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RESEARCH ARTICLE

Stochastic Modeling and Performance Optimization of Marine Power Plant with Metaheuristic Algorithms

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Abstract

For the successful operation of any industry or plant continuous availability of power supply is essential. Many of the large-scale plants established their power generation units. Marine power plant having two generators is also fall in this category. In this study, an effort is made to derive and optimize the availability of a marine power plant having two generators, one switch board and distribution switchboards. For this purpose, a mathematical model is proposed using Markov birth death process by considering exponentially distributed failure and repair rates of all the subsystems. The availability expression of marine power plant is derived. Metaheuristic algorithms namely dragonfly algorithm (DA), bat algorithm (BA) and whale optimization (WOA) are employed to optimize the availability of marine power plant. It is revealed that whale optimization algorithm outperforms over dragonfly algorithm (DA), and bat algorithm (BA) in optimum availability prediction and parameter estimation. The numerical values of the availability and estimated parameters are appended as numerical results. The derived results can be utilized in development of maintenance strategies of marine power plants and to carry out design modifications.

Keywords Markov process; Whale optimization algorithm; Dragonfly algorithm; Availability; Marine power plant

1 Introduction

The economic development of a country depends on its industrial growth. There are several factors including consistent power supply and raw material availability for successful operation of industrial entities. As well as sufficient transportation facilities are also required to transfer the manufactured material from plant to the trade centers. Marine transport is the backbone of the supply chain for international trade. For the operation of large marine entities sufficient power is essential and it is fulfilled by marine power plants established on the ship itself. To ensure the consistent power supply, it is recommended to ensure the high availability of the plant through identification of most sensitive components whose failure can impact the plants operation.

Article Highlights

- A stochastic model of marine power plant is developed using Markovian approach for performance evaluation.
- The availability of the marine power plant optimized using metaheuristics algorithms.
- It is revealed that whale optimization algorithm outperforms over other considered algorithms.

The availability analysis is a key system reliability effectiveness measure. Several studies have been conducted to improve the reliability of industrial sectors. Saini et al. (2021) developed a stochastic model for availability evaluation of urea decomposition plant. Kumar and Kumar (2021) evaluated the performance of a tripod turnstile machines by investigation the impact of simultaneous failures. Kumar et al. (2021) explored the critical perspectives of reliability on performance of cyber physical systems utilized in various industries. Gupta et al. (2021) derived reliability and maintainability measures for steam turbine power plant using Markov birth death process. Kumar et al. (2022c) utilized reliability approach in performance investigation of tube wells utilized for irrigation in agriculture.

During last few decades, several researchers tried to evaluate the reliability and performance of power sector entities including marine power plants utilizing various reliability evaluation techniques. The prominent techniques used for performance evaluation are Markov process, semi-Markov approach, RAM analysis, copula approach, and fault tree analysis. These techniques provided the local solution of the system characteristics like availability, reliability, mean time to system failure and expected number of repairs. Kumar et al. (2006) used interval valued vague sets for fuzzy reliability investigation of marine power plant. Wolfram (2006) assessed the reliability and availability of marine energy converters. Chybowski and

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Matuszak (2009) deliberated the impact of human reliability on operation of marine power plants. Chybowski and Matuszak (2010) explored the importance of reliable components in performance of marine technical systems. Stevens and Santoso (2013) investigated the reliability of a shipboard electrical power distribution system operated according to a breaker and a half topology. Hidalgo et al. (2013) explored the applications of Markov models in reliability evaluation of cargo carriers. Evangelos and Agapios (2013) assessed the availability of diesel generator system installed on a ship. Wu et al. (2013) developed a reliability model for marine power plant. The mean time between failures identified in different working conditions. Dash and Das (2014) performed availability evaluation of hydroelectric plant using Markovian approach. Dubey et al. (2015) analyzed a three-dimensional electrical power system. Kumar and Ram (2015) evaluated the performance of marine power plant having generator, main and distribution switchboard failures. Tsekouras and Kanellos (2016) performed reliability investigation of ship power system. Van et al. (2016) assessed the reliability of marine propulsion system using fault tree approach. Kumar and Saini (2018) suggested a mathematical model for fuzzy reliability investigation of marine power plant. Kazienko (2018) performed an analysis on the class survey methods and analyze impact on reliability of marine power plants. Gupta et al. (2020) investigated the availability of a generator of thermal power plant using Markovian approach and constant failure and repair rates. Gupta and Singh (2021) used Markov chain to analyze the reliability of power generating system.

