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Condition-based maintenance under an imperfect repair policy for a deteriorating production system

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Abstract. This paper presents a condition-based maintenance policy taking into account both maintenance cost and production capacity aspects for single unit deteriorating production system whose condition is periodically monitored. Imperfect preventive maintenance activities, which restore the production system to better states and might not be as good as new, are considered. We assume however that the system can be repaired only a limited number of times. In order to assess the performance of the proposed maintenance policy, both linear and non-linear imperfect preventive maintenance cost functions are investigated. A numerical example of a multi state production system is finally introduced to illustrate the performance of the proposed policy.

1. Introduction

Health monitoring equipments providing information about the system condition have evolved rapidly over the past decade. They are useful tools in maintenance decision-making framework. Based on the monitoring information, different condition-based or predictive maintenance policies which lead to avoid failure occurrence at the lowest cost can be performed, see for example Cui (2004), Iung(2008), Van Noortwijk(2009), Dovan and Berenguer(2010). In such maintenance policies, perfect preventive maintenance (or preventive replacement) is usually used. After each preventive maintenance action, the system is completely restored and considered as good as new. However, the replacement or perfect repair is often expensive. Recently, an imperfect condition-based maintenance policy has been introduced in Ponchet(2009) for a single unit deteriorating system on a finite time span. In this maintenance policy, preventive maintenance cost is limited as a linear function of the improvement level.

In many preventive maintenance policies, the decision parameters (preventive threshold, inspection schedule,...) are reached based on only the maintenance cost per unit of time criterion without taking into consideration of the production capacity which may depend on the system condition, e.g. the degradation level, see Iung(2008). Recently both maintenance cost rate and productivity have been considered in Dovan and Berenguer (2010). However, in this paper is limited on the preventive/corrective replacement policy.

The objective of this paper is to propose a condition-based maintenance policy for deteriorating production systems in which its condition (degradation behavior) is assumed to evolve like a Gamma stochastic process. The proposed maintenance policy considers imperfect preventive maintenance actions in which the restoration level depends on the current degradation level of the system at inspected time and the system's degradation level after maintenance to be optimized. From a practical point of view, the system may not be repaired an infinite number of times, see for example Kurt and Kharoufeh (2010). In this paper, we assume that the system can be repaired only a limited number of times. In order to assess the performance of the proposed imperfect maintenance policy, both linear and non-linear preventive maintenance cost functions are investigated.

This paper is organized as follows. Section 2 is devoted to the description of the system characteristics and assumptions. Section 3 focuses on the maintenance model in which the proposed imperfect maintenance policy and imperfect preventive maintenance cost are presented. The optimisation of proposed maintenance policy is considered in Section 4. To illustrate the proposed maintenance policy, a simple numerical example is introduced in Section 5. Some numerical results are in addition discussed here. Finally, the last section presents the conclusions drawn from this work.

2. Model description and assumptions

For multi-state production systems such as manufacturing production lines and power generation installations, the performances output of interest is not only the availability but also the production capacity which can settle on different levels (e.g. 100%, 90%, 80% of the nominal capacity) depending on the system conditions, see for example Kawauchi and Rausand (2002), Iung(2008), Kawa(2002), Dovan and Berenger (2010).

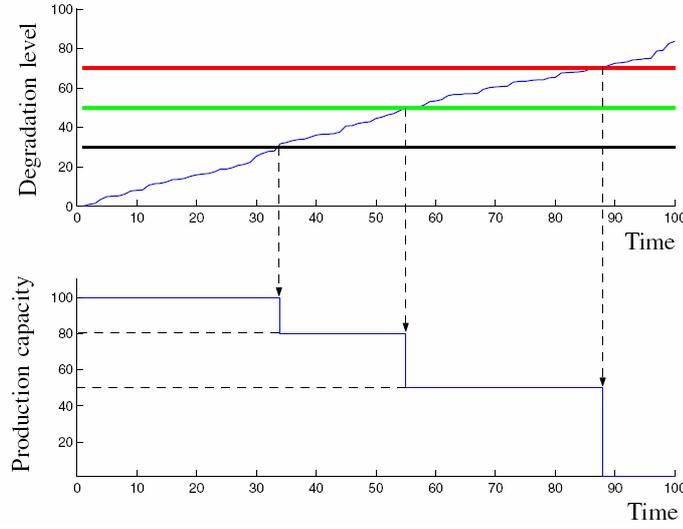


Figure 1. Illustration of degradation level and corresponding production capacities

2.1 General assumptions

We consider a single unit system in which its condition at time t can be summarized by a random ageing variable X_t . In the absence of repair or replacement actions, X_t is an increasing process. The ageing variable X_t can be e.g. the measure of a physical parameter linked to the resistance of a structure (height of a dike, length of a crack). Moreover, we suppose that the following assumptions are verified.

