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RESEARCH PAPER

A New Approach to Preventive Maintenance Planning Considering Non-Failure Stops and Failure Interdependence Between Components

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Abstract

In this paper, emphasizing the real conditions prevailing in production industries, a new optimization model is developed in order to optimally schedule preventive maintenance and repair activities in a multi-component maintainable manufacturing system addressing a novel approach. It is assumed that failures or inspections are not only causes of stopping devices but also some other activities (non-failure stops) may interrupt the production process. The presented mathematical model utilizes these interruptions as opportunities to perform some maintenance activities. Failure interaction between components is also considered and the rate of failure of each component due to shocks from other components may be increased by a certain percentage. In addition to preventive maintenance and repairs, in the case of sudden failure of any component, corrective maintenance is implemented. Besides, the cost of stopping the system for performing maintenance activities is considered dependent on the duration of maintenance execution. Due to the complexity of the structure of the proposed model, the Genetic algorithm is adapted as the solution approach and its parameters are adjusted by the Taguchi method. A numerical example is solved and analyzed. Finally, a comparison between the exact method and the developed algorithm is provided to examine its efficiency and the impacts of the rise in problem sizes on the performance of the algorithm.

Keywords:
Preventive Maintenance;
Non-Failure Stop;
Multi-Component System;
Failure Interdependence;
Genetic Algorithm;
Taguchi Method

Introduction

In view of product management, maintenance is as important as production to ensure the quality. So, the optimal preventive maintenance schedule is a key tool for keeping and improving system availability and safety, as well as production quality. System maintenance refers to all actions taken to keep material in a serviceable condition or to restore it to serviceability [1]. Therefore, the importance of maintenance planning as a part of improving production efficiency and the company's profitability strategy cannot be ignored and preventive maintenance is required to reduce downtime and maintain profitability and competitiveness in global markets. In production industries, all systems, from the simplest to the most complex, require scheduled maintenance to reduce the risk of failure. In other words, maintenance planning is a balance between the costs of preventive maintenance/replacement activities and the benefits of reducing the overall system failure rate, and the key is to find the best sequence

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of maintenance activities for each element in the system in each period across the entire planning. In addition, with the development of advanced production technologies, modern machines and equipment are increasingly automatic and intelligent to respond to market changes and increase product diversity, which in turn has made it more difficult to maintain equipment at a desirable level of reliability. Therefore, to ensure the performance of these complex machines with high reliability, human safety and environmental

protection, maintenance policies, and preventive repairs have become more important and in this regard, reliability plays an important role [2].

On the other hand, competitive conditions in the production and provision of services in the present era have led to a rapid response to customer demand as one of the strategic priorities of the industry. Consequently, equipment failure will reduce safety and cause acute problems in the timely delivery of products to customers. Therefore, reducing operating costs and abrupt stops along with increasing reliability are among the major goals in equipment management of various industries.

From an aging point of view, in many manufacturing systems, the use of equipment increases the likelihood of failure, which in turn reduces reliability and increases operating costs (such as failure costs). So, maintenance management is performed as an important unit in production systems to maintain equipment in a suitable condition with the aim of reducing breakdowns and reducing operating costs. Maintenance may also be used to increase the likelihood of continued operation effectively.

As our knowledge allows, in all studies that have been done in this field so far, it is assumed that the device does not stop until it fails while the only factor that stops the device in the real world is not the device failure. In other words, sometimes the machine has no problem continuing working, but non-failure stops (stops that are not due to failure) for reasons such as: type and continuity of work, finishing raw materials, personnel training, lunch, preparation, absence of operator, production of prototypes and testing, final discharge, carrying out projects and corrections (remedial and capital) such as painting the factory or changing the design of products, re-flooring, going through the furnace cycle (engineering process), preheating, emptying the oxide box, etc. They stop the machine and provide a suitable opportunity to perform some maintenance activities during these times, which reduces maintenance costs. Regarding these stops, it can be said that the work is done in such a way that the system stops for non-failure reasons and the duration of these stops is limited. The question is whether performing some preventive maintenance activities at these times is cost-effective and increases system availability or not. If so, some maintenance activities will be done at these points. In fact, by performing preventive maintenance activities at these times, a lower cost is paid due to not having the cost of stopping the system completely to perform maintenance activities (because no matter what maintenance activity is performed or not, the machine will stop at these times) and they are prevented from being performed at inspection points and predetermined for maintenance. The duration of access to the system is increased. At the same time, it is possible that the reliability of the system has not yet reached a critical state and there is no need to perform preventive maintenance activities at the points where non-failure stops are performed. Considering the costs of stopping the system and the costs of preventive maintenance and emergency breakdowns, it should be decided to what extent the maintenance activities should be carried out at inspection points and to what extent in non-failure stops.

The proposed mathematical model has the ability to be adapted to all production multi-component systems that can be maintained and repaired. But, its main application is in continuous production systems where outlier times can be programmed. Although various models have been developed in this field, including dead times in the model definitely adds an advantage over other previous models.

Review of Literature

Preventive maintenance and replacement optimization models have been proposed since the 1960s and have been extensively developed to find preventive maintenance schedules in a variety of systems. Since Barlow and Hunter [3] introduced the partial repair model, much effort has been put into the maintenance schedule. In the following, a number of well-known problem models are briefly stated.

Models focusing on a manufacturing system with one component have been extensively studied [4-5]. These types of models are less considered in today's world because of the increasing complexity and diversity of production systems. So, more attention has been paid to preventive maintenance on multi-component systems [6]. Some noticeable studies are reviewed in the following.