Many studies performed by researchers to optimize the performance of industrial systems by adopting various optimization techniques. Mirjalili (2016) proposed dragonfly algorithm for optimization of single objective optimization problems. Kaur and Singh (2016) used bat algorithm for scheduling the workflow in the cloud. Talafuse and Pohl (2016) explored the applications of bat algorithm in reliability allocation problems. Chakri et al. (2016) applied bat algorithm in structural reliability assessment. Ahmed et al. (2017) performed comparative analysis of genetic algorithms and whale optimization algorithms for fault identification in power systems. Yazdani et al. (2019) suggested a novel integrated method for reliability estimation based on support vector regression and variable neighborhood search technique. Lu and Ma (2018, 2021) proposed modified whale optimization algorithms for estimation of parameters of reliability growth models. Mirjalili et al. (2020) developed whale optimization algorithm and explored its applications in design photonic crystal fitters. Lodhi et al. (2021) used dragonfly algorithm for extracting the maximum power from a grid-interfaced PV system. Sharma (2021) developed an enhanced butterfly optimization for analysis of complex optimization problems. Poljak (2022) discussed configuration and configuration of marine power systems. Long et al. (2022) estimated the parameters of solar photovoltaic systems using hybrid seagull algorithm. Kumar et al. (2022a) proposed stochastic model for reliability enhancement of cooling tower using metaheuristic algorithms. Saini et al. (2022) used genetic algorithms and particle swarm optimization for availability optimization of condenser. Kumar et al. (2022b) proposed a computational system for performance optimization of e-waste management plant. It is revealed from the literature that performance optimization aspect of marine power plants needs to be explored. That's why in the present study an effort is made to optimize the availability of a marine power plant.

By keeping in mind all above facts, an effort is made to derive and optimize the availability of a marine power plant having two generators, one switch board and distribution switchboards. For this purpose, a mathematical model is proposed used Markov birth death process by considering exponentially distributed failure and repair rates of all the subsystems. The availability expression is derived and optimized using metaheuristic algorithms namely dragonfly algorithm (DA), bat algorithm (BA) and whale optimization (WOA) in the same search space. It is revealed that whale optimization algorithm outperforms over dragonfly algorithm (DA), and bat algorithm (BA) in optimum availability prediction and parameter estimation. The numerical values of the availability and estimated parameters are appended as numerical results. The derived results can be utilized in development of maintenance strategies of marine power plants and to carry out design modifications.

The whole manuscript is organized into six sections including the present introduction section. Section 2 devoted to the notations, assumptions, and system description while a stochastic model of marine power plant developed in section 3. Section 4 describe various optimization techniques employed for availability optimization. Results are shown in section 5 followed by concluding section 6.

2 System description, notations and assumptions

2.1 System description

In present study, a mathematical model is developed for a marine power plant and its availability optimized using metaheuristic algorithms namely dragonfly algorithm (DA), bat algorithm (BA) and whale optimization (WOA) in the same search space. The marine power plant is configured with two generators, two main switchboards and one distribution switchboard. One of the generators is installed at stern while other is in the bow. The distribution switchboard gets power from main switchboards which are interconnected through cables. The generators transfer the power to the main switchboards. The configuration flow chart and state transition diagrams appended in Figures 1 and 2, respectively.

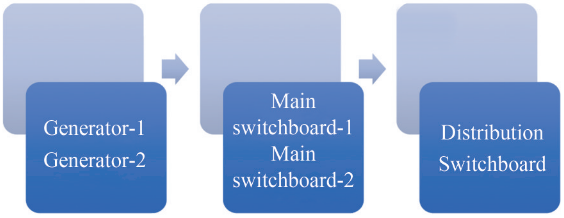

Figure 1 Configuration flowchart of marine power plant

2.2 Notations

The nomenclature in Table 1 is used to develop the transition diagram and mathematical model.

2.3 Assumptions

The following assumptions are made for the proposed system model of marine power plant for availability evaluation.

- No simultaneous failures;
- Exponentially distributed failure and repair rates;
- Repairs and maintenances are perfect;
- The marine power plant operates under reduced capacity after failure of one main switchboard;
- Sufficient repair facility always remains available with marine power plant to rectify the failures.

