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Binary Pareto Multi-Objective Whale Optimization Algorithm for Power Plant Maintenance Scheduling

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Abstract— *Maintenance scheduling is a critical challenge in all major industrial sectors, such as aeronautics, automotive manufacturing, and power generation plants. The goal of power plant maintenance scheduling is to establish a schedule plan for carrying out preventive maintenance shutdowns for each unit within a defined planning horizon. In this paper, a mathematical model for optimizing the maintenance schedule was established to maximize the supply, minimize fuel costs, and CO2 emissions from generating units. A developed Whale Optimization Algorithm called Binary Pareto Multi-Objective Whale Optimization Algorithm BPMOWOA is proposed and implemented to find optimal maintenance scheduling for a power plant. The proposed algorithm uses two different approaches. The first approach includes binary encoding, in which each generating unit and each time interval are represented in binary form. Then, in the second approach, a fixed-sized repository is integrated into the WOA for saving and retrieving the Pareto optimal solutions, and a grid mechanism is integrated into the WOA to maintain diversity in the population of non-dominated solutions. A case study was conducted on fourteen generating units adapted from a real-world power plant to validate the algorithm's efficiency. The results illustrate that the proposed algorithm was effective in optimizing the maintenance schedule in terms of coverage and non-dominated solution and improved the power plant performance by increasing electricity generation by 11.48% and decreasing fuel expenses by 6.56%, which are the main goals of the considered power plant.*

Index Terms— *maintenance scheduling, multi-objective, whale optimization algorithm, power plant.*

I. INTRODUCTION

Maintenance represents the actions necessary to ensure the dependable functionality of a product. It can be categorized into two primary types: corrective and preventive. Corrective maintenance is undertaken following a breakdown, while preventive maintenance occurs at predetermined intervals or based on specified criteria with the aim of minimizing the likelihood of failure [1].

In production systems, maintenance activities play a crucial role in influencing both the cost and performance of the systems. Maintenance within the power plant concerns generation units and transmission lines, with a time horizon that can be either long-term or short-term. In its fundamental form, the challenge of maintenance scheduling revolves around determining the optimal timing for shutting down the generating units for preventive maintenance in order to maintain system reliability and reduce overall operational costs [2]. The maintenance scheduling is a complex combinatorial optimization problem with numerous constraints necessitating the use of appropriate optimization techniques to identify the most effective and feasible maintenance schedule [3]. Scheduling preventive maintenance for generating units is a critical requirement and poses a considerable challenge within a

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power system. This process holds significant importance for reducing unexpected outages, extending the lifespan of equipment, and operational planning [4]. A variety of Artificial Intelligence (AI) techniques have been utilized to address challenges in maintenance scheduling due to the complexity of equipment failure patterns, resource availability, risks to production and society, also its offer advantages over mathematical approaches, particularly in cases where time efficiency is crucial. One primary challenge in employing artificial intelligence techniques lies in the fact that the search space explored by the algorithm grows exponentially in proportion to the size of the problem and the number of objectives [5][6]. Numerous researchers have tackled maintenance scheduling difficulties in different industrial sectors using a variety of heuristics and metaheuristic algorithms. Miao et al. developed Bio-Objective Genetic Algorithm to find optimal long-term maintenance schedules for wind farms that minimize labor cost and production losses[7]. Zhong et al developed Non Dominated Sorting Genetic Algorithm NSGAII for the preventive maintenance scheduling of offshore wind farms, considering the goals of maximizing system reliability and minimizing maintenance-related costs [8]. The Non-Dominated Sorting Genetic Algorithm NSGA-III and the Diversity-Indicator based Multi-Objective Evolutionary Algorithm (DIMOEA) were used in an evolutionary algorithm framework presented by Wang et al. for the purpose of optimizing vehicle fleet maintenance scheduling. The objective is to maximize demand while minimizing overall cost and workload [9]. Mayo introduced the Exchange Market Algorithm (EMA) to optimize the scheduling of power plant maintenance. The primary aims are cost reduction, minimizing the risk of failures, and improving overall reliability [10]. Automatic Preference-Diversity-Indicator-based Multi-Objective Evolutionary Algorithm (APDI-MOEA) was introduced by Wang et al. This algorithm was specifically developed for optimizing maintenance schedules for vehicle fleets, aiming to minimize the overall workload, costs, and the anticipated number of failures [11]. Stock-Williams and Swamy utilized a Genetic Algorithm to minimize energy loss in the maintenance scheduling of offshore wind farms [12]. Fuzi and Ismail introduced an intelligent maintenance optimization system for thermal power plant boilers, employing Analytical Hierarchy Process (AHP) and Particle Swarm Optimization (PSO) techniques aiming to minimize the maintenance cost and increase the operational duration based on prioritized maintenance activities [13]. A Modified Genetic Algorithm (MGA) for maintenance scheduling in power systems is proposed by Hadjaissa et al. aiming to minimize maintenance scheduling time and enhance energy production quality while reducing costs [14]. Belagoune et al. introduced Discrete Chaotic Jaya Optimization (DCJO) algorithm for scheduling preventive maintenance in electric power system generators by combining the discrete Jaya optimization algorithm with a move rule based on the Chaotic Local Search (CLS) technique [15]. Saravanan et al. proposed the application of the Grey Wolf Optimization Algorithm to tackle the challenge of scheduling power generation in wind power systems. They considered factors such as load balancing, reserve requirements, and constraints associated with wind power availability [16]. Saffariani et al. implemented a discrete firefly algorithm in conjunction with heuristic methods for generator maintenance scheduling [17]. The benefits of optimizing maintenance schedules have motivated researchers to explore and introduce a range of optimization methods. The Whale Optimization Algorithm (WOA) is a contemporary meta-heuristic algorithm that offers several advantages, such as simple implementation, few adjustment parameters, it incorporates an exploration mechanism that effectively guides the search towards the global optimum. Additionally, it maintains a well-balanced approach between exploration and exploitation, thereby avoiding the local optimum. Lastly, WOA has a strong optimization ability and fast convergence speed. For these reasons, the algorithm has been widely used in various fields such as image segmentation, feature selection, model prediction, path planning, and production scheduling [18][19]. However, WOA has not yet been implemented in the optimization problem of maintenance scheduling. Therefore, in this paper a developed Binary Pareto Multi Objective Whale Optimization Algorithm BPMOWOA is proposed to obtain an optimal maintenance schedule from the proposed tri objective model which is expected to