Deteriorating manufacturing systems have been studied in terms of maintenance decisions in many ways [7-11]. But Malik [12] introduced the development factor in maintenance scheduling in such systems, and since then a variety of models have been developed in such a way. Nakagawa [13] proposed two analytical models to find the optimal preventive maintenance schedule, assuming that the failure rate is incremental throughout. He considered the average cost of failure and also the costs of preventive maintenance and replacement costs, assuming that preventive maintenance activities reduce the effective age. Lane et al. [14] combined both models proposed by Nakagawa and proposed a hybrid model considering the effects of each PM activity and in terms of both immediate effects and long-lasting effects for reuse of the equipment. The authors presented two models with respect to the concepts of maintainability and non-maintainability of failure models.

Dependence between components can be categorized into three types: economic dependence, structural dependence and failure dependence. Economic dependence between components means that simultaneous maintenance and repair of components as a group reduces costs compared to maintenance and repair of each component individually [15-16]. There is structural dependence in systems where several components together structurally form a subsystem. As a result, some defective components in the subsystem must be stopped and disassembled before being repaired or replaced. Structural dependence is in fact an interdependence in the performance of maintenance activities between components [17]. Various studies include a structural dependence [18-20]. Also, if there is a failure dependence between the components, the failure of some components affects the failure of other components [21-24]. Zhang, Fouladirad & Barros [25] consider a two-component system with failure interactions. Failure of the first component either causes a random amount of damage to the other component, or it results in failure of the other component with a certain probability. Three preventive maintenance policies are analyzed numerically.

Aspects of research innovation can be enumerated in the following cases:

- As our knowledge allow, in previous works a common assumption is that the device will not be stopped until it breaks down or an inspection occurs, however in the real world they are not the only factors that stop the device. Sometimes non-failure reasons stop the system. Some examples of these reasons are continuity of work, staff training, time for having meals, preparation, production of prototypes and testing, final evacuation projects and corrections including re-flooring, preheating, oxide box emptying, etc. Considering these types of stops provides a good opportunity for implementing some maintenance activities during these times.
- Another innovation is that the cost of stopping the system depends on the duration of the stop. So far, in all research works in this field, a fixed cost has been considered for shutting down the system for maintenance activities. But in fact, with the shutdown of the system

and lack of access to the system, a cost per unit of time is imposed due to unmet demand, production waste, and so on.

- Considering the failure dependence between components is another innovation of this research. Thus, the failure of each component due to shock to other components may increase their failure rate by a percentage. To the best of our knowledge, this type of failure dependency has not been implemented for more than two components before.
- Adapting an efficient meta-heuristic algorithm to solve the proposed model in a computationally reasonable time and adjusting its parameters by the Taguchi method.

Problem Description

The problem considered in this paper is to optimize the preventive maintenance schedule for a multi-component repairable system using a mathematical model based on the concept of aging and impact factors. For achieving this purpose, the planning horizon is divided into equal intervals and at the end of each period, decisions related to the type of maintenance activity (service, repair, replacement or do-nothing) are made according to the impact of each activity on the reliability of each component. So, the overall cost is minimized and the required reliability is met.

The assumptions considered in this research are:

- Instead of using calendar age, the effective age attitude is used.
- The system at the beginning of the horizon is a new, repairable and maintainable system with a series structure.
- The learning process is ignored, so the component failure rate is incremental.
- Each component in the system has an increasing rate of occurrence of failure (ROCOF) and the failure of each component follows the non-homogeneous poisson process (NHPP).
- System failure is only due to aging of the elements and sudden failure due to reasons such as operator error is not considered.
- The planning horizon is finite and does not change with maintenance activities.
- Development factors, duration of maintenance activities, required system reliability, cost parameters and parameters related to the component life distribution function are already known and available.
- There are different types of maintenance activities, each of them has a different effect on life expectancy but all of them rejuvenate the system and consequently reduce its failure rate.
- The impact of various maintenance activities on the effective age of the elements is determined only by the development factor.
- In addition to PM activities, in the event of a sudden breakdown, maintenance and repair are performed.
- Dependence of component failure is one-way; this means that between two components, only one is effective and the other is effective, and the opposite does not happen.

In each period, it is assumed that one of the following activities is performed for each component:

a. Maintenance service (MS)

Some general MS activities include lubrication, cleaning of dust and rust, tightening of loose parts, adjusting and injecting consumables. These types of activities can adjust the subsystem to a better condition and place more emphasis on maintaining the system under normal operating conditions.

b. Maintenance Repair (MR)

It generally involves simple replacement or repair activities that rehabilitate the subsystem to achieve a better state than MS. It is mainly used for components that are not easy to prepare and purchase. It includes repairing and replacing a few simple parts such as springs, nuts, belts, complete implementation of the engine for repair, strengthening the engineering structure, and disassembly and reassembly of repaired components. Doing this type of activitiy puts components puts in a position between "good as before" and "bad as before".

c. Replacement (RP)

This type of activity is the replacement of a worn subsystem with a new subsystem, which prevents a breakdown and a serious problem. This activity is done for key components to prevent serious damage. In addition, components on which other maintenance activities have been performed several times and cannot be used may be performed on this type of activity.
Using some relations from [26-27], the problem is modeled. There is a new system with N series structured components. It is also assumed that each component in the system has an increasing failure rate with the function $\upsilon_i(t)$, where t refers to the time (t>0). The failure of each component follows the Non-homogeneous Poisson Process (NHPP) and is expressed as follows:

$$\upsilon_i(t) = \lambda_i.\beta_i.t^{\beta_i-1} \quad for \quad i = 1, \dots, N \tag{1}$$

Where λ_i and β_i are the shape and the scale parameters of component i.

