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Article

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Research paper

Markov-based performance evaluation and availability optimization of the boiler–furnace system in coal-fired thermal power plant using PSO

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ABSTRACT

The appropriate maintenance strategy is essential for maintaining the thermal power plant highly reliable. The thermal power plant is a complex system that consists of various subsystems connected either in series or parallel configuration. The boiler–furnace (BF) system is one of the most critical subsystems of the thermal power plant. This paper presents availability based simulation modeling of the boiler–furnace system of thermal power plant with capacity (500MW). The Markov based simulation model of the system is developed for performance analysis. The differential equations are derived from a transition diagram representing various states with full working capacity, reduced capacity, and failed state. The normalizing condition is used for solving the differential equations. Furthermore, the performance of the system is analyzed for a possible combination of failure rate and repair rate, which revealed that failure of the boiler drum affects the system availability at most, and the failure of reheater affects the availability at least. Based on the criticality ranking, the maintenance priority has been provided for the system.

The availability of the boiler–furnace system is optimized using particle swarm optimization method by varying the number of particles. The study results revealed that the maximum system availability level of 99.9845% is obtained. In addition, the optimized failure rate and repair rate parameters of the subsystem are used for suggesting an appropriate maintenance strategy for the boiler–furnace system of the plant. The finding of the study assisted the decision-makers in planning the maintenance activity as per the criticality level of subsystems for allocating the resources.

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1. Introduction

The high demand for electricity has brought about the importance of maintaining power generating resources on a higher priority in India. Among the various resources, the thermal power plant (TPP) is the major resource of electricity generation. It is essential to maintain the TPP continuously in an operating state. Unfortunately, this is not the case because the failure of equipment is inevitable even though it can be minimized by implementing suitable maintenance strategy. The reliability, availability, and maintenance planning of TPP have become more

significant in recent years due to the growing demand for electricity from society (Kuo and Ke, 2019). The optimum reliability and availability level is desirable not only to reduce the overall cost of production but also to reduce the risk of hazards (Yang et al., 2016). The plant failures often caused by inadequate maintenance and inability to predict problems that may occur later during plant usage. However, with wise consideration for reliability, availability, and maintainability, the frequency of failures and corresponding consequences can be reduced considerably. The available literature shows earlier researchers have used the various qualitative and quantitative methods for analyzing the system performance in terms of reliability and availability of the system. The method includes fault tree analysis (FTA) (Pariaman et al., 2015), failure mode effect analysis (Burgazzi, 2006), functional analysis (FA) (Nord et al., 2009), reliability block diagram (RBD) (Bhangu et al., 2018) Markov approach (Sagayaraj et al., 2014), Monte Carlo simulation (Du et al., 2017).

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In recent years, some studies are reported by earlier researchers related to the performance analysis of subsystems of TPP using the Markov approach for prioritizing the critical equipment as per the criticality level (Hsu et al., 2017; Rao and Naikan, 2016; Wang et al., 2017).

Gupta and Tewari (2009) developed a probabilistic model for the flue gas and air system, and the performances of the subsystems are analyzed. The maintenance priority was decided based on optimum values of failure rate and repair rate of subsystems. In addition, Gupta and Tewari (2010) highlighted the opportunities of predictive availability modeling of the steam generation system used in TPP using Markov and probabilistic approaches. The availability simulation was developed by Kumar et al. (2012) for performance evaluation of turbine subsystem used in a coal-fired TPP. Their study highlighted that the maintenance priority of the turbine-governing system should always be on a higher priority. Moreover, Kumar (2012a) proposed a decision support system for boiler subsystem of the TPP. The decision support system for the boiler system has been developed with the aid of mathematical modeling using a probabilistic approach. The decision matrices are also being developed. These matrices facilitate maintenance decisions at critical points at which a particular subsystem of the boiler system repair should be a priority. The results obtained showed that the re-heater is the most critical subsystem with regard to the maintenance aspect. Therefore, the re-heater highest priority should be given, as the impact of its failure and repair rates on the availability of the device is much higher than in other subsystems. Based on the repair rates maintenance priority should be of the order of (a) reheater (b) economizer (c) boiler drum (d) superheater (e) furnace.

Zhang et al. (2014) presented a case study, which was conducted for an industrial boiler system to evaluate system performance and simultaneously to identify opportunities for increasing energy efficiency of the system. First, the possibilities are discussed to improve the system for the emerging boiler system, z. B. resetting the system vapor pressure, installing VFDs to the FD fans, the optimization of the multi-burner using pattern and optimizing the feedwater system. In particular, the single burner mode was investigated, and the air/fuel ratio to the optimum level was set. In addition, the study provides a brief energy analysis for the development of an optimized single-burner mode. It was found that could be saved with optimized burner operation at lower loads up to 7% fuel consumption.

Kumar (2012b) and Malik and Tewari (2018) developed the decision matrix for performance evaluation of the water circulation system. The results show that the condensate extraction pump is the most critical amongst the other subsystem, which needs to maintain high priority. Kumar et al. (2011) analyzed the performance assessment of the furnace draft air cycle of the TPP. In their study, the effect of failure rate and repair rate of each subsystem on overall system availability was determined. Besides, Yogesh Kumar and Sanjeev Kumar (2013) carried out a reliability analysis of the coal handling unit of Badarpur TPP and provided the maintenance priorities as per the criticality level of subsystems.

In recent years, the area of performance optimization in various domains is of great interest to the earlier researchers. Performance optimization is one of the key parameters for process industries (Kumar et al., 2016; Raugei and Leccisi, 2016). Some studies were reported previously for analyzing the behavior of TPP using optimization techniques. The techniques includes genetic algorithm, simulated annealing (Mohanta et al., 2007), particle swarm optimization (PSO) (Kundu et al., 2019; Pant et al., 2015; Patwal et al., 2017; Roy et al., 2017; Zhao et al., 2015). Mukerji et al. (1991) revealed the use of an optimization technique for reliability assessment to reschedule plant outage. In addition,

the preventive maintenance policies were optimized using the cost reliability model by Lapa et al. (2006). Garg (2014) reported methodology for reliability, maintainability, and availability analysis of crankcase manufacturing plant by utilizing uncertain data for time-varying failure and repair rate model. The performance analysis has been carried out using PSO and fuzzy set theory, and optimal design parameters were obtained by solving the availability cost optimization model through PSO. In order to overcome the difficulty of constructing the multi-state system's reliability optimization model and the shortage of premature convergence of the PSO algorithm, Yao et al. (2013) developed a new reliability optimization model based on T-S fault tree and extended PSO algorithm.

The relevant published literature revealed that earlier researchers are continuously attempting to investigate reliability based maintenance scheduling of systems used in several process enterprises such as TPP (Hemmati et al., 2018; Kumar et al., 2018). With the objective to enhance plant availability, the optimized availability parameters can be used to decide/modify existing maintenance schedule. It is observed that previous studies were restricted to develop and analyze the theoretical models, but rarely, a few of them have tried to solve in a realistic environment. Also, till recent studies, less attention was given to employ modern optimization techniques for availability optimization for TPP subsystems. Moreover, a need for a systematic approach for performance analysis of subsystems in the case of TPP systems is precisely sensed. An attempt is made to bridge the identified research gap. In this paper, the availability simulation model based on Markov probabilistic approach for the boiler-furnace (BF) system is developed. The differential equations are established representing different states of the system, and the performance is evaluated for the known values of availability parameters (failure rate and repair rate) of the system. In addition, Markov based optimum values for the availability parameters (failure rate and repair rate) are obtained, and the maintenance priority of the BF system is provided as per the criticality level.