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make a valuable contribution by providing a practical solution to find the optimal maintenance schedule for a power plant. The rest of the research part is described as follows: The problem definition and proposed model are given in section 2. The proposed algorithm is presented in section 3. In section 4 a real-world case study and the results are presented. Finally, the conclusion and future work are given in section 5.

II. PROBLEM DEFINITION AND PROPOSED TRI OBJECTIVE MODEL

The maintenance scheduling problem primarily aims to determine a maintenance outage timetable in a manner that either maximizes or minimizes the power plant's goals. Gas turbines have a significant function in supplying energy in certain power systems. Traditionally, the scheduling of preventive maintenance for gas turbine generating units follows specific intervals determined by recommendations provided by the equipment suppliers or modified based on previous inspections. A gas turbines are a repairable system that undergoes degradation, and applying preventive maintenance typically enhances its overall performance. The preventive maintenance for a gas turbine power plant encompasses the following [20][21]:

A. Combustion inspection: The end caps, fuel nozzles, combustion liners, and transition pieces are the primary targets of this inspection.

B. Hot gas path inspection: This inspection is conducted to assess components exposed to the hot gases discharge during the combustion process. It covers a comprehensive examination of the combustion system and inspection of turbine nozzles, stationary stator shrouds, and turbine buckets.

C. Major inspection: The primary purpose of the major inspection is to perform a comprehensive check of all of the machine's internal components, including those that are spinning and those that are stationary. This inspection will begin at the machine's inlet and continue all the way through to the exhaust.

In certain power plants, the generation units that are represented by gas turbines play a significant part in the process of energy supply. Inspection and maintenance of a gas turbine should be performed on a regular basis. As a result, periodic maintenance scheduling is proposed based on the assumption that there will be four maintenance intervals with a planning horizon of one year. A tri objective generating maintenance scheduling model is proposed to meet the requirements of a real power plant. The model parameters are shown in Table I.

A. Objectives

Three objectives related to the generating units maintenance scheduling are considered including:

Maximum Power Supply

It represents the highest amount of electrical power that the power plant can produce under operating conditions. It is typically expressed in units of megawatts (MW). Maximum power supply helps to ensure that there is enough generating capacity to meet the electricity demand of the grid. The objective function of maximum power supply is stated as:

$$Max\ P = \sum_{i=1}^{I} \sum_{k=1}^{K} U_{ik}\, S_{ik} \qquad (1)$$

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Minimum Total Fuel Cost

The minimization of the overall fuel cost of a power generator is considered and stated as follows:

$$Min\ FC = \sum_{i=1}^{I}\sum_{k=1}^{K} U_{ik}\, F_{ik} \qquad (2)$$

Minimum CO2 Emission

Minimizing Carbon dioxide (CO2) emissions from power plants is crucial for mitigating climate change and reducing the environmental impact of greenhouse gases. Combustion of fossil fuels like coal, oil, and natural gas for the purpose of producing energy and transportation is the primary source of carbon dioxide. This objective aligns with global efforts to transition to more sustainable and environmentally responsible energy production, contributing to a greener and more sustainable future. This objective is stated as:

