N_{12}+\eta N_4N_{14}N_{20}$

$N_{23}=\eta N_2N_8N_{14}N_{19}+\eta N_2N_8N_{15}+\eta N_3N_{19}+\eta N_4N_{14}N_{19}+\eta N_4N_{15}$

$N_{24} = \frac{N_{22}}{T_2}$ $N_{25} = \frac{N_{23}}{T_2}$ $N_{26} = \lambda_3 + \lambda_5 + \phi - \eta(N_5 - N_6N_{22} - N_7N_{20} - N_7N_{21}N_{22} - N_8N_{12} - N_8N_{13}N_{22} - N_8N_{14}N_{20} - N_8N_{14}N_{21}N_{22}) - \mu N_{24}$

$N_{27} = \eta(N_6N_{25} + N_7N_{19} + N_7N_{21}N_{23} + N_8N_{13}N_{23} + N_8N_{14}N_{19} + N_8N_{14}N_{21}N_{23} + N_8N_{15}) + \mu N_{23} + \lambda_1$

Normalizing Condition

The probability of full working capacity P_0 is determined by summing of the probabilities of all working, reduced capacity and failed states is equal to 1.

$\sum_{i=0}^{35} P_i = 1$, therefore

$$P_0 = 1/\left[1 + M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + \frac{\lambda_2}{\psi} + \frac{\lambda_2}{\psi}M_1 + \frac{\lambda_4}{\sigma} + \frac{\lambda_4}{\sigma}M_1 + \frac{\lambda_1}{\phi}M_1 + \frac{\lambda_4}{\sigma}M_2 + \frac{\lambda_2}{\psi}M_2 + \frac{\lambda_1}{\phi}M_2 + \frac{\lambda_2}{\psi}M_3 + \frac{\lambda_4}{\sigma}M_3 + \frac{\lambda_4}{\sigma}M_3 + \frac{\lambda_3}{\mu}M_3 + \frac{\lambda_2}{\psi}M_4 + \frac{\lambda_4}{\sigma}M_4 + \frac{\lambda_5}{\eta}M_4 + \frac{\lambda_2}{\psi}M_7 + \frac{\lambda_3}{\mu}M_7 + \frac{\lambda_4}{\sigma}M_7 + \frac{\lambda_5}{\eta}M_7 + \frac{\lambda_5}{\eta}M_6 + \frac{\lambda_2}{\psi}M_6 + \frac{\lambda_1}{\phi}M_6 + \frac{\lambda_3}{\mu}M_6 + \frac{\lambda_4}{\sigma}M_6 + \frac{\lambda_5}{\eta}M_5 + \frac{\lambda_1}{\phi}M_5 + \frac{\lambda_4}{\sigma}M_5 + \frac{\lambda_2}{\psi}M_5\right]$$

Now, the availability simulation model of Condensate and Feed Water System (*Av.*) may be obtained as summation of probabilities of all full working and reduced capacity states, i.e.

$$A_{V.} = \sum_{i=0}^{7} P_i = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 \quad (14)$$

4. Performance Evaluation of Condensate and Feed Water System

The performance of Condensate and Feed Water System is predicted with the help of Availability Simulation Model as given by eqn. 14 for known input values of failure and repair rates of its subsystems. The failure and repair rates of all subsystems are taken from maintenance history sheets and through the discussions with the plant personnel. By putting these failure and repair values in the equation 14, different availability levels are obtained. Such models can be used for proper implementation of maintenance strategies for the Condensate and Feed Water System of an N.T.P.C. Plant. The model includes all possible states of nature, that is, failure events (λ_i) and repair priorities ($\emptyset, \varphi, \mu, \sigma, \eta$). Tables 1-5 represent the availability matrices for various subsystems of Condensate and Feed Water System. On the basis of analysis made, the best possible combinations ($\emptyset, \varphi, \mu, \sigma, \eta, \lambda$) can be selected.

5. Results and discussion

The different availability levels for each subsystem are obtained from the simulation model as derived from equation 14. The following conclusions are made on the basis of values given in table 1 to table 5.

