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STOCHASTIC MODELING AND SENSITIVITY ANALYSIS OF CONDENSER IN STEAM TURBINE POWER PLANTS

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Abstract. The role of electricity in human beingday-to-day life, manufacturing sector, medical sector cannot be ignored, and it gives the birth to establish new power plant for energy production. The inherent technological formulation of power plants is highly complex and require high end management strategies to improve their reliability, availability, and productivity. The target behind proposing maintenance strategies is to developsuch technique which recognize and quantify the overcritical components of the subsystems of the Steam Turbine Power Plants. To purpose maintenance strategies for plants, here reliability, availability, maintainability, and dependability methodology has been opted. Using derived results smooth functioning of the condenser is assured and it increase the efficiency and performance by taking care of the most critical component. In this direction, several stochastic models for each of the components have been designed using Markovian approach. The failure and repair times of each component are considered as exponentially distributed. The Chapman-Kolmogorov difference equations for each subsystem have been derived and numerical values of different reliability measures such as reliability function, maintainability function, dependability function, and steady-state availability have been obtained. The numerical results have been derived for system as well for subsystems. The sensitivity analysis of reliability function is also made with respect to time and various failure rates. The proposed model and results will be proved beneficial for system designers and maintenance managers in steam turbine power plants.

1. Introduction

The economic growth of the country can be evaluated by its ability to generate power. In the last few decades, India made remarkable progress in this direction and thermal power plants made a major contribution to it. Nowadays power industries have become more competitive in terms of minimizing operating costs and maximizing profit on a global basis. Though, the power crisis remains unchanged and rural areas faces the lack of electricity as the existing power plants fails to fulfil the demand. The existing power plants also faces shutdowns many times due to several reasons like weather conditions, lack of trained manpower, availability of raw material etc. The failures of power plants also suffer the supply of electricity and as a whole shortage of electricity of resulted in economic loss. So, it is demand of time that power plants designed in such way that they remain

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highly reliable and available. System designers always try to develop systems in such a way that they meet and justify its functional requirement. It is ensured by the reliability and periodic availability of the system. Reliability engineering provides us a framework for creating a proper design of a system, improving its operational characteristics, and formulating maintenance policies. Every type of power plant established in the country has the aim to get more and more profit without sacrificing humanities and want to become more and more reliable for the people as they produced power which is getting people's need day by day. So, it is very important to achieve that level of reliability and availability of the system. For this purpose, they must be aware of the overcritical component and its timely maintenance. With the help of the RAMD approach, this target can be achieved up to a great extent as it provides many toolsto identify overcritical components among all and assure to make proper maintenance policies for plants. Among various techniques of performance analysis, RAMD is one of the most reliable tools as it analyzes every component at multiple stages. Since it gives more accurate results which helps the maintenance department to prepare proper maintenance policies for the plant. In present study, various measures of effectiveness like dependability, maintainability, MTTR, MTTF, Dependability ratio and availability have been obtained for various values of failure and repair rates. An effort has been made to find most critical component of the plant by performing sensitive analysis.

Kumar et al. [10] made work on reliability and availability of the crystallization system in sugar plants and form an analytic model for it. Arora et al. [2] providedthe expression for steady-state availability and MTBF of a steam generation system in which subsystems are connected in series. The derived results are used to formulate policies that are responsible for the proper running of the system for a long time. Kumar et al. [12] presented a case study of optimizing resource allocation and profit in coal handling systems of a thermal power plant by using dynamic programming and made an operational analysis to improve system availability. Van Casteren et al. [20] made a reliability assessment in electrical power systems with the help of the Weibull-Markov stochastic model. Eti et al. [5] studied the performance of gas turbine plants in A fam electric power generating station, Nigeria. Tran et al. [19] described sensitivity analysis of probabilistic reliability evaluation of Korea power system. Gupta and Tiwari [9] used a realistic approach to develop the reliability measure for a system in an acrylic fiber mill. Topuz [18] described the basics of reliability and availability. Carazas et al. [4] discussed a methodology for evaluation of reliability and availability analysis of gas turbine power plant which is based on system reliability concept. Carazas et al. [3] gave a methodology for evaluating reliability and availability measure of system HRSGs which is a part installed in combined cycle power plant. Garg et al. [6] made behavior analysis of synthesis unit in fertilizer plant. The study revealed a technique for examining the performance of an industrial system and improve its efficiency using the concept of reliability, availability, and maintainability. It also performed sensitivity analysis for a better understanding of the system's behavior. Adhikarya et al. [1] made a relative study of two units of a coal-fired thermal power station in the eastern region of India based on reliability, availability, and maintainability. Tewari et al. [17] used an optimization technique i.e. genetic algorithm for the stock preparation unit of a paper plant. Various combinations of failure and repair rates for finding the optimum unit availability level of the stock preparation unit has been used. Garg and Sharma [7] estimated the reliability of synthesis unit of fertilizer plant. Kumar [11] presented the performance analysis of a typical coal-fired power plant in their article and also performed a sensitivity analysis to identify the most critical unit. Obeidat et al. [14] analyzed the behavior of each unit in AL-Hussein Thermal Power Station and form profitable maintenance strategies for the plant. Lal et al. [13] studied the behavior of a piston manufacturing plant. With help of a steady-state transition diagram the availability and parameters of the system has been evaluated. Guo et al. [8] gave out an improved version for reliability and sensitivity analysis of power systems. Okafor et al. [15] made analysis about of thermal power plant situated in Nigeria and derive an expression on availabilityusing the Markovian approach. Saini et al. [16] found performance parameters of the evaporation system in the sugar industry using RAMD analysis and make sensitivity analysis of the system reliability.

