Reliability Engineering and System Safety 133 (2015) 22–32

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A proactive condition-based maintenance strategy with both perfect and imperfect maintenance actions

Phuc Do*, Alexandre Voisin, Eric Levrat, Benoit Iung

Lorraine University, CRAN, CNRS UMR 7039, Campus Sciences BP 70239, 54506 Vandoeuvre, France

A R T I C L E I N F O

Article history:
Received 7 January 2013
Received in revised form
19 June 2013
Accepted 25 August 2014
Available online 6 September 2014

Keywords:
Imperfect maintenance
Condition-based maintenance
Remaining useful life
Stochastic process
Optimization

A B S T R A C T

This paper deals with a proactive condition-based maintenance (CBM) considering both perfect and imperfect maintenance actions for a deteriorating system. Perfect maintenance actions restore completely the system to the 'as good as new' state. Their related cost are however often high. The first objective of the paper is to investigate the impacts of imperfect maintenance actions. In fact, both positive and negative impacts are considered. Positive impact means that the imperfect maintenance cost is usually low. Negative impact implies that (i) the imperfect maintenance restores a system to a state between good-as-new and bad-as-old and (ii) each imperfect preventive action may accelerate the speed of the system's deterioration process. The second objective of the paper is to propose an adaptive maintenance policy which can help to select optimally maintenance actions (perfect or imperfect actions), if needed, at each inspection time. Moreover, the time interval between two successive inspection points is determined according to a remaining useful life (RUL) based-inspection policy. To illustrate the use of the proposed maintenance policy, a numerical example finally is introduced.

1. Introduction

Maintenance involves preventive and corrective actions carried out to retain a system in or restore it to an operating condition. Optimal maintenance policies aim to provide optimum system reliability/availability and safety performance at lowest possible maintenance costs [23]. In the literature, perfect maintenance actions (or replacement actions) which can restore the system operating condition to as good as new have been considered in various maintenance models. The implementation of "perfect" maintenance policies seems quite simple, however, perfect maintenance actions are often expensive. Imperfect maintenance implying that the system condition after maintenance is somewhere between the condition before maintenance and as good as new has grown recently as a popular issue to researchers as well as industrial applications, see for example [2,12,14,15,17,20]. From a practical point of view, imperfect maintenance can describe a large kinds of realistic maintenance actions [23]. In the imperfect maintenance approach, imperfection can be considered arising from two main causes:

- the "bad" realization of a perfect maintenance action due to, for instance, human factors (e.g. stress, lack of skills, lack of attention …), lack of spare parts, lack of repair time …
- the maintenance policy of decreasing costs such as contractualization which may lead to deal with "lowcost" people, spare parts, logistics …implying for instance.

While the first cause does not provide any benefit, the second one may lead to cost benefits. It may however conduct short and long-term deterioration of the maintained system because imperfect maintenance does not make the system return to as good as new state. While short deterioration may be low enough for the system, their accumulations induce long-term deterioration that could be technically or/and economically no-more acceptable. To cope with such a situation, one can image to make a perfect maintenance action at this stage making the system as good as new state, then to take over with imperfect maintenance. In this paper we propose to optimize such maintenance policy mixing perfect and imperfect maintenance actions.

Various methods and optimal policies for imperfect maintenance are summarized and discussed in [23,29]. In such maintenance models, preventive maintenance decision is however based on the system age and on the knowledge of the statistical information on the system lifetime. As a consequence, the realistic operating conditions of the system over time are not be taken into account. To face this issue, condition-based maintenance (CBM), for which preventive maintenance decision is based on the observed system condition, has been introduced. Thanks to the rapid development of monitoring equipment which provides accurate information about the system condition over time, CBM

* Corresponding author.
E-mail address: van-phuc.do@univ-lorraine.fr (P. Do).

http://dx.doi.org/10.1016/j.ress.2014.08.011
0951-8320/

Nomenclature

C_i	inspection cost
C_p	perfect (replacement) preventive maintenance cost
C_p^k	cost of the kth imperfect maintenance action
C_c	corrective (replacement) maintenance cost
C_d	unavailability cost rate of the system
$d(t)$	total time passed in failed state in $[0, t]$
$C^t(.)$	the cumulative maintenance cost in $[0, t]$
$C(.)$	long-run expected maintenance cost per unit of time
L	failure threshold
K	imperfect maintenance threshold
M	preventive maintenance threshold
$m(.)$	time interval between two successive inspection points
$N_i(t)$	number of inspection in $[0, t]$
$N_p(t)$	number of perfect preventive maintenance in $[0, t]$
$N_{ip}(t)$	number of imperfect preventive maintenance in $[0, t]$
$N_c(t)$	number of corrective maintenance in $[0, t]$
Q	failure probability between two inspection times
T_i	ith inspection time
X_t	system deterioration level at time t
Z^k	kth intervention gain
$u(.)$	degradation improvement factor
v_k	mean deterioration speed after the kth maintenance action
α_0, β	scale and shape parameters of the deterioration process when the system is as good as new
α_k	scale parameter of deterioration process after the kth imperfect maintenance action
η	a non-negative real number
γ	non-negative real number and represents the impact of imperfect maintenance actions on the deterioration speed of the system