Table 1 shows the effect of failure and repair rates of Condensate Extraction Pump on system availability. As the failure rates (λ_1) of Condensate Extraction Pump increases from 0.012(once in 83 hrs) to 0.060 (once in 16.7 hrs), the system availability decreases considerably by 13.8%. Similarly, as the repair rates ϕ increases from 0.01 (once in 100 hrs) to 0.05 (once in 20 hrs), the system availability increases hardly by 1.00%.

Table I: Effect of Failure and Repair Rates of Condensate Extraction Pump on Availability

Availability (Av.) →

λ_1 \ ϕ	**0.10**	**0.20**	**0.30**	**0.40**	**0. 50**	Constant Values
0.012	0.9011	0.9083	0.9098	0.9103	0.9106	$\lambda_2 = 0.005, \psi = 0.15$ $\lambda_3 = 0.015, \mu = 0.20$ $\lambda_4 = 0.009, \sigma = 0.15$ $\lambda_5 = 0.02, \eta = 0.15$
0.024	0.8762	0.9011	0.9065	0.9085	0.9094	
0.036	0.8423	0.8900	0.9011	0.9054	0.9074	
0.048	0.8037	0.8760	0.8942	0.9011	0.9047	
0.060	0.7635	0.8597	0.8857	0.8961	0.9011	

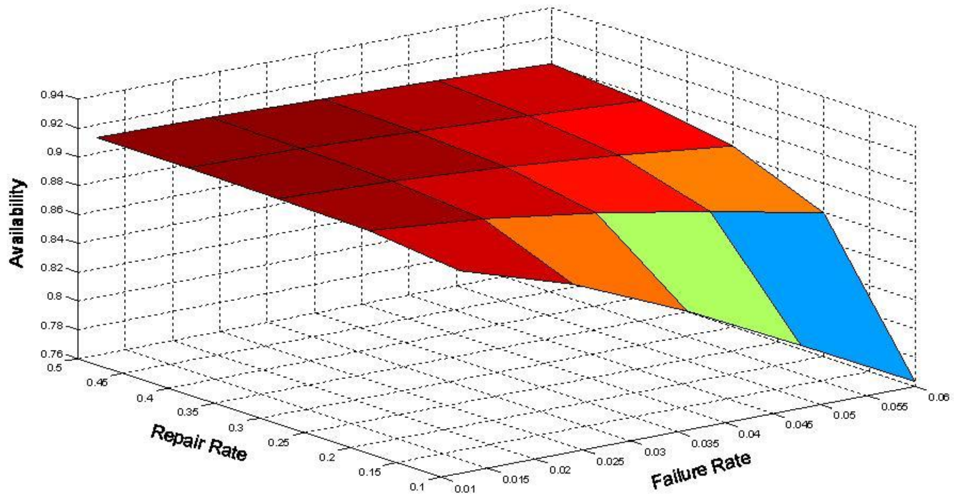


Figure 2: Effect of Failure and Repair Rates of Condensate Extraction Pump on Availability

Table 2 reveals the variation of system availability with change in failure rates (λ_2) and repair rates ψ of the Low Pressure Heater. As failure rates (λ_2) increases from 0.0005 (once in 2000 hrs) to 0.0025 (once in 400 hrs), the system availability reduces marginally by 1.1%. Similarly, when repair rates ψ increases from 0.15 (once in 6.67 hrs) to 0.75 (once in 1.33 hrs), then the system availability increases negligibly by 0.2%.

