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# ALGORITHMS FOR CORRECTIVE MAINTENANCE MANAGEMENT IN LARGE INDUSTRIAL PLANTS

BY

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**Abstract.** The authors present two algorithms for maintenance management: first one is based on repairing actions following the chronological failures or so called “first come first served” priority and the second one involves a relative repairing priority so that, in a first step, the minimum maintenance team will repair the failed component. Involving many maintenance teams and failed components, the algorithms are suitable for large industrial plants where the maintenance can be optimized in different manners. After a comprehensive presentation of the literature in the field of maintenance optimization algorithms the details are related to mathematical background of two algorithms, the approximation considered to reduce de number of systems’ states as well as to the associated availability indicators which can be calculated incorporating the maintenance management algorithms.

**Keywords:** maintenance types; algorithms; availability indices.

## 1. Introduction

A short IEEE eXplore data base survey of the specific publications during the last 10 years showed the large interest for maintenance aspects not

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only from theoretical point of view but also from that of industry practical applications: 1730 articles presented in international conferences, 382 papers published in scientific journals, 12 books, 12 standards and 11 courses given on the above mentioned subject. Concerning the maintenance optimization algorithms, it can be noted the penetration of artificial intelligence techniques. Different versions of genetic algorithm (GA) are widely used for maintenance optimisation. A virus GA is checked for scheduling optimization of reasonable maintenance work orders (Qi and Zha, 2013). GA's are used to optimize the maintenance tasks and production operations (Ettaye *et al*., 2017), to find the optimal solution holding the shortest total time span of maintenance (Zhaodong *et al*., 2010) or to evaluate total stochastic costs and to optimize the maintenance schedule (Tezuka *et al*., 2015). A single-machine-based optimization model of production scheduling and preventive maintenance under group production is solved by a GA (Liao *et al*., 2016) while a preventive maintenance scheduling method for complex series-parallel system also can be based on a GA (Yan *et al*., 2011) as well to define the planning objectives, constraints, codec in the process of virtual maintenance disassembly (Lin *et al*., 2017) or to manage the maintenance of inshore and offshore wind farms (Fonseca *et al*., 2014). A mixed integer programming model to adjust scheduling strategies considering peak power and maintenance response is based on a dual memetic algorithm that combines GA with two novel heuristic algorithms (Wang *et al*., 2020b). A modified GA is used to calculate the optimal quantities of maintenance channels and operating railway locomotives considering high system availability at minimal costs (Liu *et al*., 2011) or to create an integrated prognostic based scheduling for planning both production and predictive maintenance interventions (Ladj *et al*., 2016). A fuzzy GA was developed to integrate production, maintenance under human resource constraints (Touat *et al*., 2017) and an adaptative GA was effective for solving steelmaking continuous casting, maintenance plan and different accessibility relations between machines (Long *et al*., 2018).

A preventive maintenance period optimization was established using AFS (artificial fish school) algorithm (Li *et al*., 2011), AC (ant colony) algorithm for the case of flexible manufacturing system (Xue *et al*., 2011) and for optimal resources and configuration of equipment maintenance support (Wu *et al*., 2011) or PS (particle swarm) algorithm with a view to schedule the problem of aviation maintenance (Hui *et al*., 2012).

Data mining (DM) techniques are extremely suitable for maintenance decision support due to necessity to collect large volumes of data. Associating two rule mining algorithms – apriori and predictive apriori together with standardized descriptions as input to an association rule mining framework from which failure associations are extracted and validated, DM allowed generating causal maps of failures and, consequently a good maintenance database (Chemweno *et al*., 2016). A DM based algorithm was proposed for enhancement of maintenance management, validated by a study case in the medical equipment domain (Mokfi *et al*., 2011).