The application of particle swarm optimization method for availability optimization of the BF system is adopted in the present study. The effect of the number of particles on the performance of the BF system has been studied, and the optimum availability level of the availability is achieved. The obtained optimized availability parameters are used for modifying the existing maintenance strategy of the BF system of the plant.

2. System description

The present research work is carried out at the Dahanu Thermal Power Plant (DTPP), which is located in the western region of India, with the capacity of electricity generation 500 MW. The BF system is one of the selected major systems of the plant, which plays a major role in the generation of electricity. Hence it is selected for the availability analysis, which is reported in the present work. The basic model of the BF system is, as shown in Fig. 1. The model consists of six units in operation viz. boiler drum, boiler tubing, fuel firing system, superheater, economizer, reheater. For availability analysis, the past failure data of the selected equipment of the boiler-furnace system is collected and categorized as failure rate (λ), and repair rate (μ).

The wet steam reaches to the boiler drum from the boiler tubing. In the boiler drum, the water and steam get separated. The furnace assists the operator in controlling the fuel firing system. The steam supplies to superheater coils and acquires a temperature of 540 degrees and pressure up to 147 kg/cm². The steam passes through a high-pressure turbine (HPT) and produces mechanical energy in the form of rotation of the turbine shaft. Then the stream goes to reheater coils and further goes to

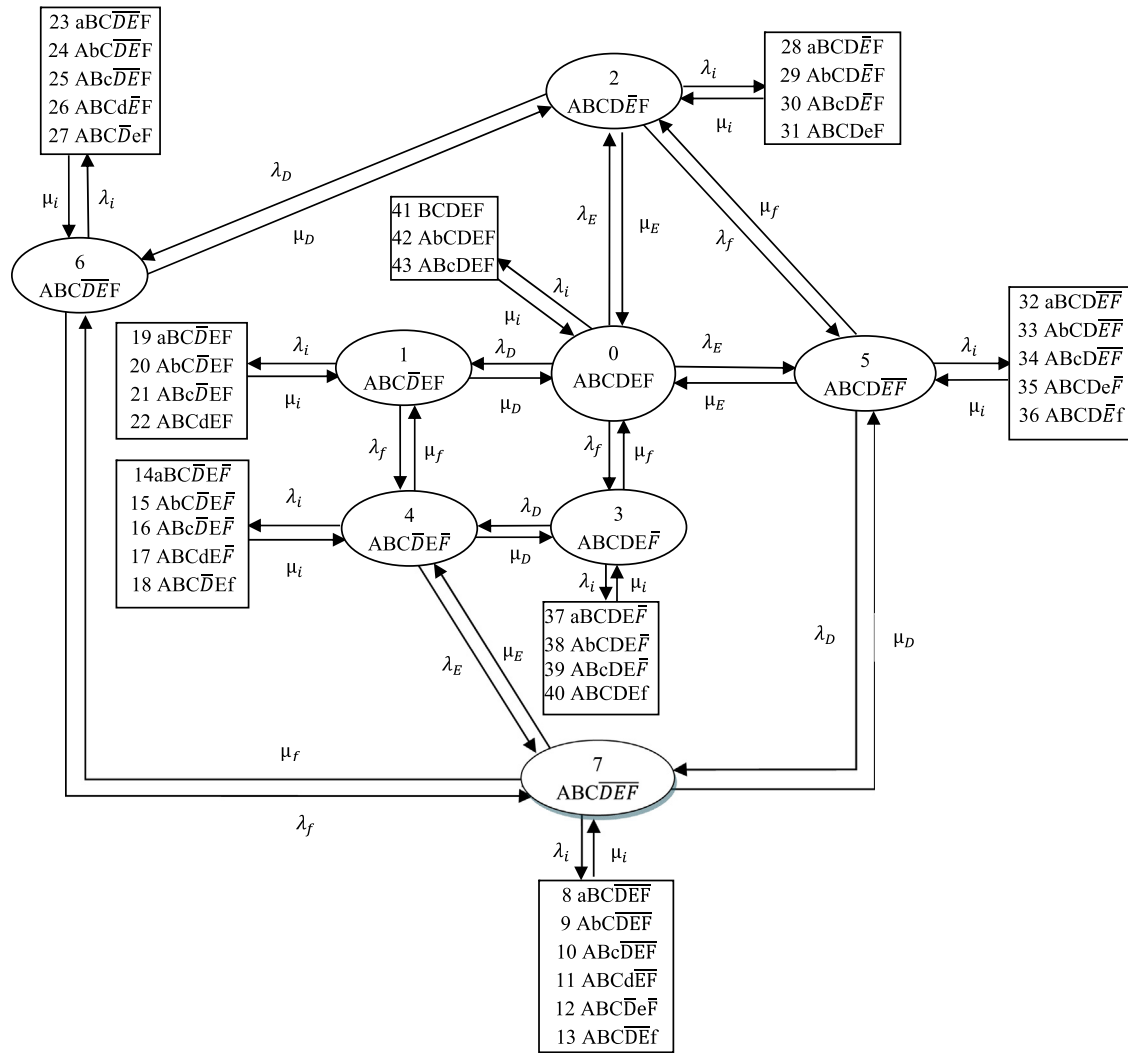


Fig. 2. Transition diagram of the BF system.

$$P'_4(t) + (\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_D + \mu_F) P_4(t) = \mu_A P_{14}(t) + \mu_B P_{15}(t) + \mu_C P_{16}(t) \quad (5)$$

$$+ \mu_D P_{17}(t) + \mu_E P_7(t) + \mu_F P_{18}(t) + \lambda_D P_3(t) + \lambda_F P_1(t)$$

$$P'_5(t) + (\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_E + \mu_F) P_5(t) = \mu_A P_{32}(t) + \mu_B P_{33}(t) + \mu_C P_{34}(t) \quad (6)$$

$$+ \mu_D P_7(t) + \mu_E P_{35}(t) + \mu_F P_{36}(t) + \lambda_E P_3(t) + \lambda_F P_2(t)$$

$$P'_6(t) + (\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_D + \mu_E) P_6(t) = \mu_A P_{23}(t) + \mu_B P_{24}(t) + \mu_C P_{25}(t) \quad (7)$$

$$+ \mu_D P_{26}(t) + \mu_E P_{27}(t) + \mu_F P_7(t) + \lambda_D P_2(t) + \lambda_E P_1(t)$$

$$P'_7(t) + (\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_D + \mu_E + \mu_F) P_7(t) = \mu_A P_8(t) + \mu_B P_9(t) + \mu_C P_{10}(t) + \mu_D P_{11}(t) \quad (8)$$