Table II: Effect of Failure and Repair Rates of Low Pressure Heater on Availability
Availability (Av.) →

ψ / λ_2	**0.15**	**0.30**	**0.45**	**0.60**	**0.75**	Constant Values
0.0005	0.9011	0.9024	0.9028	0.9031	0.9032	$\lambda_1 = 0.012, \phi = 0.10$ $\lambda_3 = 0.015, \mu = 0.20$ $\lambda_4 = 0.009, \sigma = 0.15$ $\lambda_5 = 0.02, \eta = 0.15$
0.0010	0.8983	0.9011	0.9019	0.9024	0.9027	
0.0015	0.8957	0.8997	0.9011	0.9017	0.9021	
0.0020	0.8930	0.8983	0.9001	0.9011	0.9016	
0.0025	0.8903	0.8970	0.8992	0.9004	0.9011	

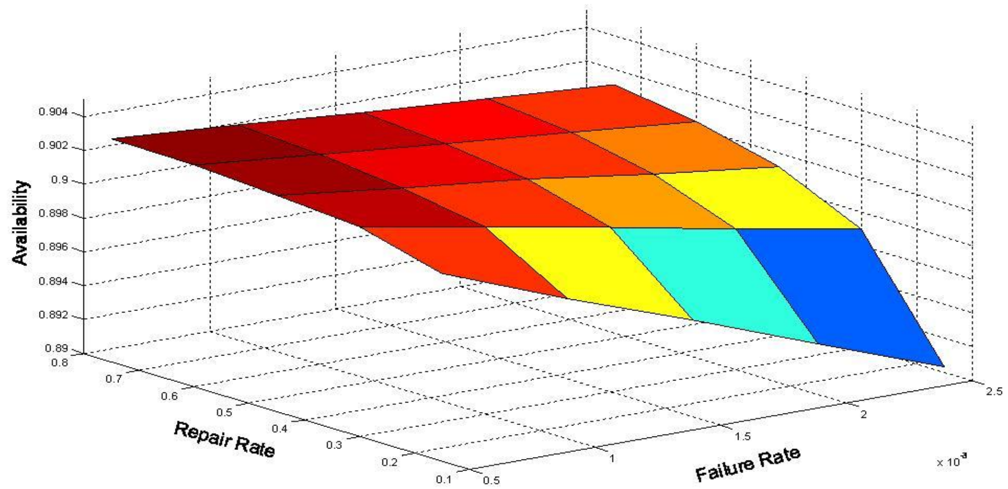


Figure 3: Effect of Failure and Repair Rates of Low Pressure Heater on Availability

From Table 3, it is observed that as failure rates (λ_3) of Boiler Feed Pump increases from 0.015 (once in 66.7 hrs) to 0.075 (once in 13.3 hrs), the system availability decreases significantly by 6.9%. Similarly, when the repair rates μ of Boiler Feed Pump increases from 0.20 (once in 5 hrs) to 1.00 (once in hr), then the system availability increases slightly by 0.5%.

Table III: "Effect of Failure and Repair Rates of Boiler Feed Pump on Availability"
Availability (Av.) →

λ_3 \ μ	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	Constant Values
0.015	0.9011	0.9038	0.9044	0.9048	0.9056	$\lambda_1 = 0.012, \phi = 0.10$ $\lambda_2 = 0.005, \psi = 0.15$ $\lambda_4 = 0.009, \sigma = 0.15$ $\lambda_5 = 0.02, \eta = 0.15$
0.030	0.8903	0.9011	0.9031	0.9039	0.9048	
0.045	0.8742	0.8963	0.9011	0.9029	0.9039	
0.060	0.8543	0.8901	0.8980	0.9011	0.9027	
0.075	0.8317	0.8825	0.8944	0.8988	0.9011	