Probabilistic approach and statistical calculus, to which this paper is very close, are obviously opportune research techniques for availability analysis of which maintenance and reliability are the two main components. An MCMC (Markov chain – Monte Carlo) based algorithm was established to achieve the lowest maintenance cost per time unit and to calculate the maintenance interval according to different maintenance strategies (Xu *et al*., 2014). An improved opportunistic maintenance policy was developed for system with two kinds of units, subjected to deterioration failure described by Gamma and Poisson functions, to finally generate a coordinated maintenance plan including the long-run associated cost (Cheng *et al*., 2012). For the case of a system with homogenous units that degrade over time according to Weibull distribution, an optimization model of imperfect grouping maintenance construct under the system reliability constraint was developed considering the life cycle cost as the main target (Wang *et al*., 2020a). Holistic approaches are useful for a sustainable asset management of wind turbines by the combined application of reliability methods and in-service information of the plant in the operation and maintenance during its life cycle, using empirical statistics data (Geiss and Guder, 2017). Discrete event and Monte Carlo simulation are used to replicate fault occurrences, minimize the cost of maintenance and provide high availability of the system (Urbani *et al*., 2020). In the case of non-periodic failure rate reduction equipment preventive maintenance, a study on the equipment maintenance time optimization problem for incomplete maintenance in a finite time interval is presented with the aims to optimize the objective function by minimizing total maintenance costs and establishing a dynamic optimization model (Guang-ping *et al*., 2013).

Two strategies for maintenance management are detailed in this paper as well the corresponding most used availability indices: steady state availability (*SSA*) and mean time to failure (*MTTF*).

## 2. Algorithms for Maintenance Management

These algorithms are based on Markov chain method applied to a system having *m* binary repairable elements. Element states are 1 = up and 0 = down. Let's consider *r* corrective maintenance (repair) teams and suppose all failure free ($\varsigma_i$) and repair ($\eta_{ij}$) continuous times are exponentially distributed:

$$p(\varsigma_i < t) = 1 - \exp(1 - \lambda_i \cdot t) \quad (1)$$

$$p(\eta_{ij} < t) = 1 - \exp(1 - \mu_{ij} \cdot t) \quad (2)$$

where $\lambda_i$ is failure rate of the element $i$, $i$ = 1,....., $m$ and $\mu_{ij}$ is the repair rate of the component $i$ by repair team $j$, $j$ = 1, ....., $r$. At the initial moment t= 0, the system is in the normal state: all elements are in state 1. Suppose also that every repair team is designated to repair a given group of elements.

The first algorithm is based on the lack of priority related to failed elements. In the case of a failure, the smallest (numerically) idle repair team will be in charge for action without interruption until the element will operate again. If there is no repair team, the failed element takes the last place in a queue for repair. When a repair is terminated and the repair queue is not empty, the team, if it can, starts to repair the first component in the queue. Otherwise this repair team remains idle.

Fig. 1 illustrates this lack-of- priority (LP) algorithm type.

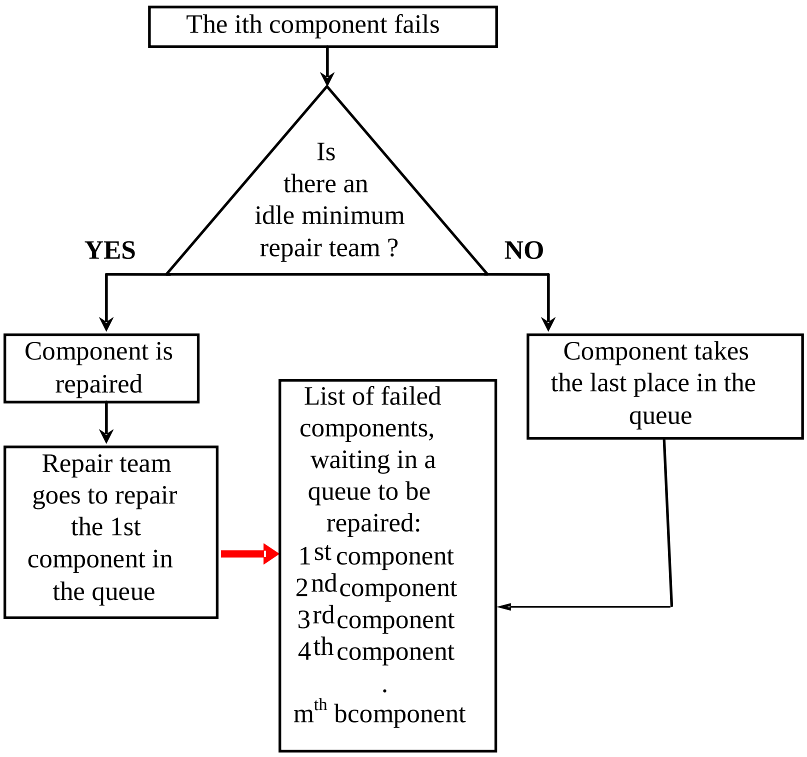


Fig. 1 – The (LP) algorithm for corrective maintenance: the components have the same priority and the repair goes to the end without interruption.