The literature study divulges that most of the researchers accomplished reliability and availability approach for performance analysis of components of the thermal power plants. Some also use maintainability parameters for this purpose. But other parameters such as dependability, MTTF, MTTR, dependability ratio are untouched in this area. Hence in the present work, an attempt has been made to analyze the performance of power plants. RAMD technique has been used to spot the overcritical component of a condenser in steam turbine power plant along with sensitivity analysis of reliability. The required values of the parameters have been chosen with the help of the maintenance personnel of the thermal power plant.

Including the present introductory section, this paper incorporates five more sections. In the second section, various definitions, and tools useful for analysis are appended. System description, notations, and assumptions are described in section third. RAMD analysis is carried out in section fourth. Sensitivity analysis of reliability is done in section fifth. Finally, section sixth is ended up with the conclusion and implication of the results derived.

2

2.1. System description, notations, and assumptions.

2.1.1. *System description.* A condenser is an equipment that is used to convert high-temperature steam coming from a steam turbine to a liquid form that is water. The exhausted steam contains a lot of energy. The condenser helps to save a part of it by condensing the steam and converting it into water. The temperature of this water is higher than normal water. So, it is used as feed water for feeding the boiler and helps to deduct the heat requirement necessary to generate steam for boiling water. By this, we can see that condenser plays an important role in improving the long-term availability, better efficiency, and trustability of the thermal power plant. Hence, it is important to increase its efficiency by taking care of its critical component and giving them proper replacement and time to time maintenance.

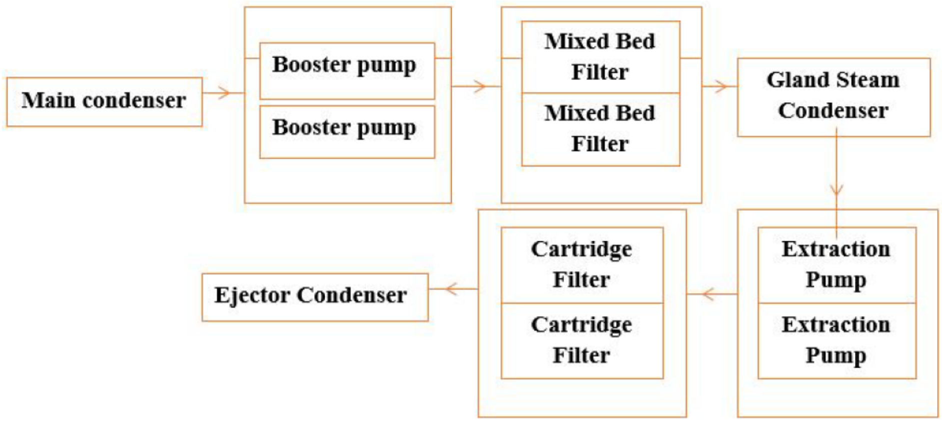

FIGURE 1. Configuration diagram of condenser

(a) Subsystem A (Main Condenser). It incorporates one unit of the main condenser. If this unit collapse, the complete system brings out the failure as it is associated in series with a subsequent unit of the system.

(b) Subsystem B (Booster Pump). It incorporates two units of booster pump whose failure rates are the same and among them, one is operative and the other is in a backup stage which is called upon only on failure of the operative unit. The system stops responding only when both the units break down as they are associated in series with subsequent of system.

(c) Subsystem C (Mixed bed filter). It incorporates two units of mixed bed filter whose failure rates are the same and among them, one is operative and the other is in the backup stage which is called upon only on failure of the operative unit. The system stops responding when both the units stop working one after the other.

(d) Subsystem D (Gland steam condenser). It incorporates one unit of gland steam condenser. If this unit collapse, the complete system brings out the failure as it is associated in series with a subsequent unit of the system.

(e) Subsystem E (Extraction Pump). It incorporates two Extraction pumps whose failure rates are the same and among them, one is operative, and the other is in the backup stage which is called upon only on failure of the operative unit. The system stops responding when both the units stop working one after another.

(f) Subsystem F (Cartridge Filter). It incorporates two units of cartridge filter whose failure rates are the same and among them, one is operative and the other is in the backup stage which is called upon only on failure of the operative unit. The system stops responding when both the units stop working one after the other.

(g) Subsystem G (Ejector condenser). It incorporates one unit of an ejector condenser. If this unit collapse, the complete system brings out the failure as it is associated in series with a subsequent unit of the system.

2.1.2. *Notation.*

○	: Designates system is in full capacity
⬭	: Designates system is in the standby state
□	: Designates system is in failed states
A, B, C, D, E, F, G	: Designates the states in which units are working with full capacity
B_1, C_1, F_1	: Designates the states in which units are working under cold standby state
$\bar{E}$	: Designates the state in which one parallel unit is failed
a, b, c, d, e, f, g	: Designates the states in which units are failed
$\beta_i \ (1 \leq i \leq 7)$	: Represent the constant failure rates of the subsystems A, B, C, D, E, F, G respectively
$\mu_i \ (1 \leq i \leq 7)$	: Represent the constant repair rates of the subsystem A, B, C, D, E, F, G respectively
$p_0(t)$	: Designate the probability that the system is in full capacity at initial time t
$p_i;\ i = 0, 1, 2$	: Steady-state probability that the system is in ith state

$$f(x) = \begin{cases} \lambda e^{-\lambda x}; & 0 \leq x \leq \infty \\ 0; & \text{otherwise : pdf of exponential distribution} \end{cases}$$

$$R(t) = P(T > t) = \int_t^{\infty} f(x)dx \ \text{ : Reliability function} \tag{1}$$

$$\text{Availability function} = \frac{\text{Life time}}{\text{total time}} = \frac{\text{Life time}}{\text{Life time} + \text{Repair time}} = \frac{MTTF}{MTTF + MTTR} \tag{2}$$

$$M(t) = P(T \leq t) = 1 - e^{\left(\frac{-t}{MTTR}\right)} \ \text{ : Maintainability function} \tag{3}$$

$$MTBF = \int_0^{\infty} R(t)dt = \int_0^{\infty} e^{-\theta t}dt = \frac{1}{\theta} \ \text{ : Mean Time Between Failures} \tag{4}$$

$$MTTR = \frac{1}{\mu} \ \text{ : Mean Time to repair} \tag{5}$$

$$\mu = \text{repair rate}; \quad \theta = \text{failure rate} \tag{6}$$

$$d = \frac{\mu}{\theta} = \frac{MTBF}{MTTR} \ \text{ : Dependability ratio} \tag{7}$$

$$D_{\min} = 1 - \left(\frac{1}{d-1}\right)(e^{-In\,d/d-1} - e^{-d\,In\,d/d-1}), \tag{8}$$

