International Journal of Mathematical, Engineering and Management Sciences
Vol. 10, No. 2, 567-582, 2025
https://doi.org/10.33889/IJMEMS.2025.10.2.029

Feeding System's Sensitivity and Reliability Analysis through Markov Decision Process

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(Received on September 13, 2024; Revised on November 9, 2024 & December 9, 2024; Accepted on January 14, 2025)

Abstract
The present study investigates a Feeding system, which is responsible for continuous coal supply to the boiler of coal fired power plants. As a result of complex working condition in the power plant, feeding system is prone to system failure. Therefore, analyzing the various reliability indices, their significance and importance of different components is pivotal. The feeding system comprises of different components, such as a primary feeder, secondary feeder, stacker reclaimer, and a set of primary and secondary conveyors. A continuous coal supply is needed for the smooth functioning of power plant boilers, and an appropriate maintenance strategy is essential. In the present study Markov process is utilized to develop a mathematical model of the Feeding system, which is used to evaluate the system's reliability parameters. Numerical results for various system parameters are obtained and illustrated with graphs. In addition, sensitivity analysis is also conducted to comprehend the impact of different failures on the system's overall performance. Also, the expected profit of the system is assessed. This research is imperative for improving operational efficiency in power plants and intensify economic benefits.

Keywords- Markov decision process, Feeding system, Sensitivity analysis, Profit function.

1. Introduction

In the current technology-driven era, reliability-based analysis has gained much attention due to their diversified applications across all fields. To increase the efficiency of a production system, a highly reliable system is needed, so industries have always been interested in finding the components of the system that affect product performance less over time or, one can say, highly reliable components. The reliability of the feeding system within power station boilers is necessary for the overall efficiency and stability of the energy generation process. If the coal supply is not continuous and consistent, it may affect the operating condition of the boiler and cause production loss. Therefore, appropriate strategies for maintaining critical components of the feeding system play a crucial role. Many researchers and engineers have contributed a lot towards enhancing the performance of various industrial systems by identifying numerous parameters that affect the performance of the systems. Ram and Kumar (2013) studied some crucial reliability measures of the coal handling system of a thermal power plant by incorporating the Markov process and driving many paramount results. A multi component multi state system by considering reboot delay and vacation policy in operation, through Markov process, is discussed by Tyagi et al. (2024). Here, author obtained several performance measures such as availability, reliability, and Mean time to failure (MTTF). Balaguruswamy (2005) has discussed various mathematical models for the analysis of availability through different methodologies and processes. Markov Model and different expressions for reliability measurements of different systems, including *k*-out-of-*n*, standby redundancy, mixed configuration system etc., in industry as well as in nature can be seen in (Kumar et al., 2024; Lisnianski et al., 2010; Li, 2016; Wang, 2019; Zheng et al., 2018). A system reliability model, subject to shock, is derived by using the concept of semi-Markov process and MTTF along with impact of shock threshold on the same is discussed by Jiang and Jia (2024). Mathematical model for industrial systems through Markov process were investigated by Kozlowski et al. (2023), Kumar and Kumar (2023), Meango and Ouali (2020), Singh et al. (2021). Markov chain modeling to estimate the availability of a sugarcane harvesting system was used by Afsharnia et al. (2020). The findings suggest optimized maintenance scheduling to improve harvesting efficiency significantly. The performance of a rotor used in an electric motor manufacturing system, through NHCTMP is discussed by Iscioglu and Kocak (2019). Raghav et al. (2022) demonstrated how availability varies over time for a critical system having a subsystem arranged in a series configuration. A RAM Model is developed to analyze the coal handling system, using the Markovian approach by Mishra and Mishra (2020). Proper maintenance procedures for the wagon tripler, coal crusher, and belt conveyor can improvise the performance of a system. Gupta et al. (2009) developed a Markov model that helps in the comparative analysis of alternative maintenance policy of coal handling units. Barabady and Kumar (2007) state that reliability and availability are the most crucial factors in performance measures for repairable systems. Kumar et al. (2019) investigates the reliability analysis of SCS using optimized MC. And successfully applied the technique to safety critical systems of nuclear power plants. The concept of warranty policy in an industrial system was discussed by Niwas and Garg (2018). Yadav et al. (2022) investigated the reliability and availability of smart micro grids along with the specific configuration of PV panels using Markov random process. Sharma and Kaur (2022) described a model that plays a substantial role in operating the system at reduced capacity to make a profitable system by achieving maximum availability. Malik and Tewari (2023) investigated coal ash handling systems through the likelihood approach. Electro Static Precipitator (ESP) is the most critical subsystem as the performability rises significantly. Jagtap et al. (2023) studied the performance of the boiler furnace system, based on the Markov approach, and suggested to plan the maintenance strategy as per components operating conditions. Liang et al. (2022) demonstrated that simplifying Markov state-based models can maintain reliability prediction accuracy while reducing computational costs for complex safety systems. Okoye et al. (2020) formulated a study between load and capacity using the IEEE reliability test system. Song and Wang (2022) discussed about a k-out-of-n system with multiple interactive mechanisms by incorporating the Markov process. The concept of conditional probability method, for a structure, for dynamic reliability calculation is used by Kubica at al. (2024). The concept of multi state flow network through node child matrix was discussed by Elahabad and Alsalami (2023). The study presented by Jyotish et al. (2023) focuses on the reliability and performance of critical instrumentation and control systems in nuclear power plants. The authors propose a framework using Batch Deterministic and Stochastic Petri Nets (BDSPNs) to evaluate these systems. Tyagi and Ram (2024) investigated how multi-state failures and repairs impact the performance of a wind-hydro power plant. The modeling approach presented by the authors reveals the effects of various operational states on system reliability and availability and highlights different strategies to enhance the performance and resilience of renewable energy systems. A glance at the literature shows the significant role of reliability measurements in various industrial systems.

Despite advancements in power plant operations, research on the reliability measures of the coal-feeding system remains limited. The existing study of feeding systems gives limited attention to the sensitivity analysis of feeding systems. This research aims to analyze different critical sub-units/components of the feeding system in power plant boilers to enhance performance and potential improvement within the subsystem. Also, authors have done component wise reliability analysis of feeding system which was not done in past and make this work novel. The findings in this research provide actionable insights into optimizing maintenance strategies and ultimately achieving greater economic returns.