$$Min\ E = \sum_{i=1}^{I}\sum_{k=1}^{K} U_{ik}\, E_{ik} \qquad (3)$$

TABLE I. PROBLEM PARAMETERS

Symbol	Description
i	index of generating units
I	total number of generating units
k	index of scheduling intervals
K	total number of intervals in the scheduling horizon
Uik	generating unit i at interval k
Sik	power supply from unit i at interval k
Fik	Fuel cost for unit i at interval k
Eik	emission from unit i at interval k
Dk	Demand of interval k
P	total power supply from the generating units for scheduling horizon
FC	total fuel cost for scheduling horizon
E	total CO2 emission from generating units for scheduling horizon

B. Constraints

A wide range of factors, including assumptions and particular requirements, are responsible for determining the limits that are placed on the maintenance schedule of a generating unit. Such limits and conditions must be satisfied by a maintenance program in order for it to be considered practical. The following is a description of the constraints that were involved in the proposed model:

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Maintenance window Constraint

The state of the generator is represented as a binary string, where 0 stands for an offline unit (under maintenance) and 1 an online unit (operational).

$$U_{ik=}\begin{cases} 0 \quad if\ unit\ i\ at\ interval\ k \\ is\ on\ maintenance\ \ (shutdown) \\ \\ 1\ \ if\ unit\ i\ at\ interval\ k \\ is\ not\ in\ maintenance\ \ (\ operated) \end{cases}$$

Each generating unit has a specified timeframe during which it can undergo preventive maintenance. The maintenance period required for each unit is equal to one interval. If a unit is to be maintained in a particular interval, the corresponding bit assumes value 0, otherwise, it is 1. This specifies that once maintenance work on a particular generating unit begins, it must be carried out continuously without any interruptions for a duration that exactly matches the maintenance duration specified for that unit. This constraint is given by:

$$\sum_{k=1}^{k=4}(1-U_{ik})=1 \qquad (4)$$

Demand constraint

This constraint mandates that the total power generation from all units within each period must equal the load demand for that specific period (often referred to as the power balance constraint). It is a fundamental principle in electrical power systems, guaranteeing that the total electrical generation matches the electrical load demand within a designated period. This constraint is of paramount importance for upholding the stability and reliability of the power grid. In accordance with this constraint, the schedule must allow for meeting the overall power demand of the plant. During any maintenance interval, the total power supply should be greater than the anticipated load, as depicted by the following:

$$\sum_{i}^{I}S_{ik}\geq D_k \qquad (5)$$

Assumption

Generally, the following assumptions for the considered power plant maintenance scheduling problem are used:

1. The preventive maintenance activities are carried out at four consecutive intervals, with each interval lasting for a duration of three months.
2. The maintenance crew, resources, and spare parts are available at each maintenance interval.

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III. PROPOSED ALGORITHM

The Whale Optimization Algorithm (WOA) as introduced by Mirjalili and Lewis in 2016, is among the most recent nature-inspired metaheuristic algorithms. It models the social behaviuor of humpback whales during their hunting process. Humpback whales use a fascinating strategy when hunting groups of krill, bringing them close to the water's surface by encircling them in a shrinking circle and generating bubbles along a path that resembles a (9) shape. This unique technique is referred to as the spiral bubble net attack method and is illustrated in *Fig. 1*. In The WOA the best solution of the current candidate is adjusted to be the target prey, and the other whale will update their position towards the best based on two different phases [22][23]:

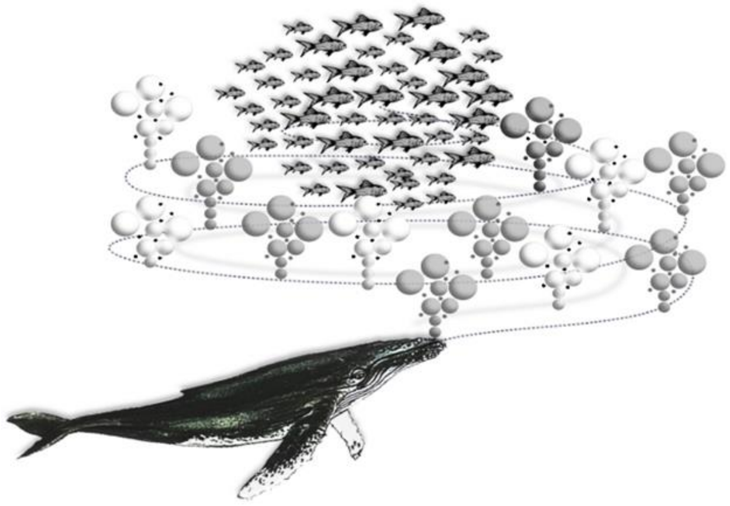

FIG. 1. THE SCHEMATIC OF THE SPIRAL BUBBLE-NET ATTACKING STRATEGY **ERROR! REFERENCE SOURCE NOT FOUND.**

Encircling prey phase: This phase exploits the search space and refines the potential solutions. It involves moving the whales towards the best solution found so far. This exploitation is divided in two processes :

