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Intelligent Optimization Systems for MaintenanceScheduling of Power Plant Generators

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Abstract: This paper presents a Genetic Algorithm (GA) and Ant-Colony (AC) optimization model for power plant generators' maintenance scheduling. Maintenance scheduling of power plant generators is essential for ensuring the reliability and economic operation of a power system. Proper maintenance scheduling prolongs the shelf life of the generators and prevents unexpected failures. To reduce the cost and duration of generator maintenance, these models are built with various constants, fitness functions, and objective functions. The Analytical Hierarchy Process (AHP), a decision-making tool, is implemented to aid the researcher in prioritizing and re-ranking the maintenance activities from the most important to the least. The intelligent optimization models are developed using MATLAB and the developed intelligent algorithms are tested on a case study in a coal power plant located at minjung, Perak, Malaysia. The power plant is owned and operated by Tenaga Nasional Berhad (TNB), the electric utility company in peninsular Malaysia. The results show that GA outperforms ACO since it reduces maintenance costs by 39.78% and maintenance duration by 60%. The study demonstrates that the proposed optimization method is effective in reducing maintenance time and cost while also optimizing power plant operation.

Keywords: Genetic Algorithm, Ant-Colony Optimization, Optimization modeling, Generator, Maintenance Scheduling.

1 Introduction

Electrical power is critical to the growth of numerous areas of the economy. Major industries and machinery in power plants such as hydropower plants, thermal power plants, and nuclear power plants are powered by electricity. Most modern advancements are powered by electricity, and most modern innovations would not be conceivable without them. The transformation of heat energy describes power generation systems into work [1] and will subsequently result in the generation of energy. Heat energy is traditionally produced by burning fossil fuels such as oil, coal, and natural gas, extracting thermal energy from renewable energy sources, or processing nuclear fuel [2]. A power plant is an industrial facility that produces electricity using primary energy. Most power plants employ generators that transform mechanical energy into electrical energy to meet society's electrical demands. A coal-fired power station, also known as a coal power plant, is a type of thermal power station that generates electricity by burning coal. There are around 8,500 coal-fired power plants in operation worldwide, with a total capacity of over 2,000 gigatons. They produce around one-third of the world's electricity [1].

The majority of the capital invested in the industry is in the machines, devices, and equipment used in any complex system. However, the equipment employed degrades with time as a result of use. Degradation leads to decreased quality and a higher total cost of ownership for such equipment. The maintenance cost accounts for a sizable component of the overall running costs of any production or manufacturing plant. Maintenance costs can range from 15% to 60% of the total cost of goods produced in any industry. The average maintenance cost in the food business is around 15% of the cost of commodities produced, but maintenance costs in the steel, iron, paper and other heavy industries are 60% of total production costs. The trend towards more automation has compelled managers to spend considerably more attention on maintaining complicated equipment and keeping it in working order. If the equipment has already failed and been repaired, corrective maintenance (CM) is required.

Preventive Maintenance (PM) is performed to avoid equipment problems before they occur; parts are replaced before they wear out [3]. PM scheduling of generating units is critical in power plants, particularly operation and planning.

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The primary aims of a power plant are to improve and maintain system reliability while also minimizing operating and maintenance expenses. The chance of service disruptions due to component failure rises as system equipment ages and deteriorates. As a result, an adequate maintenance plan is essential to provide safe and dependable electric power to its customers. An effective maintenance schedule can save money and possibly postpone some capital expenditure for power plants during periods of tighter reserve margins. Optimization is the process of achieving the best results possible given the constraints. Optimization approaches include linear programming, integer programming, dynamic programming, simulated annealing, stochastic programming, ant colony optimization, neural networks, particle swarm optimization, fuzzy optimization, and genetic algorithms.

The demand for electrical power has drastically increased in the past decade due to advanced globalization and rapid advancement in technologies around the globe. Because of the high anticipated demand for electric generation, generators in power plants frequently generate outages, which substantially impact the plant's electric output, dependability, and production cost. Therefore, the development of power system technology has become increasingly crucial to meet the demands and maintain an economical and reliable power supply. This has sparked interest in implementing a system of automated operations, production, and an automated and optimal maintenance schedule for various machines in a power plant.

Among the major concerns of such development is optimizing the power plant maintenance schedule. Maintenance Scheduling (MS) aims to provide a proper and consistent maintenance timetable for the generators, extend the lifetime of the power plant generators, and avoid premature failure of power system generation, which would lead to costly and unplanned power outages. An effective MS can satisfy load demand at the lowest possible operational cost while adhering to all plant and system constraints. As a result, following an effective Maintenance Schedule (MS) is critical for a power plant to run with high dependability and at a low cost. Finding the proper maintenance plan, on the other hand, can be difficult, especially in systems with tiny reserve margins and a high level of limitations. Adopting an intelligent system reduces the need to keep records and generate timetables manually. Implementing an automated or intelligent system enables the power plant to fully leverage the computational capacity easily accessible on real-time control systems, report, and amend schedules more quickly[3,4].

Therefore, adequate and proper maintenance must be practiced ensuring such problems do not arise. This research aims to develop an intelligent scheduling system for the best generator maintenance schedule with minimum maintenance cost and duration. An optimized maintenance schedule will help to decrease some capital expenditures for power plants while also allowing vital maintenance work to be completed.

This paper is organized as follows: Section 2 reviews the previous power plant maintenance schedules literature. Then in Section 3, the methodology and modeling of optimization models are presented. In section 4, the optimization results are compared, discussed, and validated. Finally, conclusions and future works are presented in Section 5.

