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RESEARCH PAPER

The Application of Genetic Algorithm to the Optimization of the Maintenance Schedule at a Certain Level of availability and reliability: Case study Cathodic Protection System of Gas Distribution Steel Network

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Abstract

This paper presented a preventive maintenance scheduling model to optimize the cost and improve the effective age of machines in complex repairable systems. The objective function of the developed model is to minimize the total maintenance costs while maintaining a defined level of availability and reliability. The maintenance costs include random failure cost, repair cost, replacement cost, and total planned downtime cost. Multilevel preventive maintenance actions such as inspection, repair and replacement are considered through the whole planning horizon. A metaheuristic algorithm like genetic algorithm (GA) was developed using a MATLAB program to provide a near-optimal solution for the optimization model. The proposed mathematical model was applied to a Cathodic Protection System of Gas Distribution Steel Network and the results show a reduction in the total maintenance cost by 36%.

Keywords: Preventive maintenance; Cathodic Protection System; repairable system; availability; reliability; genetic algorithm

1. Introduction

Maintenance is the set of activities that specifically designed to maintain buildings, facilities, equipment, devices and machines. In other hand, maintenance is the combination of all technical and associated administrative actions intended to prevent a device or component from failing or to restore it to a state in which it can perform its required function. In general, these actions protected the physical assets at specific level of efficacy with an acceptable cost that increasing the useful life and preventing its sudden breakdown. Potentially, by doing these actions on equipment and component, owner will gain a significant of reliability and availability. It can be classified into three categories: preventive maintenance, corrective maintenance and predictive maintenance.

Corrective maintenance (CM) is all the unscheduled maintenance and is usually performed after the system breakdown. It may be the appropriate strategy when the failure has no serious cost or safety consequences or when it is low on the priority list. In some cases, it also includes changes in design. Preventive maintenance (PM) is scheduled maintenance where all actions carried out on a timely planned base; on a periodic and specific schedule while the system is still operational. In practice, a PM schedule may include things such as cleaning, lubrication, oil

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changes, adjustments, repairs, and partial or complete overhauls that are regularly scheduled. It improves system availability, reliability and less costly than corrective maintenance as it minimizes unplanned downtime caused by equipment failure. PM reduces unexpected equipment failures and reduces the risk of injury. Increasing PM, reduces CM, but there is an optimal state of cost between these two situations. The third category is predictive maintenance (PDM) which is based on monitoring the state of the machine to predict failures that can occur. PDM is sometimes called condition-based maintenance, it is performed continuously or at intervals according to the requirements to diagnose and monitor a condition or system. PDM uses statistical tools, data, various instruments and tests. such as vibration analysis, chemical analysis of lubricants, thermography, optical tools, and audio gages to predict possible equipment failure. In this paper, the authors focus only on PM for a maintainable system to minimize the total maintenance cost. Three different PM activities are considered:

(I) Inspection (I): In this activity, there is no effect on the rate of occurrence of failure of the component and the component remains in a state of ‘as-bad-as-old’ it is called minimal repair. The inspection activities are, for example lubricating, cleaning, tightening the loose parts checking and adjusting.

(II) Repair (M): This activity addresses some expensive components and the repair action reduces the rate of occurrence of failure, but it doesn’t return the system to the state of ‘as-good-as-new’. It includes the inspection activities and replacing for some simple parts such as springs, seals, belts, and bearings, etc.

(III) Replacement (R): In this activity, the main components are replaced with new ones. It returns the state of main components such as motors, crank shafts, etc. to a state of as good as new. The main contribution in this research is balancing the cost and performance of machines, Also, integrated the downtime cost incurred due to repair as well as replacement activities into the traditional PM methods. Moreover, the constraints of the proposed model were extended beyond the reliability of the system to include the system availability as well as the manpower and spare parts resources. Furthermore, the developed model is not limited to single components or series systems only; it can be applied to the series-parallel system. The complexity, nonlinearity and recursive nature of the system under consideration urged the authors to develop a metaheuristic technique such as a genetic algorithm (GA) and used a MATLAB to optimize the preventive scheduling model.