1. shrinkage encircling technique, which is achieved by reducing the (a) values according to Equation (8). (A) $^{\rightarrow}$ is a random value in the interval [-a, a] where the (a) value decreases from two to zero over the iteration. The encircling technique is formulated mathematically as follows:

$$\vec{D} = \left| \vec{C}.\ \vec{x^*}(t) - \overrightarrow{X(t)} \right| \qquad (6)$$

$$\boldsymbol{\vec{X}(t+1) = \vec{x^*}(t) - \vec{A}.\vec{D}} \qquad \mathbf{(7)}$$

Where
D $^{\rightarrow}$: distance between current whale positon (X) and best whale position (X*)
t: current iteration
X: position vector
X*: best solution position vector
A and C are coefficients vector which is calculated as follow:

$$\boldsymbol{\vec{A} = 2\vec{a}\,.\vec{r} - \vec{a}} \qquad \mathbf{(8)}$$

$$\boldsymbol{\vec{C} = 2\vec{r}} \qquad \mathbf{(9)}$$

Where
r: is a random number in [0 1]

2. spiral position updating, a spiral pattern between the whale and its prey is established during position updating replicating the helix-shaped motion. According to Equation (10), in order to determine whether the spiral model or the shrinking encircling mechanism should be utilized, a probability of fifty percent is utilized. Consequently, the mathematical model is formulated as follows:

$$\boldsymbol{\vec{X}(t+1)} = \begin{cases} \boldsymbol{\overrightarrow{x^*}(t) - \vec{A}.\vec{D}} & \boldsymbol{if \;\; p < 0.5} \\ \boldsymbol{\overrightarrow{D'}.\, e^{bl}\cos(2\pi l) + \overrightarrow{x^*}(t)} & \boldsymbol{if \;\; p \geq \; 0.5} \end{cases} \qquad \boldsymbol{(10)}$$

Where
P: random number in [0,1]
l: randomly selected value from the range [-1, 1]
b: constant value
$\boldsymbol{\overrightarrow{D'}}$ is given by:

$$\overrightarrow{D'} = \overrightarrow{x^*}(t) - \overrightarrow{X(t)} \qquad (11)$$

Exploration phase (search for prey): The same strategy, which relies on variations in the $\vec{A}$ can be applied to search for prey during the exploration phase. Humpback whales search randomly based on their positions with each other. ($\vec{A}$) with random values greater than (1) or less than (-1) is utilized to encourage search agents to move far away from a reference whale. Unlike the exploitation phase, during the exploration phase, the position of a search agent is updated based on a randomly chosen search agent instead of the best search agent identified thus far. This mechanism and $|\vec{A}>1|$ allow WOA to conduct a comprehensive global search. The mathematical model is presented as follows:

$$\boldsymbol{\vec{D} = \left|\vec{C}.\,\overrightarrow{Xrand} - \vec{X}\right|} \qquad \boldsymbol{(12)}$$

$$\vec{X}(t+1) = \overrightarrow{X\,rand} - \vec{A}.\vec{D} \qquad (13)$$

Where
(X rand) $^{\rightarrow}$: random position vector (random whale) chosen from the current population

The developed BPMOWOA algorithm is based on Pareto dominance, stores the non-dominated solution that was found during optimization in an external repository, and involves encoding problem decision variables to represent variables in a way that is suitable for algorithmic processing. WOA was originally developed for solving single objective and continuous problems; it cannot be directly applied to tackle discrete problems. Therefore, the encoding of decision variables is done by creating a binary decision variable (0s and 1s) for each generating unit in each time interval. The binary values represent the decision to perform maintenance or not. The binary string represents the entire solution space for the maintenance scheduling problem and provides a representation of the exhaustive set of maintenance schedule permutations for the generating units. The WOA algorithm utilizes this binary string to conduct an exploration for the most optimal solution.