3 Development of stochastic model and its solution

The set of Chapman-Kolmogorov differential equations (based on Figure 2) governs the stochastic model of marine power plant are described as follows (Appendix B):

$$\begin{aligned} P_0(t+\Delta t) &= \left(1-\lambda_1-2\lambda_2-\lambda_3-\lambda_4\right)P_0(t)\Delta t \\ &\quad +\mu_1 P_1(t)\Delta t+\mu_2 P_2(t)\Delta t+\mu_3 P_4(t)\Delta t \\ &\quad +\mu_4 P_5(t)\Delta t \end{aligned}$$

Taking limit $\Delta t \rightarrow 0$, we get

$$\begin{aligned} \lim_{\Delta t\rightarrow 0}\frac{P_0(t+\Delta t)-P_0(t)}{\Delta t} &= \left(-\lambda_1-2\lambda_2-\lambda_3-\lambda_4\right)P_0(t) \\ &\quad +\mu_1 P_1(t)+\mu_2 P_2(t)+\mu_3 P_4(t)+\mu_4 P_5(t) \end{aligned}$$

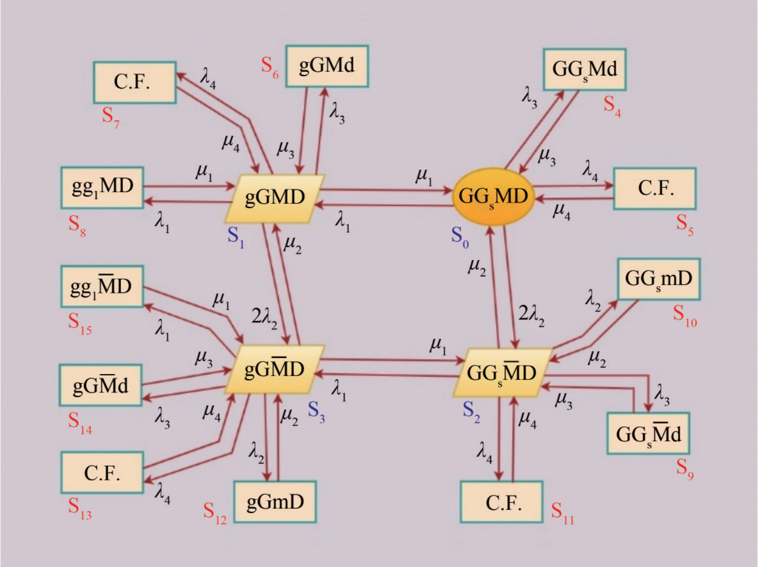

Figure 2 State transition diagram of marine power plant

Table 1 Notations of various states of marine power plant, failure, and repair rates

Sr. No.	Sub-systems	Representation			Failure rates		Repair rates	
		Operative	Standby	Fail	Original	Standby	Original	Standby
1	Generator	G	G$_s$	g	λ_1	λ_1	μ_1	μ_1
2	Main switchboard	M	$\bar{M}$	m	λ_2	λ_2	μ_2	μ_2
3	Distribution switchboard	D	....	d	λ_3	λ_3	μ_3	μ_3
4	Common cause failure	C.F.	-------		λ_4		μ_4	
5	$P_i(t)$	Probability that system remains at i^{th} state at time 't'						
6	$P_i'(t)$	Derivative of probability that system remains at i^{th} state at time 't'						

$$\Rightarrow \left(-\lambda_1 - 2\lambda_2 - \lambda_3 - \lambda_4 \right) P_0(t) + \mu_1 P_1(t) + \mu_2 P_2(t) + \mu_3 P_4(t) + \mu_4 P_5(t) = 0$$

Applying limit $t \longrightarrow \infty$, we get

$$\left(\lambda_1 + 2\lambda_2 + \lambda_3 + \lambda_4 \right) P_0 = \mu_1 P_1 + \mu_2 P_2 + \mu_3 P_4 + \mu_4 P_5 \tag{1}$$

$$\left(\mu_1 + \lambda_1 + 2\lambda_2 + \lambda_3 + \lambda_4 \right) P_0 = \lambda_4 P_0 + \mu_1 P_8 + \mu_2 P_3 + \mu_3 P_6 + \mu_4 P_7 \tag{2}$$

$$\begin{aligned} &\left(\mu_2 + \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 \right) P_0 = \\ &2\lambda_2 P_0 + \mu_1 P_3 + \mu_2 P_{10} + \mu_3 P_9 + \mu_4 P_{11} \end{aligned} \tag{3}$$

$$\begin{aligned} &\left(\mu_1 + \mu_2 + \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 \right) P_0 = \\ &\lambda_1 P_2 + 2\lambda_2 P_1 + \mu_1 P_{15} + \mu_2 P_{12} + \mu_3 P_{14} + \mu_4 P_{13} \end{aligned} \tag{4}$$