Aging increases the failure rate of components and on the other hand, the occurrence of failure of one component causes a shock to specific components and as a result causes a sudden increase in their failure rate. So we have:

$$\acute{\upsilon}_i(t) = \sum_{n=0}^{\infty} \upsilon_i(t|N_l(t) = n) \times P(N_l(t) = n) \tag{2}$$

Which,

$$\upsilon_i(t|N_l(t) = n) = \upsilon_i(t) \times (\mathrm{P}_{\mathrm{i,l}} + 1)^n \tag{3}$$

$$P(N_l(t) = n) = \frac{(\lambda_{l,t})^n \, e^{-\lambda_{l,t}}}{(n)!} \tag{4}$$

The average number of failures of component L in the range 0 to t is calculated from the following equation:

$$\lambda_{l,t} = \int_0^t \upsilon_l(t) \; dt = \int_0^t \lambda_l.\beta_l.t^{\beta_l-1} dt = \lambda_l.t^{\beta_l} \tag{5}$$

So we have:

$$P(N_l(t) = n) = \frac{\left(\lambda_l . t^{\beta_l}\right)^n . e^{-\left(\lambda_l . t^{\beta_l}\right)}}{n!} \quad (6)$$

Impact of maintenance activities

The effective age x is used instead of the calendar age and $X_{i,j}$ and $X'_{i,j}$ are considered as the effective age of the subsystem i at the beginning and end of the period j, respectively. The initial age of each component at the beginning of the planning horizon is considered zero as the following equation:

$$X_{i,1} = 0 \quad (7)$$

Maintenance activities usually return the component to a state of "better than old" and "worse than the new". Then reliability is evaluated by R(X) instead of R(t). Δt is the duration of each period. So the following relation can be concluded:

$$X'_{i,j} = X_{i,j} + \Delta t$$
$$i = 1,2, \dots , N \ ; \ j = 1,2, \dots , B \quad (8)$$

If preventive maintenance is used, effective age is assumed to be reduced immediately. The changes are modeled as below:

$$MS: \ X_{i,j+1} = X_{i,j} + \alpha_{i,j} \Delta t$$
$$= X'_{i,j} - \left(1 - \alpha_{i,j}\right) \Delta t \quad (9)$$

$$MR: X_{i,j+1} = \alpha_{i,j} X'_{i,j}$$
$$for \ i = 1,2, \dots , N \ ; \ j = 1,2, \dots , B - 1 \quad (10)$$
$$0 \leq \alpha_{i,j} \leq 1$$

Where $\alpha_{i,j}$ is improvement factor and depends on the impact of preventive maintenance activities. It is assumed that the effect of MS and MR is constant for each subsystem. So we have:

$$\alpha_{i,j} = \begin{Bmatrix} m_{i,1} \ \ for \ all \ MS \ in \ all \ periods \ , i = 1,2, \dots , N \\ m_{i,2} \ \ for \ all \ MR \ in \ all \ periods \ , i = 1,2, \dots , N \end{Bmatrix} \quad (11)$$

If the subsystem i has been replaced (at the end of interval j) we have:

$$X_{i,j+1} = 0$$
$$for \ i = 1,2, \dots , N \ ; \ j = 1,2, \dots , B - 1 \quad (12)$$

If no activity is performed, no change is made to the effective age:

$$X_{i,j+1} = X'_{i,j}$$
$$For \ i = 1,2, \dots , N \ ; \ j = 1,2, \dots , B - 1 \quad (13)$$

The above formulas can be written in an integrated form as follows:

$$X_{i,j} = (1 - ms_{i,j-1})(1 - mr_{i,j-1})(1 - r_{i,j-1})X'_{i,j-1} + ms_{i,j-1}\left[X'_{i,j-1} - (1 - m_{i,1})\Delta t\right] + mr_{i,j-1}\left(m_{i,2}X'_{i,j-1}\right) \tag{14}$$

$$ms_{i,j} + mr_{i,j} + r_{i,j} \leq 1 \tag{15}$$

$$X'_{i,j} = X_{i,j} + \Delta t \tag{16}$$

$$X_{i,1} = 0 \quad , \quad X'_{i,1} = \Delta t \qquad For \quad i = 1,2,\dots,N \quad , \quad j = 1,2,\dots,B \tag{17}$$

Preventive maintenance costs

Cost of performing preventive maintenance activities is calculated using the following equation.

$$\sum_{j=1}^{B}\sum_{i=1}^{N}(MS_i.ms_{i,j} + MR_i.mr_{i,j} + R_i.r_{i,j}) \tag{18}$$

The following constraints must be met:

$$ms_{i,j}, mr_{i,j}, r_{i,j} = 0 \ or \ 1 \tag{19}$$

$$ms_{i,j} + mr_{i,j} + r_{i,j} \leq 1 \tag{20}$$

Total system shutdown cost due to preventive maintenance activities

During the life of the system, production takes place several times which is called a production run. After each production run, the system may stop or continue to operate without stopping. If it is assumed that after k period a non-failure stop occurs (k is from 1 to B), then set F is defined as Eq. 21 to distinguish the periods containing non-failure stop from the periods in which the non-failure stop does not occur.

$$F = \left\{k.j \,\middle|\, j = 1,2,\dots,\left\lfloor\frac{B}{K}\right\rfloor\right\} \tag{21}$$

Then, cost H is modeled below. This cost consists of three terms. The first one is the fixed cost, which is taken into account by performing even one maintenance activity. The second term relates to variable costs for periods in which there is no non-failure stop. As can be seen, this term increases with the duration of maintenance activities. The third term relates to variable costs for periods in which there is a non-failure stop. The variable f_j is used to take into account the non-failure stop in the model and its effect on reducing maintenance costs. This variable will be zero if the duration of maintenance activities in period j is less than the period of non-failure stop, otherwise, it will be one.