The second algorithm involves a relative priority (RP). Similar to the previous algorithm the failed element is allocated to the smallest idle repair team which can continuously do this job. If there is no idle repair team capable to repair the element, this goes in a queue taking the last place

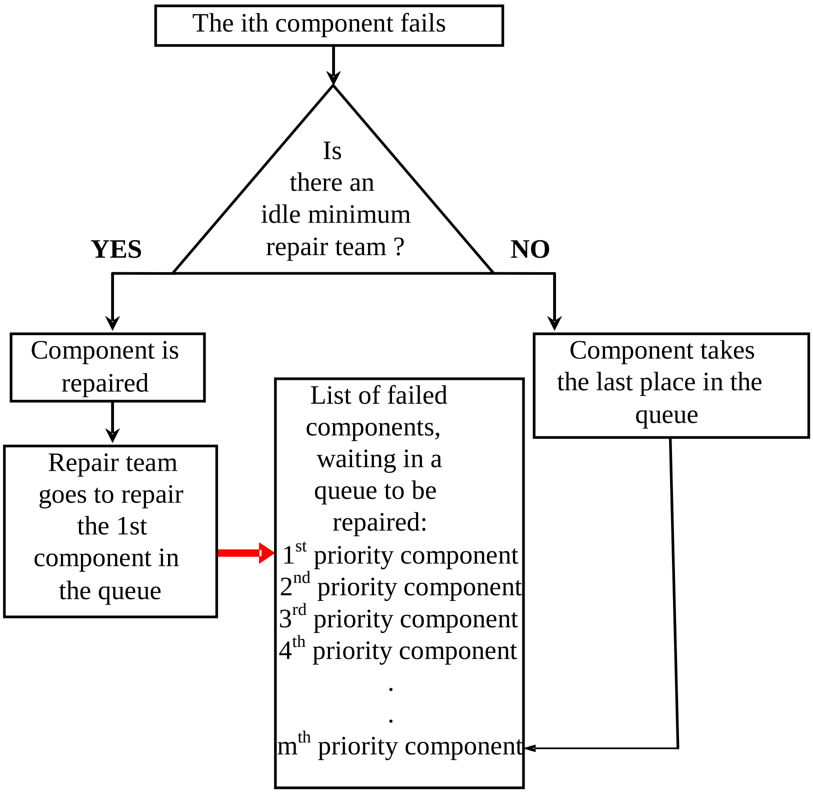


Fig. 2 – The relative priority (RP) algorithm for corrective maintenance: the components are ranked (maintenance priority) and the repair goes to the end without interruption.

For both algorithms, the system structure has to be defined including all operating and failed states:

$$v(t) = \begin{cases} 1 \text{ if the system is operating at the moment } t \\ 0 \text{ if the system failed at the moment } t \end{cases}$$

The following availability indices can be computed:

- *SSA* - steady-state availability:

$$SSA = \lim_{t \to \infty} p[v(t) = 1] \tag{3}$$

- *MTTF* – mean time to failure:

$$MTTF = \int_0^\infty R(t)dt \tag{4}$$

where R(t) is system reliability function.

The description of all system states as well as their time dependent evolution is necessary. This is a difficult task due to enormous number of states even for small systems. A practical procedure is to neglect the states with a very low probability while maintaining the results accuracy. There are two kinds of approximations:

- the series (cut-sets) type: considering a state with 1,2,3, ….. failed elements, we can prohibit elements' failures being working in this state;
- k-out-of-m type: all system states with more than k failed elements are excluded.