$$+ \mu_E P_{12}(t) + \mu_F P_{13}(t) + \lambda_D P_5(t) + \lambda_E P_4(t) + \lambda_F P_6(t)$$

$$P'_8(t) + \mu_A P_8(t) = \lambda_A P_7(t) \quad (9)$$

$$P'_9(t) + \mu_B P_9(t) = \lambda_B P_7(t) \quad (10)$$

$$P'_{10}(t) + \mu_C P_{10}(t) = \lambda_C P_7(t) \quad (11)$$

$$P'_{11}(t) + \mu_D P_{11}(t) = \lambda_D P_7(t) \quad (12)$$

$$P'_{12}(t) + \mu_E P_{12}(t) = \lambda_E P_7(t) \quad (13)$$

$$P'_{13}(t) + \mu_F P_{13}(t) = \lambda_F P_7(t) \quad (14)$$

$$P'_{14}(t) + \mu_A P_{14}(t) = \lambda_A P_4(t) \quad (15)$$

$$P'_{15}(t) + \mu_B P_{15}(t) = \lambda_B P_4(t) \quad (16)$$

$$P'_{16}(t) + \mu_C P_{16}(t) = \lambda_C P_4(t) \quad (17)$$

$$P'_{17}(t) + \mu_D P_{17}(t) = \lambda_D P_4(t) \quad (18)$$

$$P'_{18}(t) + \mu_F P_{18}(t) = \lambda_F P_4(t) \quad (19)$$

$$P'_{19}(t) + \mu_A P_{19}(t) = \lambda_A P_1(t) \quad (20)$$

$$P'_{20}(t) + \mu_B P_{20}(t) = \lambda_B P_1(t) \quad (21)$$

$$P'_{21}(t) + \mu_C P_{21}(t) = \lambda_C P_1(t) \quad (22)$$

$$P'_{22}(t) + \mu_D P_{22}(t) = \lambda_D P_1(t) \quad (23)$$

$$P'_{23}(t) + \mu_A P_{23}(t) = \lambda_A P_6(t) \quad (24)$$

$$P'_{24}(t) + \mu_B P_{24}(t) = \lambda_B P_6(t) \quad (25)$$

$$P'_{25}(t) + \mu_C P_{25}(t) = \lambda_C P_6(t) \quad (26)$$

$$P'_{26}(t) + \mu_D P_{26}(t) = \lambda_D P_6(t) \quad (27)$$

$$P'_{27}(t) + \mu_E P_{27}(t) = \lambda_E P_6(t) \quad (28)$$

$$P'_{28}(t) + \mu_A P_{28}(t) = \lambda_A P_2(t) \quad (29)$$

$$P'_{29}(t) + \mu_B P_{29}(t) = \lambda_B P_2(t) \quad (30)$$

$$P'_{30}(t) + \mu_C P_{30}(t) = \lambda_C P_2(t) \quad (31)$$

$$P_{31}'(t) + \mu_E P_{31}(t) = \lambda_E P_2(t) \quad (32)$$

$$P_{32}'(t) + \mu_A P_{32}(t) = \lambda_A P_5(t) \quad (33)$$

$$P_{33}'(t) + \mu_B P_{33}(t) = \lambda_B P_5(t) \quad (34)$$

$$P_{34}'(t) + \mu_C P_{34}(t) = \lambda_C P_5(t) \quad (35)$$

$$P_{35}'(t) + \mu_E P_{35}(t) = \lambda_E P_5(t) \quad (36)$$

$$P_{36}'(t) + \mu_F P_{36}(t) = \lambda_F P_5(t) \quad (37)$$

$$P_{37}'(t) + \mu_A P_{37}(t) = \lambda_A P_3(t) \quad (38)$$

$$P_{38}'(t) + \mu_B P_{38}(t) = \lambda_B P_3(t) \quad (39)$$

$$P_{39}'(t) + \mu_C P_{39}(t) = \lambda_C P_3(t) \quad (40)$$

$$P_{40}'(t) + \mu_F P_{40}(t) = \lambda_F P_3(t) \quad (41)$$

$$P_{41}'(t) + \mu_A P_{41}(t) = \lambda_A P_0(t) \quad (42)$$

$$P_{42}'(t) + \mu_B P_{42}(t) = \lambda_B P_0(t) \quad (43)$$

$$P_{43}'(t) + \mu_C P_{43}(t) = \lambda_C P_0(t) \quad (44)$$

Using initial conditions at time $t = 0$, $P_i(t) = 1$ for $i = 0$ otherwise $P_i(t) = 0$, for long-run availability steady state, the system is analyzed by setting $\frac{d}{dt} \rightarrow 0$ and $t \rightarrow \infty$. The above equations are solved simultaneously, and the following values are obtained for all limiting probabilities state probability, which are given from Eqs. (45) to (88) are as follows.

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F) P_0 = \mu_A P_{41} + \mu_B P_{42} + \mu_C P_{43} + \mu_D P_1 + \mu_E P_2 + \mu_F P_3 \quad (45)$$

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_D) P_1 = \mu_A P_{19} + \mu_B P_{20} + \mu_C P_{21} + \mu_D P_{22} + \mu_E P_6 + \mu_F P_4 + \lambda_D P_0 \quad (46)$$

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_E) P_2 = \mu_A P_{28} + \mu_B P_{29} + \mu_C P_{30} + \mu_D P_6 + \mu_E P_{31} + \mu_F P_5 + \lambda_E P_0 \quad (47)$$

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_F) P_3 = \mu_A P_{37} + \mu_B P_{38} + \mu_C P_{39} + \mu_D P_4 + \mu_E P_5 + \mu_F P_{40} + \lambda_F P_0 \quad (48)$$

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_D + \mu_F) P_4 = \mu_A P_{14} + \mu_B P_{15} + \mu_C P_{16} + \mu_D P_{17} + \mu_E P_7 + \mu_F P_{18} + \lambda_D P_3 + \lambda_F P_1 \quad (49)$$

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_E + \mu_F) P_5 = \mu_A P_{32} + \mu_B P_{33} + \mu_C P_{34} + \mu_D P_7 + \mu_E P_{35} + \mu_F P_{36} + \lambda_E P_3 + \lambda_F P_2 \quad (50)$$