Although maintenance planning is a hot topic in management science, this paper focuses on the effect of maintenance activities on reliability and availability as well as the different types of costs incurred during these activities. Many authors have proposed different preventive maintenance plans and studied their effect on total cost, reliability, maintainability, and availability. For example, Kattan and Hassan [1] used real data to test the effectiveness of the mathematical preventive maintenance model and its impact on both reliability and maintainability. They used different values of failure rate to determine the steady-state probability of a feed pump at normal operation. Increased failure rate reduced availability and reliability. Afefy [2] declared that PM provides a high level of availability and reliability assuming that failures follow an exponential distribution. Some researchers focused only on availability. Zhao [3] proposed a generalized availability model for repairable components and series systems. The failure pattern of repairable components is modelled by an alternating renewal process which implies that a failed component is perfectly repaired. In order to satisfy a constant demand and overcome the decreased availability, Dellagi, Rezg, and Gharbi [4] included a subcontractor machine in their proposed preventive maintenance plan. Maatouk et al.[5] proposed an optimization model to study the effect of the required availability on PM policy and system cost and indicated that when availability increases total maintenance cost increases. This policy was used to identify the good times of components to perform PM. Doostparast and Kolahan [6] minimized the maintenance cost, which was constrained by availability and resources; it was assumed that failures follow Weibull distribution. Yanget al.[7] measured the operating cost and the performance level at the steady-state availability. They developed a two-phase maintenance framework to deal with the defects of the system. In the first phase, both imperfect inspection and imperfect repair are performed to remove the defect. In the second phase, the system is shut-down for overhaul during the scheduled time window. Heydari [8] modelled the effects of identifying and removing defects on the failure process of the product and its corresponding cost through a periodic inspection policy. Several researchers optimized the maintenance cost while taking only reliability as a constraint ([9-12]). Metwalli et al.[13] minimized the scheduled and unscheduled maintenance cost to estimate the optimal maintenance intervals that relied on the reliability analysis of failures based on Weibull distribution. Some researchers have focused on the systems with multicomponent. Tam et al.[14] minimized the total cost to determine the optimal maintenance intervals for a multi-component system. Levitin and Lisnianski [15] presented a replacement schedule optimization problem of multi-state systems to minimize a total maintenance cost and the cost of unsupplied demand caused by failures at a desired level of reliability. Pargar et al.[16] developed an integrated optimization method to schedule preventive maintenance and renewal projects by grouping them to find an optimum balance between them to reduce the maintenance cost. The cost items in the objective function varied from one mathematical model to another. In his comparison between CM and PM in the automotive exhaust systems factory, Afefy [2] included the spare parts cost and downtime cost in total maintenance costs. Manzini et al.[17] proposed a model for minimizing the total cost (labor cost, spare parts cost, and failure cost) according to finite capacity constraints. Other researchers minimized long run expected cost rates; Lee and Cha [18] studied detailed properties of the optimal PM policies. They considered two periodic PM models. In the first model, the effect of PM actions was modelled by the failure intensity reduction and the deceleration of the deteriorating process. In the second PM model, it was modelled by the failure intensity reduction and the age reduction. Boonyathap and Jaturonnatee [19] formulated models of multiple periodic PM for used equipment under a lease. Peng and Zhu [20] minimized expected downtime, under different maintenance policies (age-based, condition-based, and failure based policies). Usher et al.[21] proposed a preventive maintenance model to minimize total maintenance costs using the concept that maintenance would improve the effective age of the system. Various optimization techniques have been developed and used to determine optimal PM schedules for a variety of systems. Mathematical models for maintenance planning have a large number of parameters and it may contain non-linearity and be recursive so that the metaheuristics are used to find the optimum solution. Metaheuristics include ant colony optimization, particle swarm optimization, genetic algorithms (GA), simulated annealing (SA) and tabu search (TS). The SA algorithm was introduced by Doostparast, Kolahan [6] to solve the problem of deciding optimal types and frequency of PM actions for coherent systems with deteriorating components. Bavarsad salehpour and Molla-Alizadeh-zavardehi [22] presented a novel metaheuristic method like GA, SA to portfolio selection. By their research, result demonstrated that the portfolio selected has a less risk and high return rather than another method. The GA optimization technique was used to optimize the maintenance cost due to availability and reliability constraints (Bris, Châtelet, & Yalaoui [23]; Tsai et al.[24]). Usher et al.[21] used the GA and indicated that the GA could be used successfully to find a good solution very quickly and more suited to major problems than a random search, and a branch- bound approach. Javanmard and Koraeizadeh [25] used GA to optimize the PM scheduling model to predict downtime, cost, and reliability over a predetermined time interval. Choulaei et al. [26, 27] used different shell connection to stress analysis of flanged joint bolts. Kumhar and Kumar [28] used different metaheuristic techniques such as GA, particle swarm, and evolution strategy to schedule maintenance planning for the power system and found that the GA had the most minimization cost compared to other metaheuristics. It can be shown from the above review that the consideration of reliability and availability together in the mathematical model to plan the maintenance activities is necessary to improve the equipment performance. Neglecting the downtime cost in scheduling the maintenance activities in a highly productive system affects the overall performance of the system; especially if the system is complex and includes many components. A thorough PM plan reduces the equipment failure rate and minimizes the total cost. Tambe [29] base on the machine availability criteria presented Genetic Algorithm for maintenance decision of multi-unit system. In this study, the authors consider the reliability, availability as well as manpower and spare parts in the form of constraints in the proposed mathematical model. The Downtime cost incurred due to repair as well as replacement is integrated into the total maintenance cost. Yousefi et al. [30] modeled the dynamic policy of maintenance and repairs to determine the next period of inspection of parts and equipment. Demonstrated that in their research how the replacement of defective parts in repairable equipment leads to the renewal of the entire system and changes in reliability and probability of failure. The advantage of this research is that the planning of the equipment inspection period based on the new life of the equipment is done dynamically and according to the conditions.