- the initial state X_0 is 0, the system is new;
- the system is in failed if the ageing variable is greater than a level L . The threshold L can be seen as a deterioration level which must not be exceeded for economical or security reasons;
- in the allowed operation interval (i.e. from 0 to L), N different operation modes are considered. A unique production (or treatment) capacity S_i corresponds to each operation mode (or state) i according to the degradation level of the system. More precisely:
- $X_t < L_1$: system is in nominal state denoted state 1 in which the system is functioning with nominal production capacity S_1 ;
- $L_1 \leq X_t < L_2$: system is in operational state (state 2) in which the production capacity is $S_2 < S_1$;
-
- $L_{N-1} \leq X_t < L_N = L$: system is still functioning but badly (state N), production capacity for this case is $S_N < S_{N-1}$.

The system degradation behavior and corresponding states are illustrated in Fig. 1.

2.2 Deterioration modelling

Gamma processes have been widely used to describe the degradation of systems in structural engineering Van Noortwijk (2009). Herein, the deterioration between two maintenance operations is assumed to evolve like a Gamma stochastic process $(\tilde{X}_t)_{t \geq 0}$, with the following characteristics:

- $\tilde{X}_0 = 0$ and $(\tilde{X}_t)_{t \geq 0}$ has independent increments;
- for all $0 \leq l < t$, the random increment $\tilde{X}_t - \tilde{X}_l$ follows a Gamma probability density with shape parameter $\alpha \cdot (t-l)$, α is a positive real number, and scale parameter β :

$$f_{\beta, \alpha(t-l)}(x) = \frac{1}{\Gamma(\alpha(t-l))} \beta^{\alpha(t-l)} x^{\alpha(t-l)-1} e^{-\beta x} \mathcal{I}_{\{x \geq 0\}}$$

The mean deterioration speed and its variance are $\alpha.\beta$ and $\alpha.\beta^2$ respectively. The choice of α and β allows to model various deterioration behaviours.

3. Maintenance model

3.1 Maintenance policy

A maintenance policy relies on two main decisions: when to take (preventively/correctively) maintenance actions and when to inspect.

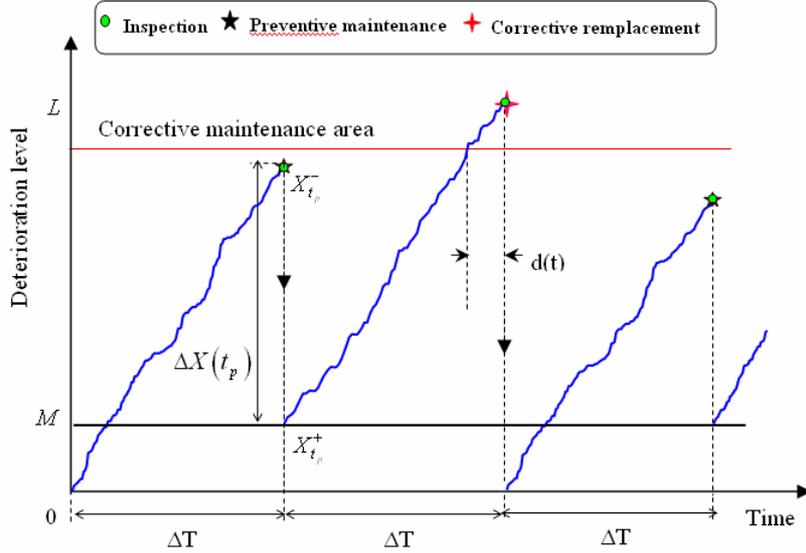


Figure 2. Model of imperfect preventive maintenance

In the framework of condition-based maintenance strategies, the system information (degradation level) is usually used in order to perform maintenance actions and to schedule inspection times. We assume that the system is periodically inspected with the inter-inspection interval length ΔT to be optimized. Let t is the preventive maintenance time and X_t the corresponding system degradation level. Assume that if a preventive maintenance action is performed then it can reduce the system degradation level to M ($0 \leq M < X_t$) to be optimized. Precisely, according to the degradation level X_t , the maintenance decision is the following:

- if $X_t \geq L$, system failed, then a corrective replacement action is performed and a cost C_c is incurred. An additional cost is incurred by the time $d(t)$ elapsed in the failed state at a cost rate C_d which may correspond to production lost per unit of time. After corrective maintenance action, the system is considered as good as new (the degradation level after corrective maintenance is assumed to equal 0);
- if $M \leq X_t < L$, system is still functioning, then an imperfect preventive maintenance action is performed at inspected time. This preventive maintenance action may restore the system to be not as good as new (case $M > 0$). We assume however that the system can be repaired only a limited number of times N_{pre}^0 ;
- if $X_t < M$ then no maintenance action is performed.