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_D + \mu_E) P_6 = \mu_A P_{23} + \mu_B P_{24} + \mu_C P_{25} + \mu_D P_{26} + \mu_E P_{27} + \mu_F P_7 + \lambda_D P_2 + \lambda_E P_1 \quad (51)$$

$$(\lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E + \lambda_F + \mu_D + \mu_E + \mu_F) P_7 = \mu_A P_8 + \mu_B P_9 + \mu_C P_{10} + \mu_D P_{11} + \mu_E P_{12} + \mu_F P_{13} + \lambda_D P_5 + \lambda_E P_4 + \lambda_F P_6 \quad (52)$$

$$\mu_A P_8 = \lambda_A P_7 \quad (53)$$

$$\mu_B P_9 = \lambda_B P_7 \quad (54)$$

$$\mu_C P_{10} = \lambda_C P_7 \quad (55)$$

$$\mu_D P_{11} = \lambda_D P_7 \quad (56)$$

$$\mu_E P_{12} = \lambda_E P_7 \quad (57)$$

$$\mu_F P_{13} = \lambda_F P_7 \quad (58)$$

$$\mu_A P_{14} = \lambda_A P_4 \quad (59)$$

$$\mu_B P_{15} = \lambda_B P_4 \quad (60)$$

$$\mu_C P_{16} = \lambda_C P_4 \quad (61)$$

$$\mu_D P_{17} = \lambda_D P_4 \quad (62)$$

$$\mu_F P_{18} = \lambda_F P_4 \quad (63)$$

$$\mu_A P_{19} = \lambda_A P_1 \quad (64)$$

$$\mu_B P_{20} = \lambda_B P_1 \quad (65)$$

$$\mu_C P_{21} = \lambda_C P_1 \quad (66)$$

$$\mu_D P_{22} = \lambda_D P_1 \quad (67)$$

$$\mu_A P_{23} = \lambda_A P_6 \quad (68)$$

$$\mu_B P_{24} = \lambda_B P_6 \quad (69)$$

$$\mu_C P_{25} = \lambda_C P_6 \quad (70)$$

$$\mu_D P_{26} = \lambda_D P_6 \quad (71)$$

$$\mu_E P_{27} = \lambda_E P_6 \quad (72)$$

$$\mu_A P_{28} = \lambda_A P_2 \quad (73)$$

$$\mu_B P_{29} = \lambda_B P_2 \quad (74)$$

$$\mu_C P_{30} = \lambda_C P_2 \quad (75)$$

$$\mu_E P_{31} = \lambda_E P_2 \quad (76)$$

$$\mu_A P_{32} = \lambda_A P_5 \quad (77)$$

$$\mu_B P_{33} = \lambda_B P_5 \quad (78)$$

$$\mu_C P_{34} = \lambda_C P_5 \quad (79)$$

$$\mu_E P_{35} = \lambda_E P_5 \quad (80)$$

$$\mu_F P_{36} = \lambda_F P_5 \quad (81)$$

$$\mu_A P_{37} = \lambda_A P_3 \quad (82)$$

$$\mu_B P_{38} = \lambda_B P_3 \quad (83)$$

$$\mu_C P_{39} = \lambda_C P_3 \quad (84)$$

$$\mu_F P_{40} = \lambda_F P_3 \quad (85)$$

$$\mu_A P_{41} = \lambda_A P_0 \quad (86)$$

$$\mu_B P_{42} = \lambda_B P_0 \quad (87)$$

$$\mu_C P_{43} = \lambda_C P_0 \quad (88)$$

Let us consider

$$P_{1-7} = L_{1-7} P_0, P_8 = K_A P_7, P_9 = K_B P_7, P_{10} = K_C P_7, P_{11} = K_D P_7,$$

$$P_{12} = K_E P_7, P_{13} = K_F P_7, P_{14} = K_A P_4,$$

$$P_{15} = K_B P_4, P_{16} = K_C P_4, P_{17} = K_D P_4, P_{18} = K_F P_4, P_{19} = K_A P_1,$$

$$P_{20} = K_B P_1, P_{21} = K_C P_1, P_{22} = K_D P_1,$$

$$P_{23} = K_A P_6, P_{24} = K_B P_6, P_{25} = K_C P_6, P_{26} = K_D P_6, P_{27} = K_E P_6,$$

$$P_{28} = K_A P_2, P_{29} = K_B P_2, P_{30} = K_C P_2,$$

$$P_{31} = K_E P_2, P_{32} = K_A P_5, P_{33} = K_B P_5, P_{34} = K_C P_5, P_{35} = K_E P_5,$$

$$P_{36} = K_F P_5, P_{37} = K_A P_3, P_{38} = K_B P_3,$$

$$P_{39} = K_C P_3, P_{40} = K_F P_3, P_{41} = K_A P_0, P_{42} = K_B P_0, P_{43} = K_C P_0,$$

where $K_A = \frac{\lambda_A}{\mu_A}, K_B = \frac{\lambda_B}{\mu_B}, K_C = \frac{\lambda_C}{\mu_C}, K_D = \frac{\lambda_D}{\mu_D}, K_E = \frac{\lambda_E}{\mu_E}, K_F = \frac{\lambda_F}{\mu_F}$

Using the matrix method of equations for solving the equation from Eqs. (45) to (88), we get $\sum_{i=0}^{43} P_i = 1$

$$P_0 = \left[1 + \sum_{i=1}^7 Li + K_A L_7 + K_B L_7 + K_C L_7 + K_D L_7 + K_E L_7 + K_F L_7 + K_A L_4 + K_B L_4 + K_C L_4 + K_D L_4 + K_F L_4 + K_A L_1 + K_B L_1 + K_C L_1 + K_D L_1 + K_A L_6 + K_B L_6 + K_C L_6 + K_D L_6 + K_E L_6 + K_A L_2 + K_B L_2 + K_C L_2 + K_E L_2 + K_A L_5 + K_B L_5 + K_C L_5 + K_E L_5 + K_F L_5 + K_A L_3 + K_B L_3 + K_C L_3 + K_F L_3 + K_A + K_B + K_C \right]^{-1} \quad (89)$$

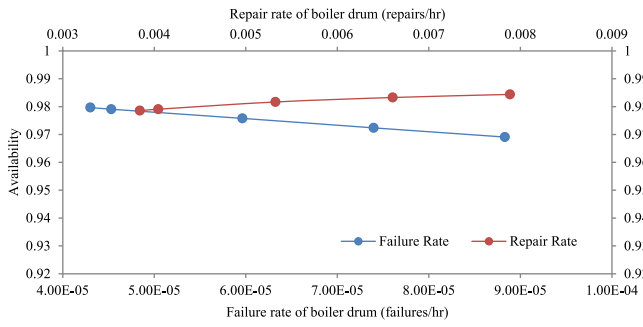


Fig. 3. Effect of failure and repair rates of boiler drum on system availability.

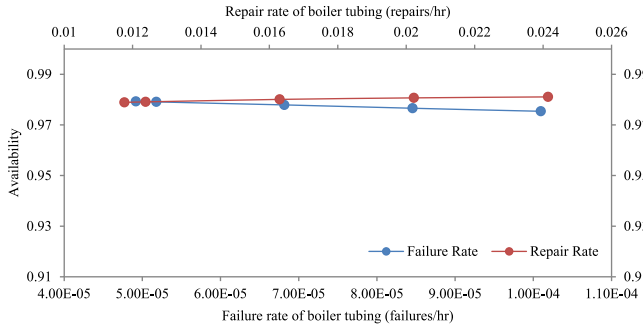


Fig. 4. Effect of failure and repair rates of boiler tubing on system availability.

The steady-state availability based simulation model for the BF system of DTPP formed with the summation of all working probability states.

$$A_V = [P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7] \quad (90)$$

$$A_V = [1 + L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7] P_0 \quad (91)$$

In order to get the availability level, the input values corresponding to the failure rate (λ), and the repair rate (μ) of the selected system is provided, and the availability matrix is obtained. In this way, the performance of each subsystem of the BF system of the plant is estimated.