2. System Description

Feeding system for a boiler that continuously supplies to the power plant boiler consists of various components such as the primary feeder that loads the coal from the bin and supplies it to a parallelly connected set of primary conveyors. Coal is transported to stacker reclaimer by primary conveyors that further lifts the coal to secondary feeders. Set of secondary conveyors connected in parallel, supplies the coal to the burner after loading coal from the secondary feeder. A system failed after the failure of the stacker reclaimer and primary and secondary feeder, and worked in degraded mode after failure of 1-out-of-2: G sets of primary and secondary conveyors. 1-out-of-2: G redundancy for the conveyors helps improve reliability by allowing one unit to take over if the other fails. This ensures that the feeding system operates continuously, which is important for the power plant's efficiency. The below **Figure 1** represents flow of feeding system.

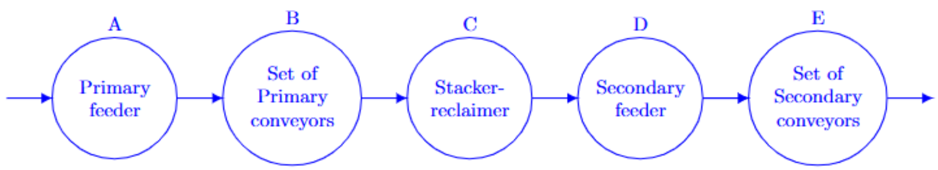

Figure 1. Flow chart.

The following assumptions are followed throughout the article,
- At t = 0, the Feeding system if defect free.
- Repair facilities are accessible at any given moment.
- After the failure of a component the complete system can be either in degraded state of in failed state.
- Conveyors are considered in 1-out of-2: G redundancy.

3. Nomenclature

The section provides the overview of notations used throughout the paper (see **Table 1**).

Table 1. Nomenclature

Notation	Description
$P_0(t)$	likelihood that feeding system is operating in good condition at any instant t.
$P_1(x,t)$	likelihood that feeding system is in failed state, at instant t, due to failure of primary feeder.
$P_2(x,t)$	likelihood that feeding system is in failed state, at instant t, due to failure of stacker reclaimer.
$P_3(x,t)$	likelihood of feeding system's failure, at any time t, due to the failure of secondary feeder.
$P_4(t)$	likelihood that feeding system, at any instant t, is working in degraded state after the failure of 1-out-of-2 primary conveyors.
$P_5(x,t)$	likelihood that feeding system, at any instant t, is in degraded state after the failure of 1-out-of-2 secondary conveyors.
$P_6(x,t)$	It represents the feeding system's failure likelihood, at any instant t, due to the failure of primary feeder after the failure of first set of primary conveyors.
$P_7(x,t)$	It represents the system's failure likelihood at any moment t due to the failure of stacker reclaimer after the failure of first set of primary conveyors.
$P_8(x,t)$	It represents the system's failure likelihood at any moment t due to the failure of secondary feeder after the failure of first set of primary conveyors.
$P_9(x,t)$	It represents the system's failure likelihood at any moment t due to the failure of 2^{nd} set of primary conveyors in succession of the failure of first set of primary conveyors.
$P_{10}(x,t)$	It represents the system's failure likelihood at any moment t due to the failure of primary feeder after the failure of first set of secondary conveyors.
$P_{11}(x,t)$	It represents the system's failure likelihood at any moment t due to the failure of stacker reclaimer after the failure of first set of secondary conveyors.

Table 1 continued…

$P_{12}(x,t)$	It represents the system's failure likelihood at any moment *t* due to the failure of secondary feeder after the failure of first set of secondary conveyors.
$P_{13}(x,t)$	It represents the system's failure likelihood, at any moment *t*, due to the failure of second set of secondary conveyors in succession of failure of first set of secondary conveyors.
$\lambda_{pf}, \lambda_{pc}, \lambda_{sr}, \lambda_{sc}, \lambda_{sf}$	Failure rate of primary feeder, primary conveyors, stacker reclaimer, secondary feeder, secondary conveyor, secondary feeder respectively.
$\mu_{pf}, \mu_{pc}, \mu_{sr}, \mu_{sc}, \mu_{sf}$	Repair rate of primary feeder, primary conveyors, stacker reclaimer, secondary feeder, secondary conveyor, secondary feeder respectively.
μ_1, μ_2	Simultaneous repair rate of primary feeder, primary conveyor, stacker reclaimer, secondary feeder which are failed after the failure of first set of primary conveyors, secondary conveyors.

4. State Transition Diagram

A state transition diagram is the geometrical representation of the various states, and their interconnection through different failure/repair, in which the system can be present (Balaguruswamy, 2005; Kumar and Kumar, 2023). Here, it is constructed through Markov process and shown in the following **Figure 2**.

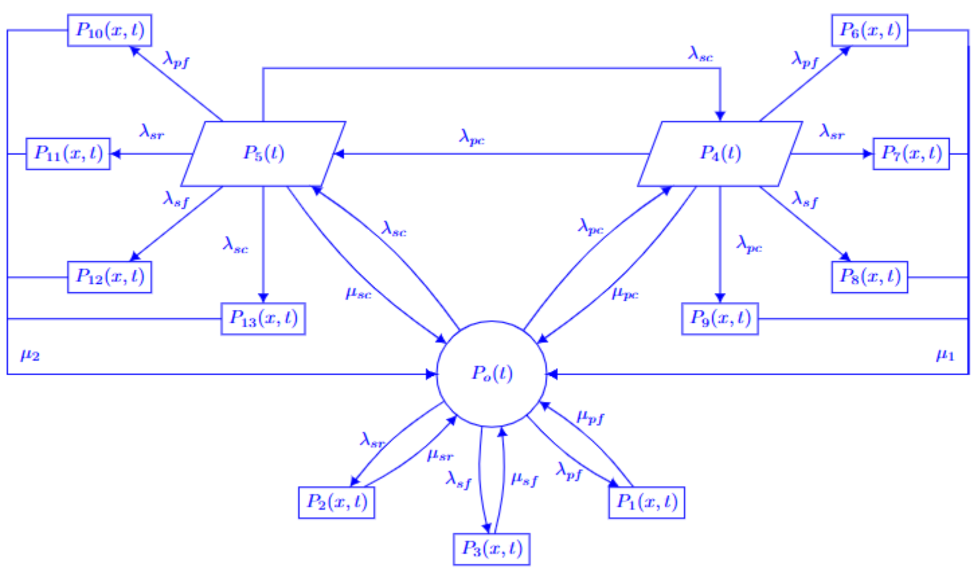

Figure 2. State transition diagram for the feeding system.