2. Modeling

The notation and definition of parameter and variable is shown in table 1.

Table 1: notation and definition

Notation	Definition	Notation	Definition
E_{ij}	The effective age of machine i at the end of period j.	Rm_0	Minimum reliability required for the system
S_{ij}	The effective age of machine i at the start of period j.	RS_j	Total reliability for a series-parallel system in period j.
Mc_i	Repair cost of machine i	Wri	Resource needed for the replacement of machine i.
Ci	Unplanned failure cost of machine i	m	Number of machines (1,2, ...,m).
βi	Shape parameter of machine i	j	Number of periods (1,2, ...,T).
Rc_i	Replacement cost of machine i	T	Length of the planning horizon.
α_i	Improvement factor of machine i	tp	PM interval
D_i	Shutdown cost for machine i	λi	Characteristic life (scale) parameter of machine i

Ic_i	inspection cost of machine i	tm_i	Repair time of machine i.
tc_i	Corrective maintenance time of machine i.	Wm_i	Resource needed for the repair of machine i.
tr_i	Replacement time of machine i.	W_i	Total resources available at the j th period.
AV_0	Minimum availability for the system	ti_i	inspection time of machine i.

$M_{i,j}$, $R_{i,j}$, $N_{i,j}$ are integer decision variable for repair, replacement and inspection respectively. Also, by assumption that one of these actions could be done, when machine i repaired or replaced or inspected at period j, these variables are 1, but 0 respectively. It is assumed that the machine failures follow nonhomogeneous Poisson process and rate of occurrence of failure at actual time t ($t > 0$) is given by:

$$f_i(t) = \lambda_i . \beta_i . t^{\beta_i - 1} \qquad \lambda, \beta>0 \quad \text{for } i=1,\ldots,m \qquad (1)$$

Where λ_i and β_i are the scale (characteristic life) and the shape parameters of machine i respectively. Nonhomogeneous Poisson process allows for a change or trend in the intensity of system failure (Crow[31]). It is assumed that the planning horizon [0, T] is divided into discrete intervals. PM actions (inspection, repair or replacement) occur at the end of each period. Repair and replacement actions reduce the effective age of the machine and the rate of occurrence of failure. If the inspection action is performed in period j, there is no effect on the rate of occurrence of failure and the effective age of the machine.

$$E_{i,j}=S_{i,j}+tp \qquad \text{for } i=1,\ldots,m , \text{ for } j=1,\ldots,T \qquad (2)$$

$$S_{i,j+1}=E_{i,j} \qquad \text{for } i=1,\ldots,m , \text{ for } j=1,\ldots,T \qquad (3)$$