Which f_j is calculated from Eq. 23.

$$H=\sum_{j=1}^{B} h_{FC}(1-\prod_{i=1}^{N}\left(1-\left(ms_{i,j}+mr_{i,j}+r_{i,j}\right)\right) + \sum_{\substack{j=1\\ j\notin F}}^{B} h_{DC}\cdot\left[\sum_{i=1}^{N}\left[ms_{i,j}.TMS_i+mr_{i,j}.TMR_i+rp_{i,j}.TRP_i\right]\right] + \sum_{j\in F} f_j.h_{DC}\left[\left[\sum_{i=1}^{N}\left[ms_{i,j}.TMS_i+mr_{i,j}.TMR_i+rp_{i,j}.TRP_i\right]\right]-X_j\right] \quad (22)$$

$$f_j=\begin{cases}0 \;\; if \;\; \sum_{i=1}^{N}\left[ms_{i,j}.TMS+mr_{i,j}.TMR+rp_{i,j}.TRP\right]\le X_j \\ 1 \quad Otherwise\end{cases} \quad \text{For } j\in F \quad (23)$$

Cost of sudden system failure

This cost is introduced to take into account the low probability that the system will fail during production. Once the system crashes, it causes a loss that is equal to C_f.

Therefore, the potential failure cost is calculated by the following expression:

$$\max\left(1-R_{sys,j}(t)\right).C_f \quad j=1,2,\dots,B \;\; ; 0\le t\le \Delta t \quad (24)$$

Because the reliability decreases steadily, the above equation can be written as follows:

$$\max\left(1-R_{sys,j}(\Delta t)\right).C_f \quad j=1,2,\dots,B \quad (25)$$

Also, the average number of component failures is:

$$E[N_{i,j}]=\int_{X_{i,j}}^{X'_{i,j}} \acute{v}_i(t)\,dt \quad (26)$$

Corrective maintenance cost

This cost is due to the corrective maintenance that is performed after a component fails and to return the system to operation. In a series system, the probability of system failure in each period is equal to the probability of failure of at least one of the components in the same period. So, the probability of failure of one of the components is obtained from the following relation:

$$\int_{X_{i,j}}^{X'_{i,j}} \acute{v}_i(t)dt \quad for \;\; i=1,2,\dots,N;\; j=1,2,\dots,B \quad (27)$$

The number of sudden system shutdowns in period j can also be calculated from the following equation:

$$\sum_{i=1}^{N} \int_{X_{i,j}}^{X'_{i,j}} \acute{\upsilon}_i(t) \tag{28}$$

The cost of sudden system shutdown during the planning horizon is obtained from the following equation:

$$(C_b.t_{b,m}) \sum_{j=1}^{B} \sum_{i=1}^{N} \int_{X_{i,j}}^{X'_{i,j}} \acute{\upsilon}_i(t) \tag{29}$$

System reliability

Assuming the system is used for the j period, the reliability of subsystem i during period j can be explained by considering the effect of the cumulative effective age of X_{ij} on the possibility that the system can survive an extra time (t). Using conditional reliability, it is defined as follows:

$$\tilde{R}_{i,j}(t) = R_i(t|X_{i,j}) \quad 0 \le t \le \Delta t \tag{30}$$

In order to calculate the reliability of the series system, first, the reliability of the component i in the period j should be calculated according to the following equation, then it should be generalized to calculate the reliability of the system along the planning horizon.

$$R_{i,j} = e^{-\left[\int_{X_{i,j}}^{X'_{i,j}} \acute{\upsilon}_i(t)\boldsymbol{dt}\right]} \quad for\ \ i = 1,2,\dots,N\ ;\ j = 1,2,\dots,B \tag{31}$$

$$R_{SYS} = \prod_{i=1}^{N} \prod_{j=1}^{B} e^{-\left[\int_{X_{i,j}}^{X'_{i,j}} \acute{\upsilon}_i(t)\boldsymbol{dt}\right]} \tag{32}$$

The reliability of the system in each period is also calculated from following equations:

$$R_{sys,j}(t) = \prod_{i=1}^{N} \tilde{R}\text{i, j(t)} \quad for\ \ 0 \le t \le \Delta t \tag{33}$$

And if the dependence between the components is considered, we should use the failure rate dependent on the failure of other components and we will have:

$$R_{SYS.j} = \prod_{i=1}^{N} e^{-\left[\int_{X_{i,j}}^{X'_{i,j}} \acute{\upsilon}_i(t)\boldsymbol{dt}\right]} \quad j = 1,2,\dots,B \tag{34}$$

To meet the desired reliability, the following relationship must be established:

$$Min\left(\prod_{i=1}^{B} e^{-\left[\int_{X_{i,j}}^{X'_{i,j}} \acute{\upsilon}_i(t)\right]}\right) > R_{req} \tag{35}$$