5. Mathematical Formulation and Solution

Considering state transition diagram **Figure 2**, which is obtained through Markov process. The following Equations (1)-(10) are generated, represent the different state probability, which is the mathematical interpretation of the considered model.

$$\left(\frac{d}{dt} + \lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc}\right).P_0(t) = \mu_{pc}P_4(t) + \mu_{sc}P_5(t) + \sum_{i,j}\int_0^\infty \mu_i\, P_j\,(x,t)\,dx \tag{1}$$

where, $i = pf, sr, sf, \mu_1, \mu_1, \mu_1, \mu_1, \mu_{2,}\, \mu_{2,}\, \mu_{2,}\, \mu_2,$
$j = 1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13.$

$$\left(\frac{d}{dt}+\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+\lambda_{pc}+\lambda_{sc}+\mu_{pc}\right).P_4(t)=\lambda_{pc}P_0(t)+\lambda_{pc}P_5(t) \tag{2}$$

$$\left(\frac{d}{dt}+\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+\lambda_{pc}+\lambda_{sc}+\mu_{sc}\right).P_5(t)=\lambda_{sc}P_0(t)+\lambda_{sc}P_4(t) \tag{3}$$

$$\left(\frac{\partial}{\partial x}+\frac{\partial}{\partial t}+\mu_j\right).P_k(x,t)=0 \tag{4}$$

where, $j = pf, sr, sf; k = 1, 2, 3.$

$$\left(\frac{\partial}{\partial x}+\frac{\partial}{\partial t}+\mu_1\right).P_m(x,t)=0 \tag{5}$$

where, $m = 6, 7, 8, 9.$

$$\left(\frac{\partial}{\partial x}+\frac{\partial}{\partial t}+\mu_2\right).P_m(x,t)=0 \tag{6}$$

where, $m = 10, 11, 12, 13.$

With initial and boundary conditions as,

$$P_i(j)=\begin{cases}1, & i=j=0\\ 0, & \text{otherwise}\end{cases} \tag{7}$$

$$P_i(0,t)=\lambda_l\,P_0(t) \tag{8}$$

where, $i = 1, 2, 3; l = pf, sr, sf.$

$$P_j(0,t)=\lambda_m\,P_4(t) \tag{9}$$

where, $j = 6, 7, 8, 9; l = pf, sr, sf, pc.$

$$P_k(0,t)=\lambda_n\,P_4(t) \tag{10}$$

where, $k = 10, 11, 12, 13; n = pf, sr, sf, sc.$

Now solving the above Equation (1)-(10) by utilizing the concept of Laplace and Inverse Laplace transform, various state transition probability of the feeding system are obtained as follows.

$$\overline{P}_0(s)=\frac{1}{H_1-H_6-H_4\left[\mu_{pc}+\dfrac{\mu_1(H_1-s-\lambda_{sc})}{(s+\mu_1)}\right]-H_5\left[\mu_{sc}+\dfrac{\mu_2(H_1-s-\lambda_{pc})}{(s+\mu_2)}\right]} \tag{11}$$

$$\overline{P}_4(s)=\frac{\lambda_{pc}(H_3+\lambda_{sc})}{H_2H_3-\lambda_{pc}\lambda_{sc}}\overline{P}_0(s) \tag{12}$$

$$\overline{P}_5(s)=\frac{\lambda_{sc}(H_2+\lambda_{pc})}{H_2H_3-\lambda_{pc}\lambda_{sc}}\overline{P}_0(s) \tag{13}$$

$$\overline{P}_i(x,s)=\frac{\lambda_j}{(s+\mu_j)}\overline{P}_0(s) \tag{14}$$

where, $i = 1, 2, 3; j = pf, sr, sf$

$$\overline{P}_i(x,s)=\frac{\lambda_j}{(s+\mu_k)}.\frac{\lambda_l(H_m+\lambda_n)}{(H_2H_3-\lambda_{pc}\lambda_{sc})}\overline{P}_0(s) \tag{15}$$

where, $i = 6, 7, 8, 9, 10, 11, 12, 13; j = pf, sr, sf, pc, pf, sr, sr, sf,$

$k = 1, 1, 1, 1, 2, 2, 2, 2; l = pc, pc, pc, pc, pf, pf, pf, pf,$

$m = 3, 3, 3, 3, 2, 2, 2, 2; n = sc, sc, sc, sc, pc, pc, pc, pc.$

Also, $H_1 = \left(s + \lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc}\right),$

$H_2 = \left(s + \lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc} + \mu_{pc}\right),$

$H_3 = \left(s + \lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc} + \mu_{sc}\right),$

$H_4 = \dfrac{\lambda_{pc}(H_3 + \lambda_{sc})}{(H_2H_3 - \lambda_{pc}\lambda_{sc})}; H_5 = \dfrac{\lambda_{sc}(H_2 + \lambda_{pc})}{(H_2H_3 - \lambda_{pc}\lambda_{sc})};$

$H_6 = \frac{\lambda_{pf}\mu_{pf}}{(s+\mu_{pf})} + \frac{\lambda_{sr}\mu_{sr}}{(s+\mu_{sr})} + \frac{\lambda_{sf}\mu_{sf}}{(s+\mu_{sf})}.$

The above state transition probabilities are used to find the working (up state) and failed (down state) state of the feeding system, through the basic rule of likelihood as follows.

$$\overline{P}_{up}(s)=\overline{P}_0(s)+\sum_{i=4,5}\overline{P}_i(s) \tag{16}$$

$$\overline{P}_{down}(s)=\sum_{i=1,2,3}\overline{P}_i(x,s)+\sum_{i=4}^{13}\overline{P}_i(x,s) \tag{17}$$

6. Reliability Measures Analysis of Feeding System

6.1 Availability Analysis

Availability is a measure of system's performance when routine repair policy is followed. Consider the numerical value of various failures as $\lambda_{pf}=0.001$, $\lambda_{sr}=0.01$, $\lambda_{sf}=0.002$, $\lambda_{sc}=0.03$, $\lambda_{pc}=0.02$, with the assumption that a repairmen is always available to repair the failed components, in Equation (16) and then taking inverse Laplace transform, we obtain the availability of the feeding system as given below.

$$Av(t) = 1388.288169(0.000055 \sinh(0.024494\ t) + 0.000052 \cosh(0.024494\ t)-0.000042)e^{-1.063t} + 0.986005 \tag{18}$$

Now to understand the nature of feeding system's availability, let us vary the time unit in Equation (18). The following **Figure 3** gives the clear understanding about the availability of the feeding system.