If the machine i is repaired in period j, the repair action reduces the age of machine i in the next period and reduces the rate of occurrence of failure.

$$S_{i,j+1}=\alpha_i.E_{i,j} \qquad \text{for } i=1,\ldots,m , \text{ for } j=1,\ldots,T \qquad (4)$$

The term α is an improvement factor that shows the effect of a repair action on the aging of a system. The improvement factor function is developed by Moghaddam and Usher [21] that is a function based on the ratio of the difference between replacement and repair costs.

$$\alpha_i=(Rc_i-Mc_i).Rc_i \qquad \text{for } i=1,\ldots,m \qquad (5)$$

Replacement action is considered when the subsystem.component in machine i is replaced at the end of period j. Hence, the subsystem.component is returned to a state of "good-as-new", and the rate of occurrence of failure drops to zero.

$$S_{i,j+1}=0 \qquad \text{for } i=1,\ldots,m , \text{ for } j=1,\ldots,T \qquad (6)$$

2.1. Total preventive maintenance cost

In all manufacturing or production plants; Maintenance costs are a major part of total operating costs. Depending on the specific industry, between 15 - 60 percent of maintenance costs can directly impact the plant profitability. For example, maintenance costs for iron and steel, pulp and paper, and other heavy industries represent up to 60 percent of the total production costs. Recent surveys of maintenance management effectiveness indicate that one-third-33 cents out of every dollar of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance. The reason for this ineffective management is the lack of factual data to quantify the actual need for repair or maintenance of plant machinery, equipment, and systems.

2.1.1. Unplanned failure cost

If the system in operation at period j carries a high rate of occurrence of failure, the cost is increased. The expected number of failures is exhibited with minimal repair. At the nonhomogeneous Poisson process assumption, the expected number of failures for machine i in period j can be calculated by:

$$EN_{i,j} = \int_{S(i,j)}^{E(i,j)} f_i(t)dt = \lambda_i (E_{i,j})^{\beta_i} - \lambda_i (S_{i,j})^{\beta_i} \qquad (7)$$

for i=1,…,m, for j=1,…,T

Assume that the cost of each failure is ci ($.failure event) which includes the average cost of corrective maintenance time. The cost of failures attributed to a machine i in period j is $C_{i,j}$:

$$C_{i,j} = C_i.\lambda_i.[(E_{i,j})^{\beta i}-(S_{i,j})^{\beta i}] \qquad \text{for } i=1,\dots,m, \quad \text{for } j=1,\dots,T \tag{8}$$

2.1.2. Repair.replacement cost

If machine i is repaired in period j, Mc_i is the repair cost for machine i. If the component subsystem in the machine i is replaced in period j, Rc_i is the replacement cost that is the purchase of a new component subsystem.

2.1.3. Planned downtime cost

For the continues production system, when machine i is repaired or replaced in period j, it is considered to be out of service (downtime) which, in turn, affects the production rate as well as the total cost. Planned downtime cost can be calculated as:

$$Sc_{i,j} = \sum_{i=1}^{m}\sum_{j=1}^{T} D_i\,(M_{i,j}.tm_i + R_{i,j}.tr_i) \quad \text{for } i=1,\dots,m, \quad \text{for } j=1,\dots,T \tag{9}$$

Di: downtime cost for machine i ($.hr) From the previous calculations of each cost item, the total maintenance cost for the series-parallel system, required to be minimized: (includes the unplanned failure cost + maintenance cost + replacement cost + planned downtime cost). The nonlinear integer binary programming model, that minimizes the total cost based on availability, reliability and resources constraints, is then formulated as follows:

$$Total\ \cos t = \sum_{i=1}^{m}\sum_{j=1}^{T}[c_i\,\lambda_i\,[(E_{i,j})^{\beta_i} - (S_{i,j})^{\beta_i}] + Mc_i.M_{i,j} + Rc_i.R_{i,j} + D_i\,(M_{i,j}.tm_i + R_{i,j}.tr_i)] \tag{10}$$

The duration of maintenance activities has an effect on the efficacy of the system under consideration. To plan PM policy based on availability, it is important to evaluate the maintenance time needed for the PM actions. The maintenance time includes:

(1) Repair time (tm) due to repair action.
(2) Replacement time (tr) due to replacement action.
(3) Corrective maintenance time (tc) where failures occur unexpectedly.

