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An exact algorithm for preventive maintenance planning of series–parallel systems

Giacomo Galante, Gianfranco Passannanti *

Dipartimento di Tecnologia Meccanica, Produzione e Ingegneria Gestionale, Università di Palermo, 90128 Palermo, Italy

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ABSTRACT

Reliability is a meaningful parameter in assessing the performance of systems such as chemical processing facilities, power plant, aircrafts, ships, etc. In the literature, reliability optimization is widely considered during the system design phase and it is carried out by an opportune selection of both system components and redundancy. On the other hand, the problem of maintaining a required level of reliability by an opportune maintenance policy has been poorly examined. The paper tackles this problem for a system whose major components can be maintained only during a planned system downtime. An exact algorithm is proposed in order to single out the set of components that must be maintained to guarantee a required reliability level up to the next planned stop with the minimum cost. In order to verify the algorithm effectiveness, it has been applied to a complex real case regarding ship maintenance.

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1. Introduction

In the last years, the interest of researchers working on the maintenance field has been focused on preventive maintenance policies for multi-component systems. Cho and Parlar [1] give the following definition about the multi-unit maintenance models: "Multi-component maintenance models are concerned with optimal maintenance policies for a system consisting of several units of machines or many pieces of equipment, which may or may not depend on each other (economically/stochastically/structurally)".

In particular, the economic dependency implies that costs can be saved whenever some components are jointly maintained rather than separately. In fact, if different maintenance actions require a system stop, then a simultaneous intervention of several maintenance crews can significantly reduce the non-operating time. Moreover, the component maintenance often requires a preparatory or set-up work that involves system unavailability costs whenever the system cannot be used during maintenance. Set-up costs can be appropriately saved grouping maintenance actions. Those authors present a wide overview about the multi-unit system maintenance models developed up to 1991 while to date overviews are reported in [2,3].

A classification due to Dekker et al. [2] regards the planning aspect: stationary or dynamic. In stationary models, a long-term stable situation is considered and an infinite planning horizon is usually assumed. This kind of models provides static rules for maintenance, which do not change over the planning horizon. They generate, for example, long-term maintenance frequencies for groups of activities or control limits for carrying out maintenance, depending on the components' state. With regard to the dynamic models, short-term information such as an unexpected component deterioration or downtime opportunities can be taken into account. Such models generate dynamic decisions that may change over the planning horizon.

The present paper proposes a preventive maintenance policy considering a stationary model; therefore, the literature review will just mention such class of models.

Models may differ for the considered objective function, for the eventual constraints and for the resolution technique. Bris et al. [4] develop availability and cost models for systems with periodically inspected and maintained components. For each system component, the research aims to optimize the maintenance policy, minimizing the cost function and respecting the availability constraint. For solving the problem, the authors propose a genetic algorithm, whose structure includes the first inspection time and durations between two maintenance interventions for each component. The availability assessment method is based on a simulation program.

A genetic algorithm approach is also employed by Tsai et al. [5] to individuate the optimal activities combination by maximizing the unit-cost life at each preventive maintenance stage. Actions that can be performed at each stage are preventive maintenance activities that change the system reliability to a newer state, and

* Corresponding author. Tel.: +39 09123861843; fax: +39 0916657039.
E-mail address: gpassa@dtpm.unipa.it (G. Passannanti).

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preventive replacement that restores the reliability curve to a new one. The preventive maintenance scheduling is stopped when the unit-cost life with maintenance is smaller than the discarded life.

Levitin and Lisnianski [6] generalize a preventive maintenance optimization problem to multi-state systems having a range of performance levels. The possible preventive maintenance actions are characterized by their ability to affect the effective component age. A universal generating function technique and a genetic algorithm are used to solve the problem with respect to system performance by the minimum maintenance cost.

In the aforementioned papers, the failure event can also be accepted within a maintenance policy aiming at global cost minimization. If a preventive maintenance is approached, failure can eventually bring to an occasional use of opportunistic policies, but that characterizes non-stationary models. For example, Wildeman et al. [7] deal with the problem of grouping the maintenance activities in order to save set-up costs, since the execution of a group of maintenance activities requires a single set-up. The authors propose a rolling horizon approach that takes the long-term tentative plan as the basis for the next adaptation according to the short-term information, as the component failure. This yields a dynamic grouping policy, which assists the maintenance manager during the planning job.

After all, the most used measure in evaluating the production system performance essentially is its stationary availability, also defined as the expected percentage of time in which the system is working.

