

Behavioral Analysis of Cooling Tower in Steam Turbine Power Plant using Reliability, Availability, Maintainability and Dependability Investigation

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Abstract

The main objective of present study is to provide a novel technique for identification of most critical component of cooling tower in steam turbine power plant. In steam turbine power plants various subsystems works in a series structure out of which cooling tower plays a prominent role in operation of plant. Cooling tower is comprised using six components in series structure. In present analysis, reliability, availability, maintainability and dependability (RAMD) approach has been utilized to find the performance measures of the cooling tower. Markov birth death process has been used to develop mathematical models for each component of cooling tower. Chapman Kolmogorov differential equations for each component has been formulated. All failure and repair time random variables follow exponential distribution, and all are statistically independent. Sufficient repair facility always remains with system. The numerical results for reliability, maintainability, dependability and steady state availability for different components of cooling tower have been derived. Other measures such as mean time to failure (MTTF), mean time to repair (MTTR) and dependability ratio, which help us to predict system performance has also been calculated. Numerical analysis reflects that availability of the system is 0.9775468, reliability of the system after 10 months is 0.703280 and become 0.085094 after 70 months. Maintainability of the system is 0.997239 and Dependability is 0.977985. Through, the derived numerical results operational performance of cooling tower has been assessed and it is recommended that findings are very useful for designers and maintenance engineers of cooling tower.

Keywords: Cooling tower, Markov Birth Death process, Reliability, Maintainability, Availability, Dependability, Mean time to failure and Mean time to repair.

1. Introduction

Condensers use relatively cool water to condense the steam from the turbines by different means. This decreases back pressure, which in turn reduces the consumption of steam and thus the consumption of gas, while at the same time increasing energy and recycling boiler water. However, the condensers need ample supply of cooling water without which they are inefficient. Then the role of cooling tower came into existence. A cooling tower is a heat-rejection machine that by cooling a water flow to a lower temperature rejects waste heat to the atmosphere. Smooth running of power plant also depends on smooth running of it as well. So, it is important to increase its reliability and availability and require adequate strategies to find its critical component and time to time proper maintenance of it. As a matter of fact, every system is always built to fulfill and justify its operational requirement, which is guaranteed by the system's reliability and time-to-time availability. Reliability technology provides designers a structure to establish a proper system design, optimize its operating characteristics and formulate maintenance policies. System designers need to be aware about the most critical component and its time-to-time maintenance for this reason. Reliability, availability, maintainability and dependability (RAMD) is one of the methods to help in achieving this goal. This helps to identify the most critical component and to

ensure that they have proper maintenance policies. Certain parameters such as performance, servicing, MTTR, MTTF, Dependability ratio are also measured.

Many researchers tried to analyze the reliability and maintainability of various industrial systems. Using Weibull-Markov stochastic method, Casteren et al. [1] performed performance tests in electrical power systems. Eti et al. [2] surveyed the output of gas turbine plants in Nigeria's A-fam power plant. Arora and Kumar [3] presented a case study to optimize resource allocation and benefit in the thermal power plant coal handling process through complex programming and operational evaluation to increase the efficiency of the system. Carazas et al. [4] proposed a methodology for the assessment of gas turbine power plant for performance and availability analysis based on the concept of process reliability. Carazas et al. [5] provided a performance and availability evaluation system for HRSGs built in a combined cycle power plant. Kumar et al. [6] addressed the use of genetic algorithms to maximize the quality of a fertilizer plant's CO shift conversion process. Adhikarya et al. [7] suggested a comparative study focused on efficiency, stability and availability of two units of a coal-fired thermal power station in eastern India. Obeidat et al. [8] evaluate each unit's actions at AL – Hussein thermal power station and establish efficient plant maintenance strategies. Aggarwal et al. [9] addressed the reliability evaluation of a fertilizer plant's urea synthesis process using a Markovian method. For various choices of system subsystem failure and repair rates long-run availability, reliability and mean time between failures have been calculated. Corvaro et al. [10] developed the technique