$j = 1,2, \dots, B$

Objective function

Finally, objective function of minimizing the total cost is presented as follows:

$$
\begin{aligned}
&\text{Min } \mathit{Total\ Cost} \\
&= \sum_{j=1}^{B} h_{FC}\Big(1 - \prod_{i=1}^{N}\big(1 - (ms_{i,j} + mr_{i,j} + r_{i,j})\big)\Big) \\
&\quad + \sum_{\substack{j=1 \\ j \notin F}}^{B} h_{DC} \cdot \left[\sum_{i=1}^{N}\left[ms_{i,j}.TMS_i + mr_{i,j}.TMR_i + rp_{i,j}.TRP_i\right]\right] \\
&\quad + \sum_{j \in F} f_j.h_{DC}\left[\left[\sum_{i=1}^{N}\left[ms_{i,j}.TMS_i + mr_{i,j}.TMR_i + rp_{i,j}.TRP_i\right]\right] - X_j\right] \\
&\quad + \sum\nolimits_{i=1}^{N}\sum\nolimits_{j=1}^{B} MS.ms_{i,j} + MR.mr_{i,j} + R.r_{i,j} \;+ \sum_{j=1}^{B} Max\left(1 - R_{sys,j}(\Delta t)\right) C_f \\
&\quad + (C_b.t_{b,m}) \sum_{j=1}^{B}\sum_{i=1}^{N}\int_{X_{i,j}}^{X'_{i,j}} \acute{v}_i(t)
\end{aligned}
\tag{36}
$$

Solving Solution Approach

The proposed preventive maintenance scheduling problem includes a large number of parameters that have strong and nonlinear interactions with each other. In fact, when the system has a large number of components or the planning horizon is long, the problem becomes very complicated. For problems of real size and with a large number of variables, traditional exact solution methods are not very effective. So, due to the complexity of the equations of the developed model, the exact methods are not effective to solve the model and caused CPU time to increase exponentially by increasing the size of the problem (See Fig. 5 and Table 8) as maintenance scheduling has proven to be an Np-hard hybrid optimization problem in many conditions and systems [13]. So, the model is first solved by solvers in GAMS. Since the runtime of the method is not acceptable which is more than 40000 seconds after 18 periods, the Genetic algorithm as a metaheuristic is coded by C# language to optimize the model.

Experimental design in order to set presented Genetic parameters

In general, all meta-heuristic algorithms use two categories of search strategies; Intensification strategies and diversification strategies. If the predominant strategy of a meta-heuristic algorithm is based on the use of intensification strategies, that algorithm becomes a kind of local search algorithm that is mainly capable of only local improvements from one / more initial responses. Similarly, if the dominant strategy in a meta-heuristic algorithm is to use diversification strategies, then the behavior of that algorithm resembles a purely random search in state space. In this sense, the behavior of the genetic algorithm varies depending on the intersection/mutation rate. Therefore, in order for the genetic algorithm to show the best performance, it is necessary to adjust the values of intersection and mutation rates along with other parameters of the algorithm using experimental design methods. To find the optimal combination of genetic algorithm parameters, first the important and influential factors affecting the algorithm performance, which include population size, number of generations, probability of crossover, probability of mutation and percentage of parental selection, are defined in 5 different levels according to Table 1.

Table 1. Parameter levels for experiments design

Level / Factor	Percentage of Parental Selection	Probability of Mutation	Probability of Crossover	Number of Generations	Population Size
1	20	0.1	0.1	50	100
2	40	0.2	0.3	100	200
3	60	0.4	0.5	200	300
4	80	0.6	0.7	400	400
5	100	1	1	800	500

In this section, the Taguchi method is used, which determines the optimal states of the parameters by designing a comprehensive experiment. Control factors that play an important role in reducing change can be easily identified by the amount of change they make in the response variable. The Taguchi method presents the S / N ratio method by converting duplicate data to another value that represents the magnitude of the changes. The S / N ratio indicates the amount of change by converting the repetition of data to a value. Using the S / N ratio, in which the mean squared is expressed using a logarithmic scale, Dr. Taguchi claims that the results behave more linearly using the S/N ratio. He acknowledges that the linear behavior of the results is a necessary assumption to express the final result under optimal conditions. Using the Taguchi method in MINITAB software, an experiment is designed and according to the different levels of each parameter in each experiment, we run the algorithm ten times and considered average values as the answer used in the software.

The cost and the other values are given in Table 2. According to Taguchi's method, the higher the S/N rate for each parameter the better the parameter. According to this point and by observing Fig 1, the optimal level for each parameter can be determined. For example, the number of generations at level 5 and the percentage of parental choice at level 4 are most desirable. Of course, according to the mean diagram, these results can also be achieved by the fact that due to the minimization of the problem, the lower the mean for a parameter the more desirable. It should be noted that as the number of generations and also the probability of mutation increase, the S/N rate has an upward trend and the algorithm will achieve better answers, but this improvement has a decreasing slope. This means that in the initial stages, increasing the number of generations will have a great impact on the answers of the algorithm, but from level 4, this effect will not be significant and in large cases, this improvement should be put aside in order to keep the execution time of the algorithm in low level. Using the parameters at the optimal levels obtained by the Taguchi method in ten times of algorithm execution, very good answers were obtained which are given in Table 3.