$$\mu_3 P_4 = \lambda_3 P_0 \tag{5}$$

$$\mu_4 P_5 = \lambda_4 P_0 \tag{6}$$

$$\mu_3 P_6 = \lambda_3 P_1 \tag{7}$$

$$\mu_4 P_7 = \lambda_4 P_1 \tag{8}$$

$$\mu_1 P_8 = \lambda_1 P_1 \tag{9}$$

$$\mu_3 P_9 = \lambda_3 P_2 \tag{10}$$

$$\mu_2 P_{10} = \lambda_2 P_2 \tag{11}$$

$$\mu_4 P_{11} = \lambda_4 P_2 \tag{12}$$

$$\mu_2 P_{12} = \lambda_2 P_3 \tag{13}$$

$$\mu_4 P_{13} = \lambda_4 P_3 \tag{14}$$

$$\mu_3 P_{14} = \lambda_3 P_3 \tag{15}$$

$$\mu_1 P_{15} = \lambda_1 P_3 \tag{16}$$

Initial conditions: $P_{i=0}(t=0) = 1$ while all other states probability is zero.

After solving equations (1)–(16) along with initial conditions, we get

$$\boldsymbol{P}_4 = \lambda_3.P_0/\mu_3 \quad \boldsymbol{P_5} = \lambda_4.P_0/\mu_4 \quad \boldsymbol{P_6} = \lambda_3.P_1/\mu_3$$
$$\boldsymbol{P_7} = \lambda_4.P_1/\mu_4 \quad \boldsymbol{P_8} = \lambda_1.P_1/\mu_1 \quad \boldsymbol{P_9} = \lambda_3.P_2/\mu_3$$
$$\boldsymbol{P}_{10} = \lambda_2.P_2/\mu_2 \quad \boldsymbol{P_{11}} = \lambda_4.P_2/\mu_4 \quad \boldsymbol{P_{12}} = \lambda_2.P_3/\mu_2$$
$$\boldsymbol{P}_{13} = \lambda_4.P_3/\mu_4 \quad \boldsymbol{P_{14}} = \lambda_3.P_3/\mu_3 \quad \boldsymbol{P_{15}} = \lambda_1.P_3/\mu_1$$

$$\boldsymbol{P_3} = (\lambda_1.P_2 + 2\lambda_2.P_1)/(\mu_1 + \mu_2)$$
$$\boldsymbol{P_2} = (\mu_1.P_3 + 2\lambda_2.P_0)/(\mu_2 + \lambda_1)$$

$$\boldsymbol{P_1} = (\lambda_1.P_0 + \mu_2.P_3)/(\mu_1 + 2\lambda_2)$$
$$P_o = (\mu_1.P_1 + \mu_2.P_2)/(\lambda_1 + 2\lambda_2)$$

After simplification above relations, $P_3 = 2\lambda_1\lambda_2 P_0/\mu_1\mu_2$ $L = P_3/P_0 = 2\lambda_1\lambda_2/\mu_1\mu_2$ $P_2 = 2\lambda_2 P_0/\mu_2$ $M = P_2/P_0 = 2\lambda_2/\mu_2$ $P_1 = \lambda_1 P_0/\mu_1$ $N = P_1/P_0 = 2\lambda_2/\mu_2$ $\boldsymbol{P}_0 = 1/[\{1 + (\lambda_3/\mu_3) + (\lambda_4/\mu_4)\}\{1 + \boldsymbol{L} + \boldsymbol{M} + \boldsymbol{N}\} + \{(\lambda_1/\mu_1)\}\{\boldsymbol{L} + \boldsymbol{N}\} + \{(\lambda_2/\mu_2)\}\{\boldsymbol{L} + \boldsymbol{M}\}]$

By using above probabilities and normalization conditions, we get the expression for steady state availability of marine power plant as follows:

$$\text{Availability (Objective function)} = P_0 + P_1 + P_2 + P_3 = \{1 + \boldsymbol{L} + \boldsymbol{M} + \boldsymbol{N}\}[\{1 + (\lambda_3/\mu_3) + (\lambda_4/\mu_4)\}\{1 + \boldsymbol{L} + \boldsymbol{M} + \boldsymbol{N}\} + \{(\lambda_1/\mu_1)\}\{\boldsymbol{L} + \boldsymbol{N}\} + \{(\lambda_2/\mu_2)\}\{\boldsymbol{L} + \boldsymbol{M}\}] \tag{17}$$

4 Optimization model

Metaheuristic algorithms are extensively utilized for predicting the performance of industrial systems as well as their parameter estimation. In this study, availability optimization of marine power plant is performed by using metaheuristic algorithms namely whale optimization algorithm (WOA), bat algorithm (BA) and dragonfly algorithm (DA) are used. Though, several algorithms exist in literature for optimization of performance of industrial systems and power plants, but metaheuristic algorithms proved more efficient as these algorithms not influenced by size and non-linearity of problem. As well as these algorithms work on the process of natural selection and reproduction theory. The simulation results are derived in the experimental setup on Windows 10 64-bit operating system having 8 GB of RAM and Intel Core i5 8th generation CPU using R and R-Studio.