To augment solution diversity, the grid mechanism is utilized to partition the multi-objective solution space into a grid of smaller regions or cells. Each cell represents a portion of the objective space. Multi-objective optimization seeks to find a diverse set of

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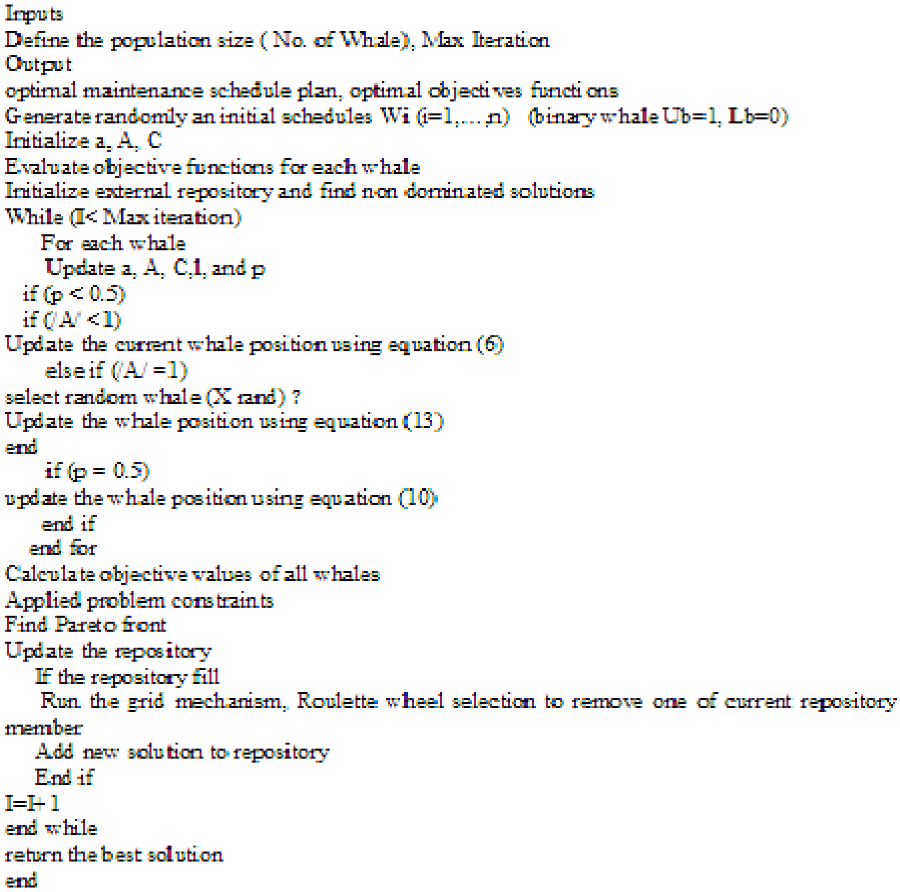
solutions that cover the trade-off between conflicting objectives. By partitioning the objectives space into grid cells and encouraging solutions to occupy different cells, it becomes easier to keep track of solutions in different parts of the space. This, in turn, helps ensure a better representation of the Pareto front, which is the set of non-dominated (optimal) solutions, and to facilitates the exploration of the solution space and the management of solutions. Finally, the roulette wheel selection is used to select a cell from a set of occupied cells. Selection probabilities are computed for each occupied cell based on the number of whales in each cell. A higher probability of being selected implies that a cell with more members in the repository is more likely to have one of its members removed from the repository. Once a cell is selected, one of its members is randomly chosen for removal. The purpose of using roulette wheel selection is to make the probability of selecting a cell proportional to its fitness, which in this case is related to the number of members in each cell. The pseudocode of the BPMOWOA is presented below:



```
Inputs
Define the population size ( No. of Whale), Max Iteration
Output
optimal maintenance schedule plan, optimal objectives functions
Generate randomly an initial schedules Wi (i=1,... ,n)   (binary whale Ub=1, Lb=0)
Initialize a, A, C
Evaluate objective functions for each whale
Initialize external repository and find non dominated solutions
While (I< Max iteration)
     For each whale
      Update a, A, C,l, and p
  if (p < 0.5)
  if (/A/ < 1)
Update the current whale position using equation (6)
      else if (/A/ =1)
select random whale (X rand) ?
Update the whale position using equation (13)
end
      if (p = 0.5)
update the whale position using equation (10)
     end if
   end for
Calculate objective values of all whales
Applied problem constraints
Find Pareto front
Update the repository
    If the repository fill
     Run the grid mechanism, Roulette wheel selection to remove one of current repository
member
    Add new solution to repository
    End if
I=I+ 1
end while
return the best solution
end
```

IV. CASE STUDY AND RESULTS

A gas power plant contains fourteen generating units is considered to demonstrate the efficiency of the proposed model to find an optimal maintenance schedule. This plant schedules its generator maintenances with the goal of maximize the power supply, minimizing fuel costs, and trying to minimize the CO2 emission for long-term schedule horizon (one year planning horizon). The failure and outage data of generating units are illustrated in previous work [24]. The raw maintenance data was collected from maintenance records, and then historical data for power supply, fuel quantities, fuel cost, and demand at each interval for fourteen generating units were used to test the system. Due to a lack of specific data concerning emissions, the CO2 emissions are calculated using the

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Intergovernmental Panel on Climate Change IPCC methodology [25]. The IPCC methodology is a set of guidelines and procedures used to estimate emissions when direct measurements or emission factors are unavailable or not reliable. Table II illustrates a sample of CO2 emission calculations for one units over one years. Table III shows generating unit specification, while Table IV shows the data for supply, fuel cost, CO2 emission, and demand for one year.