For both cases (preventive, corrective maintenance action), one assumes that maintenance durations are neglected. The illustration of degradation evolution and maintenance policy is shown in Fig. 2.

3.2 Imperfect preventive maintenance cost

If an imperfect preventive maintenance is carried out at time t then we have to pay a preventive maintenance cost C_p^j which depends on the current degradation level X_t and the improvement level $\Delta X(t) = X_t - M$. The imperfect preventive maintenance cost function is recently a popular issue to researchers. In Ponchet (2009) and Ben-Daya(1999), the preventive maintenance cost is considered as a linear function, see Fig. 3a. A non-linear one is also considered in Ben-Daya(1999). The later is illustrated in Figure 3b.

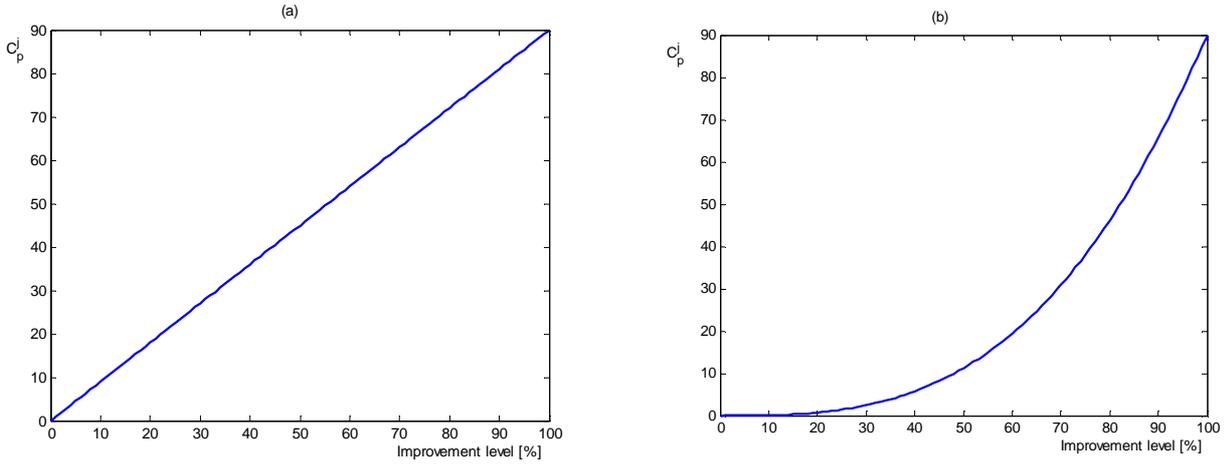


Figure 3. Imperfect preventive maintenance cost: (a) - linear case; (b)-non linear case

4. Optimization of the maintenance policy

In maintenance optimisation, maintenance cost rate is usually used. However in the framework of production system, productivity takes an important role and should be taken into account in the optimisation procedure. Hence, the maintenance cost per unit of product is recently introduced in Dovan and Berenguer (2010).

The cumulative maintenance cost at time t is:

$$C(t) = C_i \cdot N_i(t) + \sum_{j=1}^{N_p(t)} C_p^j + C_c \cdot N_c(t) + C_d \cdot d(t),$$

where:

- $N_i(t)$ is the number of inspection performed in $[0, t]$, $N_p(t)$ and $N_c(t)$ the number of preventive and corrective maintenance actions performed in $[0, t]$;
- $d(t)$ is the time passed in a failed state in $[0, t]$.

The long run expected cost rate is:

$$EC_{\infty} = \lim_{t \rightarrow \infty} [E[C(t)]/t] \quad (2)$$

The cumulative production capacity at time t is: $Pr(t) = \sum_{i=1}^N D_i(t) \cdot S_i$,

where $D_i(t)$ is time passed in state i in the interval time $[0, t]$.

In the same manner, the long run expected productivity is:

$$EPr_{\infty} = \lim_{t \rightarrow \infty} [E[Pr(t)]/t].$$

The average of maintenance cost per unit of product can be defined as the ratio of the long run expected cost rate divided by the long run expected productivity rate.

$$ECP_{\infty} = EC_{\infty} / EPr_{\infty}. \quad (3)$$

This quantity is used as a main criterion in order to optimize the propose maintenance policy.