4.1 Whale optimization algorithm

Mirjalili (2016) proposed an algorithm based on the community conduct of humpback whales. It simulated the public behavior of these animals. It is based on the bubble-net hunting strategy. The implementation procedure of the whale optimization algorithm included initialization of first random population of whales, evaluation of fitness of whales and identification of best position of whale. The next stage is updating the position of whale using appropriate strategy and position of best whale. If any new whale is identified having best position, then update the best position. Finally check the execution conditions if condition met best position is best solution otherwise go back and update the best position.

The following steps followed by algorithm to optimize the system availability:

- Initialization;
- Position upgradation;
- Check termination criteria.

4.2 Bat algorithm

Yang (2011) proposed this algorithm by motivating the echolocation of bats. The aspirant solution itself represented by bat in this algorithm. Bats movement based on the flying speed, pulse rate, loudness and pulse frequency. The optimal solution is achieved by following steps:

- Initialization of random population of bats;
- Every bat moves forward on basis of velocity and pulse frequency;
- Randomly move some bats (candidate solutions) near the global best;

- Global best is replaced by candidate solution if it achieved better fitness than global;
- Increase pulse rate and decrease loudness;
- Check stopping criteria either maximum iteration or sufficient fitness achieved exit the solution process otherwise move every bat forward.

4.3 Dragonfly algorithm

Mirjalili (2016) coined the dragonfly algorithm after getting inspiration from static and dynamic behavior of dragonflies. This algorithm works on the exploration and exploitation are designed by investigating the dragonfly's public behavior including navigation, searching and escape from enemies. Following methodology is utilized for optimization the solution in DA:

- Initialize first random population of dragonflies, determine their fitness values and identify best and worst dragonfly by utilizing the information of food source and enemy position respectively.
- Evaluate the behavior weight. Behavior weight influences the fly direction and distance. It includes separation, alignment, cohesion, attracted toward food sources and distraction from enemy.
- Renew the location of each dragonfly by utilizing behavior weight and velocity.
- Evaluate the revised fitness value, updated food and enemy position.
- Check stopping criteria if condition satisfied stop and claim food position as global solution otherwise recalculate behavior weight.

5 Numerical results and discussion

In this section, the numerical results of marine power plant's availability are derived using metaheuristic algorithms namely whale optimization algorithm (WOA), bat algorithm (BA) and dragonfly algorithm (DA). The global value of marine power plant is discovered in the search space given in Table 2.

Table 2 Search space of marine power plant

Subsystem	Failure rate	Repair rate
Generator	$\lambda_1 = [0.027, 0.913]$	$\mu_1 = [0.42, 1.08]$
Main Switchboard	$\lambda_2 = [0.039, 0.792]$	$\mu_2 = [0.69, 1.99]$
Distribution switchboard	$\lambda_3 = [0.041, 0.926]$	$\mu_3 = [0.59, 2.02]$
Catastrophic failure	$\lambda_4 = [0.021, 0.891]$	$\mu_4 = [0.76, 1.49]$

The availability of marine power plant at various iteration sizes having different populations is given in Table 3. From Table 3, it is observed that maximum availability 0.997 797 1 of marine power plant is achieved after 200 iterations on population size 2 100 While in bat algorithm maximum availability is 0.990 244 3 that is achieved initially at population size 600 after 50 iterations. The Whale optimization attained the maximum value only after 50 iterations on population size 600. Table 4 depicted that elapsed time of the whale optimization algorithm is minimum. The estimated value of the failure and repair rate parameters (decision variables) are derived and shown in Table 5 as well as in supplementary Tables A1-A5 given in Appendix A. The comparative analysis of all algorithms' estimated values is shown in Table 6 after 140 iterations and population size 600.