2.1.3. *Assumptions.*

- The failure rates and repair rates of each subsystem are statistically independent of each other and follow exponential distribution under the assumption that no concurrent failures occur among the subsystems.
- Repairmen always on duty in the plant with ample repair and replacement facilities to ensure that repaired unit is as good as new.
- The units under cold standby state are perfect.

3. RAMD analysis of the system

Here mathematical modelling of condenser with the support of Markov birth-death process has been performed. The Chapman Kolmogorov differential equations for each of subsystems have been derived. Systems followed constant failure and repair rates with parameter values appended in Table 1. The state transition diagrams for each subsystem have been shown in Figure 2-8. Further subsystem performance measures such as reliability, maintainability, availability, dependability, mean time to failure (MTTF), mean time to repair (MTTR) and dependability ratio has been obtained.

TABLE 1. Failure and repair rates of a subsystem of condenser

Subsystem	Failure Rates (β)	Repair rates (μ)
S_1	$\beta_1 = 0.004$	$\mu_1 = 0.42$
S_2	$\beta_2 = 0.0052$	$\mu_2 = 0.62$
S_3	$\beta_3 = 0.005$	$\mu_3 = 0.85$
S_4	$\beta_4 = 0.008$	$\mu_4 = 0.52$
S_5	$\beta_5 = 0.008$	$\mu_5 = 0.9$
S_6	$\beta_6 = 0.008$	$\mu_6 = 0.95$
S_7	$\beta_7 = 0.006$	$\mu_7 = 0.24$

The RAMD indices for subsystems of the condenser of STPP are computed as

3.1. RAMD indices for subsystem S_1. This subsystem incorporates with one unit only. If this unit collapse, the complete system brings out the failure. Corresponding transition diagram and related Chapman-Kolmogorov differential equations are given as

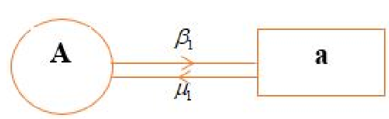

FIGURE 2. Transition diagram of main dondenser

$$P_0'(t) = -\beta_1 P_0(t) + \mu_1 P_1(t), \tag{9}$$
$$P_1'(t) = \beta_1 P_0(t) - \mu_1 P_1(t)\,. \tag{10}$$

Under steady-state, equation 9 and 10 reduces to

$$P_1 = \frac{\beta_1}{\mu_1} P_0\,. \tag{11}$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_1}{\mu_1} P_0 = 1 \Rightarrow P_0 = \frac{\mu_1}{\mu_1 + \beta_1} \tag{12}$$

Now, by using equations (1)-(5), (7)-(8) and (12) important system performance measures have been derived and appended in Table 4.

3.2. RAMD indices for subsystem S_2. It incorporates two units of booster pump whose failure rates are the same and among them, one is operative and the other is in the backup stage which is called upon only on failure of the operative unit. The system stops responding only when both the units break down. The corresponding transition diagram and related Chapman-Kolmogorov differential equations are given as

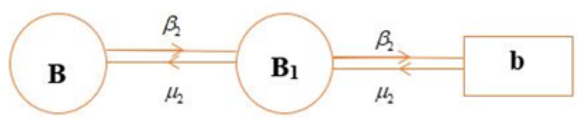

FIGURE 3. Transition diagram of Booster Pump

$$P_0'(t) = -\beta_2 P_0(t) + \mu_2 P_1(t), \tag{13}$$
$$P_1'(t) = \beta_2 P_0(t) - (\beta_2 + \mu_2) P_1(t) + \mu_2 P_2(t), \tag{14}$$
$$P_2'(t) = \beta_2 P_1(t) - \mu_2 P_2(t). \tag{15}$$

Under steady-state, equation (13), (14) and (15) reduces to

$$P_1 = \frac{\beta_2}{\mu_2} P_0 \tag{16}$$

$$P_2 = \frac{\beta_2^2}{\mu_2^2} P_0 \tag{17}$$

Now, using normalization condition:

$$P_0 + P_1 + P_2 = 1 \Rightarrow P_0 + \frac{\beta_2}{\mu_2} P_0 + \frac{\beta_2^2}{\mu_2^2} P_0 = 1 \Rightarrow P_0 = (1 + \frac{\beta_2}{\mu_2} + \frac{\beta_2^2}{\mu_2^2})^{-1} \tag{18}$$

Now, by using equations (1)-(5), (7)-(8) and (18) important system performance measures have been derived and appended in Table 4.