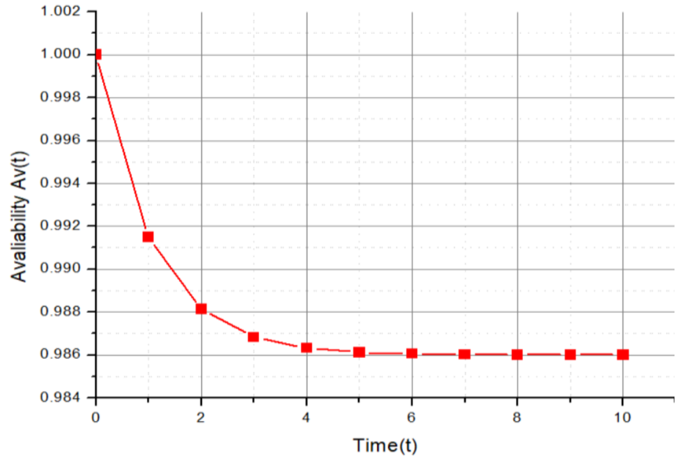

Figure 3. Graphical representation of the behavior of Availability w.r.t. time unit (t).

6.2 Reliability Analysis

Reliability is the likelihood that a system/device will successfully perform the required operations without failure. However, the reliability analysis of a feeding system become too complex due to multi-state failure and multi-state functionality. Here it is calculated based on Equation (16), with all repair as zero and then taking the inverse Laplace transform (Ram and Kumar, 2013). The reliability expression as a function of failure rates and time unit is obtained as Equation (19).

$$R(t)=e^{-(\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+\lambda_{pc}+\lambda_{sc})\,t}\left(2\cosh\left(t\sqrt{\lambda_{pc}\lambda_{sc}}\right)+\frac{\sqrt{\lambda_{pc}\lambda_{sc}}\sinh\left(t\sqrt{\lambda_{pc}\lambda_{sc}}\right)\left(\lambda_{pc}+\lambda_{sc}\right)}{\left(\lambda_{pc}\lambda_{sc}\right)}-1\right) \tag{19}$$

The following **Figure 4**, **Figure 5**, **Figure 6**, **Figure 7**, **Figure 8** represents the behavior of seeding system reliability with respect to the failure rate of primary conveyors, secondary feeder, stacker reclaimer, secondary conveyor, primary feeder along with time unit t.

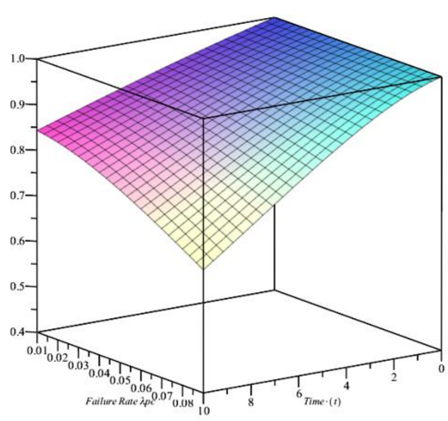

Figure 4. Reliability vs. failure rate of primary conveyors.

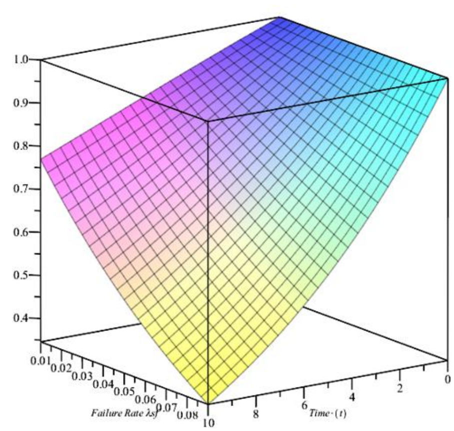

Figure 5. Reliability vs. failure rate of secondary feeder.

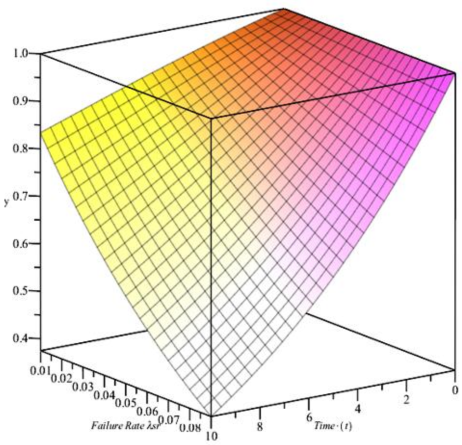

Figure 6. Reliability vs. failure rate of stacker reclaimer.

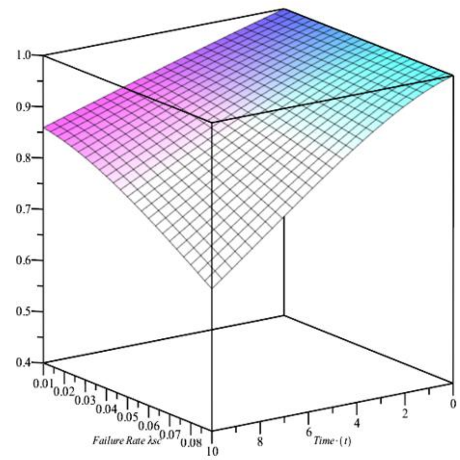

Figure 7. Reliability vs. failure rate of secondary conveyor.

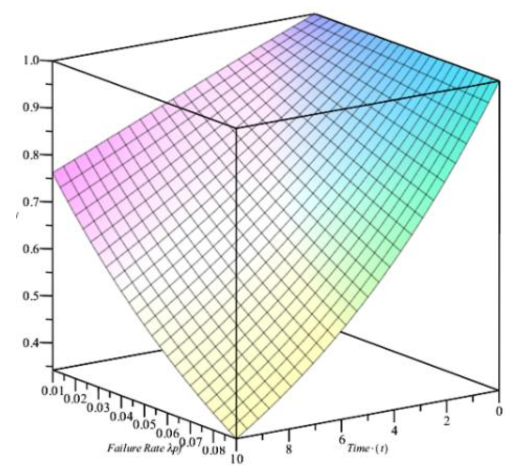

Figure 8. Reliability vs. failure rate of primary feeder.