Table 3 Availability of marine power plant

Meta heuristic techniques	Population/Iteration	600	900	1 200	1 500	1 800	2 100
DA	50	0.995 031 3	0.870 081 6	0.997 797 1	0.927 049	0.983 157	0.995 916 9
	80	0.799 655 3	0.997 761 7	0.894 959 6	0.997 797 1	0.942 621 7	0.990 836 1
	110	0.995 259	0.997 797 1	0.991 239 8	0.978 564 3	0.996 867 1	0.997 797 1
	140	0.997 732 1	0.959 658 5	0.951 281 6	0.960 795 5	0.701 411 4	0.997 712 9
	170	0.992 534 9	0.996 677 4	0.914 495	0.996 122 9	0.997 797 1	0.997 754 6
	200	0.995 830 5	0.997 796 5	0.997 795 2	0.997 601 2	0.880 245 8	0.997 797 1
BA	50	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3
	80	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3
	110	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3
	140	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3
	170	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3
	200	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3	0.990 244 3
WOA	50	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1
	80	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1
	110	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1
	140	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1
	170	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1
	200	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1	0.997 797 1

Table 4 Elapsed time of metaheuristic techniques in availability optimization of marine power plant

Meta heuristic techniques	Iteration/Population	600	900	1 200	1 500	1 800	2 100
DA	50	8.19	9.98	8.92	8.18	17.89	8.99
	80	8.61	11.13	10.11	13.28	14.29	20.18
	110	13.83	19.78	15.75	14.42	14.49	12.98
	140	13.45	12.81	13.36	13.83	14.04	17.15
	170	8.53	8.61	8.54	7.97	8.3	8.5
	200	7.85	8.65	8.5	8.88	8.47	11.27
BA	50	0.53	0.49	1.36	1.28	1.28	1.2
	80	0.48	0.55	0.51	0.49	0.48	1.14
	110	0.48	1.12	1.11	1.01	0.5	1.34
	140	0.47	1.28	1.2	1.13	1.22	1.28
	170	0.47	0.49	0.5	1.17	0.5	1.22
	200	0.47	1.24	1.16	0.49	0.5	0.53
WOA	50	1.91	0.56	0.53	1.52	1.29	1.27
	80	0.76	1.19	0.53	1.53	1.36	1.47
	110	0.55	0.56	1.39	1.32	1.57	1.42
	140	0.53	1.28	1.36	1.4	0.56	1.44
	170	0.53	0.56	0.57	0.54	0.56	0.53
	200	0.86	0.53	0.55	0.55	0.55	1.89

Table 5 Decision variables estimated value at different iterations with population size = 50

Meta heuristic techniques	Iteration	600	900	1 200	1 500	1 800	2 100
DA	λ_1	0.002 7	0.002 7	0.002 7	0.522 167 7	0.002 7	0.002 7
	λ_2	0.003 9	1.051 058	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.025 317 16	0.002 1
	μ_1	2.08	2.08	2.08	1.679 649	1.614 23	0.42
	μ_2	0.69	2.99	2.99	2.99	1.875 106	2.99
	μ_3	1.327 625	3.02	3.02	2.167 779	0.59	3.02
	μ_4	1.145 487	0.76	2.49	0.76	2.49	0.780 827 5
BA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	0.42	0.42	0.42	0.42	0.42	0.42
	μ_2	0.69	0.69	0.69	0.69	0.69	0.69
	μ_3	0.59	0.59	0.59	0.59	0.59	0.59
	μ_4	0.76	0.76	0.76	0.76	0.76	0.76
WOA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	2.08	2.08	2.08	2.08	2.08	2.08
	μ_2	2.99	2.99	2.99	2.99	2.99	2.99
	μ_3	3.02	3.02	3.02	3.02	3.02	3.02
	μ_4	2.49	2.49	2.49	2.49	2.49	2.49

Table 6 Comparative Analysis of availability of marine power plant at 600 iterations and population size 140

Algorithm	Optimum variables								Optimum availability	Elapsed time
	λ_1	λ_2	λ_3	λ_4	μ_1	μ_2	μ_3	μ_4		
DA	0.002 7	0.003 9	0.004 1	0.002 1	2.08	0.69	3.02	2.49	0.997 732 1	13.45
BA	0.002 7	0.003 9	0.004 1	0.002 1	0.42	0.69	0.59	0.76	0.990 244 3	0.47
WOA	0.002 7	0.003 9	0.004 1	0.002 1	2.08	2.99	3.02	2.49	0.997 797 1	0.53

6 Conclusion

In present investigation, a stochastic model developed to optimize the performance of the marine power plant. As availability is a key system effectiveness measure so an effort is made to predict the availability of marine power plant using metaheuristic algorithms. The estimated values of parameters are derived for identification of most sensitive subsystem. From the above discussed numerical results, it is revealed that distribution switchboard is the most sensitive subsystem in marine power plant and special maintenance strategies are required for its proper functionality. The optimum availability is predicted by whale optimization algorithm at minimum population size after least iterations in minimum elapsed time. So, the system designers can utilize the information of failure and repair rates in proposing the maintenance strategies. It is very helpful for the system designers of marine power plants. Further the study can be extended to identify the effect of simultaneous failures, warm redundancy and arbitrary distribution of failure and repair rates of subsystems on system performance. The proposed methodology can be applied in other kind of power plants as well as process industries.