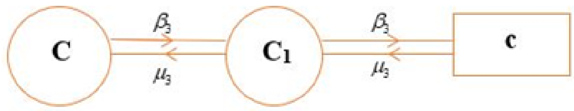

FIGURE 4. Transition diagram of Mixed bed filter

3.3. RAMD indices for subsystem S_3. It incorporates two units of mixed bed filter whose failure rates are the same and among them, one is operative and the other is in a backup stage which is called upon only on failure of the operative unit. The system stops responding when both the units stop working one after the other. The transition diagram and related Chapman- Kolmogorov differential equations associated with it are given as

$$P_0'(t) = -\beta_3 P_0(t) + \mu_3 P_1(t)\,, \tag{19}$$

$$P_1'(t) = \beta_3 P_0(t) - (\beta_3 + \mu_3) P_1(t) + \mu_3 P_2(t)\,, \tag{20}$$

$$P_2'(t) = \beta_3 P_1(t) - \mu_3 P_2(t)\,. \tag{21}$$

Under steady-state, equation (19), (20) and (21) reduces to

$$P_1 = \frac{\beta_3}{\mu_3} P_0\,, \tag{22}$$

$$P_2 = \frac{\beta_3^2}{\mu_3^2} P_0\,. \tag{23}$$

Now, using normalization condition:

$$P_0 + P_1 + P_2 = 1 \Rightarrow P_0 + \frac{\beta_3}{\mu_3} P_0 + \frac{\beta_3^2}{\mu_3^2} P_0 = 1 \Rightarrow P_0 = \left(1 + \frac{\beta_3}{\mu_3} + \frac{\beta_3^2}{\mu_3^2}\right)^{-1}\,. \tag{24}$$

Now, by using equations (1)-(5), (7)-(8) and (24) important system performance measures have been derived and appended in Table 4.

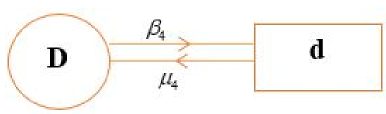

FIGURE 5. Transition diagram of Gland steam condenser

3.4. RAMD indices for subsystem S_4. This subsystem incorporates with one unit only. If this unit collapse, the complete system brings out the failure. Corresponding transition diagram and related Chapman-Kolmogorov differential equations are as follows

$$P_0'(t) = -\beta_4 P_0(t) + \mu_4 P_1(t)\,, \tag{25}$$

$$P_1'(t) = \beta_4 P_0(t) - \mu_4 P_1(t)\,. \tag{26}$$

Under steady-state, equation (25) and (26) reduces to

$$P_1 = \frac{\beta_4}{\mu_4} P_0 \,. \tag{27}$$

Now, using normalization condition:

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_4}{\mu_4} P_0 = 1 \Rightarrow P_0 = \frac{\mu_4}{\mu_4 + \beta_4} \,. \tag{28}$$

Now, by using equations (1)-(5), (7)-(8) and (28) important system performance measures have been derived and appended in Table 4.

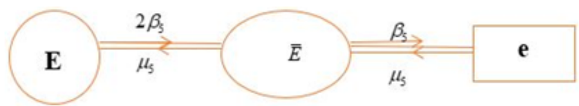

FIGURE 6. Transition diagram of Extraction Pump

3.5. RAMD indices for subsystem S_5. It incorporates two Extraction pumps whose failure rates are the same and among them, one is operative and the other is in a backup stage which is called upon only on failure of the operative unit. The system stops responding when both the units stop working one after another. The corresponding transition diagram and related Chapman-Kolmogorov differential equations associated with it are given as

$$P_0'(t) = -2\beta_5 P_0(t) + \mu_5 P_1(t) \,, \tag{29}$$

$$P_1'(t) = 2\beta_5 P_0(t) - (\beta_5 + \mu_5) P_1(t) + \mu_5 P_2(t) \,, \tag{30}$$

$$P_2'(t) = \beta_5 P_1(t) - \mu_5 P_2(t) \,. \tag{31}$$

Under steady-state, equation (29), (30), and (31) reduces to

$$P_1 = \frac{2\beta_5}{\mu_5} P_0 \,, \tag{32}$$

$$P_2 = \frac{2\beta_5^2}{\mu_5^2} P_0 \,. \tag{33}$$

Now, using normalization condition:

$$P_0 + P_1 + P_2 = 1 \Rightarrow P_0 + \frac{\beta_5}{\mu_5} P_0 + \frac{\beta_5^2}{\mu_5^2} P_0 = 1 \Rightarrow P_0 = \left(1 + \frac{\beta_5}{\mu_5} + \frac{\beta_5^2}{\mu_5^2}\right)^{-1} \,. \tag{34}$$

Now, by using equations (1)-(5), (7)-(8) and (34) important system performance measures have been derived and appended in Table 4.

FIGURE 7. Transition diagram of Cartridge Filter

3.6. RAMD indices for subsystem S_6. It incorporates two units of cartridge filter whose failure rates are the same and among them, one is operative and the other is in the backup stage which is called upon only on failure of the operative unit. The system stops responding when both the units stop working one after the other. The corresponding transition diagram and correlating Chapman Kolmogorov differential equations are given as

$$P_0'(t) = -\beta_6 P_0(t) + \mu_6 P_1(t)\,, \tag{35}$$

$$P_1'(t) = \beta_6 P_0(t) - (\beta_6 + \mu_6) P_1(t) + \mu_6 P_2(t)\,, \tag{36}$$

$$P_2'(t) = \beta_6 P_1(t) - \mu_6 P_2(t)\,. \tag{37}$$

Under steady-state, equation (35), (36), and (37) reduces to

$$P_1 = \frac{\beta_6}{\mu_6} P_0\,, \tag{38}$$

$$P_2 = \frac{\beta_6^2}{\mu_6^2} P_0\,. \tag{39}$$

Now, using normalization condition:

$$P_0 + P_1 + P_2 = 1 \Rightarrow P_0 + \frac{\beta_6}{\mu_6} P_0 + \frac{\beta_6^2}{\mu_6^2} P_0 = 1 \Rightarrow P_0 = \left(1 + \frac{\beta_6}{\mu_6} + \frac{\beta_6^2}{\mu_6^2}\right)^{-1}. \tag{40}$$

Now, by using equations (1)-(5), (7)-(8) and (40) important system performance measures have been derived and appended in Table 4.

