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Orchestration of preventive maintenance interventions

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Abstract: **The paper has the objective of planning the preventive maintenance of a system subject to different failure modes. The preventive maintenance is planned by means of the maximization of the system reliability. The reliability of a system depends on many factors. One of these is the arrangement of the maintenance interventions in a specified time horizon and this is an aspect that has received low attention by literature. A reliability-centered maintenance optimization model is developed in the paper and the optimization can be tackled by means of two methods, according to the fact that the concept of joint replacement is introduced or not.**

Keywords: reliability; failure mode; preventive maintenance; maintenance scheduling

1. INTRODUCTION

The quantification of the performance of a system is of primary importance. The three main performance measures to characterize an equipment from the maintenance perspective are the so-called RAM parameters: Reliability, Availability and Maintainability (Nakagawa, 2005; Furlanetto and Garetti, 2006). The quantification of how long an equipment can operate without failure is made by means of the reliability, which is defined as the probability that the equipment will perform a required function under stated conditions for a stated period of time (Macchi et al. 2012a). When equipment is replaced upon failure or are preventively maintained, the focus is on the ratio at which equipment can operate, i.e. availability (Macchi et al. 2012b). Another important aspect is the ease and rapidity with which a system or equipment can be restored to operational status following a failure, i.e. maintainability. The three performance measures are closely related: if a system is very reliable, it is generally also highly available, while a system that is available may or may not be reliable, depending on maintainability. In fact, it is possible to achieve high availability also considering components that are not very reliable. In a system composed of many low reliable components, if the components are replaced quickly, the overall system can achieve a high availability. So the three parameters together are necessary to give a complete overview of the system performance, in order to deploy a competitive maintenance business model (Holgado et al. 2015).

It is important to keep reliability at high level when failure cost is high (e.g. spare parts replacement cost, damages cost, etc.) and when failures have dramatic consequences, where safety is of primary importance (e.g. in the case of airplanes, nuclear and chemical plants); on the other hand, availability is important when hidden costs are high (loss of production, service unavailability, etc.) (Furlanetto and Garetti 2006). In the former, maintenance costs have to be minimized while keeping the risks within strict limits and meeting satisfactory requirement.

The system reliability R_{sys} depends on many factors, the main ones are discussed hereafter.

R_{sys} depends on the reliabilities of the various equipment that suffer possible failure modes. It is thus possible to logically link the reliability to the single failure mode: R_i. The reliability of a generic failure mode i depends on the parameters used to describe its failure behaviour. If the failure behaviour is described by the Weibull distribution, three parameters have to be considered: the typical life α, the shape factor β and the time scale factor γ (Macchi et al. 2012a).

The system reliability depends on the number of interventions that are possible in the planning horizon. The planning horizon is the time window in which the maintenance must be planned. Generally speaking, the reliability of the system can be kept at high level with an elevated number of maintenance interventions.

The human factor influences the system reliability. Sometimes, the operators do not perform the maintenance intervention perfectly and, as a consequence, a partial (or even null) improvement of the reliability follows. The human factor is strictly related to the concept of imperfect maintenance, which can be applied to either preventive and corrective maintenance policies. The preventive maintenance interventions (PMs) can be categorized into three types: inspection only (the component is restored to its operating condition without any improvement on its reliability), low-level repair (it improves the state of the component in terms of reliability, but does not make it as-good-as-new) and high-level repair (it restores the system to an as-good-as-new condition) (Jardine, 2005; Doostparast et al., 2014). On the other hand, two types of corrective maintenance interventions (CMs) can be typically performed: minimal repair (the component is maintained in an as-bad-as-old state) and corrective replacement (the component is restored to an as-good-as-new condition) (Lie & Chun 1986; Tsai et al. 2001).

A last factor that influences the system reliability is the arrangement of the maintenance interventions in the planning horizon, i.e. the disposition of the interventions in the time window under consideration. Keeping the same number of interventions in the planning horizon, a proper disposition of the interventions can lead to higher system reliability: the disposition that maximize the reliability can be found. The

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search of the best disposition of the interventions to maximize the reliability is herein defined as *orchestration*. This concept is not much treated in literature. This paper wants to contribute on the research about the impact of this novel factor on the system reliability.

The work focuses on a generic system and its failure modes that are assumed to be maintainable, independent and in a series-wise configuration (Fedele and Furlanetto, 2004). A failure mode is maintainable if the reliability can be improved by means of a maintenance action (Zequeira & Be 2006; Castro 2009; Lin et al. 2000). Two failure modes are independent if an intervention to face the first failure mode does not affect the other failure mode and vice versa (Zequeira & Be 2006).