Table 2. Results of Taguchi method experiments

Experiment number	Avarage Cost	CPU time	Standard deviation	Percentage of mean deviation	Lowest cost
1	51743	10	1744	3.37	49565
2	45884	14	757	1.64	44310
3	40659	45	543	1.33	39908
4	39426	70	363	0.92	38897
5	41479	160	675	1.62	40686
6	43597	20	970	2.22	42488
7	47690	48	990	2.07	46484
8	40722	70	395	0.96	39901
9	39537	160	401	1.01	39022
10	39648	280	296	0.74	39056
11	45592	25	513	1.12	44559
12	41163	50	768	1.86	40281
13	39266	97	513	1.30	38748
14	42078	210	734	1.74	40996
15	39340	350	497	1.26	38763
16	48143	65	894	1.85	46899
17	43649	70	742	1.69	42401
18	39583	120	521	1.31	38935
19	39326	230	516	1.31	38763
20	39445	430	599	1.51	38385
21	42730	50	457	1.06	41790
22	40447	85	551	1.36	39632
23	45465	250	968	2.12	44423
24	39924	300	412	1.03	39275
25	39064	550	331	0.84	38737

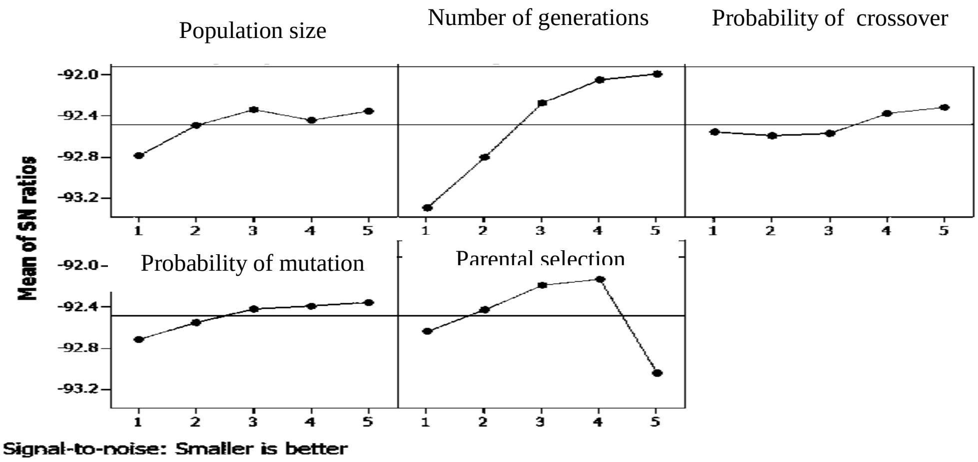

Fig. 1. Main effects plot for SN ratios

Table 3. Algorithm results after parameter setting

CPU Time (Second)	Percentage of Mean Deviation	Worst Solution	Best Solution	Average Solution
330	0.55	38897	38245	38504

Numerical examples

A numerical example for a four-component system is solved and diagrams are plotted. Tables 4, 5 and 6 show the problem parameters. It should be noted, after investigating other related articles [15,26,27] we used data that are logical and also can cover the range of the selected parameters. There are 70, 40, 150, and 30 non-failure stops in period 4, 8, 12, and 16, respectively. Also, improvement factors are equal to 0.5.

Table 4. Numerical example parameters

Parameter	R_{req}	C_f	$t_{b,m}$	C_b	h_{FC}	h_{DC}	B
Value	0.85	5000	100	30	500	0.5	20

Table 5. Parameters for each component of the numerical example

Component Parameter	**1**	**2**	**3**	**4**
MS_i	25	20	30	24
MR_i	100	110	145	100
RP_i	520	700	600	650
TMS_i	25	25	25	25
TMR_i	40	40	40	40
TR_i	70	70	70	70
λ_i	0.0022	0.0035	0.0038	0.0033
β_i	2.2	2.05	2.1	2.2

Table 6. Percentage dependence of components failure rate

Influential component / **Affected component**	1	2	3	4
1	0	50	0	0
2	0	0	0	0
3	0	0	0	0
4	20	0	0	0

The Optimal preventive maintenance schedule can be seen in Table 7 and it is clear that there is a tendency to perform maintenance activities in non-failure stops. When maintenance activity is performed, the effective age of the components is reduced and a declining trend in reliability can be observed, indicating an increasing pattern in the system failure rate. But, the points where maintenance activity has been performed have reduced the effective age of the components and increased the reliability to keep it higher than the required level (see Fig. 2). In the initial stages, due to the newness of the components, without performing any maintenance activities, the desired reliability will be met and there is no need to spend maintenance costs. However, as time progresses and the components become more worn, preventive maintenance and service activities lose their economic efficiency to some extent and the need for replacement is felt. As can be seen, in the 16th period, due to the reduction of the impact of the service activities, three components were replaced at the same time.

Table 7. Optimal preventive maintenance schedule

Component / Period	1	2	3	4
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	MR	MS	RP	MR
5	-	-	-	-
6	-	-	-	-
7	-	-	-	-
8	RP	MR	-	RP
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	-	RP	RP	MR
13	-	-	-	-
14	-	-	-	-
15	-	-	-	-
16	RP	-	RP	RP
17	-	-	-	-
18	-	-	-	-
19	-	-	-	-
20	-	-	-	-

