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Evaluating maintenance policies by quantitative modeling and analysis

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ABSTRACT

The growing importance of maintenance in the evolving industrial scenario and the technological advancements of the recent years have yielded the development of modern maintenance strategies such as the condition-based maintenance (CBM) and the predictive maintenance (PrM). In practice, assessing whether these strategies really improve the maintenance performance becomes a fundamental issue. In the present work, this is addressed with reference to an example concerning the stochastic crack growth of a generic mechanical component subject to fatigue degradation. It is shown that modeling and analysis provide information useful for setting a maintenance policy.

1. Introduction

In the last decades, the fast evolution of the industrial scenario has boosted the economic relevance of maintenance in all sectors of industry; the main reasons are:

- The extensive mechanization of industry has reduced the number of production personnel and expanded the capital inventories; this has led to an increment of the portion of the employees working in maintenance and of the maintenance costs; for example, in refineries the maintenance and operations departments are usually the largest [8] and in various sectors maintenance costs constitute a portion of 15% to 70% of the total production costs [5].
- The enhancement of the functionality requirements of the systems, linked to the just-in-time production philosophies (which require high availability of the equipment), to the market demand for products of high quality (which calls for production systems maintained and calibrated so to meet the strict tolerance ranges of the products), etc. [8,9].
- The outsourcing of maintenance, which has required the clear specification of the maintenance activities beyond the day-by-day routine [8,9].
- The increased complexity of the systems and the rising costs of material and labor; i.e., systems are made up of a number of components larger than in the past; these components are more expensive, need to be maintained, and the maintenance actions are also more costly [22].
- The tightening of health and safety legislations in some industries (e.g., air traffic management, aircrafts, nuclear power plants, hospital patient monitoring systems, etc.), which call for maintenance policies capable of guaranteeing that systems fulfill the applicable safety levels during the whole lifetime [7].
- The opening of the energy market, which has forced the producers to be more competitive by reacting promptly and reliably to the demand/offer dynamics, while avoiding the penalties related to the occurrence of service black-out also through more efficient and effective maintenance [34].

Interest in maintenance can be expected to continue increasing in the next future, as the industrial scenario continues to evolve. An example is the development of non-fossil-fuel energy production plants (nuclear, solar, wind, etc.), which is receiving worldwide attention in the last decades (e.g., [1]): maintenance represents a major portion of the total production cost of such technologies, and its optimization can play a role for their competitiveness with respect to fossil-fuel energy production plants.

Given the dimension, complexity and economic relevance of the problem, maintenance must be supported by modeling. In this respect, a huge amount of approaches to maintenance modeling, optimization and management have been propounded in the

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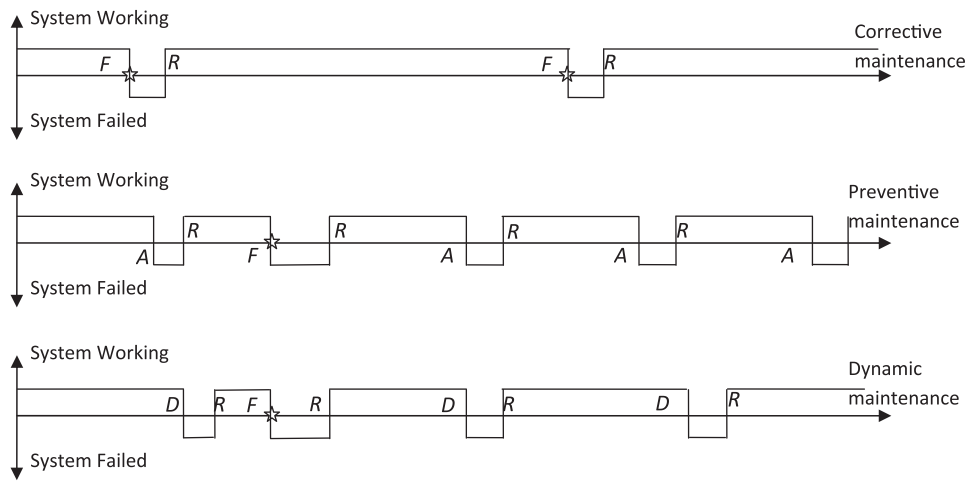

Fig. 1. Synoptic of the maintenance policies.

literature to cope with the maintenance problem, in the evolving technological context. Usually these approaches are divided into two main groups: corrective maintenance (CM) and scheduled maintenance.