TABLE II. THE CO2 EMISSION FOR ONE UNITS OVER ONE YEARS

Fuel type	**Consumed Fuel**	**NCV**	**Emission Factor**	**CO2 Emission(Tone)**
Crude (LT)	178360420	0.0423Tj/t	73300kg/Tj	471175.20
N. Gas (Kg)	127837440	0.048Tj/t	56100kg/Tj	344241
Gas oil (LT)	1035200	0.043Tj/t	74100kg/Tj	2770.70

Energy= Mass*Net Calorific Value (NCV)
CO2 Emission= Energy* Emission Factor

TABLE III. GENERATION UNITS SPECIFICATIONP

Units No.	**Types**	**Installed Capacity**	**Max.Deployment Capacity(MW)**
1,2,3,4	GE Frame9	123	95
5,6,7,8	GE LM6000	43	35
9,10	GE Frame 9E	123	110
11,12,13,14	GE Frame 9E	115	90

TABLE IV. POWER PLANT DATA FOR ONE YEAR

Unit No.	**Supply (MW)**	**Fuel Cost (Crude, N. Gas, Gas oil) (ID)**	**CO2 Emission(Tone)**
1	703.73	6.79E+09	438753
2	846.07	7.11E+09	525423
3	794.69	3.48E+10	818186
4	775.99	9.91E+09	495650
5	201.13	2.31E+10	112327
6	214.43	2.42E+10	117997
7	190.13	4.29E+10	223854
8	206.20	6.52E+10	339719
9	674.85	3.05E+10	421724
10	800.68	2.65E+10	469455
11	815.37	2.09E+10	499654
12	873.78	3.32E+10	559993
13	860.27	3.34E+10	505802
14	932.57	3.36E+10	530282

Demand (MW)

Demand for interval 1	Demand for interval 2 and 4	Demand for interval 3
1230	1200	2100

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The BPMOWOA carried out in MATLAB R 2020a, and applies to different populations and iterations. The pareto front solutions obtained from the runs of BPMOWOA for one year long-term power generation maintenance scheduling are tabulated in Table V with the values of maximum power supply, minimum fuel cost and CO2 emissions for the fourteen generating units. The obtained optimal scheduling solutions satisfy load demand, which creates a measure of the system ability to meet the expected demand and result in a more reliable power generating system. Table VI illustrates the results from Run 4, which is selected as the optimal maintenance scheduling plan for the power plant to meet the plant goal of offering the highest supply while still satisfyeing constraints and other objectives to an acceptable degree. The selected optimal solution led to asignificant improvement in the supply and fuel cost of the plant when compared to the actual supply and fuel cost. The results depicted a reduction in fuel cost from (3.13386 E+11) to (2.9281 E+11) and an increase in power supply from (6142 MW) to (6847 MW). However, it's important to note that there has been an increase in CO2 emissions from (3.8030 E+06) to (4.6895 E+06) due to increase in power generation. This trade-off between increased power generation, decreased fuel cost, and the subsequent increased in CO2 emissions is a common challenge in the energy optimization problem. While the results have positively impacted the supply and fuel cost, the increase in CO2 emissions raises the environmental impact, necessitating more attention from the plant managers and further assessment of the combustion processes and the types of fuel used to minimize CO2 emission and contribute to more sustainable environment. *Fig. 2* shown non- dominated solution and the convergence graph for BPMOWOA for 70 populations (whales) and 100 iterations (Run 4). Finding the right combination of populations and iterations is crucial. A large population size allows for more diverse exploration of the solution space. It can help to avoid local optima, but also requires more computational time and might be slow down the convergence. A large population may require fewer iterations, while a small population might require more iterations to explore the solution space. From *Fig. 2,* the progress of the algorithm over iterations in terms of achieving the desired objectives is presented. The x-axis of the convergence graph represents the number of iterations, indicating how many times the algorithm has gone through the optimization process. While the y-axis represents the fitness values of the solutions generated by the algorithm. The algorithm iteratively improves the solutions to find optimal or near-optimal solutions with better fitness values. The figure shows that the fitness value converges to a finite value only after 12 iterations, and computation time (after 100 iterations) is less than one minute, which is demonstrates the efficiency, feasibility, and capability of the proposed algorithm to be implemented on maintenance scheduling problem and find optimal solutions.