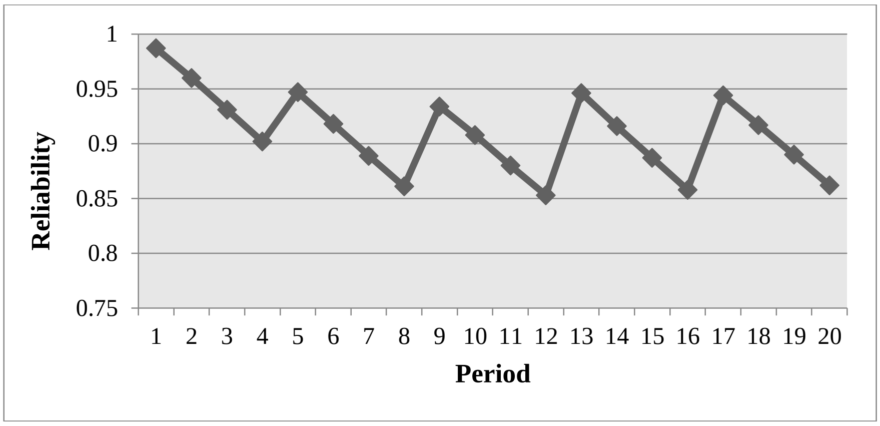

Fig. 2. The effect of maintenance on the system reliability

Comparison of the Exact method and the Genetic algorithm

To analyze the efficiency and accuracy of the metaheuristic algorithm and compare it with the exact method in preventive replacement and maintenance scheduling problems, the model developed in this field has been solved in GAMS software with BARON solver and also with Genetic metaheuristic algorithm in Visual Studio software by #C language. This model has been developed to determine a schedule of activities, including maintenance or replacement for each component of the system over the planning horizon. The goal is to minimize costs subject to reaching the required reliability of the system.

To perform this analysis, a comprehensive experiment has been designed and implemented. The optimization model is solved with three sets of data for a series system with 1, 2 and 3 components during 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 periods. The results of this experiment are shown in Charts 3 to 5. The results include the values of the objective function, the difference of the objective function obtained by the metaheuristic algorithms in comparison with the value obtained by the exact algorithm, the computational time and also the deviation from the mean of the answers of the genetic algorithm. The standard deviation of the algorithm is very small and never exceeds three and a half percent, which indicates the ability of the algorithm and its reliability.

It is obvious that the value of the objective functions obtained by GAMS is always less than the value of the functions obtained by the meta-heuristic algorithm (see Fig. 3). This is because meta-heuristic algorithms can achieve near-optimal solutions and these algorithms do not guarantee the general and accurate optimization of the obtained solutions. In addition, exact methods do not violate the limits, but meta-heuristic algorithms in some cases have a slight violation of the limit. As can be seen from Fig. 4 in the one-component system, the distance of the objective functions of the answers obtained from GA to the exact method varies by about two percent and this distance is often fixed by increasing the size of the problem. It can be concluded that meta-heuristic algorithms work well for large size problems.

The computational time (CPU time) of the algorithms is also examined (see Fig. 5 and Table 8). It can be seen that this time increases exponentially for accurate methods by increasing the size of the problem. It is noteworthy that a logarithmic scale is used in Fig. 5 to make it easier to see ranges. As can be seen, for any size of the problem, the computational time of metaheuristic algorithms in both models is quite constant and is always less than eight minutes, which is very suitable for large size problems. As mentioned earlier, the problem of preventive replacement and the maintenance schedule has been proven to be a matter of Np-hard compound optimization. Therefore, small to medium scale problems can be solved in an acceptable time by an exact method, but it is not possible to solve large size models. Based on the analysis of computational results, large-scale models can be quickly solved by meta-heuristic algorithms and near-optimal solutions can be used to determine the preventive replacement and maintenance program for multicomponent systems.

Table 8. Comparison of solution methods

Number of components	Number of periods	Minimum required reliability	Solution approach	Computational time (Second)
	2		GA	12
			EXACT	1
	8		GA	42
			EXACT	17
	20		GA	164
1		0.95	EXACT	8594
	2		GA	8
			EXACT	0
	8		GA	108
			EXACT	21418
2	20	0.95	GA	245
			EXACT	More than 40000
	2		GA	10
			EXACT	1
	8		GA	124
			EXACT	More than 40000
	20	0.95	GA	
3			EXACT	More than 40000