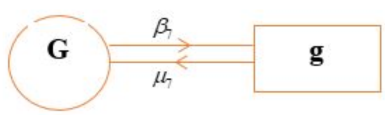

FIGURE 8. Transition diagram of Ejector condenser

3.7. RAMD indices for subsystem S_7. This subsystem also incorporates one unit only. If this unit collapse, the complete system brings out the failure. Corresponding transition diagram and related Chapman-Kolmogorov differential equations are as follows

$$P_0'(t) = -\beta_7 P_0(t) + \mu_7 P_1(t)\,, \tag{41}$$

$$P_1'(t) = \beta_7 P_0(t) - \mu_7 P_1(t)\,. \tag{42}$$

Under steady-state, equation (41) and (42) reduces to

$$P_1 = \frac{\beta_7}{\mu_7} P_0 \,. \tag{43}$$

Now, using normalization condition:

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_7}{\mu_7} P_0 = 1 \Rightarrow P_0 = \frac{\mu_7}{\mu_7 + \beta_7} \,. \tag{44}$$

Now, by using equations (1)-(5), (7)-(8) and (44) important system performance measures have been derived and appended in Table 4.

3.8. System reliability. Here all the seven subsystems are connected in series through each other. So, failure of one lead to complete system failure. The overall system reliability of the condenser is given by

$$\begin{aligned} R_{Sys}(t) &= R_{S_1}(t) * R_{S_2}(t) * R_{S_3}(t) * R_{S_4}(t) * R_{S_5}(t) * R_{S_6}(t) * R_{S_7}(t) \\ &= e^{-(\beta_1 + 2\beta_2 + 2\beta_3 + \beta_4 + 3\beta_5 + 2\beta_6 + \beta_7)t} \\ \Rightarrow \quad R_{Sys}(t) &= e^{-0.0784t} \,. \end{aligned} \tag{45}$$

The variation in reliability concerning different time instant is compiled in Table 2.

TABLE 2. Variation of reliability of subsystems with time

Time (in months)	$R_{S1}(t)$	$R_{S2}(t)$	$R_{S3}(t)$	$R_{S4}(t)$	$R_{S5}(t)$	$R_{S6}(t)$	$R_{S7}(t)$	$R_{Sys}(t)$
0	1	1	1	1	1	1	1	1
10	0.960789	0.901225	0.904837	0.923116	0.786628	0.852144	0.941765	0.456576
20	0.923116	0.812207	0.818731	0.852144	0.618783	0.726149	0.886920	0.208462
30	0.886920	0.731982	0.740818	0.786628	0.486752	0.618783	0.835270	0.095179
40	0.852144	0.659680	0.670320	0.726149	0.382893	0.527292	0.786628	0.043456
50	0.818731	0.594521	0.606531	0.670320	0.301194	0.449329	0.740818	0.019841
60	0.786628	0.535797	0.548812	0.618783	0.236928	0.382893	0.697676	0.009059
70	0.755784	0.482874	0.496585	0.571209	0.186374	0.326280	0.657047	0.004136
80	0.726149	0.435178	0.449329	0.527292	0.146607	0.278037	0.618783	0.001888
90	0.697676	0.392193	0.406570	0.486752	0.115325	0.236928	0.582748	0.000862
100	0.670320	0.353455	0.367879	0.449329	0.090718	0.201897	0.548812	0.000394

3.9. System availability. Here, all the seven subsystems are connected in series through each other. So, failure of one leads to complete system failure. The overall system availability of condenser is given by

$$A_{Sys} = A_{S_1} * A_{S_2} * A_{S_3} * A_{S_4} * A_{S_5} * A_{S_6} * A_{S_7} = 0.95144892 \,. \tag{46}$$

3.10. System maintainability. Here, all the seven subsystems are connected in series through each other. So, failure of one leads to complete system failure. The overall system maintainability of the condenser is given by

$$\begin{aligned} M_{Sys}(t) &= M_{S_1}(t) * M_{S_2}(t) * M_{S_3}(t) * M_{S_4}(t) * M_{S_5}(t) * M_{S_6}(t) * M_{S_7}(t) \\ &= (1-e^{-0.42t}) * (1-e^{-1.24t}) * (1-e^{-1.7t}) * (1-e^{-0.52t}) * (1-e^{-1.8t}) \\ &\quad * (1-e^{-1.9t}) * (1-e^{-0.24t}) \\ &= 1-e^{-0.378t}\,. \end{aligned} \tag{47}$$

The variation in maintainability concerning different time instant is compiled in Table 3.

TABLE 3. Variation of maintainability of subsystems with time

Time (in months)	$M_{S1}(t)$	$M_{S2}(t)$	$M_{S3}(t)$	$M_{S4}(t)$	$M_{S5}(t)$	$M_{S6}(t)$	$M_{S7}(t)$	$M_{Sys}(t)$
0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
10	0.985004	0.999996	1.000000	0.994483	1.000000	1.000000	0.909282	0.890702
20	0.999775	1.000000	1.000000	0.999970	1.000000	1.000000	0.991770	0.991517
30	0.999997	1.000000	1.000000	1.000000	1.000000	1.000000	0.999253	0.999250
40	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	0.999932	0.999932
50	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	0.999994	0.999994
60	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	0.999999	0.999999
70	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
80	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
90	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
100	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000

3.11. System dependability. Here all the seven subsystems are connected in series through each other. So, failure of one leads to complete system failure. The overall system dependability of the condenser is given by

$$\begin{aligned} D_{\min(Sys)} &= D_{\min(S_1)} * D_{\min(S_2)} * D_{\min(S_3)} * D_{\min(S_4)} * D_{\min(S_5)} * D_{\min(S_6)} \\ &\quad * D_{\min(S_7)} \\ &= 0.954093084\,. \end{aligned} \tag{48}$$