2 Review on Previous Generator Maintenance Scheduling Practices

Annually, power plant companies spend billions of dollars on maintenance. The failure of power plant generation units has an impact on system dependability as well as the cost of producing installations. According to Al-analysis, Najjar's Sweden spent roughly United States Dollar \$1.95 x10^9 on maintenance and safety alone [3]. Inadequate maintenance efforts generate extra expenditures that surpass the generator's own cost. According to Mobley's research, the industry's maintenance operations use around 28% of the manufacturing expenses of a finished product [5]. According to the British Department of Trade and Industry, the UK industry spends around United States Dollar \$1.95x10^9 each year on harmful and unsafe maintenance [6].

The maintenance cost varies by industry and ranges from 15% to 70% of the total operational budget. After the energy budget, the cost of maintenance operations has shown to be the second most important budget for a power plant. This demonstrates that an optimal maintenance schedule is critical in any power plant and is responsible for a significant portion of the operational scheduling issues. Maintenance is often performed manually by competent and knowledgeable humans about the equipment. However, manual professional maintenance may not be the best technique or the most optimal option for power plant maintenance. The goal of an efficient maintenance schedule is to determine the limits and restrictions [7]. An ideal generator maintenance schedule for power plants is developed using this knowledge.

The planning process at a plant is critical for ensuring that the facility's maintenance processes are both cost-effective and safe. Long-term system planning and short-term operational planning (from a few minutes to a few years) are the two types of planning activity [5]. System planning includes long-term power system investment, new generating units, and new energy transmission links. Operational planning refers to planning maintenance, economic displacement, and unit tasks of power units. The maintenance schedule sets how much time is spent on maintenance work to ensure reduced operating expenditures while keeping a certain level of margin reserve.

Maintenance scheduling considers various elements, such as the accessibility of the maintenance staff, the history of repair work, and the particular unit maintenance order requirements. The maintenance scheduling approach can be formalized as an integer or mixed-integer scheduling issue and, therefore, reduced to a combined optimization problem [8]. This means that as the number of manufacturing units increases, so does the complexity of maintenance issues.

There are numerous types of maintenance schedules that power plants use. Among the approaches is dynamic programming [8]. This technique aims to achieve several goals, including optimizing the minimum net reserve and lowering the risk of power supply failure [8,9]. Dynamic programming suffers from the curse of dimensionality for significant problems such as maintenance scheduling.

Then there is integer programming and mixed-integer programming, which implement arbitrary limitations like the specifications of each unit, which are only kept once throughout time [8,9]. Furthermore, integer programming makes explaining complicated limits in real-world maintenance planning difficulties. Furthermore, rule-based and frame-based expert systems are among the strategies used for maintenance scheduling: The Branch and Bound approach [10] has been effective when combined with the heuristic method [11], although it remains difficult for specialists to manage. Furthermore, expert systems cannot guarantee an appropriate maintenance plan. The key issues are gathering information, validating it, and maintaining consistency. Finally, there is the Artificial Neural Network. While artificial neural networks are still a long way from mimicking human brain functions, several practical applications have been discovered in power systems, such as maintenance scheduling [12].

However, previous research had focused on implementing complicated, intelligent algorithms to reduce maintenance costs. The methodology implemented in these researches, including complex constraints and sophisticated algorithms, did not guarantee minimal cost. The methodology adopted for this research was explored using a simple genetic algorithm and ant colony optimization that guarantees the lowest maintenance cost and duration. This research aims to provide a detailed comparison between the two optimization methods and to identify the superior method with the lowest cost and duration. Such comparisons were not evident in previous research. The previous researchers did not emphasize maintenance duration reduction. The Analytical Hierarchy Process (AHP) will be utilized to reduce the duration further. Harsher and stricter constraints will be implemented to ensure that the algorithms do not break any of the constraints given by the power plant company.

3 Research Methodology

The methodology of this research is divided into two phases. Phase 1 is the Analytical Hierarchy Process (AHP) to prioritize and re-rank the maintenance activities according to the maintenance optimization criteria. Phase 2 is the meta-heuristics modeling which involves pre-determining the optimization parameters, fitness function, an objective function and simulation of the data in MATLAB to reduce the maintenance cost and duration. This section provides the methodologies' background and determines the intelligent systems' formulae and parameters.

3.1 Phase 1: Analytical Hierarchy Process (AHP)

The main idea of AHP is to structure multiple criteria choices into a hierarchy and to assess their relative importance [13]. This method's maintenance optimization criteria are crucial, as mentioned in section 2. The selected criteria are listed in Table 1.

Table 1: Criteria used for this research

M1	Maintenance costs
M2	Maintenance availability
M3	Maintenance reliability
M4	Inventory of spare parts
M5	Maintenance safety
M6	Output quality
M7	Number of maintenance intervention
M8	Maintenance time

The pairwise comparison works by evaluating each criterion relative to the objective. The pairwise comparison of the eight criteria is shown in Table 1. The pairwise is a technique for determining the relative relevance of each criterion and alternative. This will assist in selecting the ideal criterion or alternative to the chosen criteria and the aim. The weights and comparisons are quantified using Saaty's nine-point scale, as illustrated in Table 2.

Table 2: Weights as quantified by [14]

Weights	Level of Importance
1	Equally Preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred
2,4,6,8	Intermediate values

The pairwise comparison works by evaluating each criterion relative to the objective. It also evaluates each alternative to the relativity of its parent criterion. The evaluation can be performed using top-down or bottom-up pairwise assessment depending on which is more important, the criterion or alternatives. The number of matrices is dependent on the relative ranking of the hierarchy and the number of criteria and alternatives. After the order of the matrices is established based on the linking between the criterion and alternatives, the relative weights (Eigenvectors), the maximum Eigenvalue (λmax), and the global weights for each matrix are calculated. These equations are adapted from research [15]. The maximum Eigenvalue (λmax) is calculated as follows:

$\lambda max = \text{Priority Vector x Sum of M}$ —— (1)

The λmax values are applied to validate the consistency of the pairwise comparison matrix.