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for evaluating reciprocating compressor output with the aid of efficiency, availability, maintenance (RAM) and taking failure and repair rates as distributed exponentially. Tsarouhas [11] analyzed the quality of the wine packaging production line using the RAMD methodology and derives various estimates of system performance and identified the best suited distribution. Recently, Saini et al. [12] and Goyal et al. [13] used RAMD methodology to identify most sensitive component of serial processes like evaporation system in the sugar industry and water treatment plant. In this study, the performance indices of the power generating system through STP have been broken down. For analyze the power system, basic principles of probability theory and Markovian birth-death process have been used. In a Markov process, as the process moves from one stage to the next, the probability of its moving from a particular state 'i' to another state 'j' is independent of how the process arrived at state 'i' in the first place. The system follows the memoryless property. The paper consists of four sections, including present introductory section. System description, and assumptions are explained in section second. RAMD analysis is performed in section 3. Finally, section 4 is devoted to conclusion and implication of the results.

2. System description and assumptions

(i) System description

In this section, a brief description of cooling tower in steam turbine power plant has been given. Cooling tower mainly consists of seven components namely hydro turbine, hydraulic valves, water spray system, automatic deaerator valves, cooling water pump, motor valves and standpipe. All components are arranged in series configuration. The pictorial representation of components is appended in fig. 1.

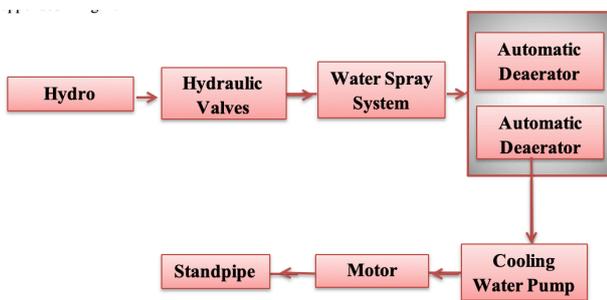


Fig. 1. Configuration Diagram of Cooling Tower Subsystem

a) Subsystem A (Hydro Turbine)

It consists of one unit of hydro turbine. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

b) Subsystem B (Hydraulic Valves)

It consists of one set of hydraulic valves. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

c) Subsystem C (Water Spray System)

It consists of one unit of water spray system. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

d) Subsystem D (Automatic Deaerator Valves)

It consists of two sets of automatic deaerator valves; one is operative and other is in cold standby. The failure rate of both the units are same and failure of both units tends to system failure.

e) Subsystem E (Cooling Water Pump)

It consists of one unit of Cooling water Pump. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

f) Subsystem F (Motor Valves)

It consists of one set of motor valves. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

g) Subsystem G (Stand Pipe)

It consists of one set of motor valves. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

(ii) Assumptions

- The failure rates and repair rates of each subsystem follows exponential distribution.
- The failure and repair rates are statistically independent to each other.
- There are no simultaneous failures among the subsystem.
- There are enough repair and replacement facilities. Repairmen always present in plant and performance wise repaired system is as good as new.
- The switchover devices used for standby subsystems are perfect.

RAMD analysis of the system

By considering Markov birth death process for mathematical modeling of the cooling tower Chapman Kolmogorov differential equations for each of the sub-systems have been derived. All failure and repair rates of each subsystem has been considered as constant as shown in table 1. For each subsystem, a state transition diagram has been formulated. In each subsystem, by solving corresponding Chapman-Kolmogorov differential equations in a steady state and simultaneously using normalizing conditions, system performance measures such as maintainability, availability, reliability, mean time to failure (MTTF), mean time to repair (MTTR) and reliability ratio has been derived.

Table 1. Failure and Repair rates of components of cooling tower

Subsystem	Failure Rates (β)	Repair rates (μ)
S ₁	$\beta_1 = 0.003$	$\mu_1 = 0.42$
S ₂	$\beta_2 = 0.0073$	$\mu_2 = 1.25$
S ₃	$\beta_3 = 0.0009$	$\mu_3 = 0.09$
S ₄	$\beta_4 = 0.006$	$\mu_4 = 0.52$
S ₅	$\beta_5 = 0.0025$	$\mu_5 = 0.18$
S ₆	$\beta_6 = 0.005$	$\mu_6 = 0.95$
S ₇	$\beta_7 = 0.0045$	$\mu_7 = 0.75$