3.1. Results and discussion based on the Markov approach

The availability of the BF system is majorly affected by the failure rate and repair rate of its subsystems. For this cause, the failure rate and repair rate of selected equipment of the BF system were analyzed for performance evaluation and availability analysis. The performance evaluation of the BF system was carried out based on the Markov approach. The various state probabilities have been cited in the transition diagram and used for developing the availability matrix. The evaluated availability levels of the BF system are tabulated from Tables 1 to 6. Moreover, Figs. 3 to 8 represented the effect of the failure rate and repair rate of the equipment on the overall availability of the BF system.

Fig. 3 represents the effect of failure and repair rates of the boiler drum on overall system availability. It revealed that, as the failure rates of boiler drum increase from $4.3021\text{E}-05$ to $8.8306\text{E}-05$, the availability decreases by about 1.06%. Similarly, as repair rates of boiler drum increase from 0.003842 to 0.007886, the system availability increases by 0.58%.

Fig. 4 represents the effect of failure and repair rates of boiler tubing on overall system availability. It revealed that, as the failure rates of boiler tubing increases from $4.9189\text{E}-05$

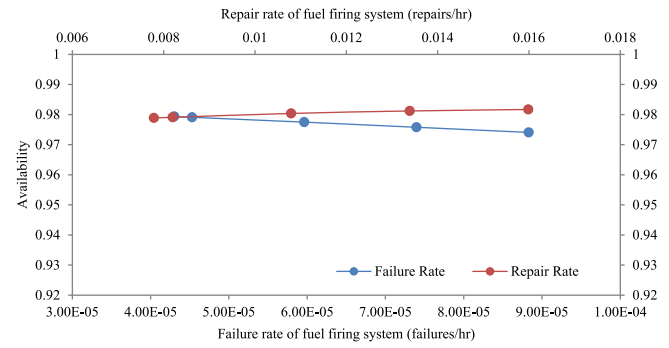


Fig. 5. Effect of failure and repair rates of fuel firing system on system availability.

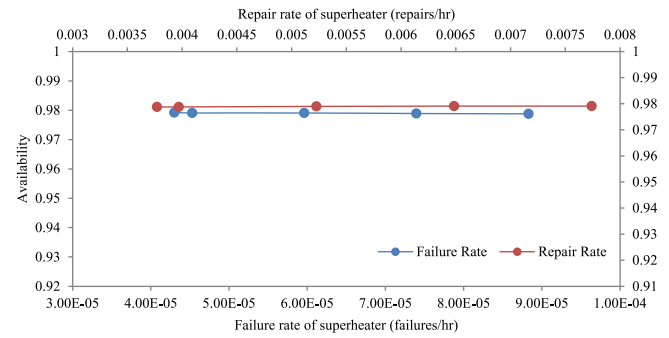


Fig. 6. Effect of failure and repair rates of superheater on system availability.

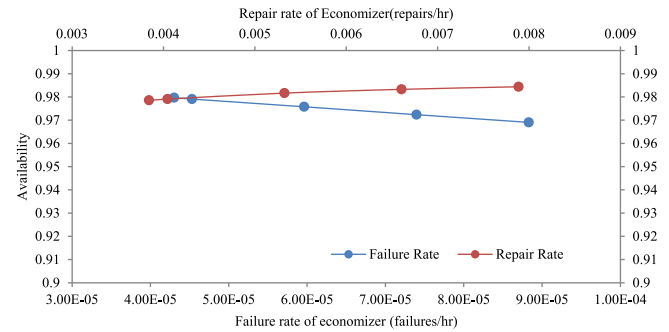


Fig. 7. Effect of failure and repair rates of an economizer on system availability.

to 0.00010097, the availability decreases by about 0.39%. Similarly, as repair rates of boiler tubing increases from 0.011765 to 0.024149, the system availability increases by 0.22%.

Fig. 5 represents the effect of failure and repair rates of the fuel firing system on overall system availability. It revealed that, as the failure rates of fuel firing system increase from $4.3021\text{E}-05$ to $8.8306\text{E}-05$, the availability decreases by 0.53%. Similarly, as repair rates of fuel firing system increase from 0.007787 to 0.015984, the system availability increases by 0.28%.

Fig. 6 represents the effect of failure and repair rates of a superheater on overall system availability. It revealed that, as the failure rates of superheater increases from $4.3021\text{E}-05$ to $8.8306\text{E}-05$, the availability decreases by about 0.04%. Similarly, as repair rates of superheater increases from 0.003772 to 0.007742, the system availability increases by about 0.03%.

Fig. 7 represents the effect of failure and repair rates of an economizer on overall system availability. It revealed that, as the failure rates of economizer increase from $4.3021\text{E}-05$ to $8.8306\text{E}-05$, the availability decreases by 0.04%. Similarly, as

Table 1

Availability matrix for boiler drum.

$\mu 1$	$\lambda 1$						Constant values
	0.000043	0.000045	0.000060	0.000074	0.000088		
0.003842	0.9792	0.9786	0.975	0.9715	0.968		$\lambda 2 = 0.000052, \mu 2 = 0.012384$
0.004044	0.9797	0.9791	0.9758	0.9724	0.9691		$\lambda 3 = 0.000045, \mu 3 = 0.008197$
0.005324	0.9822	0.9817	0.9792	0.9766	0.974		$\lambda 4 = 0.000045, \mu 4 = 0.003971$
0.006605	0.9837	0.9833	0.9812	0.9791	0.9771		$\lambda 5 = 0.000045, \mu 5 = 0.004009$
0.007886	0.9847	0.9844	0.9827	0.9809	0.9791		$\lambda 6 = 0.000045, \mu 6 = 0.003904$

Table 2

Availability matrix for boiler tubing.

$\mu 2$	$\lambda 2$						Constant values
	0.000049	0.000052	0.000068	0.000085	0.000101		
0.011765	0.9791	0.9789	0.9776	0.9763	0.9749		$\lambda 1 = 0.000045, \mu 1 = 0.004044$
0.012384	0.9793	0.9791	0.9779	0.9766	0.9754		$\lambda 3 = 0.000045, \mu 3 = 0.008197$
0.016305	0.9803	0.9801	0.9791	0.9782	0.9772		$\lambda 4 = 0.000045, \mu 4 = 0.003971$
0.020227	0.9808	0.9807	0.9799	0.9791	0.9784		$\lambda 5 = 0.000045, \mu 5 = 0.004009$
0.024149	0.9812	0.9811	0.9804	0.9798	0.9791		$\lambda 6 = 0.000045, \mu 6 = 0.003904$

Table 3

Availability matrix for fuel firing system.