TABLE V. ALGORITHM RUNS AND THE OPTIMAL OBJECTIVES VALUE

<table>
<tr><th>Run NO.</th><th>Parameter</th><th>Supply (MW)</th><th>Fuel cost (ID)</th><th>CO2 emission (T)</th></tr>
<tr><td>1</td><td>Population size: 30
Iteration No. :70</td><td>6.7327E+03</td><td>3.1752 E+11</td><td>4.4002 E+06</td></tr>
<tr><td>Maintenance schedule Plan</td><td colspan="4"><table>
<tr><th>U₁</th><th>U₂</th><th>U₃</th><th>U₄</th><th>U₅</th><th>U₆</th><th>U₇</th><th>U₈</th><th>U₉</th><th>U₁₀</th><th>U₁₁</th><th>U₁₂</th><th>U₁₃</th><th>U₁₄</th></tr>
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</table></td></tr>
<tr><td>2</td><td>Population size: 50
Iteration No. :70</td><td>6.7064 E+03</td><td>3.0653 E+11</td><td>4.6470 E+06</td></tr>
</table>

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	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14}
	1	1	0	1	1	1	1	0	1	1	0	1	0	1
Maintenance schedule Plan	1	0	1	0	1	1	0	1	1	0	1	0	1	1
	1	1	1	1	1	0	1	1	1	1	1	1	1	0
	0	1	1	1	0	1	1	1	0	1	1	1	1	1

3	Population size: 50 Iteration No. :100	6.6559 E+03	2.8598 E+11	4.2490 E+06

	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14}
	0	1	1	1	0	1	0	1	0	1	1	1	1	1
Maintenance schedule Plan	1	1	1	0	1	0	1	0	1	0	1	1	0	1
	1	1	1	1	1	1	1	1	1	1	0	1	1	1
	1	0	0	1	1	1	1	1	1	1	1	0	1	0

4	**Population size: 70 Iteration No.:100**	**6.8473 E+03**	**2.9281 E+11**	**4.6895 E+06**
5	Population size: 70 Iteration No.:150	6.7932 E+03	2.9951 E+11	4.7102 E+06

	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14}
	1	1	1	0	1	1	1	1	0	1	1	1	1	0
Maintenance schedule Plan	0	0	0	1	1	1	1	1	1	0	0	1	1	1
	1	1	1	1	1	1	0	1	1	1	1	0	1	1
	1	1	1	1	0	0	1	0	1	1	1	1	0	1

6	Population size: 90 Iteration No. :50	6.7676 E+03	2.8812 E+11	4.5652 E+06

	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14}
	1	1	0	1	1	0	1	1	1	0	0	1	1	1
	1	0	1	1	1	1	0	0	1	1	1	0	0	1
Maintenance schedule Plan	0	1	1	1	0	1	1	1	1	1	1	1	1	1
	1	1	1	0	1	1	1	1	0	1	1	1	1	0

7	Population size: 100 Iteration No. :200	6.7058 E+03	3.1690 E+11	4.6411 E+06

	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14}
	1	1	0	1	1	1	1	1	1	1	1	0	0	1
Maintenance schedule Plan	0	0	1	1	1	1	1	0	0	0	1	1	1	1
	1	1	1	1	0	1	1	1	1	1	1	1	1	0
	1	1	1	0	1	0	0	1	1	1	0	1	1	1

TABLE VI. PROPOSED MAINTENANCE SCHEDULING PLAN AND OPTIMAL OBJECTIVES

Maintenance Scheduling Plan for One year														
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14
Interval 1	1	1	1	0	0	0	1	1	1	1	0	1	1	1
Interval2	0	0	0	1	1	1	1	1	0	0	1	1	1	1
Interval 3	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Interval4	1	1	1	1	1	1	0	0	1	1	1	0	0	1

Supply (MW)	**Fuel Cost (ID)**	**CO2 Emission**
6.8473 E+03	2.9281 E+11	4.6895 E+06