Availability is the function of the mean uptime (MUT) and the mean downtime (MDT), assuming that the PM actions are grouped at the same time to reduce the downtime. Hence, the system is stopped when a machine is repaired or replaced.

$$Av_j = \frac{tp - \sum_{i=1}^{m} tc_i\,.\lambda_i\,[(E_{i,j})^{\beta_i} - (S_{i,j})^{\beta_i}]}{tp + \sum_{i=1}^{m}[M_{i,j}.tm_i + R_{i,j}.tr_i]} \tag{11}$$

$$\mathrm{Re}_{i,j} = e^{-[\lambda_i\,(E_{i,j})^{\beta_i} - \lambda_i\,(S_{i,j})^{\beta_i}]} \tag{12}$$

The reliability (RE) for machine i in the period j can be expressed by following. If X machines in series, If Y machines in parallel then RE calculated respectively:

$$\prod_{i=1}^{X} \mathrm{Re}_{i,j}\ ,\ 1 - \prod_{i=1}^{Y}(1 - \mathrm{Re}_{i,j}) \tag{13}$$

Resources (manpower) used during the period j should not exceed the available resources (W).

$$\sum_{i=1}^{m} R_{i,j} Wr_i + \sum_{i=1}^{m} M_{i,j} Wm_i \leq W_j \qquad (14)$$

for i=1,…,m, for j=1,…,T

3. Optimization

The recursive behaviour of the proposed mathematical model, as well as its complexity and nonlinearity, urged the authors to develop a metaheuristic technique such as a genetic algorithm to optimize the preventive scheduling model. Genetic algorithm (GA), developed by John Holland, is one of the most widely used evolutionary optimization techniques. It is a popular, universal tool for solving various optimization problems due to its advantages, and has been successfully applied to an abundance of optimization problems in reliability engineering as well as maintenance optimization problems. Figure 1 shows that the algorithm at about iteration 500 reached to the best generation.

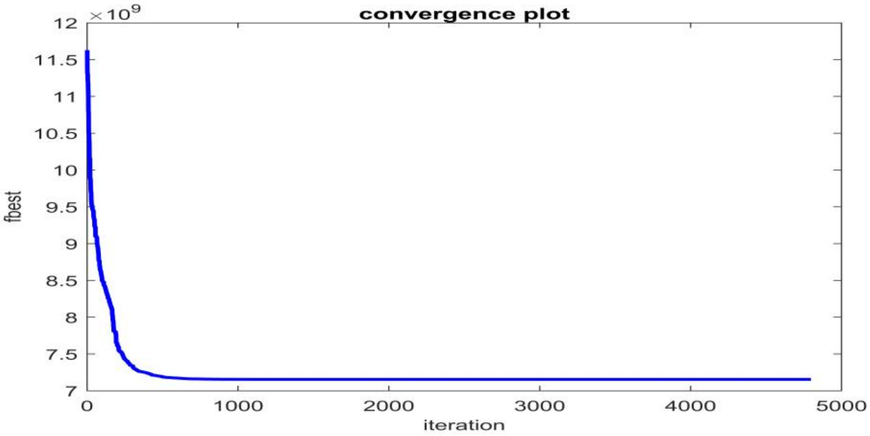

Fig.1: Convergence plot

3.1. Chromosome encoding

The Chromosome is defined as an array with length 2(m × T) as m number of machines and T number of periods. The cell in this array represents PM actions, I: inspection action, M: repair action, R: replacement action. The inspection action depends on the repair and replacement action; if the repair and replacement actions aren’t taken, inspection action is performed. The chromosome is divided into two arrays: 1- repair action array and 2- replacement action array each of length (m × T). First, the repair action array where each cell contains 1 or 0 means that the repair action is considered or not respectively. Secondary, the replacement action array where each cell contains 1 or 0 means that the replacement action is taken or not respectively. Taking into account the constraint $M_{i,j}+ R_{i,j} \leqslant 1$, an initial population of size n is generated.

One point crossover: a random crossover point is selected and the tails of its two parents are swapped to get new offspring.