## 3. Determination of Availability Indices *SSA* and *MTTF*

To compute the above mentioned availability indices it is necessary to construct the transition intensities matrix $TIM = |a(i,j)|$ and to solve the corresponding system of linear equations using recursive algorithms. A quickly convergence of these algorithms is based on reliability interpretation.

Compared to usual method for TIM construction, here it is necessary to include more system states due to maintenance. Any system state can be uniquely identified by a vector v = ($v_1$, $v_2$, ...., $v_m$) where m is the number of elements and $v_i$ identifies the state of $i^{th}$ element:

$$v_i = \begin{cases} 0 & \text{if element } i \text{ is in operating stare} \\ -j & \text{if element } i \text{ is repaired by team } j \\ k & \text{if element } i \text{ is failed and takes place } k \ (k > 0) \\ & \text{in a queue to be repaired} \end{cases}$$

The current system state is noted as

$$s_n = \begin{cases} 1 & \text{if the system is operating in state } n \\ 0 & \text{if the system is failed in state } n \end{cases} \tag{5}$$

Construction of TIM is very close to the maintenance algorithms adopted, LP or RP and it is not the subject of this paper.

**Calculation of *SSA***

Suppose that TIM, a sparse matrix due to numerous non-existing transitions as well as due to the approximations above mentioned, is fully specified:

$$TIM = \left\| a(i,j) \right\|_{i,j=0}^{N} \tag{6}$$

It is known (Nelson, 1995) that *SSA* can be calculated as

$$SSA = \left( \begin{bmatrix} 1 & 1 & . & . & . & 1 \\ a(1,0) & a(1,1) & . & . & . & a(1,N) \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a(N,0) & a(N,1) & . & . & . & a(N,N) \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 \\ 0 \\ . \\ . \\ . \\ 0 \end{bmatrix} \right)^{T} = \begin{bmatrix} s_0 \\ s_1 \\ . \\ . \\ . \\ s_N \end{bmatrix} \tag{7}$$

where ($s_n$) are defined according to eq. (5). The system can be solved using a recursive Gauss-Seidel method. Let the initial vector be as

$$x_o^{[0]} = 1, \quad x_1^{[0]} = 0, \quad ...., \quad x_N^{[0]} = 0 \tag{8}$$

The subsequent approximations for the steady state probabilities are given by using the following recursive formula, for k = 1,2, ….:

$$x_i^{[k+1]} = \frac{1}{a(i,i)} \left[ b_i - \sum_{j=0}^{i-1} a(i,j) \cdot x_j^{[k+1]} - \sum_{j=i+1}^{N} a(i,j) \cdot x_j^{[k]} \right], \quad i = 0,....., N \tag{9}$$

where $b_0 = 1$, $b_1 = 0$, ....., $b_N = 0$. Note the $k^{th}$ approximation for 1-*SSA* as:

$$1 - SSA(k) = \sum_{i=0}^{N} (1 - s_i) \cdot x_i^{[k]} \tag{10}$$

The inequality (11) is the criterion to stop de recursive algorithm:

$$\frac{\left| SSA(k) - SSA(k-1) \right|}{1 - SSA(k-1)} < \varepsilon \tag{11}$$

It is well known that the Gauss-Seidel method can converge or diverge for any initial state while the converging sufficient condition is the matrix positive definiteness which is impossible to verify. As the examples show, the algorithm (7), (8), can diverge only for unreliable systems which are of no interest in practice. To solve this specific aspect of Gauss-Seidel method there is a technique based on interpretation of reliability. This method includes an algorithm producing a monotone increasing sequence converging in all cases.

The main relation used is:

$$1-SSA=\frac{W}{T} \tag{12}$$

where W is the mean time of a system failed state within a repairing period. A *repairing period* is a time interval when at least one element is failed. T is the mean time between two *regenerating moments*. A moment t is considered a *regeneration point* if some element fails at this moment and all other elements are in operating states.

The same algorithm can be used to compute both W and T.