The RAMD indices for subsystems of cooling tower of steam turbine power plant (STPP) are computed as

a) RAMD indices for subsystem S₁

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

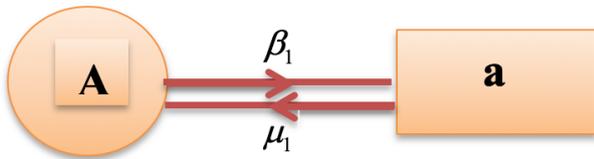


Fig. 2. Transition diagram of hydro turbine

$$P'_0(t) = -\beta_1 P_0(t) + \mu_1 P_1(t) \quad (1)$$

$$P'_1(t) = \beta_1 P_0(t) - \mu_1 P_1(t) \quad (2)$$

Under steady state, equation 9 and 10 reduces to

$$P_1 = \frac{\beta_1}{\mu_1} P_0 \quad (3)$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_1}{\mu_1} P_0 = 1 \Rightarrow P_0 = \frac{\mu_1}{\mu_1 + \beta_1} \quad (4)$$

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

b) RAMD indices for subsystem S₂

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

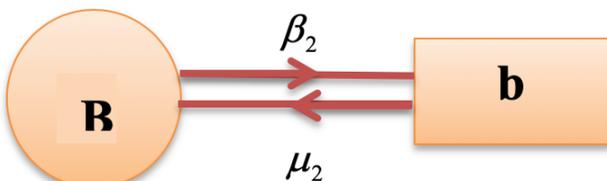


Fig. 2. Transition diagram of hydraulic valves

$$P'_0(t) = -\beta_2 P_0(t) + \mu_2 P_1(t) \quad (5)$$

$$P'_1(t) = \beta_2 P_0(t) - \mu_2 P_1(t) \quad (6)$$

Under steady state, equation 13 and 14 reduces to

$$P_1 = \frac{\beta_2}{\mu_2} P_0 \quad (7)$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_2}{\mu_2} P_0 = 1 \Rightarrow P_0 = \frac{\mu_2}{\mu_2 + \beta_2} \quad (8)$$

Now, by using equations (1-5, 7-8 & 16) important system performance measures have been derived and appended in table 4.

c) RAMD indices for subsystem S₃

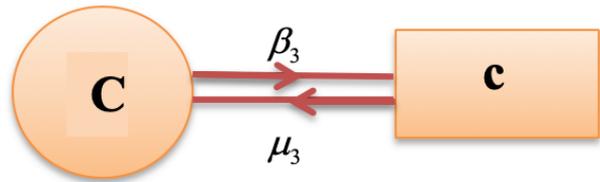


Fig. 3. Transition diagram of water spray system

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

$$P'_0(t) = -\beta_3 P_0(t) + \mu_3 P_1(t) \quad (9)$$

$$P'_1(t) = \beta_3 P_0(t) - \mu_3 P_1(t) \quad (10)$$

Under steady state, equation 17 and 18 reduces to

$$P_1 = \frac{\beta_3}{\mu_3} P_0 \quad (11)$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_3}{\mu_3} P_0 = 1 \Rightarrow P_0 = \frac{\mu_3}{\mu_3 + \beta_3} \quad (12)$$

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

d) RAMD indices for subsystem S₄

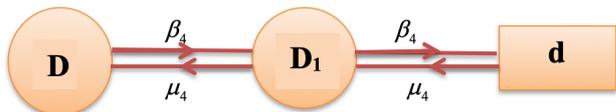


Fig. 4. Transition diagram of automatic deaerator valves

This subsystem has single unit working at a time only but with one cold standby unit. Failure of both leads to complete system failure. The transition diagram and Chapman Kolmogorov differential equations associated with it are given as:

$$P'_0(t) = -\beta_4 P_0(t) + \mu_4 P_1(t) \quad (13)$$

$$P'_1(t) = \beta_4 P_0(t) - (\beta_4 + \mu_4) P_1(t) + \mu_4 P_2(t) \quad (14)$$

$$P'_2(t) = \beta_4 P_1(t) - \mu_4 P_2(t) \quad (15)$$

Under steady state, equation 21, 22 and 23 reduces to

$$P_1 = \frac{\beta_4}{\mu_4} P_0 \quad (16)$$

$$P_2 = \frac{\beta_4^2}{\mu_4^2} P_0 \quad (17)$$

Now, using normalization condition:

$$P_0 + P_1 + P_2 = 1 \Rightarrow P_0 + \frac{\beta_6}{\mu_6} P_0 + \frac{\beta_6^2}{\mu_6^2} P_0 = 1 \Rightarrow \quad (18)$$

$$P_0 = \left(1 + \frac{\beta_6}{\mu_6} + \frac{\beta_6^2}{\mu_6^2}\right)^{-1}$$