In Section 2, an overview on the maintenance optimization models is given. A new maintenance reliability-based optimization model is presented in Section 3. The optimization can be developed by means of two different methods, according to the fact that the concept of joint replacement is introduced or not. Eventually, Section 4 provides conclusions on the proposed methods.

2. OVERVIEW ON MAINTENANCE OPTIMIZATION MODELS

A maintenance optimization model is a mathematical model in which both costs and benefits of maintenance are quantified and in which an optimum balance between both is obtained, while taking all kinds of constraints into account (Dekker 1996; Vasili et al. 2011). Many optimization models to plan maintenance are presented in literature but they are often very complicated, i.e. it is difficult to apply them in real industrial environments. On the other hand, there are methods (such as the Reliability Centered Maintenance - RCM) that are often too qualitative and, therefore, cannot be used as mathematical bases for quantitative optimization model (Zio 2009; Vatn et al. 1996; Lopez Campos et al. 2010). A need emerges: having a practical and user-friendly tool to plan the maintenance with, at the same time, a mathematical background to quantify numerically the performance and the effectiveness of the system under study.

According to the above mentioned literature background, the authors propose a classification between the methods used to plan the maintenance according to their objectives:

- *Cost-based approach*: the objective function is the minimization of the maintenance costs.
- *Availability-based approach*: the objective function is the minimization of downtimes (maximization of availability) or the minimization of maintenance costs while respecting constraints regarding the system availability.
- *Reliability-based approach*: the objective function is the maximization of the reliability of the system or the minimization of maintenance costs while respecting constraints regarding the system reliability.

An item is subject to sudden failure, and when failure occurs, the item has to be replaced. In order to reduce the number of failures, preventive replacements can be scheduled to occur at specified intervals. However, a balance is required between the amount of resources spent on the preventive replacements and their resulting benefits, that is, reduced failure replacements. The main objective of the cost-based approach to PM planning is to determine the optimum maintenance interval that will balance the system failure repair costs and the PM costs (Jardine, 2005; Lie & Chun 1986; Jayabalan 1992). In some cases, the required replacement policy may be the one that minimizes total downtime per unit time or, equivalently, maximizes availability. Then, the problem is to determine the best times at which replacements should occur to minimize total downtime per unit time. The basic conflicts are that, as the preventive replacement frequency increases, there is an increase in downtime due to these replacements, but a consequence of this is a reduction of downtime due to failure replacements, and the best balance between them should be reached (Jardine 2005; Cassady and Kutanoglu 2003; Ruiz et al. 2007; Pham and Wang 2000).

In the present work, a particular attention to the reliability-based approach has been paid since the reliability is the performance measure that has been taken into account. The model presented in Section 3 is a maintenance optimization model where the objective function is the maximization of the system reliability and the orchestration of the interventions is also taken into account. In literature, few authors focus their attention to the reliability as a performance indicator; they prefer optimizing the maintenance plan with respect to the system availability or to maintenance costs. In general, the reliability is only taken into account as a constraint of the optimization model.

Next to the decision regarding when is more convenient (under the cost point of view or under the reliability point of view) to perform a PM, if the concept of imperfect maintenance is introduced in the optimization model, the additional decision regarding what type of PM to perform has to be taken (Lie and Chun 1986; Jayabalan 1992).

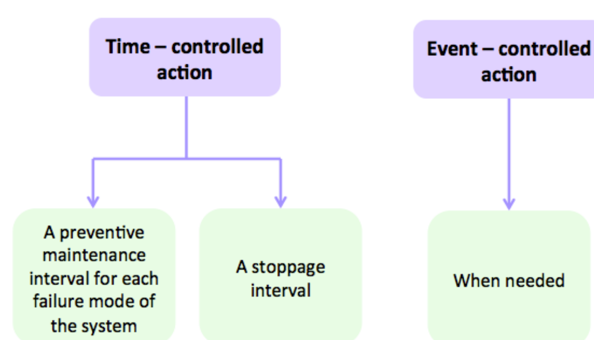

Figure 1: different types of maintenance actions

Maintenance interventions can be performed when needed (event-controlled actions) or at regular intervals (time-controlled action) (Lie and Chun 1986; Kong et al. 2003). In particular, in the latter case, two sub-cases can be adopted. For each failure mode *i* of the system, the preventive maintenance interval T_{pi} that allows the fulfilment of an objective function can be found (maximization of reliability, minimization of maintenance costs, etc.) or a stoppage interval T_p can be found and, whenever a system stop occurs, the decision about on which failure mode to act is taken. Performing more than one intervention when there is a system stoppage can lead to cost