Uniform mutation: mutation changes randomly in the new offspring. For binary encoding, the mutation is done by changing a few randomly chosen bits from 1 to 0 or from 0 to 1. A crossover and mutation for repair action array and replacement action array are performed. A roulette wheel mechanism is adopted to probabilistically select individuals based on their performance. In roulette wheel parents are selected based on their fitness; a chromosome with a higher fitness value (lower cost) is selected.

3.2. Solution decoding

The structure of the solution comprises two matrices; the matrix $[M_{i,j}]$ consisting of genes that indicate machine i when repaired or not in period j; and the matrix [$R_{i,j}$] consisting of genes that indicate machine i when replaced or not in period j. The two matrices are decoded to the optimal preventive maintenance scheduling solution.

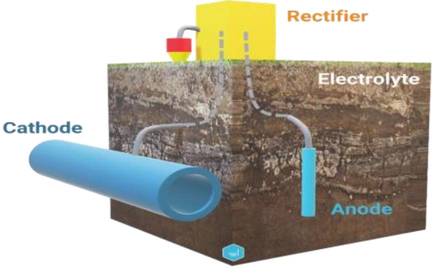

Fig 2: Cathodic protection system

4. Case study

Cathodic protection system (CPS) is a proven corrosion control method for protection of underground and undersea metallic structures, such as oil and gas pipelines, cables, utility lines and structural foundations. Cathodic protection is now widely applied in the protection of oil drilling platforms, dockyards, jetties, ships, submarines, condenser tubes in heat exchangers, bridges and decks, civil and military aircraft and ground transportation systems. Cathodic protection works by placing an anode or anodes (external devices) in an electrolyte to create a circuit (see Fig.2). As a result, current flows from the anode through the electrolyte to the surface of the structure. Corrosion moves to the anode to stop further corrosion of the structure. The proposed preventive maintenance scheduling model was applied to the Khuzestan Gas Company (KHGC). The Cathodic Protection system (CPS) consists of 20 transes. The failure time data collected from the computerized maintenance management system (CMMS) are used to calculate scale parameter (λ) and shape parameter (β) of non-homogeneous Poisson process as in Crow [31] , and Gannon [32] . The scope of replacement includes the main parts that the failure of each causes the failure of the trans. The main parts of trans as shown at figure 2 consist of coating, anode, cable and component of trans. The scope of repair includes the parts that must be repaired for efficient operation of the trans. A representative data set based on practical data for CPS is shown in Table 2.

The distribution of gas operates 24 hours a day and 7 days a week. Downtime cost is considered to be 20,000,000 Rial.hour. The regular constant time of the inspection including, washing, cleaning and increasing oil motor or hydraulic oil, can be ignored compared to other times. The planning horizon is one year with monthly PM intervals. For all intervals, minimum system reliability and availability are required to be 90% and 95% respectively.

5. Result and discussion

The proposed mathematical model was applied to the case study and solved to an optimal PM schedule. The computer code is written in MATLAB (R2019 b) software on a laptop computer (Intel.Core 7, 2.40 GHz and 4 GB RAM). The chromosome with length 480 was divided into two chromosomes, the 1:240 genes are the repair action, and the 241:480 genes are the replacement action. For GA parameters, 300 generations have been used, population size = 50, crossover rate = 0.8, mutation rate = 0.4. This resulted in a 6,939, 865,646.67 Rial total maintenance cost, as the value of the objective function. The corresponding optimal PM schedule is shown in Table 3 where N, M, R stands for inspection, repair, and replacement actions respectively. The total maintenance costs (spare parts cost-random failure cost-planned downtime cost) spent in the year 2023 was 9,438,279,247,47 Rial. Figure 3 indicates a comparison between the current maintenance plan and the proposed maintenance plan cost. The proposed plan results in a reduction of total maintenance costs with a percentage of 36%.

Reliability increased when performing PM actions (repair. Replacement) as PM actions reduce the hazard rate. The availability of the proposed optimal PM plan is higher than the actual plan, as unscheduled downtime is decreased due to PM actions (see Fig.3).