$\mu 3$	$\lambda 3$						Constant values
	0.000043	0.000045	0.000060	0.000074	0.000088		
0.007787	0.9791	0.9789	0.9771	0.9753	0.9736		$\lambda 1 = 0.000045, \mu 1 = 0.004044$
0.008197	0.9794	0.9791	0.9775	0.9758	0.9741		$\lambda 2 = 0.000052, \mu 2 = 0.012384$
0.010792	0.9806	0.9804	0.9791	0.9779	0.9766		$\lambda 4 = 0.000045, \mu 4 = 0.003971$
0.013388	0.9814	0.9812	0.9802	0.9791	0.9781		$\lambda 5 = 0.000045, \mu 5 = 0.004009$
0.015984	0.9819	0.9817	0.9809	0.98	0.9791		$\lambda 6 = 0.000045, \mu 6 = 0.003904$

Table 4

Availability matrix for superheater.

$\mu 4$	$\lambda 4$						Constant values
	0.000043	0.000045	0.000060	0.000074	0.000088		
0.003772	0.9791	0.9791	0.979	0.9789	0.9788		$\lambda 1 = 0.000045, \mu 1 = 0.004044$
0.003971	0.9792	0.9791	0.9791	0.9789	0.9788		$\lambda 2 = 0.000052, \mu 2 = 0.012384$
0.005228	0.9792	0.9792	0.9791	0.9791	0.979		$\lambda 3 = 0.000045, \mu 3 = 0.008197$
0.006485	0.9792	0.9792	0.9792	0.9791	0.9791		$\lambda 5 = 0.000045, \mu 5 = 0.004009$
0.007742	0.9792	0.9792	0.9792	0.9792	0.9791		$\lambda 6 = 0.000045, \mu 6 = 0.003904$

Table 5

Availability matrix for economizer.

$\mu 5$	$\lambda 5$						Constant values
	0.000043	0.000045	0.000060	0.000074	0.000088		
0.003809	0.9791	0.9791	0.979	0.9789	0.9788		$\lambda 1 = 0.000045, \mu 1 = 0.004044$
0.004009	0.9792	0.9791	0.9791	0.9789	0.9788		$\lambda 2 = 0.000052, \mu 2 = 0.012384$
0.005279	0.9792	0.9792	0.9791	0.9791	0.979		$\lambda 3 = 0.000045, \mu 3 = 0.008197$
0.006548	0.9792	0.9792	0.9792	0.9791	0.9791		$\lambda 4 = 0.000045, \mu 4 = 0.003971$
0.007818	0.9792	0.9792	0.9792	0.9792	0.9791		$\lambda 6 = 0.000045, \mu 6 = 0.003904$

repair rates of economizer increase from 0.003809 to 0.007818, the system availability increases by 0.01%.

Fig. 8 represents the effect of failure and repair rates of reheater on overall system availability. It revealed that, as the failure rates of reheater increase from $4.3021\text{E}-05$ to $8.8306\text{E}-05$, the availability decreases by 0.04%. Similarly, as repair rates of reheater increases from 0.003709 to 0.007613, the system availability increases by 0.01%.

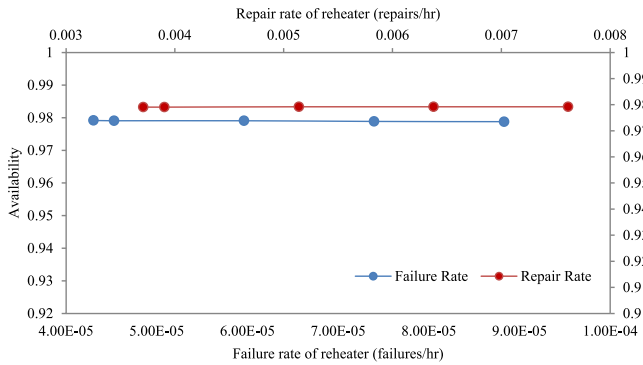
Further, the optimum values were obtained for the availability level with a possible combination of failure rate and repair rate of the BF system, which is tabulated in Table 7.

The study results reflected that the failure of the boiler drum affected the system performance rapidly and reduced overall system availability by 1.06%. Therefore, the boiler drum is identified as the most critical equipment of the BF system, with a failure rate of 0.000045 (failures/h). Similarly, reheater is the least critical subsystem with a failure rate of 0.000045 (failures/h). Therefore, from optimum values of failure rate and repair rate of the BF system, the maintenance priority should be provided as per the following order.

- (1) Boiler drum
- (2) Fuel firing system

Table 6
Availability matrix for reheater.

μ_6	λ_6					Constant values
	0.000043	0.000045	0.000060	0.000074	0.000088	
0.003709	0.9791	0.9791	0.979	0.9789	0.9787	$\lambda_1 = 0.000045, \mu_1 = 0.004044$
0.003904	0.9792	0.9791	0.9791	0.9789	0.9788	$\lambda_2 = 0.000052, \mu_2 = 0.012384$
0.00514	0.9792	0.9792	0.9791	0.9791	0.979	$\lambda_3 = 0.000045, \mu_3 = 0.008197$
0.006377	0.9792	0.9792	0.9792	0.9791	0.9791	$\lambda_4 = 0.000045, \mu_4 = 0.003971$
0.007613	0.9792	0.9792	0.9792	0.9792	0.9791	$\lambda_5 = 0.000045, \mu_5 = 0.004009$

**Fig. 8.** Effect of failure and repair rates of reheater on system availability.**Table 7**
Optimum values failure and repair rates of BF system of DTPP.

Equipment name	Failure rate (λ_i)	Repair rate (μ_i)	Decrease in Av due to (λ_i)	Increase in Av due to (μ_i)
Boiler drum	0.000045	0.004044	1.06%	0.58%
Boiler tubing	0.000052	0.012384	0.39%	0.22%
Fuel firing system	0.000045	0.008197	0.53%	0.28%
Superheater	0.000045	0.003971	0.04%	0.03%
Economizer	0.000045	0.004009	0.04%	0.01%
Reheater	0.000045	0.003904	0.04%	0.01%

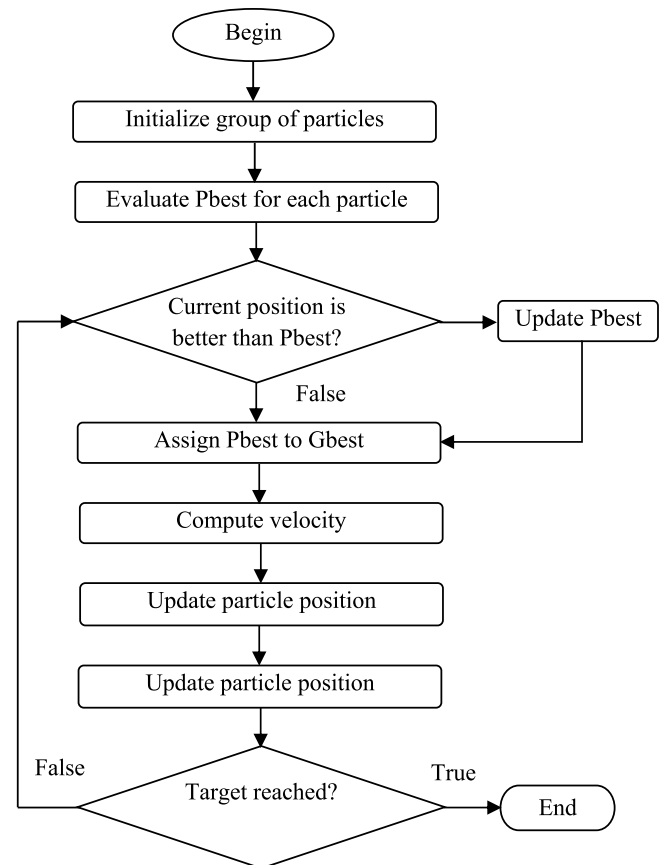
- (3) Boiler tubing
- (4) Superheater
- (5) Economizer
- (6) Reheater