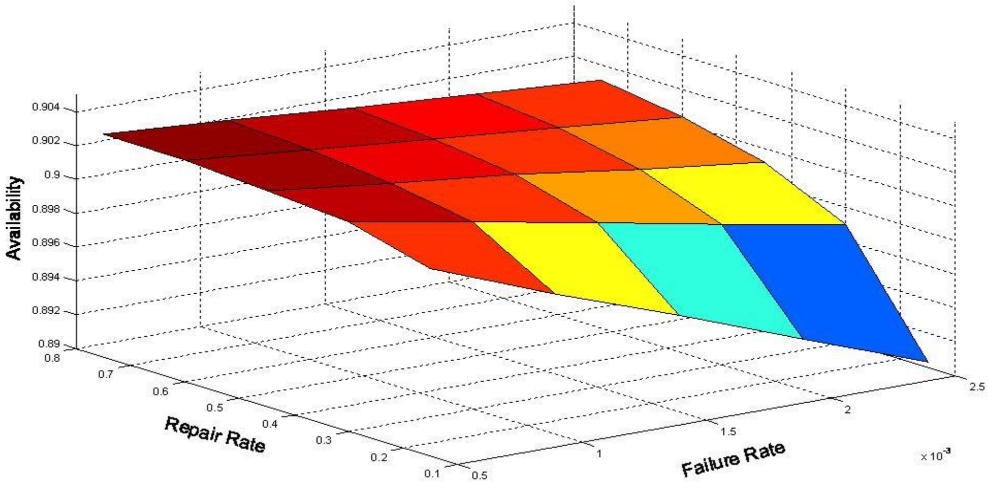
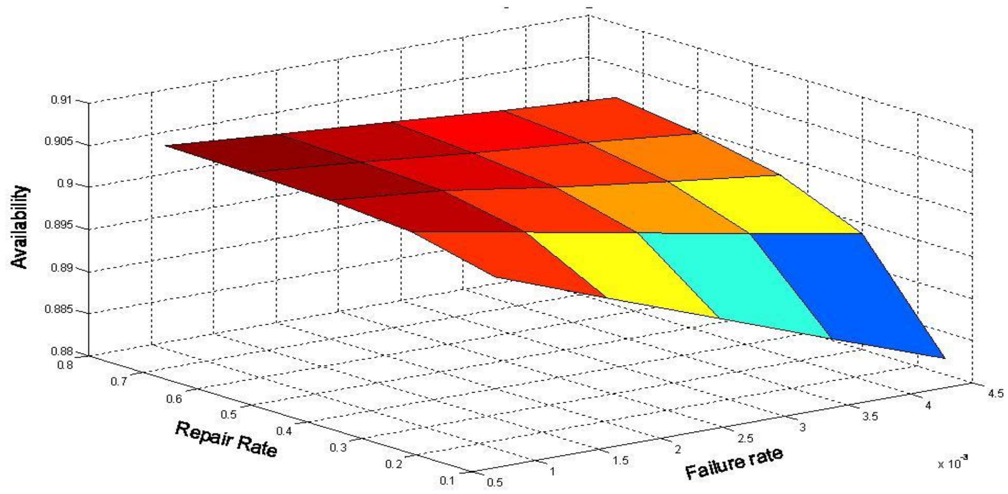


Figure 4: Effect of Failure and Repair Rates of Boiler Feed Pump on Availability

Table 4 reveals the variation of system availability with change in failure rates (λ_4) and repair rates σ of the High Pressure Heater. As failure rates (λ_4) increases from 0.0009 (once in 1111 hrs) to 0.0045 (once in 222 hrs), the system availability reduces slightly by 1.9%. Similarly, when repair rates σ increases from 0.15 (once in 6.67 hrs) to 0.75 (once in 1.33 hrs), then the system availability increases hardly by 0.4%.

Table IV: "Effect of Failure and Repair Rates of High Pressure Heater on Availability"
Availability (Av.) →

λ_4 \ σ	**0.15**	**0.30**	**0.45**	**0.60**	**0.75**	Constant Values
0.0009	0.9011	0.9035	0.9043	0.9047	0.9049	$\lambda_1 = 0.012, \phi = 0.10$ $\lambda_2 = 0.005, \psi = 0.15$ $\lambda_3 = 0.015, \mu = 0.20$ $\lambda_5 = 0.02, \eta = 0.15$
0.0018	0.8962	0.9011	0.9031	0.9035	0.9039	
0.0027	0.8914	0.8986	0.9011	0.9022	0.9030	
0.0036	0.8866	0.8962	0.8994	0.9011	0.9020	
0.0045	0.8819	0.8938	0.8978	0.8998	0.9011	



Similarly, Table 5 shows the variation in availability of Economizer with the change in failure and repair rates of sub-system Economizer (λ_5, η). As failure rates (λ_5) increases from 0.02 (once in 50 hrs) to 0.10 (once in 10 hrs), the system availability reduces drastically by 41.8%. Similarly, when repair rates η increases from 0.06 (once in 16.7 hrs) to 0.30 (once in 3.3 hrs), then the system availability increases sharply by 6.9%.