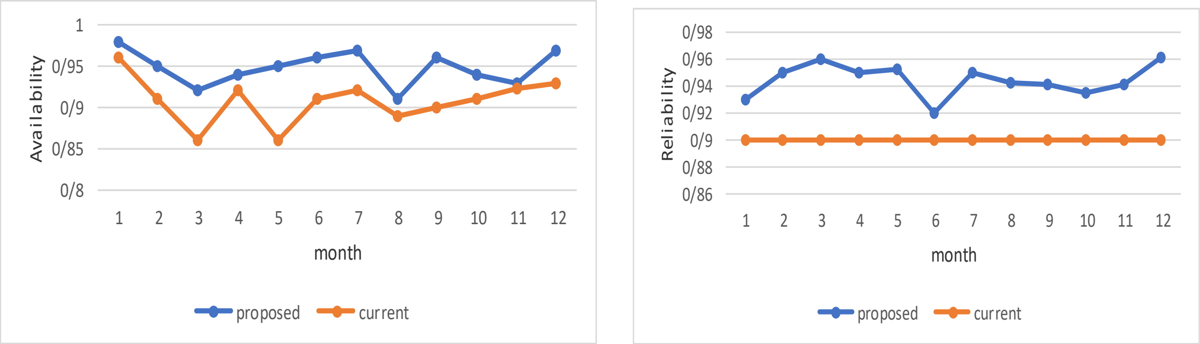

Fig 3: Availability & Reliability for a current and proposed plan.

Table.2: The input parameters for PM scheduling.

NO	λ	β	α	C (1000 rial)	mc (1000 rial)	rc (1000 rial)	ic (1000 rial)	tr (min)	tm (min)	tc (min)
1	0.002358	0.963	0.63	6200	2000	40000	5000	7200	3000	1500
2	0.003872	1.44	0.67	14700	2000	30000	3000	8000	3600	2000
3	0.00005706	1.399	0.4	25000	2000	10000	12000	7500	2500	1000
4	0.000000734	1.971	0.6	19400	2000	10000	1000	8000	2000	2500
5	0.000000734	1.971	0.6	19400	2000	10000	1000	5000	3600	1000
6	2.7E-09	2.57	0.7	22200	2000	50000	5000	4000	3000	2200
7	0.004825	1.03	0.4	19400	2000	10000	1000	12000	3500	1500
8	0.006771	0.85	0.5	15000	2000	20000	2000	7500	4000	1000
9	0.04028	0.563	0.5	35000	2000	30000	2000	5000	4000	2110
10	0.0017414	1.12	0.31	225000	2000	18000	1800	6500	4800	2000
11	0.0007898	1.23	0.31	210000	2000	18000	1800	11000	3000	3000
12	0.007558	0.976	0.33	15000	2000	30000	2000	9000	1800	3000
13	0.00001294	1.782	0.67	12000	2000	30000	2000	8500	3000	4200
14	0.00000115	1.782	0.47	5500	2000	15000	1500	9500	1500	6000
15	0.001657	1.018	0.6	16500	2000	25000	1050	7000	4000	1800
16	0.0020077	0.863	0.5	16000	2000	50000	1000	8200	3000	4000
17	0.0020077	0.863	0.5	16000	2000	50000	1000	12000	3000	3600
18	0.0001002	1.304	0.6	11500	2000	25000	1500	14000	2000	6000
19	0.000007366	1.73	0.64	15000	2000	50000	2000	13000	4000	2000
20	0.000007366	1.73	0.64	15000	2000	5000	2000	10000	4000	3000

Table.3: Optimal PM plan

NO	T											
	1	2	3	4	5	6	7	8	9	10	11	12
1	I	I	I	M	I	I	I	I	I	M	I	I
2	R	R	R	R	R	R	R	R	R	R	R	I
3	I	I	I	I	I	I	I	I	I	I	I	I
4	R	R	R	R	R	R	R	R	R	R	R	I
5	R	R	R	R	R	R	R	R	R	R	R	I
6	R	R	R	R	R	R	R	R	R	R	R	I
7	I	I	I	I	I	M	M	M	I	I	I	I