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

e) **RAMD indices for subsystem S₅**

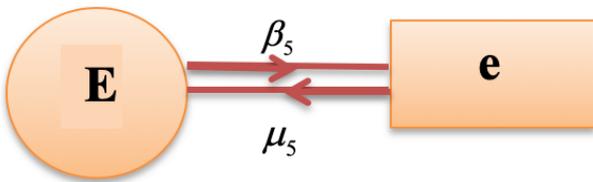


Fig. 5. Transition diagram of cooling water pump

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

$$P_0'(t) = -\beta_5 P_0(t) + \mu_5 P_1(t) \quad (19)$$

$$P_1'(t) = \beta_5 P_0(t) - \mu_5 P_1(t) \quad (20)$$

Under steady state, equation 27 and 28 reduces to

$$P_1 = \frac{\beta_5}{\mu_5} P_0 \quad (21)$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_5}{\mu_5} P_0 = 1 \Rightarrow P_0 = \frac{\mu_5}{\mu_5 + \beta_5} \quad (22)$$

Now, by using equations (1-5, 7-8 & 30) important system performance measures have been derived and appended in table 4.

f) **RAMD indices for subsystem S₆**

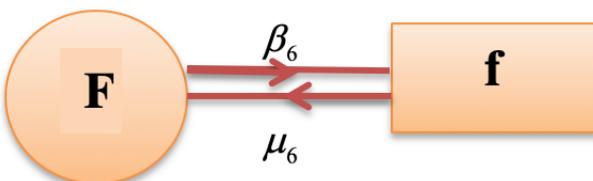


Fig. 6. Transition diagram of motor valves

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

$$P_0'(t) = -\beta_6 P_0(t) + \mu_6 P_1(t) \quad (23)$$

$$P_1'(t) = \beta_6 P_0(t) - \mu_6 P_1(t) \quad (24)$$

Under steady state, equation 23 and 24 reduces to

$$P_1 = \frac{\beta_6}{\mu_6} P_0 \quad (25)$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_6}{\mu_6} P_0 = 1 \Rightarrow P_0 = \frac{\mu_6}{\mu_6 + \beta_6} \quad (26)$$

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

g) **RAMD indices for subsystem S₇**

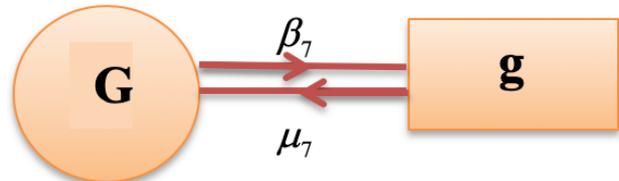


Fig. 7. Transition diagram of stand pipe

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

$$P_0'(t) = -\beta_7 P_0(t) + \mu_7 P_1(t) \quad (27)$$

$$P_1'(t) = \beta_7 P_0(t) - \mu_7 P_1(t) \quad (28)$$

Under steady state, equation 27 and 28 reduces to

$$P_1 = \frac{\beta_7}{\mu_7} P_0 \quad (29)$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\beta_7}{\mu_7} P_0 = 1 \Rightarrow P_0 = \frac{\mu_7}{\mu_7 + \beta_7} \quad (30)$$

Now, by using equations (Appendix 1-5, 7-8 & 30) important system performance measures have been derived and appended in table 4.