5. Numerical example

The purpose of this section is to show how the proposed maintenance policy can be used in maintenance optimisation of production deteriorating systems through a simple example.

Considering a single unit production system in which its degradation behavior is assumed to be described by a Gamma process with scale parameter $\alpha=1$ and shape parameter $\beta=5$. The nominal production capacity of the system is 100 products / unit of time ($S_{nominal} = 100$). The production capacity can be changed according to the degradation level of the system. More precisely:

- when the degradation level $X_t < 20$, the system is in state 1 (normal operation state), production capacity is $S_1 = S_{nominal} = 100$;
- $20 \leq X_t < 40$, the system is in state 2, production capacity is $S_2 = 60$;
- $40 \leq X_t < 60$ (state 3), production capacity is $S_3 = 40$;
- and when $60 \leq X_t$ (system fails), production capacity is $S_4 = 0$.

Assume that inspection, preventive and corrective replacement costs are $C_i = 20, C_p^0 = 90, C_c = 100, C_d = 100$ and the system can be repaired only 10 times ($N_{pre}^0 = 10$). Imperfect preventive maintenance cost depends on the improvement level and the degradation at inspected time. Here, two following cases are considered:

- Case 1: the cost of the j^{th} imperfect preventive maintenance action C_p^j is proportional to the improvement level: $C_p^j = C_p^0 * \Delta X(t) / X_t$ (see Fig. 3a);
- Case 2: C_p^j is a non-linear function w.r.t. the improvement level: $C_p^j = C_p^0 * [\Delta X(t) / X_t]^3$ (see Fig. 3b).

For both cases, the simulations are done on a very large interval of time so that t is assumed to tend infinity. Fig. 4 sketches the mean maintenance cost per unit of product for different values of the inter-inspection time ΔT and the preventive maintenance level M in the first case. A numerical optimisation scheme was used; the optimum values of the decision parameters are $\Delta T^* = 8, M^* = 0$ (see Fig. 4.b) for an optimal cost of 0.1989 ($ECP_\infty^* = 0.1989$). This means that this optimal policy corresponds to a perfect periodic preventive maintenance policy, see Dovan and Berenguer (2010).

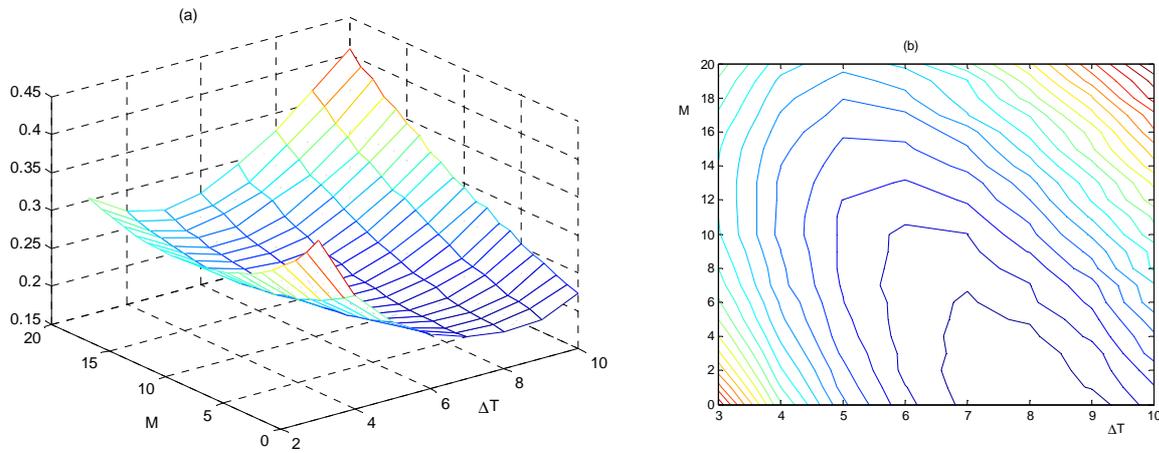


Figure 4. Mean maintenance cost per unit of product ECP_∞ (a) and its iso-level (b)

For the second case, the mean maintenance cost per unit of product and its iso-level are represented respectively in Fig.5a and Fig.5b. The optimal mean cost per unit of product is 0.1497 $ECP_\infty^* = 0.1497$ for $\Delta T^* = 5, M^* = 12$. To compare with the results obtained in the first case, this cost rate is lower about 24.8%. Overmore, if we use a perfect aperiodic policy, based on the residual useful life, which seems to be the best one in the framework of perfect condition-based maintenance policies, the optimal mean cost per unit of product is then 0.1721 (see Dovan and Berenguer (2010)). This result is still, however, higher about 13%.