6.3 MTTF Analysis

Mean time to failure of a system is a maintenance metric that measures the average operating time before experiencing a failure. It can directly be obtained by using below Equation (20) (Ram and Kumar, 2013).

$$\text{MTTF} = \int_0^\infty R(t)\,dt \tag{20}$$

$$\text{MTTF} = \frac{1}{\left(\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+\lambda_{pc}+\lambda_{sc}\right)} \left\{1+\frac{\lambda_{pc}\left(\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+\lambda_{pc}+2\lambda_{sc}\right)+\lambda_{sc}\left(\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+2\lambda_{pc}+\lambda_{sc}\right)}{\left(\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+\lambda_{pc}+\lambda_{sc}\right)^2-\lambda_{pc}\lambda_{sc}}\right\} \tag{21}$$

For understanding the feeding system MTTF behavior put the failure rates as $\lambda_{pf}=0.001$, $\lambda_{sr}=0.01$, $\lambda_{sf}=0.002$, $\lambda_{sc}=0.03$, $\lambda_{pc}=0.02$ and then varying these failure one by one in Equation (21), one can get following **Figure 9**, which clearly depict the feeding system's MTTF measure.

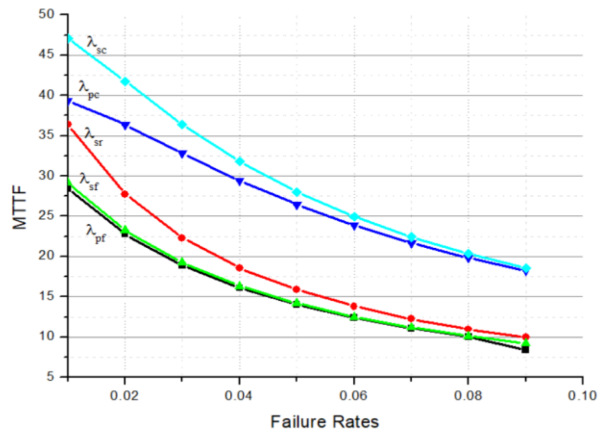

Figure 9. MTTF vs. Failure rates.

6.4 Sensitivity Analysis

Sensitivity analysis for reliability and MTTF helps identify which components impact system performance most. For reliability, it highlights the parts whose failures would most disrupt the system's operation. For MTTF, it identifies components that most influence the average time before a failure happens.

6.4.1 Sensitivity Analysis for Feeding System Reliability

It is a methodology, which is utilize, to understand that how a system's overall performance change with change in various failure rates of its components. Many researchers/engineering incorporate this technique to find out the most/least importance component in a system. Here, sensitivity assessment for reliability of the Feeding system is performed to check the critical component of the same. It uses the concept of partial derivative. Now taking the partial derivative of the Equation (19) with respect to various failure rates and then substituting failure rates as $\lambda_{pf}=0.001$, $\lambda_{sr}=0.01$, $\lambda_{sf}=0.002$, $\lambda_{sc}=0.03$, $\lambda_{pc}=0.02$, authors obtain following **Table 2** and **Figure 10** which represent the sensitivity of feeding system's reliability with different failure rates.

Table 2. Sensitivity of reliability.

Time unit (t)	$\frac{\partial R(t)}{\partial \lambda_{pf}}$	$\frac{\partial R(t)}{\partial \lambda_{sr}}$	$\frac{\partial R(t)}{\partial \lambda_{sf}}$	$\frac{\partial R(t)}{\partial \lambda_{pc}}$	$\frac{\partial R(t)}{\partial \lambda_{sc}}$
0	0	0	0	0	0
1	-0.9864	-0.9864	-0.9864	-0.019	-0.0284
2	-1.9438	-1.9438	-1.9438	-0.0723	-0.1081
3	-2.8696	-2.8696	-2.8696	-0.1547	-0.2311
4	-3.7616	-3.7616	-3.7616	-0.2615	-0.3902
5	-4.6182	-4.6182	-4.6182	-0.38867	-0.5791
6	-5.4382	-5.4382	-5.4382	-0.5322	-0.7921
7	-6.2205	-6.2205	-6.2205	-0.6889	-1.0241
8	-6.9645	-6.9645	-6.9645	-0.8557	-1.2707
9	-7.6700	-7.6700	-7.6700	-1.0301	-1.5279
10	-8.3367	-8.3367	-8.3367	-1.2096	-1.7922

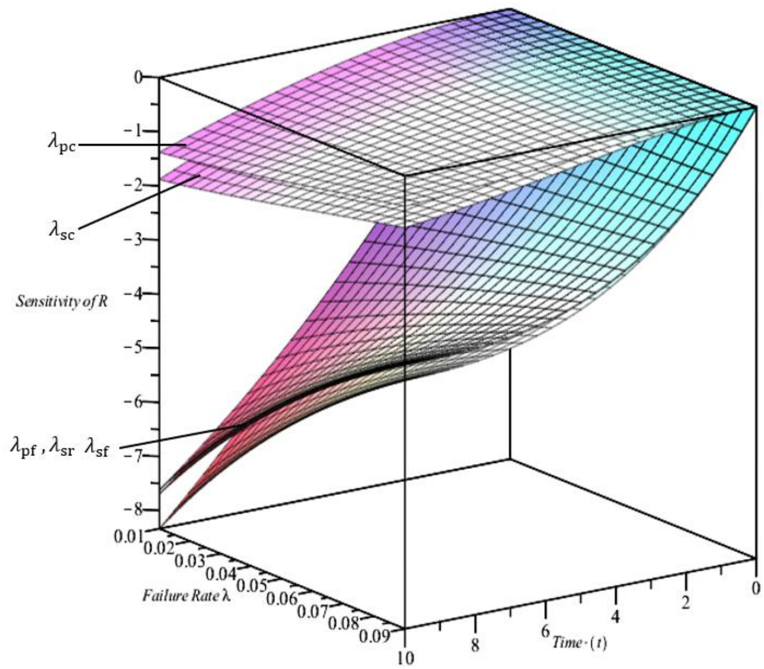

Figure 10. Sensitivity w. r. t. reliability of feeding system.