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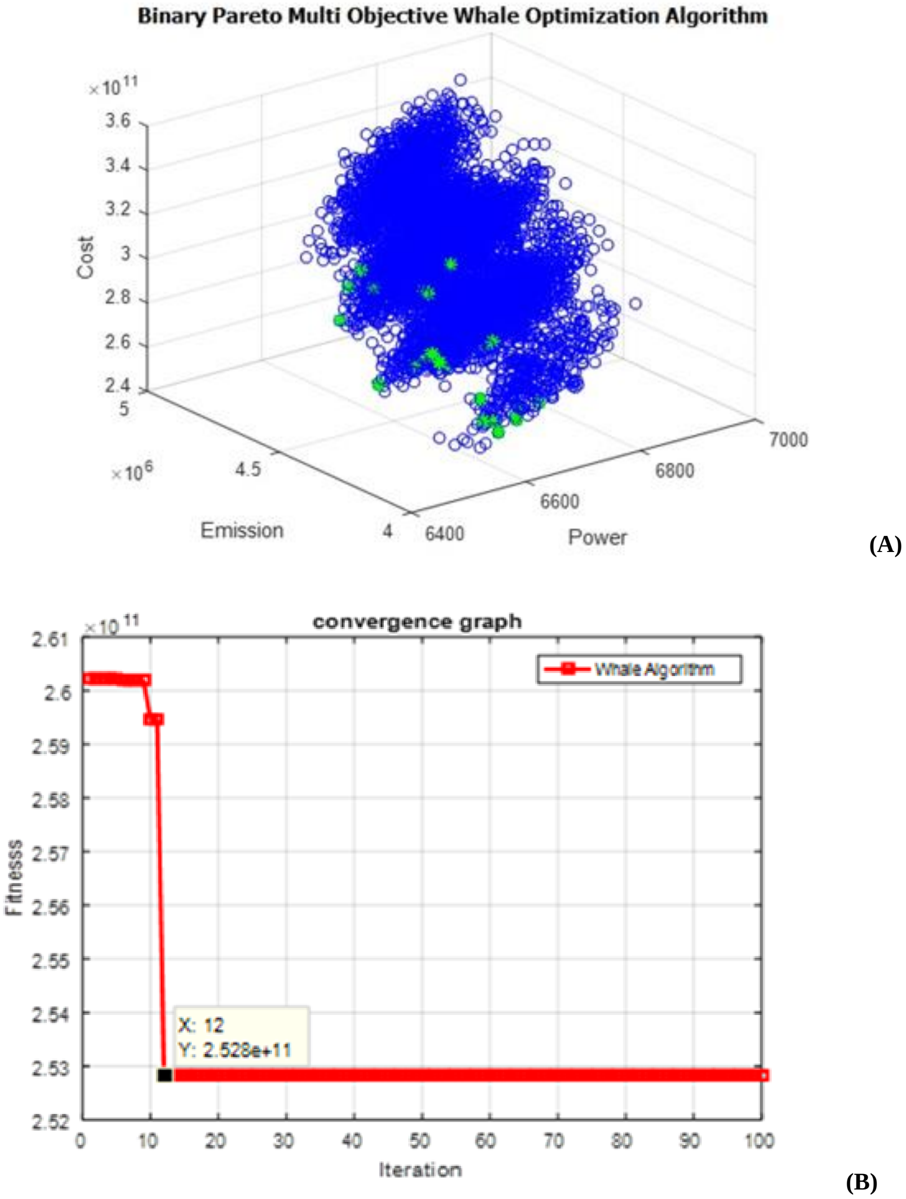

FIG. 2. A. NON DOMINATE SOLUTION OBTAINED FROM BPMOWOA B. CONVERGENCE GRAPHS FOR OPTIMAL MAINTENANCE SCHEDULING PLAN

V. CONCLUSIONS AND SUGGESTION FOR FUTURE WORK

Optimal maintenance scheduling is crucial for the efficient and reliable operation of production systems. This paper proposed maintenance scheduling plan by developing an algorithm called BPMOWOA to tackle the issue of maintenance scheduling for generators in a power plant while ensuring that the schedule meets the power system constraints. The developed algorithm satisfyed the constraints and considered three objectives instead of a single objective, which reflects a more realistic model of the power generating system. Many simulations have demonstrated the effectiveness of the algorithm in finding an optimal maintenance schedule plan to assist power plant managers in enhancing the maintenance scheduling program of generating units, consistently increasing electricity, and decreasing fuel expenses. The observed trade-offs, particularly the rise in CO2 emissions emphasize the need for an assessment of the operational conditions of the turbine and the type of fuel used. In the case of the power plant under consideration, it utilizes three types of fuel (crude oil, natural gas, and

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gas oil), and simple cycle turbines, which are less efficient compared to combined cycle turbines. Consequently, simple cycle turbines require a greater quantity of fuel to generate more electricity. All these reasons contribute to the overall rise in CO2 emissions and need concerted efforts to minimize their impact on environmental and human health. For future work, an environmental constraint can be included in the algorithm to striking a balance between power plant objectives, and safety factors can also be included as a priority constraint. The operating hours and start- up times of the generating unit can be considered as additional constraints for deciding the maintenance outage intervals. Furthermore, the whale optimization algorithm is still a relatively novel algorithm, and there is still experience in its parameter values. The change of the control parameters has a greater impact on the performance of the entire algorithm. Therefore, it is worth continuing to study the parameter changes for the developed algorithm and hybridization with other metaheuristic algorithms to improve the algorithm's convergence.

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