The consistency ratio (CR) is obtained using equation 2.2 below [16]:

$CR = CI/RI$ —— (2)

Where the consistency index (CI) for each matrix with the order (n) is obtained using equation 2.3 below [16]:

$CI = (\lambda max-n)/(n-1)$ —— (3)

Phase 2: Meta-heuristics Modelling

Heuristics techniques harness artificial intelligence to provide an optimal solution if the constraints and parameters are too challenging to be solved by conventional methods. Genetic Algorithm was employed due to its ability to provide multiple solutions to the given problem as it utilizes several sets of search space to identify the optimal solution. GA utilizes the mutation and crossover operators to ensure the newer solutions produced in the new population are more suitable and optimal than its previous population. GA ensures a higher chance of obtaining a globally optimal solution than other algorithms. A single objective function is required when modeling GA to calculate the solution's fitness. This ensures simplicity and accuracy when modeling GA.

ACO also possesses its advantages as it is being considered self-organizing. Self-organizing is the process of increasing the system's entropy without external influences. This is also the system changing from disorderly to orderly, which is the case for ACO. This means that the organizing instructions come from the system itself. Individual ants search for the solutions in a disorderly manner at the start of the algorithm, then the algorithm proceeds through a sequence of optimization calculations. Then, these individual ants will find the second-best solution spontaneously through the deposited pheromones. This shifts the process from disorderly to orderly. Thus, making ACO self-organizing. This subsection explains the constraints, objective function, and evaluation function used for GA and ACO. The formulae adopted in this section were a combination of research [15,17,18] with a few additions to ensure harsher and stringent constraints further.

3.2.1 Identify the Constraints

Maintenance Window: Each unit must be maintained precisely once, and the maintenance for each unit must occupy the required time duration without any interruption. If Wi is the start week of maintenance for unit I, the constraint is formulated as below:

$$X_{it} = \begin{cases} 1 \text{ for } Si \leq t \leq di, \text{ for } Si \text{ such that } ei \leq Si \leq li \\ 0 \text{ otherwise} \end{cases}$$

Where e_i = the earliest week for maintenance of unit to start

l_i = latest week for maintenance of unit i to start di = duration of maintenance of unit i

Crew Constraints: Only a limited number of generator units may be serviced at a time due to labor availability. Therefore, only 100 people are available for Maintenance work weekly. The number and type of labor for each stage of maintenance of each unit are given as below:

$$\sum_{i=1}^{N} X_{it} L_{itj} \leq AL_{tj}$$

Where L_{itj} = Labor of type j needed by unit i at period t AL_{tj} = Available labor of type j at period t

j = 1,2, 3, …. j = type of labor

3.2.2 Objective Functions

The objective function of this study is to reduce the maintenance cost subjected to the system constraints. The objective function is given by:

$$\sum_{i=1}^{N} [L_{it} + IL_{it} + M_{it} + IM_{it}] \, (s)$$

Where L_{it} = Direct labor cost for generator i at time t. IL_{it} = Indirect labor cost for generator i at time t.

M_{it} = Direct material cost for generator i at time t, respectively.

IM_{it} = Indirect material cost for generator i at time t, respectively.

3.2.3 Determine the Evaluation and Penalty Function

Evaluation Function = {$\sum_{c} Wc$ x (The amount of "k" violation) + Wo (Objective Function)} (4)

Wc and Wo are the weighting coefficients for the kth constraint violation and the objective function. These coefficients are calculated so that harsher constraints, such as system constraints, are punished more and are assigned a greater penalty value, while softer constraints, such as maintenance constraints, are not penalized at all.

4 Case Study, Result Analysis and Discussion

TNB Janamanjung Sdn. Bhd is a wholly-owned subsidiary of Tenaga Nasional Berhad incorporated in 1996. Perak state produces 30% of the power generating capacity and is the largest electric power producer in Peninsular Malaysia. TNB Janamanjung generates 3100MW of electricity from its three units of 700MW and one unit of 1000 MW coal-fired plant. This is the most efficient power plant in South-East Asia that utilizes the latest ultra-supercritical combustion technology. The 1000MW of generated power is equivalent to the electricity needs of 2 million households in peninsular Malaysia. The generator raw data was obtained from Tenaga Nasional Berhad, TNB, Janamanjung power plant.

4.1 Data Preparation and Model Inputs

A total of 10 generator units with a total generating capacity of 4361MW are considered in this study. The details of the 10 generators are given in Table 3. The maximum generating capacity required by the power plant to maintain optimal operation is 2369MW. The outage refers to the number of weeks the particular generator can undergo maintenance. TNB requires 100 personnel to perform the maintenance activities per week, and the total maintenance duration is 15 days. Table 4 below shows the generator maintenance costs. The maintenance costs are divided into two categories. The first is Direct Maintenance Cost. This cost is comprised of the labor cost, which is an hourly rate for skilled technicians who perform the maintenance weeks on the generator multiplied by the service life in hours. Preventive Maintenance (PM) and material expenses also fall in the Direct Maintenance Cost category. PM is a type of maintenance typically performed before the machine fails, including replacing or repairing a component that is predicted to fail soon. Maintenance material expenses include the materials, components, and equipment needed for the generator maintenance period. The second labor expenditures like social security, health care, and technical training are included in the indirect maintenance costs. This is expressed as a percentage of labor's annual compensation. Other material expenses such as storage, inventory, shipping charges, and test equipment are indirect maintenance material costs. These costs are expressed as a proportion of material procurement costs and spare components.