RAMD indices computed above for all the subsystems of the condenser are appended as follows:

Table 4. RAMD indices for the condenser in STPP

RAMD indices	Subsystem							
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	System
Reliability	$e^{-0.004t}$	$e^{-0.0104t}$	$e^{-0.01t}$	$e^{-0.008t}$	$e^{-0.024t}$	$e^{-0.016t}$	$e^{-0.006t}$	$e^{-0.0784t}$
Maintainability	1-$e^{-0.42t}$	1-$e^{-1.24t}$	1-$e^{-1.7t}$	1-$e^{-0.52t}$	1-$e^{-1.8t}$	1-$e^{-1.9t}$	1-$e^{-0.24t}$	1-$e^{-0.378t}$
Availability	0.990566	0.999930	0.999966	0.984848	0.999845	0.999930	0.975610	0.951449
MTBF	250.0000	96.1538	100.0000	125.0000	41.6667	62.5000	116.6667	791.9872
MTTR	2.381000	0.006755	0.003440	1.923100	0.006469	0.004395	4.166670	8.491830
Dependability or $D_{\min}$	0.990890	0.999930	0.999966	0.985600	0.999845	0.999930	0.977255	0.954093
Dependability ratio	105.00	14233.87	29069.62	65.00	6440.51	14220.11	40.00	

4. Sensitivity analysis

In sensitivity analysis, the effect of the independent variable i.e. failure and repair rates on the dependent variable, which is the performance of the system under some set of assumptions, is analyzed. By this technique, it is identified that how the system is sensitive concerning change in values of parameters of model and change in structure also. Through this process, the most sensitive component of the system has also been found. Here, sensitivity analysis of system reliability w.r.t various failure rate parameters β_1, β_2, β_3, β_4, β_5, β_6 and β_7 has been made.

For this purpose, the system reliability is partially differentiated concerning β_1, β_2, β_3, β_4, β_5, β_6 and β_7 and the following expressions are derived

$$\frac{\partial R_{Sys}}{\partial \beta_1} = -te^{-(\beta_1+2\beta_2+2\beta_3+\beta_4+3\beta_5+2\beta_6+\beta_7)t}, \tag{49}$$

$$\frac{\partial R_{Sys}}{\partial \beta_2} = -2te^{-(\beta_1+2\beta_2+2\beta_3+\beta_4+3\beta_5+2\beta_6+\beta_7)t}, \tag{50}$$

$$\frac{\partial R_{Sys}}{\partial \beta_3} = -2te^{-(\beta_1+2\beta_2+2\beta_3+\beta_4+3\beta_5+2\beta_6+\beta_7)t}, \tag{51}$$

$$\frac{\partial R_{Sys}}{\partial \beta_4} = -te^{-(\beta_1+2\beta_2+2\beta_3+\beta_4+3\beta_5+2\beta_6+\beta_7)t}, \tag{52}$$

$$\frac{\partial R_{Sys}}{\partial \beta_5} = -3te^{-(\beta_1+2\beta_2+2\beta_3+\beta_4+3\beta_5+2\beta_6+\beta_7)t}, \tag{53}$$

$$\frac{\partial R_{Sys}}{\partial \beta_6} = -2te^{-(\beta_1+2\beta_2+2\beta_3+\beta_4+3\beta_5+2\beta_6+\beta_7)t}, \tag{54}$$

$$\frac{\partial R_{Sys}}{\partial \beta_7} = -te^{-(\beta_1+2\beta_2+2\beta_3+\beta_4+3\beta_5+2\beta_6+\beta_7)t}. \tag{55}$$

The graphical representation of sensitivity analysis of condenser reliability is given in Figure **??**. This is obtained by putting the values of parameters

$$\beta_1 = 0.004,\ \beta_2 = 0.0052,\ \beta_3 = 0.005,\ \beta_4 = 0.008,\ \beta_5 = 0.008,\ \beta_6 = 0.008 \text{ and } \beta_7 = 0.006$$

in the above set of equations and varying time $t = 0$ to $t = 100$.

4.1. Discussion and conclusion. The variation in reliability and maintainability of the condenser and its subsystem at different time instant is carried out in Table 2 and Table 3 respectively. All other RAMD indices are given in Table 4. From the numerical interpretation described in Table 2, it is noticed that the reliability of the system is 0.095178615 for 30 months. Since the reliability of subsystem 5 is very low, so designers should pay more attention to forming the maintenance policies for it. The changes in reliability behavior of various subsystems concerning different time instant have been shown in Tables 5, 6, 7, 8, 9, 10, and 11 and from this analysis, it is clear that subsystem 5 i.e. extraction pump is overcritical and oversensitive and preferred special attention to increasing condenser reliability. From above, it is concluded that if we control the failure rates of the extraction pump by making proper maintenance policies, we can increase the reliability and working hours of the condenser.

TABLE 5. Impact of the failure rate of the main condenser on subsystem and system reliability

Time	System				Subsystem 1			
(in months)	$\beta_1 = 0.002$	$\beta_1 = 0.004$	$\beta_1 = 0.006$	$\beta_1 = 0.008$	$\beta_1 = 0.002$	$\beta_1 = 0.004$	$\beta_1 = 0.006$	$\beta_1 = 0.008$
0	1	1	1	1	1	1	1	1
10	0.465799	0.456576	0.447535	0.438673	0.980199	0.960789	0.951229	0.923116
20	0.216969	0.208462	0.200288	0.192434	0.960789	0.923116	0.904837	0.852144
30	0.101064	0.095179	0.089636	0.084416	0.941765	0.886920	0.860708	0.786628
40	0.047076	0.043456	0.040115	0.037031	0.923116	0.852144	0.818731	0.726149
50	0.021928	0.019841	0.017953	0.016245	0.904837	0.818731	0.778801	0.670320
60	0.010214	0.009059	0.008035	0.007126	0.886920	0.786628	0.740818	0.618783
70	0.004758	0.004136	0.003596	0.003126	0.869358	0.755784	0.704688	0.571209
80	0.002216	0.001888	0.001609	0.001371	0.852144	0.726149	0.670320	0.527292
90	0.001032	0.000862	0.000720	0.000602	0.835270	0.697676	0.637628	0.486752
100	0.000481	0.000394	0.000322	0.000264	0.818731	0.670320	0.606531	0.449329