System reliability

All seven subsystems are connected through one another in sequence. Just one failure leads to complete failure of the system. The overall system reliability of the cooling tower is determined by

$$\begin{aligned}
 R_{Sys}(t) &= R_{S_1}(t) * R_{S_2}(t) * R_{S_3}(t) * R_{S_4}(t) * R_{S_5}(t) * R_{S_6}(t) * R_{S_7}(t) \\
 &= e^{-(\beta_1 + \beta_2 + \beta_3 + 2\beta_4 + \beta_5 + \beta_6 + \beta_7)t} \\
 \Rightarrow R_{Sys}(t) &= e^{-0.0352t}
 \end{aligned}
 \tag{31}$$

The variation in reliability with respect to different time instant is compiled in table 2

Table 2. Variation of reliability of subsystems with time

Time (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	0.97044	0.92960	0.99104	0.88692	0.97531	0.95122	0.95599	0.70328
20	0.94176	0.86415	0.98216	0.78662	0.95122	0.90483	0.91393	0.49460
30	0.91393	0.80332	0.97336	0.69767	0.92774	0.860708	0.873716	0.34784
40	0.88692	0.74676	0.96464	0.61878	0.904837	0.818731	0.835270	0.24463
50	0.86070	0.69419	0.95599	0.54881	0.882497	0.778801	0.798516	0.17204
60	0.83527	0.64532	0.94743	0.48675	0.860708	0.740818	0.763379	0.12099
70	0.81058	0.59989	0.93894	0.43171	0.839457	0.704688	0.729789	0.08509
80	0.78662	0.55766	0.93053	0.38289	0.818731	0.670320	0.697676	0.05984
90	0.76337	0.51840	0.92219	0.33959	0.798516	0.637628	0.666977	0.04208
100	0.74081	0.48190	0.91393	0.30119	0.77880	0.60653	0.63762	0.02959

System availability

All seven subsystems are connected through one another in sequence. Just one failure leads to complete failure of the system. The overall system availability of the cooling tower is determined by

$$\begin{aligned}
 A_{Sys} &= A_{S_1} * A_{S_2} * A_{S_3} * A_{S_4} * A_{S_5} * A_{S_6} * A_{S_7} \\
 &= 0.9775468
 \end{aligned}
 \tag{32}$$

System maintainability

All seven subsystems are connected through one another in sequence. Just one failure leads to complete failure of the system. The overall system maintainability of the cooling tower is determined by

$$\begin{aligned}
 M_{Sys}(t) &= M_{S_1}(t) * M_{S_2}(t) * M_{S_3}(t) * M_{S_4}(t) * M_{S_5}(t) * M_{S_6}(t) * M_{S_7}(t) \\
 &= (1 - e^{-0.62t}) * (1 - e^{-1.25t}) * (1 - e^{-0.92t}) * (1 - e^{-4.48t}) * (1 - e^{-0.75t}) * (1 - e^{-0.95t}) * (1 - e^{-1.8t}) \\
 &= 1 - e^{-4.0966t}
 \end{aligned}
 \tag{33}$$

The variation in maintainability with respect to different time instant is compiled in table 3.

Table 3. Variation of maintainability of subsystems with time

Time (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	0.997971	0.999996	0.999899	1.000000	0.999447	0.999925	1.000000	0.997239
20	0.999996	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	0.999996
30	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
40	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
50	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
60	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
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

System dependability

All seven subsystems are connected through one another in sequence. Just one failure leads to complete failure of the system. The overall system dependability of the cooling tower is determined by

$$\begin{aligned}
 D_{\min(Sys)} &= D_{\min(S_1)} * D_{\min(S_2)} * D_{\min(S_3)} * D_{\min(S_4)} * D_{\min(S_5)} * D_{\min(S_6)} * D_{\min(S_7)} \\
 &= 0.977984582
 \end{aligned}
 \tag{34}$$

The summarized form of all the RAMD indices computed above for all the subsystems of cooling tower is given in table 4 which is as follows

