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Preventive maintenance policy for multi-component systems subject to random environmental damage generation

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Abstract: This paper presents a preventive maintenance strategy for multi-component systems subject to risk of environmental damage generation. The proposed policy aims to maximize the profit, which takes into account the cost of penalties due to the environmental damage generated by each component. A numerical procedure is used to determine the optimal maintenance strategy to be adopted for each component.

*Keywords:*Cost-benefit analysis, environmental impact, maintenance strategies, routine releases, non-routine releases.

1. INTRODUCTION

Companies are confronted to environmental risks related to their production processes. They have to swiftly react to an increasing number of local and international legislations. Environment legislation is usually based on the polluter-pays principle i.e. the polluter should pay for the environment damage it caused (EEA (2011)). This leads companies to assess environment performance in economic terms.

It is obvious that maintenance has an important role to help companies to meet the legislation requirements and enhance their profitability (Hong et al. (2011)).

Numerous efforts have recently emerged to address the environment issues related to impacts assessment and cost evaluation (Silva et al. (2009)).

L.J. Zaragova(1987) divided the environmental risks into two main types (1) The routine releases: which consist of the damage to environment due to the plant operation e.g. process effluent streams, energy consumption, waste generation, etc (Vassiliadis et al. (2000a)), and (2) the non-routine release (accidental release) from process plants damaging the environment, which may occur due to deviations from planned operation and unexpected events such as equipment breakdown, leaks, etc (Topuz et al. (2011), Devarun Ghosh (2009), Wessberg et al. (2008)).

ISO 14001:2004 presents an example of environmental aspects which could cause environmental impact e.g. emissions to air, releases to water, releases to land, use of raw materials and natural resources, energy emitted, waste and by-products, and physical attributes.

Research related to environmental impact evaluation follow on one hand, a qualitative methodology using tools such as FMEA (Sharma et al. (2008)), Fault Tree Analysis - FTA (Čepin et al. (1999)) and HAZOP (McKelveyT.C. (1988)), and on the other hand, a quantitative methodology. We present below, a brief review of available quantitative approaches.

JornVatn et al. (1996)) developed an approach to identify the preventive maintenance schedule that minimizes the maintenance cost which incorporates, among others, the environment loss. Stefaniset al. (1995) proposed a methodology for environmental impact minimization - MEIM - based on life cycle analysis. The aim of this methodology is the identification of the best process design taking into consideration the environmental impact and the economics design.

Maximizing the profit of process and minimizing the environmental risk were the objectives of the work of Vassiliadiset al.(2000a). They developed an optimization framework which takes into account the environmental risks and the operability characteristics at the early stage of process design. This framework permits the identification of optimal preventive maintenance schedule.

Devarun Ghosh (2009) presents an approach based on Criteria Decision-Making methodology (MCDM) for selecting the optimal mixture of maintenance strategies. The optimization model consists in maximizing the profit generated. It integrates the non-routine environmental risk cost.

Most of the researches mentioned above have demonstrated the trend to use different kind of environment factors as criterion to plan maintenance tasks. The threshold level of environment risks was not considered.

In the same context, this paper develops a preventive maintenance policy for a multi-component system subjected to environmental risks generation (routine and non-routine). This policy incorporates the threshold level ofenvironment risks as a new criterion to plan preventive maintenance. The remainder of this paper is organized as follows. Section 2 is devoted to the definition of the maintenance strategy. The corresponding mathematical model is developed in Section 3. In Section 4, the solution procedure is provided for searching the optimal preventive maintenance policy which maximizes the total profit. A numerical example is discussed in Section 5. Finally, some comments and conclusions are drawn in the last section.

2. STRATEGY DEFINITION

Consider a system composed of a set of M components subject to random failures. Let g_1, $g_2 \ldots g_M$ be the probability density functions associated to life times of components 1,2,...,M respectively. Each component j is considered to generate a risk of environmental damage, e.g. resources consumption, toxic releases and etc. we suppose that the random environmental damage quantity generated by component j is proportional to the degradation level.

If the cumulative quantity of environmental damage reaches a specific threshold level, the component j is stopped and a preventive maintenance action is undergone; otherwise, it is left as it. In the other case, when the component j fails it provokes huge damages to environment and lot of expenditures e.g. environmental penalties', costs of tasks to restrict or to clean the damage. In this case, corrective maintenance action is performed.
After a maintenance action (preventive and corrective), the system's state is considered to be as good as new.
The following notation will be used:

- λ : increment of maintenance actions.
- M : number of process components.
- H : time horizon.
- N: number of maintenance actions performed over the horizon H.
- Sj : threshold level of environmental damage quantity.
- rev_k : the revenue generated per unit time during a state k.
- τ_λ : The duration of λ th maintenance action.
- Pr_k : Probability of occurrence of the state k.
- $PA_{\lambda,k}(t)$: The probability to be in a state k after the λ th maintenance action and before the (λ+1)th one.
- $PD_{\lambda,k}(t)$: The probability to be in a state k during the λ th maintenance action.
- $F_{\lambda,j}$: Cumulative function associated to environmental impact generated by the component *j* after the λ th maintenance action.
- tp,j (tc,j): the duration of preventive (corrective) maintenance action for unit *j*.
- Cp,j (Cc,j): the cost of preventive (corrective) maintenance action for unit *j*.
- Cj,i : the cost of environmental impact generated per unit time by the component *j* :
  - i=1 during its functioning.
  - i=2 due to its failure.
- $G_{\lambda,j}$ ($\overline{G}_{\lambda,j}$): Cumulative distribution function associated with lifetimes of component *j* after (during) the λ th maintenance action.
- OP (k) ($\overline{OP}(k)$) : the set of operable (inoperable) components in state k.

Other notations will be introduced through the next sections.

The main assumptions are the following:

- Only one maintenance type (corrective or preventive) can be performed.
- At each time, only one component is maintained.
- Failure events are independent.
- Failures are detected instantaneously.
- All resources are available for each maintenance action.
- Each component can generate at most one environmental impact.
- The environmental impacts are independent; the generation of environmental impact of a component cannot influence the way the other components environmental impacts.

3. MATHEMATICAL MODEL

Our objective is to determine the optimal preventive maintenance schedule which maximizes the profit generated during a finite time horizon with respect to both the maintenance constraints and the environmental impact constraints.

The following analysis will lead to the expression of the total profit over a finite time horizon H. This profit corresponds to the revenue generated subtracted the maintenance costs and the environment risks costs during the same period.
The maintenance constraints correspond to assumptions previously mentioned and requirements of actions achievement and the environmental impact constraints are the threshold amount of release for each component *j* (Sj) either predetermined by the company or settled by legislation.

We use the decision variables of the proposed maintenance strategy:

- N: number of maintenance actions performed over a time horizon H.
- t_λ, time instant of the λ th maintenance action.
- $\begin{cases} \Lambda_{\lambda,j} = 1 \Rightarrow \text{if the } \lambda \text{ th maintenance action is performed on the component } j. \\ \Lambda_{\lambda,j} = 0 \Rightarrow \text{if the } \lambda \text{ th maintenance action is performed on a component other than } j. \end{cases}$
- $\begin{cases} u_\lambda = 1 \Rightarrow \text{if the } \lambda\text{th maintenance action is preventive.} \\ u_\lambda = 0 \Rightarrow \text{if the } \lambda\text{th maintenance action is corrective.} \end{cases}$

We present below the analytical expressions of different costs of profit terms.

3.1 Revenue