Table 5 below shows the detailed maintenance activities required on one generator. These activities must be conducted on-site with mandatory supervision from professional technicians. These details were obtained from TNB.

4.2 Analytical Hierarchy Process Analysis

The AHP relies heavily on the pairwise comparison table. The pairwise comparison works by evaluating each criterion relative to the objective. The pairwise comparison of the eight criteria is shown in Table 6. The red boxes (aii) are equal to 1 and serve as the datum for effective comparisons, while the yellow boxes (aij = k) are values selected by the decision-maker based on past case study knowledge and expertise. Table 2 shows the values based on the preference scales. The blue boxes are derived from the formula aji = 1/k. The total of each column is presented in green boxes, which are essential for computing the overall weight in the following step.

The total weight is derived using Table 7 by dividing each item by the sum of the columns from Table 6. The green boxes represent the total of each column and row. Each criterion's total weight must be between 0 and 1. The cumulative weights will equal one.

The priority vector is calculated from the normalized λmax vector of the matrix. The priority vector for each criterion is equal to the average using equation 1. A sample calculation is as follows:

For M1 = $\frac{Sum\ M1(Horizontal)}{n}$ ------ (5)

M1 $= \frac{1.33}{8}$ x 100 = 16.63 % The maximum Eigenvalue (λmax) is calculated using equation 2.1 as follows:

λmax = (0.1663x9.17) + (0.08x17.86) + (0.1125x12.24) + (0.0225 x 41) + (0.0375 x 26.33) + (0.05x22.75) +

(0.2188 x 4.57) + (0.3125 x 2.75) = 8.7783

The λmax value is crucial to validate the evaluation's consistency and determine if the decision-makers judgment is valid. CI/R calculates the Consistency Ratio.

Based on the equation, the sample calculation for CI using equation 2.3 is as below:

$$CI = \frac{\lambda\max - n}{n-1} = \frac{8.7783-8}{8-1} = 0.1112$$

The random consistency based on Table 3 for n = 8 is illustrated below

Table 3: Generator data obtained from TNB

Unit	Capacity per unit (MW)	Allowed period to undergo maintenance (Week)	Outage (Week)
1	555	1-13	7
2	555	14-26	5
3	180	1-13	2
4	180	1-13	1
5	640	14-26	5
6	640	1-13	3
7	640	1-13	3
8	555	14-26	6
9	276	1-13	10
10	140	1-13	4
Manpower required (per week)			100
Total Maintenance Duration (Days)			15

Table 4: Total cost of maintenance for the 10 generators

Labor cost and Service	RM 718,856.00
Spare Part and Consumable	RM 367,677.50
Total Maintenance Cost	RM 1,086,533.50

The random consistency based on Table 3 for n = 8 is 14. The acceptable Consistency Ratio (CR) is assumed to be any value less than 10%. The CR is calculated using equation 2.2 as follows:

$$CR = \frac{CI}{RI} = \frac{0.1112}{1.4} = 0.07942 = 7.94\% < 10\ \%\ \text{(valid)}$$

4.3 Results Analysis and Discussion

The Analytical Hierarchy Process (AHP) was implemented to prioritize and rank the generator maintenance activities. The initial 18 maintenance activities described in Table 5 were evaluated based on the eight maintenance criteria as shown in Table 1. The AHP analysis had started the construction of the hierarchy tree to determine and link the goals, criteria, and alternatives. Next, the pairwise comparison table was generated to evaluate the criterion with another criterion to determine the most crucial criterion for the maintenance activities. Then, the priority vector was calculated to determine the ranking of the maintenance activities. The criterion with a higher priority vector will be given more priority. AHP was conducted based on the decision-maker's judgment and previous case studies. The accuracy and validity of the analysis are proven by the calculation of the Consistency Ratio (CR). If the CR is below 10%, the judgment is valid. As a result of the analysis, the initial 15 maintenance activities were grouped into only 8 based on the decision maker's judgment and the evaluation scale, as shown in Figure 1. The criterion with low priority vectors was grouped since the prioritization value was too low. The maintenance activities were grouped as below with the priority vector in brackets shown in Figure 2: M8 (31.25) M7 (21.88) M1 (16.63) M3 (11.25) M2 (8.00) M6 (5.00) M5 (3.75) M4 (2.25). Table 8 shows the final eight maintenance steps.