Appendix A Estimated values of parameters at various population sizes

Table A1 Decision variables estimated value at different iterations with population size = 80

Meta heuristic techniques	Iteration/Population	600	900	1 200	1 500	1 800	2 100
DA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.558 400 3	0.079 440 28
	λ_2	0.003 9	0.003 9	0.783 953 9	0.003 9	0.003 9	0.003 9
	λ_3	0.753 903 8	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	1.273 85	0.478 371 2	0.42	2.08	2.08	2.08
	μ_2	0.825 976 1	2.99	2.585 056	2.99	2.039 729	2.99
	μ_3	3.02	3.02	2.704 694	3.02	2.025 484 2	0.59
	μ_4	2.49	2.49	2.49	2.49	1.150 296	2.49
BA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	0.42	0.42	0.42	0.42	0.42	0.42
	μ_2	0.69	0.69	0.69	0.69	0.69	0.69
	μ_3	0.59	0.59	0.59	0.59	0.59	0.59
	μ_4	0.76	0.76	0.76	0.76	0.76	0.76
WOA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	2.08	2.08	2.08	2.08	2.08	2.08
	μ_2	2.99	2.99	2.99	2.99	2.99	2.99
	μ_3	3.02	3.02	3.02	3.02	3.02	3.02
	μ_4	2.49	2.49	2.49	2.49	2.49	2.49

Table A2 Decision variables estimated value at different iterations with population size = 110

Meta heuristic techniques	Iteration/Population	600	900	1 200	1 500	1 800	2 100
DA	λ_1	0.000 27	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.323 371	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	1.984 255	2.08	0.42	2.08	1.838 82	2.08
	μ_2	0.717 245	2.99	1.715 347	2.99	2.594 337	2.99
	μ_3	1.064 207	3.02	0.59	2.360 61	1.850 885	3.02
	μ_4	2.49	2.49	1.152 107	2.49	2.285 843	2.49
BA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	0.42	0.42	0.42	0.42	0.42	0.42
	μ_2	0.69	0.69	0.69	0.69	0.69	0.69
	μ_3	0.59	0.59	0.59	0.59	0.59	0.59
	μ_4	0.76	0.76	0.76	0.76	0.76	0.76
WOA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	2.08	2.08	2.08	2.08	2.08	2.08
	μ_2	2.99	2.99	2.99	2.99	2.99	2.99
	μ_3	3.02	3.02	3.02	3.02	3.02	3.02
	μ_4	2.49	2.49	2.49	2.49	2.49	2.49

Table A3 Decision variables estimated value at different iterations with population size = 140

Meta heuristic techniques	Iteration/Population	600	900	1 200	1 500	1 800	2 100
DA	λ_1	0.002 7	0.002 7	0.404 303 1	0.411 3904	0.611 685 1	0.002 7
	λ_2	0.003 9	0.470 897	0.165 751 15	0.003 953 422	0.008 932 097	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 166 693	0.0041	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 147 224	0.648 979 1	0.002 1
	μ_1	2.08	1.175 834	2.08	2.08	1.248 821	0.836 765 9
	μ_2	0.69	2.99	2.99	2.99	2.99	0.69
	μ_3	3.02	1.251 324	0.738 222 9	0.59	1.349 64	3.02
	μ_4	2.49	2.49	1.907 282	2.49	2.49	2.49
BA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	0.42	0.42	0.42	0.42	0.42	0.42
	μ_2	0.69	0.69	0.69	0.69	0.69	0.69
	μ_3	0.59	0.59	0.59	0.59	0.59	0.59
	μ_4	0.76	0.76	0.76	0.76	0.76	0.76
WOA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	2.08	2.08	2.08	2.08	2.08	2.08
	μ_2	2.99	2.99	2.99	2.99	2.99	2.99
	μ_3	3.02	3.02	3.02	3.02	3.02	3.02
	μ_4	2.49	2.49	2.49	2.49	2.49	2.49