Nevertheless, for some continuous operating systems (chemical processing facilities, power plants, aircrafts, ships, etc.) the failure event can be dangerous, too expensive or even disastrous. For these reasons, a high level of reliability is required. Reliability expresses the probability that the system operates without failure for a fixed period of time under some stated conditions. So, for these systems the reliability constitutes another meaningful parameter for performance appraisal.

Cassady et al. [8] tackle the problem of singling out the set of elements on which to operate during a planned downtime between two missions aiming at maximizing system reliability for the next mission. Maintenance activities need to be completed within a stated time and a fixed cost. This decision-making process is referred to as "selective maintenance". The problem is formulated by a mathematical programming model and two numerical examples with 10 and 12 components being, respectively, reported. The cost or time minimization with a reliability constraint is also considered.

An extension of the previous model is proposed by the same authors [9]. The components' failure time is assumed to be a Weibull distribution while the decision-maker can adopt multiple maintenance actions: minimal repair on failed components, failed components' replacement and functioning components' replacement (preventive maintenance). Starting from a simple system, a simulation model is used to calculate the mission reliability.

Rajagopalan and Cassady [10] approach the same problem of reliability maximization for a system constituted by a series arrangement of subsystems, each one containing a set of identical elements arranged in parallel, considering a constraint on maintenance time. All elements have a constant failure rate and therefore maintenance action reduces to the replacement of some failed elements. The decision variable is the number of failed elements to be replaced for each subsystem. The problem is formulated as a nonlinear knapsack problem and four improvements are proposed to speed up the total enumeration approach originally proposed by Rice et al. [11].

The present paper is interested in solving maintenance problems by proposing a new exact algorithm capable of quickly solving big-size problems of different kinds.

It starts from the Kettele [12] algorithm. In order to illustrate how it works and the relative efficiency, the following selective maintenance problem is tackled: given a system whose components can be maintained during a fixed planned period, it is aimed to individuate the set of components to be maintained so as a required reliability level is warranted up to the next stop with the minimum cost.

The paper is organized as follows. The problem is mathematically formulated in the next section. In Section 3 the original Kettele's algorithm for the redundancy optimization of series systems and the new proposal for the series systems maintenance optimization are reported. Subsequently (Section 4), it is shown how the algorithm can be extended to series–parallel systems. Section 5 presents a case study solved by the proposed algorithm and final considerations about its performance. Conclusions and ideas for further developments conclude the paper.

2. Problem formulation

To make the algorithm comprehension easier, it is opportune to previously formulate the problem which the approach has been applied on.

Fig. 1 shows a series–parallel system consisting of components arranged in series that can be constituted by a single element (as h in the figure) or by parallel–series macro-components (as component j).

This system needs to be maintained at a stated instant so that its reliability does not go down an accepted level until the next scheduled maintenance intervention. It is supposed that the maintenance actions also on elements arranged in parallel must be just carried out within the planned system downtime. Each maintenance action makes the element as good as new and it involves a cost and a time for execution. Another cost arises from the system unavailability.

The problem can be mathematically formulated as follows:

min C

with

$$C = \sum_{i \in I} (c_{si} + c_c t_i) + c_u \frac{\sum_{i \in I} t_i}{n} \tag{1}$$

s.t.

$$R_S \geqslant R_S^* \tag{2}$$

where c_{si} is the cost of spare parts of element i, c_c the crew cost for unit time, c_u the cost for unit time of system unavailability, t_i the time to perform maintenance actions on element i, n the number of maintenance crews, I the set of elements on which maintenance actions are performed, R_S^* the minimum accepted value of reliability at the time T_{next} and T_{next} the instant of the next scheduled stop.

The number of crews to be employed is determined from the maximum resource availability or from some constraints

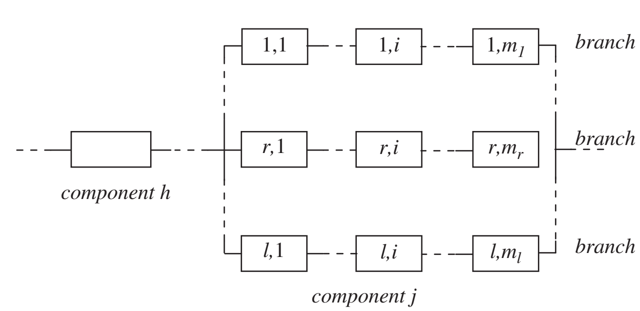

Fig. 1. Series–parallel system.

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