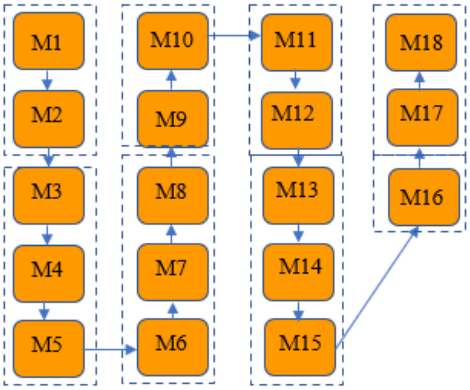

Fig. 1: Grouping of generator maintenance activities

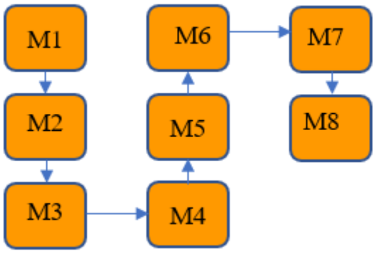

Fig. 2: Finalized grouping of maintenance activities

Table 5: Generator maintenance activities

Activity Number	Description of activities
M1	Strip cylinder heads, clean exhaust deposits, and water jacket scale discard injector tips, valve springs, and seals
M2	Inspect heads, gauge valve seats and guides, check head flatness, dye-penetrant inspection for cracks.
M3	Clean and gauge valves, regrind if necessary, lap into seats
M4	Gauge valve rocker bushes and shafts, clear oil ways
M5	Reassemble heads using new seals
M6	Strip, clean, and inspect the pass valve (if applicable). Renew parts as required and reassemble
M7	Clean and inspect Turbocharger: Visually check turbine and impeller, measure shaft end float and radial deflection. Check that shaft spins freely. Blower: Check rotor lobe clearances and gear backlash. Check rotor end float and radial bearing clearance.
M8	Strip, clean, and calibrate fuel injection pumps and injectors. Renew parts as required and reassemble
M9	Drain oil from the governor, flush clean and check linkages and linkage shaft for excessive wear, inspect internals, renew parts as required and reassemble.
M10	Disassemble piston/connecting rod assemblies. Clean con rod oil ways and carbon deposits from the piston crown. Discard rings
M11	Gauge con rod oversized end bearings and small end bushes
M12	Measure piston diameters, gauge ring grooves, and gudgeon pin bushes. Reassemble piston/connecting

	rod assemblies using new rings
M13	Clean camshaft and check straightness. Gauge cam profiles and bearing journals. Dye penetrate inspection for cracks
M14	Strip, clean, and examine the starter motor. Check proof coating on starter pinion. Renew parts as required and reassemble.
M15	Strip, clean, and examine lube pump oil. Check gears and bushes for exercise wear seals for leakage. Renew parts as required and reassemble.
M16	Strip, clean, and examine the water pump. Check impeller and casing for erosion, bearing for wear, and seals for leakage. Renew parts as required and reassemble
M17	Test all pressure, speed, and temperature instruments
M18	Pack components and dispatch to site

Table 6: Pair-wise comparison matrix of the criteria

Criteria	M1	M2	M3	M4	M5	M6	M7	M8
M1	1	5	3	7	6	3	0.33	0.25
M2	0.20	1	0.33	5	3	3	0.20	0.33
M3	0.33	3.00	1	6	3	4	0.5	0.20
M4	0.14	0.20	0.33	1	0.33	0.25	0.14	0.13
M5	0.17	0.33	0.33	3	1	0.5	0.2	0.17
M6	0.33	0.33	0.25	4	2	1	0.2	0.17
M7	3.00	5	2	7	5	5	1	0.5
M8	4.00	3	5	8	6	6	2	1
Sum	9.17	17.86	12.24	41	26.33	22.75	4.57	2.75

4.3.1 Duration of Generator Maintenance- Genetic Algorithm

The parameters must first be determined before simulating to ensure that the final result obtained adheres to the constraints set by the researcher. The parameters for GA and ACO were determined based on previous case studies conducted on 21 and 22 generator systems. These values were identified to be the best settings for the given problem. The parameters used for GA are simplified in Table 9.

The ideal duration for maintenance generator activities is 9.1874 days which equals nine days. The intelligent optimizations were simulated in MATLAB R2020b.

4.3.2 Duration of Generator Maintenance- Ant Colony Optimization

For this research, a population size of 100 is used. The Roulette wheel selection method is applied. The pheromone exponential and heuristic exponential rates are set to 1.0 and 1.0. the evaporation rate is set to 0.05. The parameters were determined by previous case studies conducted on a 21 and 22 generator system in [19,20], and it was found to be the best setting as it promises the best results. The parameters used for ACO are simplified in Table 10.

Table 7: Overall weight that is assigned to each criterion

Criteria	M1	M2	M3	M4	M5	M6	M7	M8	Sum	Priority vector (%)
M1	0.11	0.28	0.25	0.17	0.23	0.13	0.07	0.09	1.33	16.63
M2	0.02	0.06	0.03	0.12	0.11	0.13	0.04	0.12	0.64	8.00
M3	0.04	0.17	0.08	0.15	0.11	0.18	0.11	0.07	0.90	11.25
M4	0.02	0.01	0.03	0.02	0.01	0.01	0.03	0.05	0.18	2.25
M5	0.02	0.02	0.03	0.07	0.04	0.02	0.04	0.06	0.30	3.75
M6	0.04	0.02	0.02	0.10	0.08	0.04	0.04	0.06	0.40	5.00
M7	0.33	0.28	0.16	0.17	0.19	0.22	0.22	0.18	1.75	21.88
M8	0.44	0.17	0.41	0.20	0.23	0.26	0.44	0.36	2.50	31.25
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00	100

Table 8: Grouped generator maintenance activities

Activity Number	Description of activities
M8	Test all pressure, speed, and temperature instruments. Pack components and dispatch to site
M7	Strip, clean, and examine the water pump. Check impeller and casing for erosion, bearing for wear, and seals for leakage. Renew parts as required and reassemble

M1	Strip cylinder heads, clean exhaust deposits, and water jacket scale discard injector tips, valve springs, and seals. Inspect heads, gauge valve seats and guides, check head flatness, dye-penetrant inspection for cracks.
M3	Strip, clean, and inspect the pass valve (if applicable). Renew parts as required and reassemble. Clean and inspect Turbocharger: Visually check turbine and impeller, measure shaft end float and radial deflection. Check that shaft spins freely. Blower: Check rotor lobe clearances and gear backlash. Check rotor end float and radial bearing clearance. Strip, clean, and calibrate fuel injection pumps and injectors. Renew parts as required and reassemble
M2	Clean and gauge valves, regrind if necessary, lap into seats. Gauge valve rocker bushes and shafts, clear oil ways. Reassemble heads using new seals
M6	Clean camshaft and check straightness. Gauge cam profiles and bearing journals. Dye penetrate inspection for cracks. Strip, clean, and examine the starter motor. Check proof coating on starter pinion. Renew parts as required and reassemble. Strip, clean, and examine lube pump oil. Check gears and bushes for exercise wear seals for leakage. Renew parts as required and reassemble.
M5	Gauge con rod oversized end bearings and small end bushes. Measure piston diameters, gauge ring grooves, and gudgeon pin bushes. Reassemble piston/connecting rod assemblies using new rings
M4	Drain oil from the governor, flush clean and check linkages and linkage shaft for excessive wear, inspect internals, renew parts as required and reassemble. Disassemble piston/connecting rod assemblies. Clean con rod oil ways and carbon deposits from the piston crown. Discard rings