Table V: "Effect of Failure and Repair Rates of Economizer on Availability"

Availability (Av.) →

λ_5 \ η	**0.06**	**0.12**	**0.18**	**0.24**	**0.30**	Constant Values
0.02	0.9011	0.9522	0.9638	0.9682	0.9703	$\lambda_1 = 0.012, \phi = 0.10$ $\lambda_2 = 0.005, \psi = 0.15$ $\lambda_3 = 0.015, \mu = 0.20$ $\lambda_4 = 0.009, \sigma = 0.15$
0.04	0.7732	0.9011	0.9373	0.9521	0.9596	
0.06	0.6550	0.8381	0.9011	0.9290	0.9436	
0.08	0.5591	0.7733	0.8597	0.9011	0.9237	
0.10	0. 4834	0.7116	0.8164	0.8703	0.9011	

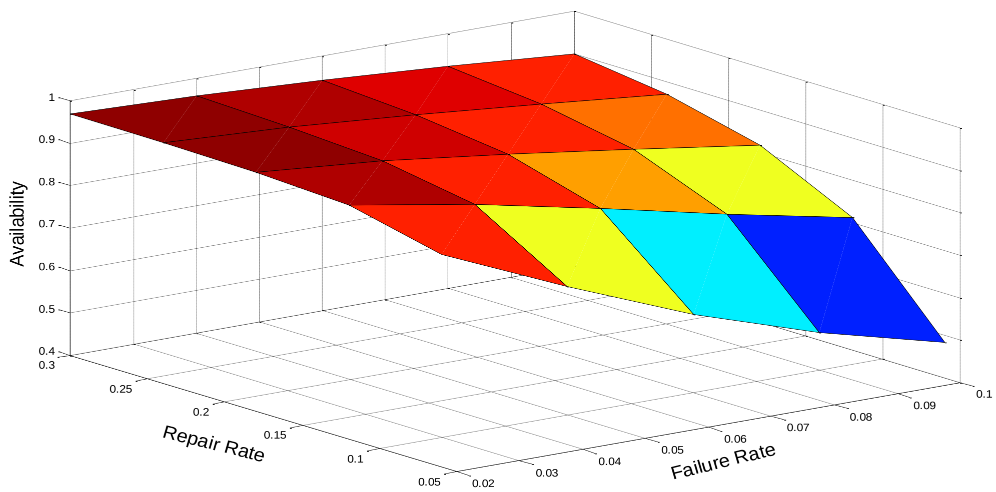


Figure 6: Effect of Failure and Repair Rates of Economizer on Availability

6. Conclusions

The simulation modelling of Condensate and Feed Water System has been done to analyze the system performance in terms of availability values. The various availability levels (Av.) for different combinations of failure and repair rates have been shown by decision matrices tables 1 to 5. One may select the best possible combination of failure events and repair priorities for each subsystem. Table 5 clearly depicts that the Economizer is the most critical subsystem as far as maintenance is concerned. So, the Economizer 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 High pressure Heater, Low pressure heater, Condensate extraction pump and Boiler feed pump. Therefore, on the basis of repair rates, maintenance priorities should be set as follows:

1. Economizer should be on first priority
2. Second priority should be given to Condensate Extraction Pump
3. Third priority should be given Boiler Feed Pump
4. High Pressure Heater and Low Pressure Heater may be given fourth and fifth priorities.

The concerned model would certainly assist the maintenance team to decide the maintenance strategies for critical components, so that, the system operates with the utmost efficiency. The results derived using mathematical simulation model, are discussed with the plant management. They have been found in great congruence as experience by the senior plant personnel. The maintenance priorities have also seems to be valuable for improving the overall plant availability by selecting the optimal failure and repair rates.

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