Table A4 Decision variables estimated value at different iterations with population size = 170

Meta heuristic techniques	Iteration/Population	600	900	1 200	1 500	1 800	2 100
DA	λ_1	0.023 881 36	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.787 175 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	2.08	1.613 278	2.08	0.560 086	2.08	0.990 710 6
	μ_2	2.99	1.202 833	2.99	2.99	2.99	0.980 460 9
	μ_3	0.627 926 1	3.02	2.355 051	1.359 365	3.02	3.02
	μ_4	2.49	1.078 574	2.49	2.49	2.49	2.49
BA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	0.42	0.42	0.42	0.42	0.42	0.42
	μ_2	0.69	0.69	0.69	0.69	0.69	0.69
	μ_3	0.59	0.59	0.59	0.59	0.59	0.59
	μ_4	0.76	0.76	0.76	0.76	0.76	0.76
WOA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	2.08	2.08	2.08	2.08	2.08	2.08
	μ_2	2.99	2.99	2.99	2.99	2.99	2.99
	μ_3	3.02	3.02	3.02	3.02	3.02	3.02
	μ_4	2.49	2.49	2.49	2.49	2.49	2.49

Table A5 Decision variables estimated value at different iterations with population size = 200

Meta heuristic techniques	Iteration/Population	600	900	1 200	1 500	1 800	2 100
DA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.054 855 27	0.003 9	0.003 9	0.003 9	0.983 713 7	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	0.42	2.08	1.541 957	2.08	0.42	2.08
	μ_2	1.900 512	2.798 75	2.99	0.69	2.99	2.99
	μ_3	3.02	3.02	3.02	3.02	1.017 272	3.02
	μ_4	2.002 375	2.49	2.49	2.154 07	2.159 438	2.49
BA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	0.42	0.42	0.42	0.42	0.42	0.42
	μ_2	0.69	0.69	0.69	0.69	0.69	0.69
	μ_3	0.59	0.59	0.59	0.59	0.59	0.59
	μ_4	0.76	0.76	0.76	0.76	0.76	0.76
WOA	λ_1	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7	0.002 7
	λ_2	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9	0.003 9
	λ_3	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1	0.004 1
	λ_4	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1	0.002 1
	μ_1	2.08	2.08	2.08	2.08	2.08	2.08
	μ_2	2.99	2.99	2.99	2.99	2.99	2.99
	μ_3	3.02	3.02	3.02	3.02	3.02	3.02
	μ_4	2.49	2.49	2.49	2.49	2.49	2.49

Appendix B Development of Chapman-Kolmogorov Equations

As per the assumption that failure and repair rates of marine power plants are exponentially distributed. So, by using Markov birth death process the set of Chapman-Kolmogorov differential difference equations are derived as follows:

Suppose at time t, the system is present in state Si, then probability of system remain in that state is described as: Probability that system is in state Si at time t and remain there during time interval $(t,t+\Delta t)$ and/or if system is at any other state at time t, then it should come back at state Si in time interval $(t,t+\Delta t)$ subject to transition between states and $\Delta t \rightarrow 0$.

Applying above definition, the probability that system remain at state S0 in time $(t,t+\Delta t)$ is given by:

$$P_0(t+\Delta t) = \left(1-\lambda_1-2\lambda_2-\lambda_3-\lambda_4\right)P_0(t)\Delta t$$
$$+\mu_1 P_1(t)\Delta t+\mu_2 P_2(t)\Delta t+\mu_3 P_4(t)\Delta t+\mu_4 P_5(t)\Delta t$$

Taking limit $\Delta t \rightarrow 0$, we get

$$\lim_{\Delta t \to 0}\frac{P_0(t+\Delta t)-P_0(t)}{\Delta t} = \left(-\lambda_1-2\lambda_2-\lambda_3-\lambda_4\right)P_0(t)$$
$$+\mu_1 P_1(t)+\mu_2 P_2(t)+\mu_3 P_4(t)+\mu_4 P_5(t)$$

$$\Rightarrow \left(-\lambda_1-2\lambda_2-\lambda_3-\lambda_4\right)P_0(t)+\mu_1 P_1(t)+\mu_2 P_2(t)$$
$$+\mu_3 P_4(t)+\mu_4 P_5(t)=0$$

Applying limit $t \rightarrow \infty$, we get

$$\left(\lambda_1+2\lambda_2+\lambda_3+\lambda_4\right)P_0=\mu_1 P_1+\mu_2 P_2+\mu_3 P_4+\mu_4 P_5$$

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