6.4.2 Sensitivity Analysis for Feeding System MTTF

Sensitivity assessment of MTTF is important to understand the impact of failure rates and it is derived by partial differentiation of MTTF with respect to failure rates. Setting up various failure rates as $\lambda_{sr} = 0.01,$ $\lambda_{sf} = 0.002,$ $\lambda_{sc} = 0.03,$ $\lambda_{pc} = 0.02$ in the obtained partial derivatives. one can compute MTTF sensitivity, which is reflected in the following **Table 3** and **Figure 11**.

Table 3. Sensitivity of feeding system's MTTF.

Failure rate	$\frac{\partial(\text{MTTF})}{\partial\lambda_{pf}}$	$\frac{\partial(\text{MTTF})}{\partial\lambda_{sr}}$	$\frac{\partial(\text{MTTF})}{\partial\lambda_{sf}}$	$\frac{\partial(\text{MTTF})}{\partial\lambda_{pc}}$	$\frac{\partial(\text{MTTF})}{\partial\lambda_{sc}}$
0.01	-700.257	-1108.204	-733.659	-210.952	-455.415
0.02	-460.504	-669.013	-478.594	-346.188	-562.275
0.03	-323.749	-443.389	-334.547	-353.180	-501.252
0.04	-238.969	-313.451	-245.887	-319.204	-415.36
0.05	-183.060	-232.332	-187.737	-276.665	-338.948
0.06	-144.387	-178.552	-147.686	-236.532	-277.422
0.07	-116.600	-141.195	-119.008	-201.837	-229.173
0.08	-96.005	-114.262	-97.813	-172.805	-191.424
0.09	-68.171	-94.246	-81.733	-148.786	-161.687

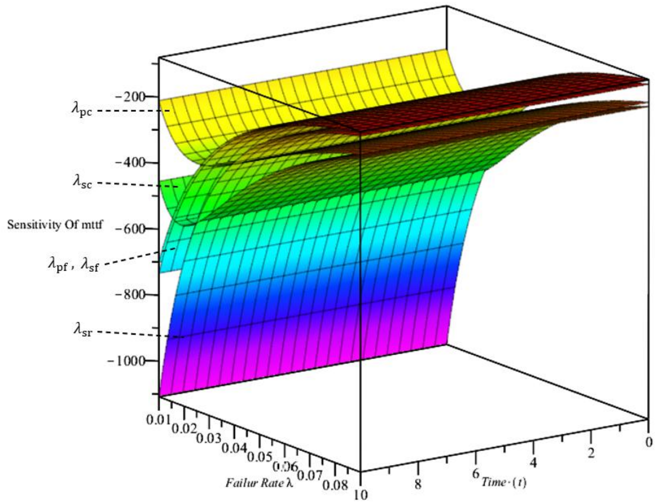

Figure 11. Sensitivity w.r.t MTTF of feeding system.

6.5 Profit Function

As repairmen is accessible throughout the time, the expression for the profit function $E_p(t)$ in the interval $[0, t)$ is given as (Ram and Kumar, 2013),

$$E_p(t) = X_r \int_0^t P_{up}(t)\, dt - tX_{sc} \tag{22}$$

where, X_r is Revenue generated from the system and X_{sc} is service cost for the same. Using Equation (16) in Equation (22), one can derive following expression for expected function of the feeding system.

$$E_p(t) = X_r(0.0148 + 0.0557 \sinh(1.0630t)\ \ 0.9860\, t\ + 0.0721 \sinh(1.0385t) \\ + 0.0557 \cosh(1.0630t) - 0.0721 \cosh(1.0385t) + 0.0015 \cosh(1.0874t)) - tX_{sc} \tag{23}$$

Now by putting revenue and service cost in Equation (23) and varying time unit *t*, one can understand the nature of profit function from the feeding system. For making it clearer, let us consider $X_r = 1$ unit and varying X_{sc} in Equation (23), **Figure 12** is obtained, which depict the nature of profit function for the feeding system.

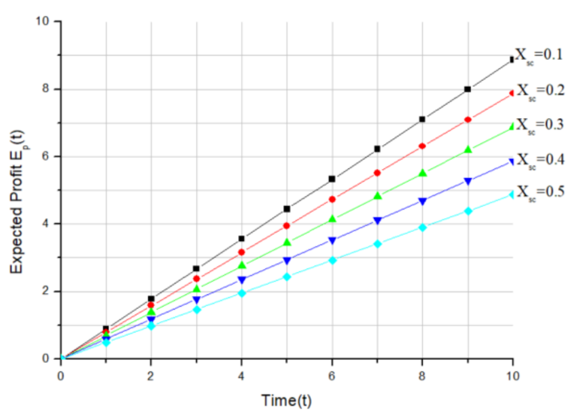

Figure 12. Expected profit function nature from feeding system.

7. Results and Discussion

The objective of this work is to analyze the reliability, availability, MTTF and sensitivity analysis of the feeding system used in power plant boiler. The performance analysis of the system is carried out by employing Markov approach. **Figure 3** represent the nature of feeding system availability as time passes. From the plot, we can conclude that availability decreases over the time passes and becomes constant after 6 unit of time at 0.9760. The data ensures that system is designed for consistent performance. Similarly, **Figure 4, Figure 5, Figure 6, Figure 7, Figure 8** demonstrate that the reliability declines rapidly as compared to availability. Initially the system is highly reliable, observations reveal that system deteriorates over time, which shows the significance of maintenance strategy. Further MTTF has been shown in **Figure 9** with variation in failure rate. From **Figure 9**, author can conclude that the feeding system's MTTF decreases as the failure rate increases and the trend is consistent for all subsystem. The primary feeder, primary and secondary conveyors have slightly better reliability and be less prone to failure under same conditions. Stacker reclaimer and secondary feeder need more attention as they consistently show lower MTTF values at each failure rate. Sensitivity analysis is essential because it lets maintenance teams prioritize their focus on the components that affect system uptime and reliability the most. The sensitivity of Reliability is shown in **Figure 10** represents a sharp decrease in reliability w. r. t. the failure rates of primary feeder, secondary feeder, and stacker reclaimer. It reflects that the reliability of the Feeding system is having highest impact of the failure rate of primary and secondary feeder and stacker reclaimer. The sensitivity assessment of MTTF is represented in **Figure 11**. It reflects that the MTTF of the feeding system is most sensitive w. r. t. the failure rate of the stacker reclaimer. **Figure 12** reflects that the profit function of the feeding system decreases as service costs increases. Therefore, to enhance the profit, service cost must be controlled by choosing the optimal maintenance policy.