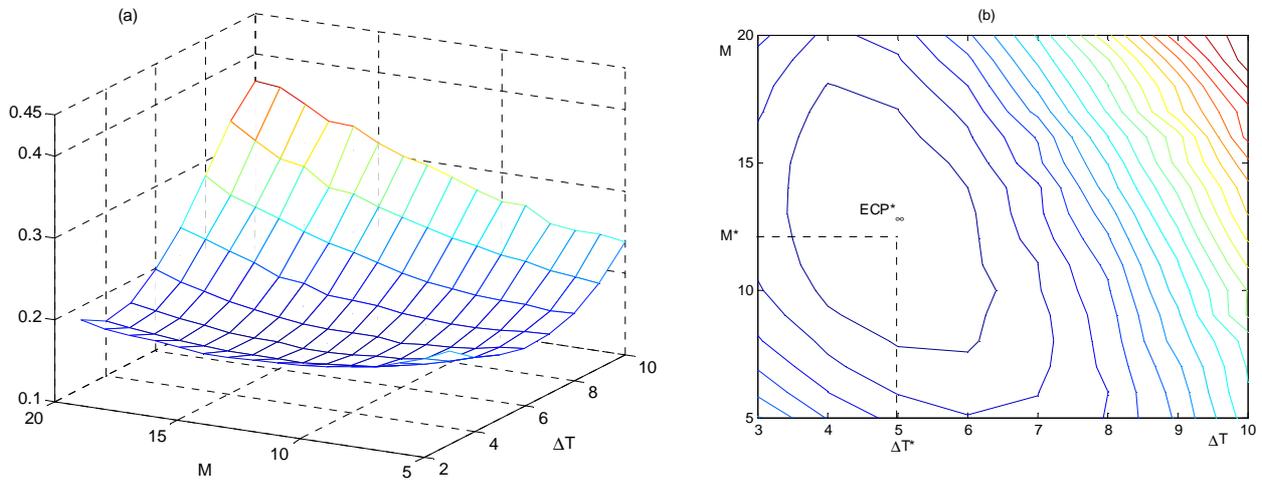


Figure 5. Mean maintenance cost per unit of product ECP_∞ (a) and its iso-level (b)

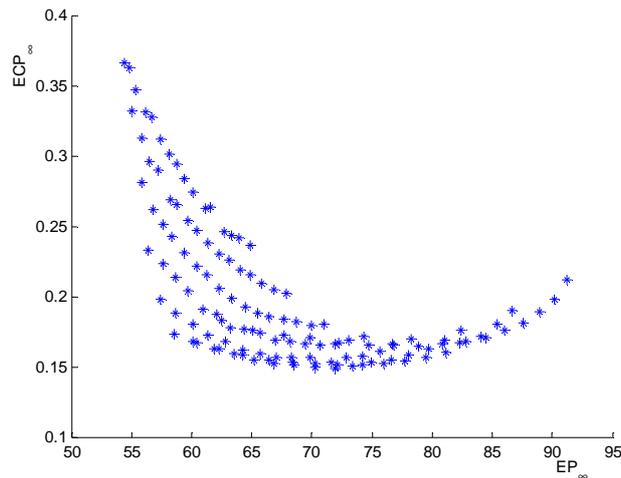


Figure 6. Mean maintenance cost per unit of product as a function of production capacity

Fig.6 shows the relationship between the mean maintenance cost per unit of product and the mean production capacity (for the second case). Each point corresponds to a couple of decision parameters ($M, \Delta T$). These results show that according to a demand on the production capacity level, relying on a production campaign for example, an optimal decision based on the minimal mean cost per unit of product can be reached.

6. Conclusions

In this work, a condition-based maintenance under an imperfect repair policy for a deteriorating production system is described. Both cost and productivity are taken into account in the optimisation procedure. This can help to find an adaptive optimal decision under a production level demand. The results show that the efficiency of imperfect maintenance actions may depend on the imperfect preventive maintenance cost which is a function of the improvement level. When compared to the perfect periodic preventive maintenance policies, the proposed maintenance policy can provide better results depending on the imperfect preventive cost function.

Our future research work will focus on the development this maintenance policy to a multi-unit system with different degradation behaviors.

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