Denote:

- $x_i$, $i$ = 1 ...., $N$ is the mean time of the system staying in failed states within a repairing period starting with state $i$;
- $x_i^{[k]}$, $k \geq 0$, $I$ = 1, …, $N$ is the mean time of the system staying in failed states within a repairing period starting with state $i$ provided that no more than $k$ failures are produced within this repairing period;
- $y_i$, $I$ = 1, …, $N$ is the mean time of a repairing period starting with state I;
- $y_i^{[k]}$, $k \geq 0$, $I$ = 1, …, $N$ is the mean time of a repairing period starting with state $I$ provided that no more than $k$ failures are produced within this period.

Then, W and T satisfy the following relations:

$$W=\frac{1}{\lambda_0}\sum_{i=1}^{m}\lambda_i\cdot x_i \qquad T=\frac{1}{\lambda_0}+\frac{1}{\lambda_0}\sum_{i=1}^{m}\lambda_i\cdot\mu_i \tag{13}$$

and

$$\lambda_0=\sum_{i=1}^{m}\lambda_i \tag{14}$$

From (12) and (13) it follows that

$$1-SSA=\frac{\sum_{i=1}^{m}\lambda_i\cdot x_i}{1+\sum_{i=1}^{m}\lambda_i\cdot y_i} \tag{15}$$

Remember that a state *i*, $i \in (1,2, ...., m)$ is a state with only one element failed. Iterations $\{x_i^{[k]}, k \geq 0\}$ and $\{y_i^{[k]}, k \geq 0\}$ have two important properties:

- are monotone increasing;
- $x_i^{[k]} \underset{k\to\infty}{\rightarrow} x_i\,,\quad y_i^{[k]} \underset{k\to\infty}{\rightarrow} y_i\,,\quad i = 1,\ldots,N$

These properties make it possible to calculate 1-*SSA* using (15). Iteration $\{x_i^{[k]}, k \geq 0, i = 1, \ldots, N\}$ is evaluated according to the following recursive algorithm:

$$x_i^{[0]} = -\frac{1-s_i}{a(i,i)},\ i = 1,..., m \tag{16}$$

$$x_i^{[0]} = -\frac{1}{a(i,i)}\left[1 - s_i + \sum_{j=1}^{i-1} a(j,i)\cdot x_j^{[0]}\right],\quad i = m+1,.....N \tag{17}$$

$$x_i^{[k]} = -\frac{1}{a(i,i)}\left[1 - s_i + \sum_{j=1+1}^{N} a(j,i)\cdot x_j^{[k-1]}\right],\quad i = 1,...m,\, k \geq 1 \tag{18}$$

$$x_i^{[k]} = -\frac{1}{a(i,i)}\left[1 - s_i + \sum_{j=1}^{N} a(j,i)\cdot x_j^{[k]} + \sum_{j=i+1}^{N} a(j,i)\cdot x_j^{[k-1]}\right] \tag{19}$$
$$i = m+1,...N,\, k \geq 1$$

If

$$B(k) = \sum_{i=1}^{m} \lambda_i \cdot x_i^{[k]}\quad, \tag{20}$$

the condition to stop the iterations on some $k^*$ is

$$k^* = \min\{k : B(k) < B(k-1) + \varepsilon B(k-1)\} \tag{21}$$

Iteration $\{y_i^{[k]}, k \geq 0, I = 1, \ldots, N\}$ satisfy the same recursive relations (16) – (19) with only one difference: all system states must be considered as failed states, *i.e.* $s_i = 0$ for all $I = 1, \ldots., N$.

**Calculation of *MTTF***

Similar to previous case, it is supposed that *TIM*, Eq. (6), is constructed and fully specified. *MTTF*, according to its general definition, is a solution of the following system of linear equations:

$$MTTF = -\begin{bmatrix} a(0,0) & a(0,1) & . & . & . & a(0,N) \\ a(1,0) & a(1,1) & . & . & . & a(1,N) \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a(N,0) & a(N,1) & . & . & . & a(N,N) \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 \\ 1 \\ . \\ . \\ . \\ 1 \end{bmatrix} \quad (22)$$

Both Gauss-Seidel and the recursive algorithm can be used to compute *MTTF* with a given accuracy. Let

$$x_o^{[0]} = 0, \quad x_1^{[0]} = 0, \quad ...., \quad x_N^{[0]} = 0$$

be the initial vector. The subsequent approximations are obtained from the recursive formula, according to Gauss-Seidel algorithm, for $k = 1, 2, ...$:

$$x_i^{[k+1]} = -\frac{1}{a(i,i)}\left[ b_i + \sum_{j=0}^{i-1} a(i,j) \cdot x_j^{[k+1]} - \sum_{j=i+1}^{N} a(i,j) \cdot x_j^{[k]} \right], \quad i = 0,..., N \quad (23)$$

where $b_0$ = -1, $b_1$ = +1, …., $b_N$ = -1. The iteration stop condition is similar to (21) while the zig-zag method (Birkens *et al*., 2019) can be used to accelerate the convergence.