The brainstorming sessions with domain experts at DTPP concluded that the proposed approach and corresponding results would help to schedule maintenance activity as per the criticality level of the BF system of the plant. The identified critical equipment and corresponding maintenance priority would take the lead in maintenance planning and allocating the overall availability of the plant. Some salient features of proposed availability simulation model are concluded as; (a) the proposed model presents an interracial modeling as well as analysis framework for performance evaluation of a BF system, (b) the proposed model combines strong mathematical foundation with intuitive graphical representation, (c) the transition diagram represents the possible states of the system.

Further study is extended to optimize the availability of the BF system using the particle swarm optimization method, which is discussed next.

4. Particle swarm optimization-based availability analysis of thermal power plant

The modern optimization methods such as genetic algorithm, simulated annealing, ant colony optimization, neural network-based methods are developed and adopted by earlier researchers for various applications. The particle swarm optimization (PSO)

**Fig. 9.** Flowchart of PSO algorithm.

method has an advantage over the other optimization method. The leading cause is that it is not profoundly influenced by the size and nonlinearity of the problem. PSO is an evolutionary computation method. The PSO is driven more by stimulating the social reaction than by the evolution of nature as with the various evolutionary algorithms. PSO is sociologically motivated when it is considered that the algorithm is based on sociological measures that correlate with the flock of birds.

In this study PSO method is adopted for finding optimized availability parameters for the BF system of DTPP subsystems. The PSO code is generated for availability optimization purpose. The flow chart of PSO algorithm used in this study is as shown in Fig. 9.

In the PSO method, randomly generated particles (swarm and random velocity) allocated to each particle, which generates in search space towards optima over the number of iterations. The best position P_{best} attained by each particle and the best value of fitness G_{best} (Pant et al., 2015).

Table 8
PSO parameter of BF system.

S.N.	Parameter	Value	Remark
1	Inertia weight	0.9	Lies between 0–1
2	Cognitive component c1	1.5	Randomly selected between 0–2
3	Social component c2	1.5	Randomly selected between 0–2
4	Number of particles	10–100	To find optimum performance

Let, $X_i = \{X_i\}$ and $V_i = \{V_i\}$ for $i = 1$ to n , PSO updating the rules for velocity and position,

$$V_i = W * V_i + c1r1(Pbest - X_i) + c2r2(Gbest - X_i) \quad (92)$$

$$X_i = X_i + V_i \quad (93)$$

where $r1$ and $r2$ are a random number (0 to 1) as well as $c1$ and $c2$ are acceleration constant for $Pbest$ and $Gbest$. The inertia weight is W (Kumar and Tewari, 2017). The PSO algorithm code is generated for the BF system, and further optimized availability parameters are obtained.

4.1. Optimization modeling

The study intended to search for the availability level of the BF system by considering the several features viz. (i) the various possible combination of failure rate and repair rate of the subsystem, (ii) the effect of the number of particles on system availability. The failure rate and repair rate parameters of the BF system are considered for evaluating the optimum availability of the system. The numbers of parameters are 12 [six values of failure rate ' λ ' as $\lambda_1 \in (0.0000430, 0.0000883)$, $\lambda_2 \in (0.0000492, 0.00010097)$, $\lambda_3 \in (0.0000430, 0.0000883)$, $\lambda_4 \in (0.0000430, 0.0000883)$, $\lambda_5 \in (0.0000430, 0.0000883)$, $\lambda_6 \in (0.0000430, 0.0000883)$ and six values of repair rate ' μ ' as $\mu_1 \in (0.003842, 0.007886)$, $\mu_2 \in (0.011765, 0.024149)$, $\mu_3 \in (0.007787, 0.015984)$, $\mu_4 \in (0.003772, 0.007742)$, $\mu_5 \in (0.003809, 0.007818)$, $\mu_6 \in (0.003709, 0.007613)$]. The real coded structure used with parameters Inertia weight $w = 0.9$, Cognitive information coefficient ($c1$), and social information coefficient ($c2$) both are 1.5, selected randomly. The independent runs made to tune the parameters and the best results listed. The termination criterion set for either a maximum number of generations or the value of the objective function start decreasing. Initially, the optimum number of particles decided to keep generations equal to 10. The performance of the system is examined by imposing constraints on failure and repair parameters, i.e., minimum and maximum value. The PSO parameters used in the present study are tabulated in Table 8.

Table 9
Effect of the number of particles on system availability.

Parameters	No of particles									
	10	20	30	40	50	60	70	80	90	100
λ_1	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05
λ_2	4.92E–05	4.92E–05	4.92E–05	4.92E–05	4.92E–05	4.92E–05	4.92E–05	4.92E–05	4.92E–05	4.92E–05
λ_3	8.83E–05	5.16E–05	4.30E–05	8.83E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	8.83E–05	4.30E–05
λ_4	8.83E–05	6.90E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	8.83E–05	4.30E–05	4.30E–05
λ_5	4.30E–05	4.99E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05	4.30E–05
λ_6	4.30E–05	5.61E–05	4.30E–05	4.30E–05	8.83E–05	4.30E–05	8.83E–05	4.30E–05	4.30E–05	4.30E–05
μ_1	0.007886	0.007708	0.007886	0.007886	0.007886	0.007886	0.007886	0.007886	0.007886	0.007886
μ_2	0.024149	0.019617	0.011765	0.024149	0.024149	0.024149	0.024149	0.024149	0.024149	0.011765
μ_3	0.007787	0.012602	0.015984	0.015984	0.015984	0.015984	0.007787	0.007787	0.015984	0.015984
μ_4	0.003772	0.007742	0.007742	0.007742	0.003772	0.007742	0.007742	0.007742	0.007742	0.007742
μ_5	0.003809	0.004401	0.007818	0.007818	0.003809	0.007818	0.003809	0.007818	0.003809	0.007818
μ_6	0.007613	0.003903	0.007613	0.003709	0.007613	0.007613	0.003709	0.007613	0.007613	0.007613
Availability	0.999743	0.999791	0.999804	0.999819	0.999817	0.999845	0.99982	0.999798	0.999819	0.999804

Table 10
Optimized availability parameters for BF system of DTPP.