Under the CM strategy, the components are operated until failure (events F in Fig. 1, top); then, repair or renovation actions are performed (events R in Fig. 1, top). This is the oldest approach to maintenance and is nowadays still adopted in some industries, especially for equipment which is neither safety-critical nor crucial for the production performance of the plant, and whose spare parts are easily available and not expensive (Zio & Compare 2012[37]).

Scheduled maintenance policies can be further divided into three groups: Preventive Maintenance (PM), condition-based maintenance (CBM) and predictive maintenance (PrM).

Preventive maintenance (PM) encompasses all actions performed in an attempt to retain an item in specified conditions by providing systematic inspection, detection and prevention of incipient failures [18].

The first scientific approaches to PM date back to the 1960's ([17,4]). Since then, a huge number of PM models and optimization methods have been introduced with the aim of reducing failures, for safety reasons, and unplanned downtime, for economic reasons (see [26] for a survey). For example, the so-called 'age-replacement' models (a very well-known class of PM models, see for example [38]) consider that a component is preventively maintained at some predetermined age A or repaired at failure, whichever comes first (Fig. 1, middle).

In recent years, the relative affordability of on-line monitoring technology has led to a growing interest in new maintenance paradigms such as the CBM and PrM (e.g., [27–31]). These are founded on the possibility of monitoring the system to obtain information on its conditions, which is then used to both identify problems at an early stage and predict their evolution in the future. On this basis, a decision is taken on the next maintenance action. This allows a dynamic approach to maintenance based on failure anticipation, aimed at optimizing the equipment lifetime usage. Fig. 1, bottom shows that in case of CBM and PrM the maintenance actions are performed upon either the dynamic event D or failure, where D represents the achievement of the safety threshold in case of CBM or the prognosticated failure time in case of PrM.

Any company interested in pursuing such maintenance strategies must consider the risks related to the lack of experience and the capital expenditures needed to purchase the necessary instrumentation and software. This requires an evaluation of the opportunity of adopting such advanced maintenance policies founded on specialized knowledge and modern technology. In this sense, evaluating under which conditions and to which extent the CBM and PrM settings can improve the plant performance becomes a fundamental issue. Such evaluation must be made in comparison to the performance of the 'traditional' CM and PM policies.

In the present work, this evaluation analysis is carried out by way of a reference example concerning the stochastic crack growth of a mechanical component subject to fatigue degradation. Different maintenance approaches are applied to show decision makers a way to go for gaining full understanding of the characteristics of the different maintenance policies, and of their benefits.

The remainder of the paper is organized as follows: Section 2 introduces the reference example; the performance of the CM policy is assessed in Section 3, and is compared to that of the PM policy in Section 4. Sections 5 and 6 apply the CBM and PrM policies, respectively, to the considered component and compare the resulting performances with those of the PM and CM schemes. In particular, the prognostic method which the PrM approach relies on is the Particle Filtering (PF) technique (e.g., [2]). A general discussion is proposed in Section 7, whereas Section 8 concludes the work.

2. Reference example

In this Section, the example concerning the fatigue degradation process of a mechanical component is presented. It constitutes the workbench for the comparison of the different maintenance policies, aimed at identifying the conditions under which one is to be preferred over another.

The reference mission time T does not end with the failure of the component; it is set to $T=10{,}000$ h. As it will be explained below, this entails that the performances of the maintenance strategies are assessed with regards to the transient period, rather than to the steady state.

The crack growth mechanism due to fatigue is a complex physical phenomenon, which has been widely investigated in the literature in several contexts (for example, see [15,24] for surveys). It initiates from micro defects such as the foundry flaws, subject to oscillating loads that locally strain the component. This leads to the creation of small cracks. Once initiated, the degradation process can propagate under stressful operating conditions, and the depth of the crack can grow up to limits threatening the