TABLE 6. Impact of the failure rate of booster pump on subsystem and system reliability

Time	System				Subsystem 2			
(in months)	$\beta_2 = 0.0042$	$\beta_2 = 0.0052$	$\beta_2 = 0.0062$	$\beta_2 = 0.0072$	$\beta_2 = 0.0042$	$\beta_2 = 0.0052$	$\beta_2 = 0.0062$	$\beta_2 = 0.0072$
0	1	1	1	1	1	1	1	1
10	0.465799	0.456576	0.447535	0.438673	0.404947	0.901225	0.883380	0.865888
20	0.216969	0.208462	0.200288	0.192434	0.163982	0.812207	0.780360	0.749762
30	0.101064	0.095179	0.089636	0.084416	0.066404	0.731982	0.689354	0.649209
40	0.047076	0.043456	0.040115	0.037031	0.026890	0.659680	0.608962	0.562142
50	0.021928	0.019841	0.017953	0.016245	0.010889	0.594521	0.537944	0.486752
60	0.010214	0.009059	0.008035	0.007126	0.004409	0.535797	0.475209	0.421473
70	0.004758	0.004136	0.003596	0.003126	0.001786	0.482874	0.419790	0.364948
80	0.002216	0.001888	0.001609	0.001371	0.000723	0.435178	0.370834	0.316004
90	0.001032	0.000862	0.000720	0.000602	0.000293	0.392193	0.327588	0.273624
100	0.000481	0.000394	0.000322	0.000264	0.000119	0.353455	0.289384	0.236928

TABLE 7. Impact of the failure rate of mixed bed filter on subsystem and system reliability

Time	System				Subsystem 3			
(in months)	$\beta_3 = 0.003$	$\beta_3 = 0.005$	$\beta_3 = 0.007$	$\beta_3 = 0.009$	$\beta_3 = 0.003$	$\beta_3 = 0.005$	$\beta_3 = 0.007$	$\beta_3 = 0.009$
0	1	1	1	1	1	1	1	1
10	0.475209	0.456576	0.438673	0.421473	0.941765	0.904837	0.869358	0.83527
20	0.225824	0.208462	0.192434	0.177639	0.88692	0.818731	0.755784	0.697676
30	0.107314	0.095179	0.084416	0.07487	0.83527	0.740818	0.657047	0.582748
40	0.050996	0.043456	0.037031	0.031556	0.786628	0.67032	0.571209	0.486752
50	0.024234	0.019841	0.016245	0.0133	0.740818	0.606531	0.496585	0.40657
60	0.011516	0.009059	0.007126	0.005606	0.697676	0.548812	0.431711	0.339596
70	0.005473	0.004136	0.003126	0.002363	0.657047	0.496585	0.375311	0.283654
80	0.002601	0.001888	0.001371	0.000996	0.618783	0.449329	0.32628	0.236928
90	0.001236	0.000862	0.000602	0.00042	0.582748	0.40657	0.283654	0.197899
100	0.000587	0.000394	0.000264	0.000177	0.548812	0.367879	0.246597	0.165299

TABLE 8. Impact of the failure rate of gland steam condenser on subsystem and system reliability

Time	System				Subsystem 4			
(in months)	$\beta_4 = 0.006$	$\beta_4 = 0.008$	$\beta_4 = 0.010$	$\beta_4 = 0.012$	$\beta_4 = 0.006$	$\beta_4 = 0.008$	$\beta_4 = 0.010$	$\beta_4 = 0.012$
0	1	1	1	1	1	1	1	1
10	0.465799	0.456576	0.447535	0.438673	0.941765	0.923116	0.904837	0.88692
20	0.216969	0.208462	0.200288	0.192434	0.88692	0.852144	0.818731	0.786628
30	0.101064	0.095179	0.089636	0.084416	0.83527	0.786628	0.740818	0.697676
40	0.047076	0.043456	0.040115	0.037031	0.786628	0.726149	0.67032	0.618783
50	0.021928	0.019841	0.017953	0.016245	0.740818	0.67032	0.606531	0.548812
60	0.010214	0.009059	0.008035	0.007126	0.697676	0.618783	0.548812	0.486752
70	0.004758	0.004136	0.003596	0.003126	0.657047	0.571209	0.496585	0.431711
80	0.002216	0.001888	0.001609	0.001371	0.618783	0.527292	0.449329	0.382893
90	0.001032	0.000862	0.00072	0.000602	0.582748	0.486752	0.40657	0.339596
100	0.000481	0.000394	0.000322	0.000264	0.548812	0.449329	0.367879	0.301194

TABLE 9. Impact of the failure rate of extraction pump on sub-system and system reliability