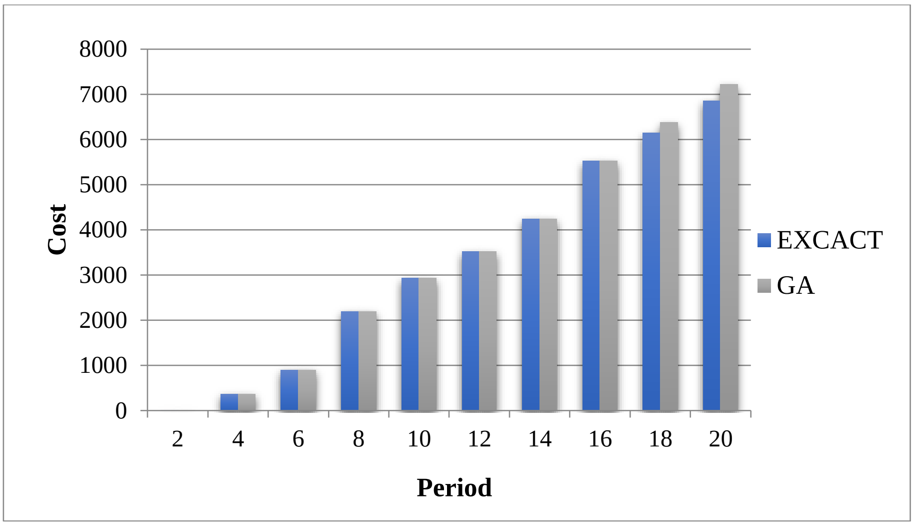

Fig. 3. The total cost of system at the end of each period

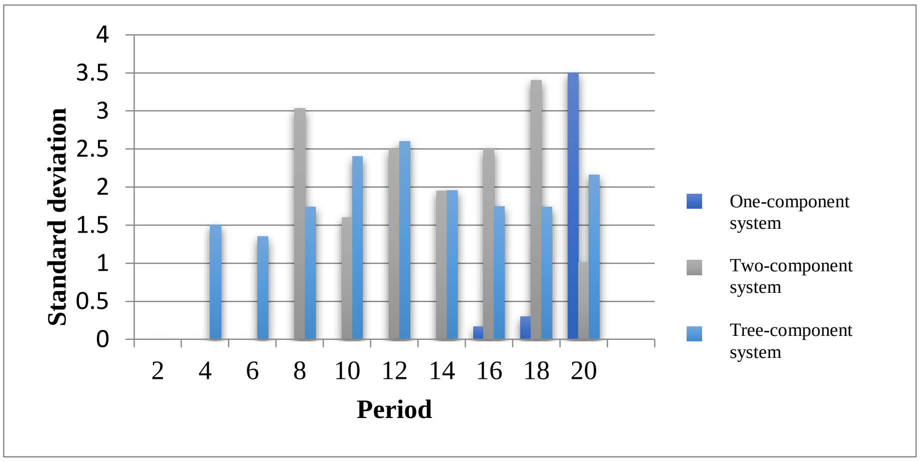

Fig. 4. Standard deviation of the Genetic algoithm solutions

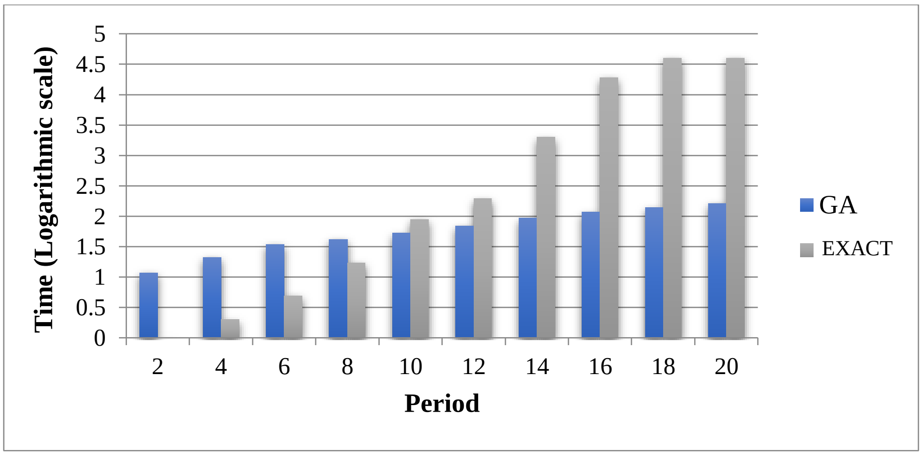

Fig. 5. CPU time

Conclusion

Economic profitability in industries relies on the implementation of a proper maintenance policy to increase reliability and reduce equipment operating costs. In the present paper, modeling and optimization of preventive maintenance programs in manufacturing multi-component systems with repairable dependent components were discussed. Given the increasing rate of failure of each component and the application of the concepts of age reduction and improvement factors, a non-linear mixed integer model aims to minimize system operating costs under the required reliability constraint. Considering non-failure shutdowns provide a good opportunity to perform some maintenance activities during these times and prevent the system from continuing to shut down for maintenance activities. In addition to preventive maintenance and repairs, in case of sudden failure of any component, corrective maintenance and repairs were also considered and also the cost of a complete shutdown of the system to perform maintenance activities were considered depending on the execution time. Due to the complexity of the proposed model, in order to solve the problem in large dimensions, a Genetic meta-heuristic algorithm is adapted. The computational results indicated the efficiency of the algorithm.

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Appendix A. Tables

NOMENCLATURE			
i	Component number	h_{DC}	Variable system shutdown cost for performing maintenance activities per unit time
j	Period number	h_{FC}	Fixed system shutdown cost for performing maintenance activities
MS_i	Cost of performing maintenance service activity on component i	X_j	Duration of Non-failure stop in period j
MR_i	Cost of repairing component i	C_b	System shutdown cost due to implementation of corrective maintenance (CM) in time unit
RP_i	Component i replacement cost	$t_{b,m}$	Average time of performing corrective maintenance for each sudden shutdown
TMS_i	Time required to perform the maintenance service activity on component i	C_f	The cost of sudden failure
TMR_i	Time required to perform repair on component i	R_{req}	Minimum required reliability
TR_i	Time required to replace component i	$ms_{i,j}$	Decision variable, if in the period j a maintenance service activity is done on component i, the value is one, otherwise it is zero.
B	Total number of periods during the planning horizon	$mr_{i,j}$	Decision variable, if in the period j, a repair activity is done on component i the value is one, otherwise it is zero.
K	Number of periods before a non-failure stop occures	$r_{i,j}$	Decision variable, if in the period j component i is replaced by new one, the value is one, otherwise it is zero.
λ_i	Scale parameter of component i	$x_{i,j}$	Effective age of component i in the beginning of period j
β_i	Shape parameter of the component i	$x'_{i,j}$	Effective age of component i at the end of period j
Δt	Duration of the system operating between two periods	$\upsilon_i(t)$	The average failure rate of the component i without effect of other component during time t
$m_{i,1}$	Development factor related to maintenance service activity for component i	$\upsilon'_i(t)$	The failure rate of component i under effect of other components until time t.
$m_{i,2}$	Development factor related to repair activity for component i	$N_l(t)$	The number of failures of the component L from the beginning of the planning horizon until time t.
N	Number of system components	$P_{i,l}$	Amount of increase in percentage of component i failure rate due to any failure occurred in component l