*MTTF* can be approximately calculated using the relation

$$MTTF \approx \frac{T}{q} \quad (24)$$

where q is the system probability failure in a regeneration period and T is the mean time between regeneration points. The algorithm to calculate T was presented in previous section.

The following notations are introduced:

- $q_i$ = 1, *I* = 1, …, *N*, probability of a system failure within a repairing period starting with state *I*;
- $q_i^{[k]}$, $k \geq 0$, *I* = 1, …, *N*, the probability of system failure within a repairing period starting with state *I*, provided that no more than *k* failures are existing within this repairing period.

MTTF can be calculated also using a relation similar to (15):

$$MTTF \approx \frac{1 + \sum_{i=1}^{m} \lambda_i \cdot y_i}{\sum_{i=1}^{m} \lambda_i \cdot q_i} \quad (25)$$

in which ($y_i$) are defined as in the previous section. The iteration $q_i^{[k]}$ has the same proprieties as $y_i^{[k]}$ and it can be calculated according the following recursive algorithm:

$$q_i^{[0]} = 0, I = 1, 2, \ldots, N \tag{26}$$

All $N$ states are operating system's states and for any $k = 1, 2, \ldots.$ :

$$q_i^{[k]} = -\frac{1}{a(i,i)}\left[ f_i + \sum_{j=1}^{i-1} a(i,j)\cdot q_j^{[k]} + \sum_{j=i+1}^{N} a(i,j)\cdot q_j^{[k-1]} \right], \quad i = 1,\ldots, N \tag{27}$$

$$f_i = -\left[ a(i,i) + \sum_{j=1}^{i-1} a(i,j) + \sum_{j=i+1}^{N} a(i,j) \right], \quad i = 1,\ldots, N \tag{28}$$

The condition to stop the iterations is identical to (20) and (21) but where $x_i^{[k]}$ is replaced by $q_i^{[k]}$.

## 4. Conclusions

For large industrial plants or organisations, maintenance management is suitable due to many specialized maintenance teams and a high value of involved asset. The paper present two algorithms for maintenance management based on the maintenance prioritisation, or not, of the elements of any technical system. The system state is defined by a vector including its element states while any element can be in three different situations: operating, repairing or waiting in a queue to be repaired. The usual availability indices like steady-state availability or mean time to failure are also calculated considering a modified Gauss-Seidel technique and a recursive algorithm.

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## ALGORITMI PENTRU MANAGEMENTUL MENTENANȚEI CORECTIVE ÎN COMPANII INDUSTRIALE MARI

(Rezumat)

În lucrare, autorii prezintă doi algoritmi pentru managementul mentenanței: primul este fundamentat pe ordonarea cronologică a acțiunilor de mentenanță corectivă urmărind succesiunea defectărilor pe baza principiului ”primul venit primul servit”; al doilea algoritm include o prioritizare relativă a reparațiilor astfel încât, într-un prim pas, echipa cu un număr minim de membri, intervine pentru a repara componenta, stabilită anterior, drept prioritară. Implicarea mai multor echipe de mentenanță și mai multe componente defecte, fac ca acești algoritmi să fie potriviți pentru a fi utilizați în companiile industriale sau organizațiile mari în care mentenanța poate fi optimizată în diverse moduri. După o trecere în revistă a literaturii de specialitate cu subiecte din domeniul prezentei lucrări, detaliile se referă la suportul matematic al algoritmilor prezentați ca și la modul în care pot fi calculați indicatori asociați, uzuali: disponibilitatea staționară și durata medie de funcționare până la defectare.