Table 4. RAMD indices for cooling tower in STPP

RAMD indices	Subsys S ₁	Subsys S ₂	Subsys S ₃	Subsys S ₄	Subsys S ₅	Subsys S ₆	Subsys S ₇	System
Reliability	$e^{-0.003t}$	$e^{-0.0073t}$	$e^{-0.0009t}$	$e^{-0.012t}$	$e^{-0.0025t}$	$e^{-0.005t}$	$e^{-0.0045t}$	$e^{-0.0352t}$
Maintainability	$1-e^{-0.62t}$	$1-e^{-1.25t}$	$1-e^{-0.92t}$	$1-e^{-4.48t}$	$1-e^{-0.75t}$	$1-e^{-0.95t}$	$1-e^{-1.8t}$	$1-e^{-4.0966t}$
Availability	0.995185	0.994194	0.999023	0.999993	0.996678	0.994764	0.997506	0.977547
MTBF	333.3333	136.9863	111.1111	83.3333	400.0000	200.0000	222.2222	1486.9863
MTRR	1.612903	0.800000	1.086957	0.000600	1.333333	1.052632	0.555556	6.441981
Dependability or Dmin	0.995285	0.994334	0.999028	0.999993	0.996730	0.994881	0.997537	0.977985
dependability ratio	206.6667	171.2329	1022.2222	138810.2292	300.0000	190.0000	400.0000	

Table 5. Impact of failure rate of subsystems S₁ & S₂ on their reliability

Time (in months)	System S ₁		Subsystem S ₂	
	$\beta_1=0.002$	$\beta_1=0.006$	$\beta_2=0.005$	$\beta_2=0.015$
0	1.000000	1.000000	1.000000	1.000000
10	0.980199	0.941765	0.951229	0.860708
20	0.960789	0.886920	0.904837	0.740818
30	0.941765	0.835270	0.860708	0.637628
40	0.923116	0.786628	0.818731	0.548812
50	0.904837	0.740818	0.778801	0.472367
60	0.886920	0.697676	0.740818	0.406570
70	0.869358	0.657047	0.704688	0.349938
80	0.852144	0.618783	0.670320	0.301194
90	0.835270	0.582748	0.637628	0.259240
100	0.818731	0.548812	0.606531	0.223130

Table 6. Impact of failure rate of subsystems S₃ & S₄ on their reliability

Time (in months)	Subsystem S ₃		Subsystem S ₄	
	$\beta_3=0.0002$	$\beta_3=0.007$	$\beta_4=0.001$	$\beta_4=0.009$
0	1.000000	1.000000	1.000000	1.000000
10	0.998002	0.932394	0.980199	0.835270
20	0.996008	0.869358	0.960789	0.697676
30	0.994018	0.810584	0.941765	0.582748
40	0.992032	0.755784	0.923116	0.486752
50	0.990050	0.704688	0.904837	0.406570
60	0.988072	0.657047	0.886920	0.339596
70	0.986098	0.612626	0.869358	0.283654
80	0.984127	0.571209	0.852144	0.236928
90	0.982161	0.532592	0.835270	0.197899
100	0.980199	0.496585	0.818731	0.165299

Table 7. Impact of failure rate of subsystems S₅ & S₆ on their reliability

Time (in months)	Subsystem S ₅		Subsystem S ₆	
	$\beta_5=0.0012$	$\beta_5=0.0040$	$\beta_6=0.001$	$\beta_6=0.009$
0	1.000000	1.000000	1.000000	1.000000
10	0.988072	0.960789	0.990050	0.913931
20	0.976286	0.923116	0.980199	0.835270
30	0.964640	0.886920	0.970446	0.763379
40	0.953134	0.852144	0.960789	0.697676
50	0.941765	0.818731	0.951229	0.637628
60	0.930531	0.786628	0.941765	0.582748
70	0.919431	0.755784	0.932394	0.532592
80	0.908464	0.726149	0.923116	0.486752
90	0.897628	0.697676	0.913931	0.444858
100	0.886920	0.670320	0.904837	0.406570