Equipment	MTBF	MTTR
Boiler drum	23 244	127
Fuel firing system	20 330	41
Boiler tubing	23 244	63
Superheater	23 244	129
Economizer	23 244	128
Reheater	23 244	131

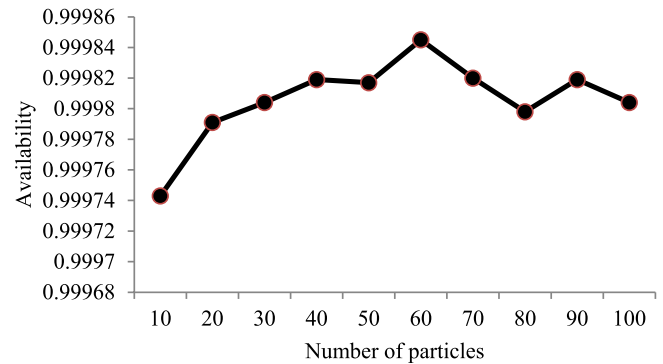


Fig. 10. Effect of the number of particles on system availability.

4.2. Result and discussion based on the particle swarm optimization method

The PSO method employed successfully for availability analysis and performance evaluation of the BF system of DTPP. Intending to obtain the optimum availability level, the effect of several particle sizes on system availability is evaluated. Fig. 10 shows the influence of change in particle size on system availability. Initially, the particle size of 10 is taken into considerations, and its effect on availability is noted. Furthermore, the particle size is increased up to a level of 100 particle size, and the conclusions are noted.

It is observed from Fig. 10 that up to 40 particles, the system availability has increased to 99.9819%, but for a particle size of 50, it suddenly drops to 99.9817%. Moreover, for 60 particle size, the system availability increases rapidly to 99.9845%, but afterward, with an increase in the number of particles up to 100, the system availability remains at a low level. Hence, the optimum value for system availability is obtained for 60 particles, i.e., 99.9845%. The corresponding best possible combination of failure and repair parameters are obtained viz. $\lambda_1 = 0.0000430$, $\lambda_2 = 0.0000492$, $\lambda_3 = 0.0000430$, $\lambda_4 = 0.0000430$, $\lambda_5 = 0.0000430$, $\lambda_6 = 0.0000430$, $\mu_1 = 0.007886$, $\mu_2 = 0.024149$, $\mu_3 = 0.015984$, $\mu_4 = 0.007742$, $\mu_5 = 0.007818$, $\mu_6 = 0.007613$ which is also tabulated in Table 9.

Table 11

Existing maintenance schedule of the BF system of DTPP.

Equipment	Preventive Maintenance (PM)	Average Breakdown Maintenance (BM)	Condition-based Maintenance (CBM)	Concluding remark
	Required time/month (h) ^a	Required time (h) ^a	Vibration monitoring frequency/month	
Boiler drum	5 h	247	NA	PM and BM are suitable
Fuel firing system	5 h	81	NA	PM and BM are suitable
Boiler tubing	5 h	122	NA	PM and BM are suitable
Superheater	5 h	252	NA	PM and BM are suitable
Economizer	5 h	249	NA	PM and BM are suitable
Reheater	5 h	256	NA	PM and BM are suitable

^aActual observed time in hours.**Table 12**

PSO based optimized maintenance schedule of the BF system of DTPP.

Equipment	Preventive Maintenance (PM)	Average Breakdown Maintenance (BM)	Condition-based Maintenance (CBM)	Concluding remark
	Required time/month (h) ^a	Required time (h) ^a	Vibration monitoring frequency/month	
Boiler drum	5 h	127	NA	Recommended to use PM frequently
Fuel firing system	5 h	41	NA	Recommended to use PM frequently
Boiler tubing	5 h	63	NA	Recommended to use PM frequently
Superheater	5 h	129	NA	Recommended to use PM frequently
Economizer	5 h	128	NA	Recommended to use PM frequently
Reheater	5 h	131	NA	Recommended to use PM frequently

^aActual observed time in hours.

The PSO obtains the results for the optimum value of mean time between failure (MTBF) and mean time to repair (MTTR) of the BF system of DTPP. The optimum values are used for modifying the appropriate maintenance strategy. Table 10 represented the optimized availability parameters of the BF system. The existing maintenance strategy of the BF system is represented in Table 11.

The existing maintenance strategies of the BF system of DTPP are dependent on preventive maintenance (PM) and breakdown maintenance (BM). It is required to complete the task of preventive maintenance for 5 h of time per month. The breakdown maintenance consumes maximum time to carry out the maintenance activity. The PM and BM are suitable for the BF system as per the existing maintenance schedule but consumes more time for BM. Therefore through this study, the result obtained by the PSO method recommended for modifying the existing maintenance strategy of the BF system of DTPP, which is tabulated in Table 12.

The study results advocated for rescheduling BM for subsystems of the BF system, which reduces the required time. Such results are beneficial for the maintenance personnel, which saves time and cost. In addition, it is recommended to use PM frequently to avoid the early failures of systems. As per Table 11, it is recommended to use the preventive maintenance for the boiler tubing, superheater, reheater, economizer. In normal operation, it is very difficult to do this activity. Therefore, in such conditions, when the unit/plant is in overhaul condition, complete preventive maintenance is carried out. Moreover, for those possible components of the BF system, the lubrication, cleaning, greasing, etc. such types of preventive maintenance activities can be performed.

5. Conclusion

The maintenance planning is reliant on the criticality of the equipment. The frequency of failure of the system facilitates the allocating of maintenance resources. As well as the required repair time of the system assists in planning the maintenance activity. In order to improve the maintenance planning of the BF system, this study recommended prioritizing the system as per the criticality level, which in turn assists the maintenance person

to plan accordingly. In order to evaluate the effect of failure rate and repair rate on the availability of a BF system of the TPP, an availability simulation model based on the Markov approach for the performance evaluation is developed and reported in the present study. The availability matrices have been developed on the basis of the Markov probabilistic model. For which, the performance of the selected equipment of the boiler furnace is evaluated for the known values of failure rate (λ) and repair rate (μ). The effect of the increased failure rate provides sufficient insights that the availability of the system has been decreased. Moreover, with an increase in repair rate, the availability of the system has been observed to increase up to the mark. Therefore the results obtained from the Markov approach are considered acceptable based on the probabilistic approach. The optimum values for possible combinations of failure rate and repair rate are obtained, and maintenance priority is decided as per criticality level. The Markov based results revealed that the boiler drum is the most critical equipment because its effect of failure rate and repair rate on unit availability is higher as compared to the other system of the BF system. Therefore, the availability of a boiler drum which needs to maintain high priority as far as the maintenance is concerned.

The application of the particle swarm optimization method for evaluating the optimum value of availability level for BF system of the TPP is reported. Moreover, the effect of the number of particles on the performance of the BF system has been studied, and the optimum availability level is obtained for two parameters viz. (i) failure rate (λ), (ii) repair rate (μ). These optimized parameters are used for optimizing preventive and breakdown maintenance activities and effectively allocating resources for maintenance. The study result advocated use of PSO for optimizing the preventive and breakdown maintenance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Hanumant Jagtap: Conceptualization, Methodology. **Anand Bewoor:** Data curation, Writing - original draft. **Ravinder Kumar:** Supervision, Visualization, Investigation. **Mohammad Hossein Ahmadi:** Investigation, Writing - review & editing. **Giulio Lorenzini:** Validation.

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