Table 9: Parameters for Genetic Algorithm

No	Parameter	Value
1	Number of Run	5
2	Population Size	100
3	Crossover Probability	0.8
4	Mutation Probability	0.010
5	Type of Selection	Roulette
6	Type of Crossover	One-Point

The intelligent optimizations were simulated in MATLAB R2020b. The optimal duration for the maintenance generator activities is 11.5589 days which equals 12 days.

Table 10: Parameters for Ant Colony Optimization

No	Parameter	Value
1	Number of Run	5
2	Population Size	200
3	Pheromone Exponential Rate, α	1.0
4	Heuristic Exponential Rate, β	1.0
5	Evaporation Rate, ρ	0.05
6	Type of Selection	Roulette

4.3.3 Duration Optimization Analysis

This study used a basic genetic algorithm and Ant System's simple ant colony optimizer. Similar parameters were utilized for both optimization strategies to achieve a fair and impartial result. These comparable parameters include the generation size, population size, and the number of runs, which were set to 100, 100, and 5. As mentioned in equation 3.3, the objective function is to reduce the cost and duration of generator maintenance activities in the power plant. The objective function value rises as generation rises. This is due to the intelligent algorithm expanding and scanning the search space as the generation grows to discover the best answer. As a result, the graphs rise linearly, demonstrating that the objective function gets further decreased with each iteration. The simulation was run five times to achieve a more accurate estimate based on the average value. The ideal duration for the genetic algorithm is 9 days, whereas the optimal duration for ant colony optimization is 12 days. As a result, the genetic algorithm proved to be the superior optimization strategy, reducing the maintenance duration from an initial 15 days to only 9 days. GA had significantly reduced the duration of maintenance by 6 days.

4.3.4 Cost of Generator Maintenance- Genetic Algorithm

The simulation was performed to optimize the cost of generator maintenance. The same parameters set in Table 9 were used. However, the generation value was increased from 100 to 200. Figure 3 shows the costs obtained for each generation represented by a graph.

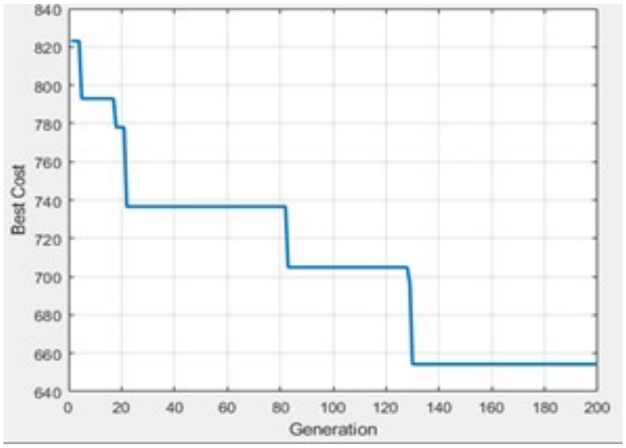

Fig. 3: GA convergence graph for each iteration

Based on Figure 3, the optimal cost for the generator maintenance for GA is RM654,290.00

4.3.5 Cost of Generator Maintenance- Ant Colony Optimization

The simulation was performed to optimize the cost of generator maintenance. The same parameters set in Table 10 were used. However, the generation value was increased from 100 to 200.

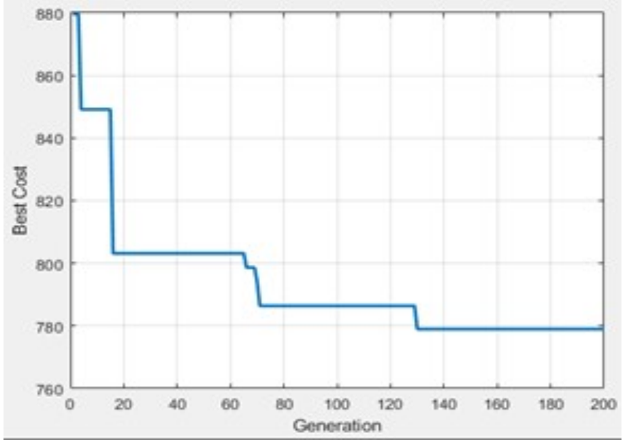

Fig. 4: ACO convergence graph for each iteratio

Based on Figure 4, the optimal cost for the generator maintenance for ACO is RM778,980.00.