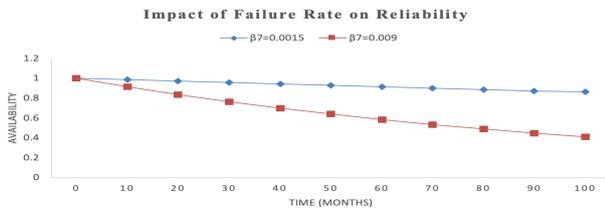


Fig 8. Effect of failure rate of subsystem S7 on subsystem’s reliability

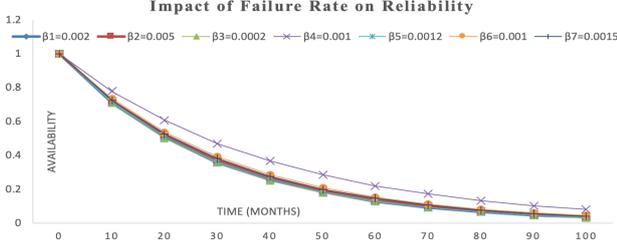


Fig. 9. Impact of failure rate of various subsystem’s failure rate on system reliability

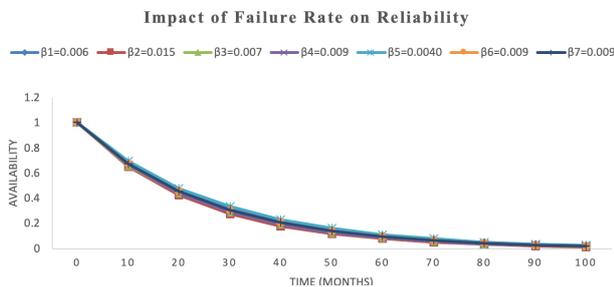


Fig. 10. Impact of increased failure rate of various subsystem’s failure rate on system reliability

4. Discussion and conclusion

Empirical study for a particular case has been carried out by assigning numerical values to various parameters as given in Table 1 to obtain reliability measures of the various subsystems and system. Results for several subsystem’s reliability and maintenance behaviors have been provided in Tables 2 and 3 respectively. Table 4 summaries all other RAMD measures. From the numerical analysis mentioned in table 2, it is revealed that after operation of 50 months cooling tower’s reliability remains 0.172044864 only while automatic deaerator valves reliability is very low among all the subsystems and needs special attention. Hence system designers must plan some maintenance policy for it. From tables 5-7 and figures 3.8-3.10, it is revealed that as the failure rate increases the system’s reliability sharply decreases. From this study, it is concluded that subsystem S4 i.e. deaerator valves are most critical and highly sensitive components and it require special attention to improve the reliability of the cooling tower. It is inferred that by monitor the failure rates of the deaerator valves and applying proper maintenance policies, management can improve the efficiency of the cooling tower and its working hours.

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List of notations and definitions

	System is working with full capacity
	System is in failure state
A, B, C, D, E and F	Represent states at which subsystem is working with full capacity
a, b, c, d, e and f	Represent states at which subsystem is failed
D_1	Represent states at which subsystem D is in cold standby state
$\beta_i \quad i = 1,2,3,4,5,6,7$	Failure rate of subsystem A, B, C, D, E, F and G respectively
$\mu_i \quad i = 1,2,3,4,5,6,7$	Repair rate of subsystems A, B, C, D, E, F and G respectively
$p_0(t)$	Probability that system is in initial state with full capacity
$p_i \quad ; i=0,1,2$	Steady state probability that the system is in i^{th} state
$f(x) = \begin{cases} \lambda e^{-\lambda x}, & 0 \leq x \leq \infty \\ 0, & otherwise \end{cases}$	Probability density function of exponential distribution
$R(t) = P(T > t) = \int_t^{\infty} f(x) dx$	Reliability function (1)
$Availability \ function = \frac{Life \ time}{total \ time} = \frac{Life \ time}{Life \ time + Repair \ time} = \frac{MTTF}{MTTF + MTTR}$	(2)
$M(t) = P(T \leq t) = 1 - e^{(\frac{-t}{MTTR})}$	Maintainability function (3)
$MTBF = \int_0^{\infty} R(t) dt = \int_0^{\infty} e^{-\theta t} dt = \frac{1}{\theta}$	Mean Time Between Failures (4)
$MTTR = \frac{1}{\mu}$	Mean Time to repair (5)
$\mu = \text{repair rate} ; \quad \beta = \text{failure rate}$	(6)
$d = \frac{\mu}{\beta} = \frac{MTBF}{MTTR}$	Dependability ratio (7)
$D_{min} = 1 - (\frac{1}{d-1}) (e^{-1nd/d-1} - e^{-d1nd/d-1})$	(8)