8	I	I	I	I	I	I	I	I	I	I	I	I
9	I	I	I	I	I	I	I	R	I	I	I	I
10	R	R	R	R	R	R	R	R	R	R	R	I
11	R	R	R	R	R	R	R	R	R	R	R	I
12	I	I	I	I	M	I	I	M	I	I	I	I
13	**R**	**R**	**R**	**R**	**R**	**R**	**R**	**R**	**R**	**R**	**R**	I
14	I	**R**	M	M	**R**	**R**	M	**R**	M	M	**R**	I
15	I	I	I	I	I	I	I	M	I	I	I	I
16	I	I	I	I	M	M	M	I	I	I	I	I
17	I	I	I	I	M	I	M	I	I	M	I	I
18	I	M	I	I	R	I	M	I	M	I	M	I
19	R	R	R	R	R	R	R	R	R	R	R	I
20	R	R	R	R	R	R	R	R	R	R	R	I

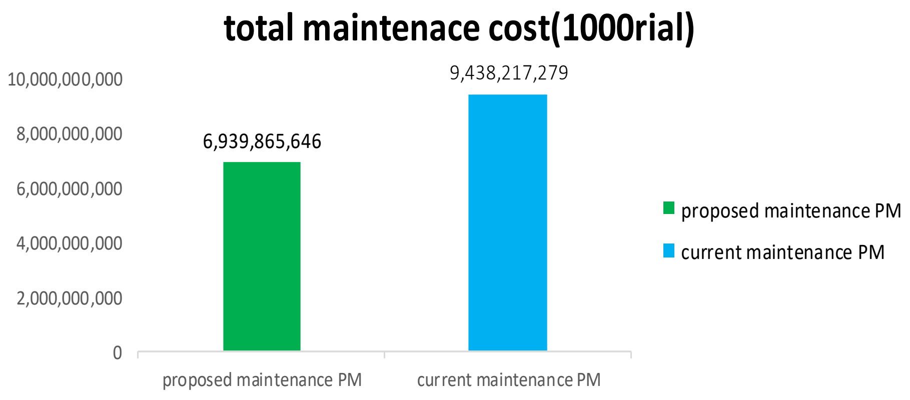

Fig 3: comparison between the current and proposed maintenance plan cost

5.1. Sensitivity analysis

The scale and shape parameters play the most important role in the configuration of the optimal schedules. To further verify the performance and applicability of the proposed maintenance policy, a sensitivity analysis is carried out using two critical parameters: (I) scale parameter (λi); and (II) shape parameter (βi). The trans 13 and the trans 14 have the same shape parameter, but the trans 13 has a scale parameter larger than the trans 14. This resulted in more replacement activities for the trans 14 as shown in Table 3. On the other hand, the scale parameter has more effect on the structure of the optimal schedules. Another example, assume that the scale parameter is constant, by decreasing shape parameter from 1.782 to 1.5 on trans 13, then the number of replacements decrease from 11 to 6. This resulted in less replacement activities for the trans 13. This indicates that less reliable transes with higher failure rates are replaced more frequently than the more reliable transes with lower failure rates. Increasing the scale and shape parameters increase the expected number of failures that decrease the system reliability and therefore the unplanned failure cost increases (see table.4).

6. Conclusion

In this paper, the authors propose an integrated preventive maintenance scheduling mathematical model that minimizes the total maintenance costs subject to the reliability, availability. The total maintenance cost includes multilevel PM actions such as inspection, repair, and replacements as well as downtime cost. The presented model allows the maintenance planner to make decisions that include the determination of the best PM actions at any period, with respect to the total cost, reliability, availability requirements and another constraint. The proposed mathematical model is nonlinear and recursive. Hence, the GA algorithm is adopted to solve the model. The GA approach is quite capable of obtaining a near-optimal solution for PM scheduling in reasonable computational times. When a preventive maintenance scheduling model has been implemented in the KHGC, a 36% reduction in annual total maintenance cost is achieved for a minimum of system reliability and availability of 90% and 95% respectively. Sensitivity analysis is performed to study the effect of the scale and shape parameters. The study indicates that an increase in the λ and β parameters causes a decrease in system reliability and an increase in the unplanned failure cost. A non-periodic optimal PM schedule to maintain a certain level of reliability and availability is considered for future researches.

Table.4: Optimal preventive maintenance plan after changing λ and β parameters

NO	**T**											
	1	2	3	4	5	6	7	8	9	10	11	12
13	**R**	I	**R**	I	**R**	I	**R**	**R**	M	I	**R**	I
14	M	M	R	M	M	M	R	M	M	R	M	I

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