8. Conclusion

This research presents the time dependent performance analysis of the Feeding system, considering redundancy at the sub-system level, for a boiler used in coal fired power plant. Investigation has been done through Markov decision process. From the last section of results and discussion, it is concluded that the MTTF of the feeding system is more affected by failure rates of stacker reclaimer and secondary feeder. So, proper maintenance policy should be adopted to take care of these failures. The reliability of the Feeding system is more affected by the failure rates of primary feeder, secondary feeder, and stacker reclaimer. In addition, the MTTF of the system is more sensitive to the failure of the stacker reclaimer. So, to make the feeding system highly reliable and least sensitive we must control these failure rates by incorporating proper and optimal maintenance strategy. The difference between profit levels across the values of repair rates widens over time, emphasizing the significance of the repair rates on long-term profitability. The proposed model of the Feeding system contributes to a better understanding of how each component impacts the overall system's reliability, offering a framework for optimizing maintenance strategies and ensuring the continuous operation of the feeding system. The result of this study can be utilized by the plant management for the corrective execution of maintenance and performance enhancement of the Feeding system.

The present work can be extended as

- For optimizing the profit function PSO can be used.
- Incorporating fuzzy methodology for more robust understanding of the system.
- More failure rate e.g. human error, CCF etc. can be considered for the analysis.
- Extending the current model to analyze and optimize the entire power plant system, including interactions between different subsystems.

Conflicts of Interest
The authors declare no conflict of interest.

AI Disclosure
The author(s) declare that no assistance is taken from generative AI to write this article.

Acknowledgments
This work is supported by Symbiosis Institute of Technology, Pune Campus, Symbiosis International (Deemed University) (SIU), Pune, Maharashtra, India.

Appendix
The intro-differential equations by considering state transition diagram **Figure 2** can be generated with following process. The probability that the system in the good state $P_0(t)$ in the interval $(t\,, t+\Delta t)$ is as follows,

$$P_0(t+\Delta t) = (1-\lambda_{pf}\Delta t)\,(1-\lambda_{sr}\Delta t)\,(1-\lambda_{sf}\Delta t)\,(1-\lambda_{pc}\Delta t)\,(1-\lambda_{sc}\Delta t)\,.\,P_0(t) + \mu_{pc}P_4(t) + \mu_{sc}P_5(t) + \sum_{i,j}\int_0^\infty \mu_i P_j(x,t)dx.$$

where, $i = pf, sr, sf, \mu_1, \mu_1, \mu_1, \mu_1, \mu_{2,}\mu_{2,}\mu_{2,}\mu_2,$
$j = 1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13.$

$$\frac{P_0(t+\Delta t) - P_0(t)}{\Delta t} + (\lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc}).P_0(t) = \mu_{pc}P_4(t) + \mu_{sc}P_5(t) + \sum_{i,j}\int_0^\infty \mu_i P_j(x,t)dx.$$

Taking limit as $\Delta t \to 0$,

$$\lim_{\Delta t\to 0} \frac{P_0(t+\Delta t)-P_0(t)}{\Delta t} + (\lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc}).P_0(t) = \mu_{pc}P_4(t) + \mu_{sc}P_5(t) + \sum_{i,j}\int_0^\infty \mu_i P_j(x,t)dx.$$

$$\Rightarrow \left(\frac{d}{dt} + \lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc}\right).P_0(t) = \mu_{pc}P_4(t) + \mu_{sc}P_5(t) + \sum_{i,j}\int_0^\infty \mu_i P_j(x,t)dx.$$

The probability that the system in the degraded state $P_4(t)$ in the interval $(t\,, t+\Delta t)$ is as follows,

$$P_4(t+\Delta t) = (1-\lambda_{pf}\Delta t)(1-\lambda_{sr}\Delta t)(1-\lambda_{sf}\Delta t)(1-\lambda_{pc}\Delta t)(1-\lambda_{sc}\Delta t)(1-\mu_{pc}\Delta t).P_4(t) + \lambda_{pc}P_0(t) + \lambda_{pc}P_5(t).$$

$$\frac{P_4(t+\Delta t) - P_4(t)}{\Delta t} + (\lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc} + \mu_{pc})\,.\,P_4(t) = \lambda_{pc}P_0(t) + \lambda_{pc}P_5(t).$$

Taking limit as $\Delta t \to 0$,

$$\lim_{\Delta t\to 0} \frac{P_4(t+\Delta t) - P_4(t)}{\Delta t} + (\lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc} + \mu_{pc}).P_4(t) = \lambda_{pc}P_0(t) + \lambda_{pc}P_5(t).$$

$$\Rightarrow \left(\frac{d}{dt} + \lambda_{pf} + \lambda_{sr} + \lambda_{sf} + \lambda_{pc} + \lambda_{sc} + \mu_{pc}\right).P_4(t) = \lambda_{pc}P_0(t) + \lambda_{pc}P_5(t).$$

Similarly,

$$\left(\frac{d}{dt}+\lambda_{pf}+\lambda_{sr}+\lambda_{sf}+\lambda_{pc}+\lambda_{sc}+\mu_{sc}\right).P_5(t)=\lambda_{sc}P_0(t)+\lambda_{sc}P_4(t).$$

For failed state,

$$P_1(x+\Delta x\,,t\,+\,\Delta t)=\,(1-\mu_{pf}\,\Delta t).P_1(x,t),$$

$$\lim_{\Delta x\,,\Delta t\to 0}\,\frac{P_1(x+\Delta x\,,t\,+\Delta t)\,-P_1(x,t)}{\Delta t}+\mu_{pf}P_1(x,t)=0.$$

$$\Rightarrow\,\left(\frac{\partial}{\partial x}+\frac{\partial}{\partial t}+\mu_{pf}\right).P_1(x,t)=0.$$

References

Afsharnia, F., Marzban, A., Asoodar, M.A., & Abdeshahi, A. (2020). Availability modeling of sugarcane harvesting system by using Markov chain. *Journal of Biosystems Engineering*, *45*, 145-154.

Balaguruswamy, E. (2005). *Reliability engineering*, *3rd ed*. Tata McGraw-Hill Publication, New Delhi, India.

Barabady, J., & Kumar, U. (2007). Availability allocation through importance measures. *International Journal of Quality and Reliability Management*, *24*(6), 643-657.

Elahabad, M.F., & Alsalami, O.M. (2023). Using a node–child matrix to address the quickest path problem in multistate flow networks under transmission cost constraints. *Mathematics*, *11*(24), 4889. https://doi.org/10.3390/math11244889.