becomes nowadays more and more popular approach in industrial application. Various CBM policies have been proposed and applied for many industrial systems, see for example [9,10,21,27,28]. Starting from the CBM policy, new trend of maintenance strategy has lead to anticipate the failure. Hence, the degradation monitoring is followed by a prognostic step. Among such strategies, one finds CBM+, PHM (Prognostics and Health Management), proactive maintenance. The use of prognostic is dedicated to the forecast of the remaining useful life (RUL) before the failure occurs. Moreover, it is usually performed during the use of the material/system in order to adapt the maintenance policy. Indeed, the prognostic algorithms are fed with monitored data in order to predict the RUL in the current condition. In the prognostic review [11,26], one can classify the prognostic approaches into 3 groups:

- model based: in this class the prognostic approaches are based on a model representing the physics of the degradation process built with specific experiments;
- data based: this class includes approaches using monitored data in order to construct the model;
- statistics/experience based: this class corresponds to reliability or stochastic models based on feedback data (i.e. mainly failure data).

While the first two approaches require monitored data and are used on-line, the last one may be used off-line. In such a way, using feedback data one can use experience based prognostic model in order to optimize a priori maintenance policy. In the proposed CBM maintenance policy, RUL prognosis is used in order to plan the next inspection time at which maintenance decision will be taken.

It has been recently shown in [18,22,24] that combining CBM and imperfect maintenance is well suited. Indeed, according to the observed condition of the system, an optimal maintenance action represented by an optimal intervention gain is preventively carried out. However, in such maintenance policies, only imperfect preventive or imperfect repair actions are considered and the system is assumed to be imperfectly maintained an infinite number of times. From a practical point of view, this assumption may not always be relevant since, in a variety of engineering and service applications, systems can be maintained only a limited number of times due to technical or economical reasons [13]. Furthermore, as mentioned in [22], each imperfect maintenance action may make the system more susceptible to future deterioration. To this end, a fixed number of allowable imperfect maintenance actions is introduced in maintenance models in [13,5] and considered as a decision parameter. However, the value of this decision parameter is arbitrary chosen and they do not describe how the imperfect repair actions affect the deterioration evolution of the system. As a consequence, two important issues arise. The first one concerns the investigation on the impacts of imperfect maintenance actions to the deterioration of the system. The second issue relies on how to determine the optimal number of imperfect maintenance actions for each life cycle of the system.

To overcome these issues, the aim of this paper is to propose a proactive condition-based maintenance policy with both perfect and imperfect maintenance actions for a deteriorating system. The first original contribution of the paper concerns the investigations of imperfect maintenance actions. Both positive and negative impacts are considered. Positive impact means that it can reduce the deterioration level of the system with reduced maintenance cost. Negative impact implies that (i) the deterioration level of the system after imperfect maintenance may not be reset to zero and (ii) each imperfect preventive action may accelerate the speed of the system's deterioration process. The second original contribution of the paper is to propose an adaptive maintenance policy. Different maintenance rules which can help to select optimally maintenance actions at each inspection time are proposed. Based on the proposed maintenance policy, the optimal number of imperfect maintenance action for each cycle of the system is determined. Moreover, in CBM practice, inspections are usually performed at regular intervals. However, it may not be always profitable to inspect the system at regular intervals of time, especially when the inspection procedure is costly. The present paper proposes to use an aperiodic inspection policy which is based on the prognosis of the residual useful life (RUL) of the system, see [3,8,30].

The rest of the paper is organized as follows. Section 2 is devoted to the descriptions of the characteristics of the system to be maintained and the related assumptions. Deterioration modeling is also described. Section 3 focuses on the investigations of the impacts of imperfect maintenance actions. Their related cost model are also described and discussed. An adaptive maintenance policy is described in Section 4. To illustrate the proposed maintenance policy, some numerical values of the considered system and its related context are introduced in Section 5. Some numerical results are in addition discussed here. Finally, the last section presents the conclusions drawn from this work.