Time	System				Subsystem 5			
(in months)	$\beta_5 = 0.0065$	$\beta_5 = 0.0080$	$\beta_5 = 0.0095$	$\beta_5 = 0.0105$	$\beta_5 = 0.0065$	$\beta_5 = 0.0080$	$\beta_5 = 0.0095$	$\beta_5 = 0.0105$
0	1	1	1	1	1	1	1	1
10	0.477591	0.456576	0.436486	0.423585	0.822835	0.786628	0.752014	0.729789
20	0.228093	0.208462	0.19052	0.179425	0.677057	0.618783	0.565525	0.532592
30	0.108935	0.095179	0.083159	0.076002	0.557106	0.486752	0.425283	0.38868
40	0.052027	0.043456	0.036298	0.032193	0.458406	0.382893	0.319819	0.283654
50	0.024847	0.019841	0.015843	0.013637	0.377192	0.301194	0.240508	0.207008
60	0.011867	0.009059	0.006915	0.005776	0.310367	0.236928	0.180866	0.151072
70	0.005668	0.004136	0.003018	0.002447	0.255381	0.186374	0.136014	0.110251
80	0.002707	0.001888	0.001318	0.001036	0.210136	0.146607	0.102284	0.08046
90	0.001293	0.000862	0.000575	0.000439	0.172907	0.115325	0.076919	0.058719
100	0.000617	0.000394	0.000251	0.000186	0.142274	0.090718	0.057844	0.042852

TABLE 10. Impact of the failure rate of cartridge filter on sub-system and system reliability

Time	System				Subsystem 6			
(in months)	β_6=0.0055	β_6=0.008	$\beta_6 = 0.0105$	$\beta_6 = 0.0130$	$\beta_6$0.0055	$\beta_6 = 0.008$	$\beta_6 = 0.0105$	$\beta_6 = 0.0130$
0	1	1	1	1	1	1	1	1
10	0.479985	0.456576	0.434309	0.413127	0.895834	0.852144	0.810584	0.771052
20	0.230386	0.208462	0.188624	0.170674	0.802519	0.726149	0.657047	0.594521
30	0.110582	0.095179	0.081921	0.07051	0.718924	0.618783	0.532592	0.458406
40	0.053078	0.043456	0.035579	0.02913	0.644036	0.527292	0.431711	0.353455
50	0.025476	0.019841	0.015452	0.012034	0.57695	0.449329	0.349938	0.272532
60	0.012228	0.009059	0.006711	0.004972	0.516851	0.382893	0.283654	0.210136
70	0.005869	0.004136	0.002915	0.002054	0.463013	0.32628	0.229925	0.162026
80	0.002817	0.001888	0.001266	0.000849	0.414783	0.278037	0.186374	0.12493
90	0.001352	0.000862	0.00055	0.000351	0.371577	0.236928	0.151072	0.096328
100	0.000649	0.000394	0.000239	0.000145	0.332871	0.201897	0.122456	0.074274

TABLE 11. Impact of the failure rate of ejector condenser on subsystem and system reliability

Time	System				Subsystem 7			
(in months)	$\beta_7 = 0.005$	$\beta_7 = 0.006$	$\beta_7 = 0.007$	$\beta_7 = 0.008$	$\beta_7 = 0.005$	$\beta_7 = 0.006$	$\beta_7 = 0.007$	$\beta_7 = 0.008$
0	1	1	1	1	1	1	1	1
10	0.461165	0.456576	0.452033	0.447535	0.951229	0.941765	0.932394	0.923116
20	0.212673	0.208462	0.204334	0.200288	0.904837	0.88692	0.869358	0.852144
30	0.098077	0.095179	0.092366	0.089636	0.860708	0.83527	0.810584	0.786628
40	0.04523	0.043456	0.041752	0.040115	0.818731	0.786628	0.755784	0.726149
50	0.020858	0.019841	0.018873	0.017953	0.778801	0.740818	0.704688	0.67032
60	0.009619	0.009059	0.008531	0.008035	0.740818	0.697676	0.657047	0.618783
70	0.004436	0.004136	0.003856	0.003596	0.704688	0.657047	0.612626	0.571209
80	0.002046	0.001888	0.001743	0.001609	0.67032	0.618783	0.571209	0.527292
90	0.000943	0.000862	0.000788	0.00072	0.637628	0.582748	0.532592	0.486752
100	0.000435	0.000394	0.000356	0.000322	0.606531	0.548812	0.496585	0.449329

TABLE 12. Sensitivity analysis of Condenser reliability

t (time)	SS1	SS2	SS3	SS4	SS5	SS6	SS7
0	0	0	0	0	0	0	0
10	-4.565760	-9.131521	-9.131521	-4.565760	-13.697281	-9.131521	-4.565760
20	-4.169234	-8.338468	-8.338468	-4.169234	-12.507701	-8.338468	-4.169234
30	-2.855358	-5.710717	-5.710717	-2.855358	-8.566075	-5.710717	-2.855358
40	-1.738251	-3.476502	-3.476502	-1.738251	-5.214753	-3.476502	-1.738251
50	-0.992055	-1.984109	-1.984109	-0.992055	-2.976164	-1.984109	-0.992055
60	-0.543538	-1.087076	-1.087076	-0.543538	-1.630614	-1.087076	-0.543538
70	-0.289528	-0.579055	-0.579055	-0.289528	-0.868583	-0.579055	-0.289528
80	-0.151076	-0.302152	-0.302152	-0.151076	-0.453227	-0.302152	-0.151076
90	-0.077600	-0.155200	-0.155200	-0.077600	-0.232799	-0.155200	-0.077600
100	-0.039367	-0.078734	-0.078734	-0.039367	-0.118101	-0.078734	-0.039367

SS1: Main Condenser, SS2: Booster Pump, SS3: Mixed bed filter, SS4: Gland steam condenser, SS5: Extraction Pump, SS6: Cartridge Filter, SS7: Ejector condenser.

5. Decision-making inferences

Every industry wants to increase the reliability of its working unit. For this purpose, they used various reliability evaluation technique which were highly mathematical and not easy to understand by everybody. RAMD analysis is one of the techniques which is easily approachable by a non-mathematician and easy to apply also. It helps in finding different reliability measures such as MTBF, MTTR, dependability ratio, and availability of the system for forming various maintenance policies. It also helps in estimating the nature of the system at different failure and repair rates and making different repair policies. It determines the most critical and sensitive component in the system and distribution of failure and repair rates.

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