4.3.6 Cost Optimization Analysis

The same parameters were employed for the cost study using the genetic algorithm and ant colony optimization. Minor changes were made to the cost analysis method for both optimization techniques. The generation value was increased from 100 to 200 to expand the search space and obtain the desired results. The other characteristics remained unchanged, as stated in Tables 9 and 10. Figures 3 and 4 provide a graph of the best cost versus generation. The overall cost of maintenance falls linearly with each generation. The newly produced generation in the genetic algorithm has experienced crossover and mutation to produce offspring with the best traits from the parent chromosome. The younger generation will be the elite generation. For each generation, crossover and mutation will occur, guaranteeing that the population for each generation is more elite than the preceding generation until only the best offspring with the greatest features remain. As a result, the best option is found. In ACO, the ants will create an initial solution by randomly traversing the search space to find an initial solution. When the ants had identified the location, they left pheromones for the other ants to follow. The greater the pheromone deposited, the better the solution. As a result, the ants will migrate to the search space to pursue a more optimum solution as the population grows. As a result, the optimization aims to lower maintenance costs. The best maintenance cost acquired for the genetic algorithm is RM654,290.00, and the best maintenance cost obtained for ant colony optimization is RM778,980.00. As a result, the genetic algorithm proved to be the superior optimization strategy, reducing the maintenance duration from an initial RM 1,086,533.50 to just RM654,290.00. GA had decreased the maintenance costs by RM432,243.50.

4.3.7 Comparison of Intelligent Optimization Result

This subsection aims to analyze and discuss the results obtained from the Genetic Algorithm and Ant- Colony Optimization simulation. Table 11 shows the comparison between the duration and cost obtained from GA add ACO.

Table 11: Comparison of Optimization Results

Genetic Algorithm	Comparison	Ant Colony Optimization
9	Duration (Days)	12
654,290.00	Cost (RM)	778,980.00.
- 6	Duration Reduction from initial (Days)	- 3
- 432,243.50	Cost Reduction from initial (Cost)	- 307,553.50

As a consequence of this simulation, it is clear that the genetic algorithm is preferable to ant colony optimization since GA takes less time and has a lower cost value. GA had reduced the maintenance duration and cost by 6 days and RM 432,243.50 respectively, whereby ACO had reduced only 3 days and RM 307,553.50 respectively. GA is an evolution-inspired randomized search strategy. ACO is a metaheuristic approach inspired by ant colonies' foraging behavior. This is the primary reason for comparing these two intelligent optimization algorithms, as both are motivated by evolution and various natural occurrences. GA used crossover and mutation to create an elite population to identify the best solutions. ACO is dependent on the ant pheromone deposition intensities in the initial solution. The ants in ACO will roam randomly over the search area to find the optimum solution, and the quality of the solution is determined by the number of pheromones deposited. Evaporation occurs with these pheromones. The ants will be wandering in the search space once the pheromones have disappeared. As a result, the ant is unable to identify an ideal solution. On the other hand, GA will continue to traverse the search space at random to identify the best answer. Crossover and mutation are regularly carried out to improve the population's quality. Nothing in GA will prevent the algorithm from finding the optimum answer. This is the reason why GA outperforms ACO in this study. The roulette wheel selection method is employed in these studies because it is the most used selection form in generator maintenance schedules.

4.4 Final Maintenance Schedule

One of the objectives of this research was to model intelligent maintenance scheduling systems. In this subsection, the final maintenance schedule for the 10-generator system is generated. The total maintenance cost and duration were successfully reduced in the previous subsection using the Genetic Algorithm and Ant Colony Optimization. Figure 5 shows the final maintenance schedule of the 10 generators units from week 1 to week 2.

Based on Figure 5, it is evident that the maintenance start week of any unit does not clash with the other units. This shows that there is no violation of constraint 1: Maintenance Window.

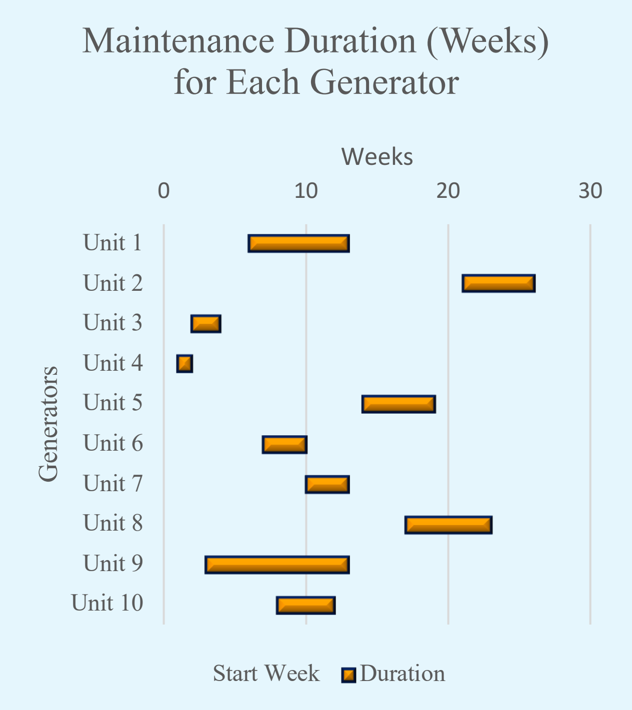

Fig. 5: Final maintenance schedule of the 10 generators in 26 weeks

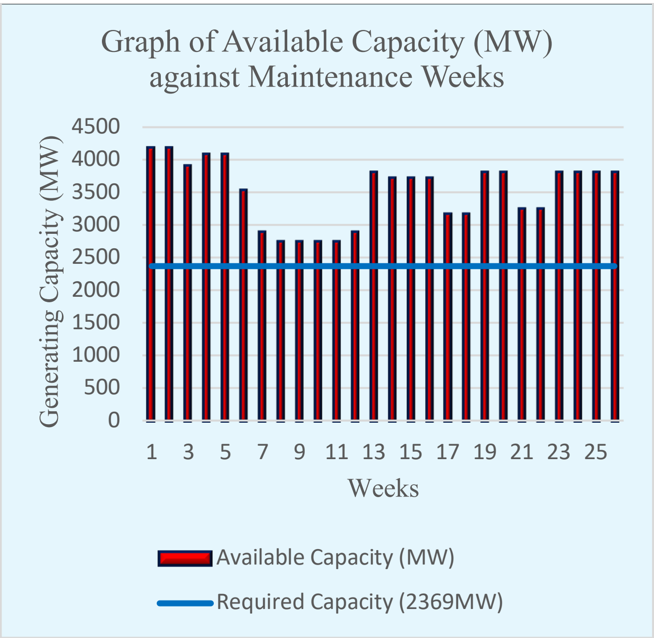

Fig. 6: Available generating capacity for each week

The blue horizontal line represents the minimum generating capacity for each week. The generating capacity for each week is above the required capacity. This proves that there were no violations to Constraints 2: Load Constraints, whereby the system's peak load is 2369MW.