Gupta, S., Tewari, P.C., & Sharma, A.K. (2009). A Markov model for performance evaluation of coal handling unit of a thermal power plant. *Journal of Industrial and Systems Engineering*, *3*(2), 85-96.

Iscioglu, F., & Kocak A. (2019). Dynamic reliability analysis of a multi-state manufacturing system. *Eksploatacja i Niezawodnosc–Maintenance and Reliability*, *21*(3), 451-459.

Jagtap, H.P., Bewoor, A.K., Kumar, R., Ahmadi, M.H., Assad, M., & Sharifpur, M. (2023). Ram analysis and availability optimization of thermal power plant water circulation system using PSO. *Energy Reports*, *7*, 1133-1153.

Jiang, S., & Jia, X. (2024). Reliability assessment under continuous fatigue degradation and shock based on Markov renewal process. *Reliability Engineering & System Safety*, *248*, 110151. https://doi.org/10.1016/j.ress.2024.110151.

Jyotish, N., Singh, L, Kumar, C., & Singh, P. (2023). Reliability and performance evaluation of safety-critical instrumentation and control systems of nuclear power plant. *IEEE Transactions on Reliability*, *73*(1), 422-437.

Kozłowski, E., Borucka, A., Oleszczuk, P., & Jałowiec, T. (2023). Evaluation of the maintenance system readiness using the semi-Markov model taking into account hidden factors. *Eksploatacja I Niezawodnosc – Maintenance and Reliability*, *25*(4). http://doi.org/10.17531/ein/172857.

Kubica, J., Ahmed, B., Muhammad, A., & Aslam, M.U. (2024). Dynamic reliability calculation of random structures by conditional probability method. *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, *26*(2). http://doi.org/10.17531/ein/181133.

Kumar, A., Kumar, P., & Eelahabad, M.F. (2024). Multistate system performance analysis incorporating human error, mathematical modeling and reliability approach. *Advances in Systems Science and Applications*, *24*(1), 114-128.

Kumar, P., & Kumar, A. (2023). Quantifying reliability indices of garbage data collection iot-based sensor systems using Markov birth-death process. *International Journal of Mathematical, Engineering and Management Sciences*, *8*(6), 1255-1274.

Kumar, P., Singh, L.K., & Kumar, C. (2019). An optimized technique for reliability analysis of safety- critical systems: A case study of nuclear power plant. *Quality and Reliability Engineering International*, *35*(1), 461-469.

Li, J. (2016). Reliability calculation for dormant k-out-of-n systems with periodic maintenance. *International Journal of Mathematical, Engineering and Management Sciences*, *1*(2), 68-76.

Liang, Q., Yang, Y., Zhang, H., Peng, C., & Lu, J. (2022). Analysis of simplification in Markov state-based models for reliability assessment of complex safety systems. *Reliability Engineering & System Safety*, *221*, 108373.

Lisnianski, A., Frenkel, I., & Ding, Y. (2010). *Multi-state system reliability analysis and optimization for engineers and industrial managers*, *1st ed*. Springer, London, United Kingdom.

Malik, S., & Tewari, P.C. (2023). Performability and maintenance decisions for coal ash handling system of a subcritical thermal power plant. *International Journal of System Assurance Engineering and Management*, *14*(1), 45-54.

Meango, T.J.M., & Ouali, M.S. (2020). Failure interaction model based on extreme shock and Markov processes. *Reliability Engineering & System Safety*, *197*, 106827.

Mishra, A., & Mishra, R.P. (2020). Ram modeling for performance analysis of a coal handling system. *Materials Today: Proceedings*, *28* (4), 2149-2155.

Niwas, R., & Garg, H. (2018). An approach for analyzing the reliability and profit of an industrial system based on the cost-free warranty policy. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *40*(5), 265. https://doi.org/10.1007/s40430-018-1167-8.

Okoye, M.O., Yang, J., Lei, Z, Yuan, J., Ji, H., Wang, H., Feng, J., Otitoju, T.A., & Li, W. (2020). Predictive reliability assessment of generation system. *Energies*, *13*(17), 4350.

Raghav, D., Sahani, S.K., Singh, V.V, & Chaudhary, S. (2022). Performance assessment of a complex repairable system with k-out-of-n: G operational scheme and copula repair approach. *Journal of Industrial Engineering International*, *18*(3), 35-49.

Ram, M., & Kumar, A. (2013). Reliability measures improvement and sensitivity analysis of a coal handling unit for thermal power plant. *International Journal of Engineering*, *26*(9), 1059-1066.

Sharma, U., & Kaur, R. (2022). Performance analysis of system where service type for boiler depends upon major or minor failures. *Reliability: Theory Applications*. *17*(2(68)), 317-325.

Singh, V.V., Poonia, P.K., & Rawal, D.K. (2021). Reliability analysis of repairable network system of three computer labs connected with a server under 2-out-of-3 g configuration. *Life Cycle Reliability and Safety Engineering*, *10*(3), 19-29.

Song, Y., & Wang, X. (2022). Reliability Analysis of the multi-state k-out-of-n: F systems with multiple operation mechanisms. *Mathematics*, *10*(23), 4615.

Tyagi, V., & Ram, M. (2024). Performance analysis of wind–hydro power plant under multi-state failures and repairs. *International Journal of System Assurance Engineering and Management*, *15*(4), 1424-1433.

Tyagi, V., Ram, M., Manglik, M., & Arora, R. (2024). Vacation policy for k-out-of-n redundant system with reboot delay. *International Journal of Mathematical, Engineering and Management Sciences*, *9*(2), 366-384. https://doi.org/10.33889/IJMEMS.2024.9.2.020.

Wang, Y., Guo, L., Wen, M., & Yang, Y. (2019). Availability analysis for a multi-component system with different *k*-out-of-*n*: G warm standby subsystems subject to suspended animation. *Eksploatacja i Niezawodnosc– Maintenance and Reliability*, *21*(2), 289-300.

Yadav, G., Joshi, D., Gopinath, L., & Soni, M.K. (2022). Reliability and availability optimization of smart microgrid using specific configuration of renewable resources and considering subcomponent faults. *Energies*, *15*(16), 5994.

Zheng, J., Okamura, H., & Dohi, T. (2018). Reliability importance of components in a real-time computing system with standby redundancy schemes. *International Journal of Mathematical, Engineering and Management Sciences*, *3*(2), 64-89.

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