4.5 Comparison Study

This section compares the simulation results obtained from this research with previous researchers. The validation is performed by calculating the error percentage between the final maintenance cost obtained and the previous researchers. The validation is calculated below in Table 12:

Table 12: The validation process

	Formula	Calculation	Result
Percentage Error	$\left\lvert \frac{Actual\ Cost - Expected\ Cost}{Expected\ Cost} \right\rvert$x100 %	$\left\lvert \frac{RM\ 654{,}290 - RM\ 707{,}876}{RM\ 707{,}876} \right\rvert$ x100%	7.57%
Percentage of Maintenance Cost Reduction (Previous Research)	$\frac{Initial\ Cost - Final\ Cost}{Initial\ Cost}$ x 100%	$\frac{RM\ 16{,}070{,}000 - RM\ 13{,}660{,}000}{RM\ 16{,}070{,}000}$ x100%	14.99%
Percentage of Maintenance Cost Reduction (This Research)	$\frac{Initial\ Cost - Final\ Cost}{Initial\ Cost}$ x 100	$\frac{RM\ 1{,}086{,}533.50 - RM\ 654{,}290}{RM\ 1{,}086{,}533.50}$ x100%	39.78%

According to the above calculation, there is a 7.57% difference between the final costs obtained in this study and [15]. It is also clear that the maintenance cost in this study is only RM654,290, which is significantly lower than RM707,876 in [15]. This results in a substantial difference of RM 139,460 between the two studies. This is because this study's constraints and penalty functions were more stringent and punitive than [16]. The research includes two additional constraints not included in [13,15,17]: Load Constraints and Crew Constraints. The fitness function utilized in this study had a more significant role in punishing intelligent optimization if any of the constraints were broken. The researcher in [15] was only able to reduce the maintenance cost by 14.99%, whereas this research had reduced the cost by 39.78%. This proves that the methodology, constraints, and fitness function used in this research were deemed more effective in reducing the maintenance cost.

5 Conclusions and Future Work

This research aimed to reduce power plant generators' total maintenance cost and duration. AHP was implemented in this research to re-rank and re-prioritize the maintenance activities. AHP relies on the researcher to give weights to each criterion, fluctuating from one researcher to another. The Consistency Ratio is employed to validate the researcher's decision whether it is deemed acceptable or not. The decision is valid so long as the Consistency Ratio is calculated to be less than 10%, which was true for this research. AHP had successfully reduced the generator maintenance from 18 steps to only eight steps with the aid of a pairwise comparison table. Through this, the priority vector of the optimization criteria was calculated, and the criteria were ranked from most important to least.

Next, the constraints, objective function, and evaluation function were determined. The constraints were imposed to ensure that all the requirements set by TNB were adhered to in terms of the maintenance outages, workforce required, and the minimum generating load. The cost functions for generators are assumed to be quadratic, with the same coefficients for all generators to ensure uniformity and simplicity. One of the benefits of GA and ACO is that the objective function to minimize maintenance cost for this research can be summed and weighted to obtain a single formula.

Furthermore, the GA and ACO simulations were performed using MATLAB R2020B using the parameters in Table 9 and Table 10. The results show that GA had reduced the maintenance duration by 6 days from an initial 15 days and the cost by RM 432,243.50 from an initial RM 1,086,533.50. ACO had reduced the maintenance duration by 3 days from an initial 15 days and the cost by RM 307,553.50 from an initial RM 1,086,533.50. This concludes that GA is superior to ACo as it had reduced the maintenance cost by 39.78% compared to ACO only by 28.31%.

The methodology employed in this research requires no prior experience in the generator maintenance schedule. To conclude, an optimum maintenance schedule was generated with no constraints and objective function violations. The final maintenance duration and cost is significantly lower than the initial values. The final maintenance cost was compared with similar case studies, and the final cost in this research was significantly lower, which guarantees more optimal methods and results. The successful comparison between GA and ACO was highlighted, and GA proves to be the superior optimization method.

Despite the merits of the modeled Genetic Algorithm and Ant Conly Optimization used in this study, there are possibilities that the modeling of the algorithms can be enhanced with future research. The generator data were obtained from multiple sources obtained from TNB and the benchmarked researchers. Due to company privacy concerns, it was impossible to collect the essential data from a single source.

Future research may concentrate on acquiring data from a single source, which would increase the accuracy of the final results in the case study. The generator maintenance cost functions were developed and expected to be quadratic with the same coefficient for all generators. It is recommended to use a separate cost function for each generator. This research's objective functions (Eq 3.3) were summed and weighted to form a single formula. The weighting coefficients were calculated empirically. Further research could utilize multi-objective scheduling techniques by using each objective function as an individual for the same problem in this thesis. Finally, the generator maintenance scheduling problem's goal was to reduce the cost and duration of generator maintenance. Further study might look into other goals, such as lowering the cost of generator operations, generating power, or reducing the generators' income loss during the operational planning time.

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Conflict of interest

The authors declare that there is no conflict regarding the publication of this paper.

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