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Optimal replacement and overhaul decisions with imperfect maintenance and warranty contracts

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Abstract

In this article, we develop a model to help a maintenance decision making situation of a given equipment. We propose a novel model to determine optimal life-cycle duration and intervals between overhauls by minimizing global maintenance costs. We consider a situation where the costumer, which owns the equipment, may negotiate a better warranty contract by offering an improved preventive maintenance program for the equipment. The equipment receives three kind of actions: repairs, overhauls, and replacement. An overhaul represents an imperfect maintenance action, that is, the failure rate is improved but not a point that the equipment is as good as new. Corrective maintenance actions are minimal, in the sense that the failure rate after each repair is the same as before the failure. The proposed strategy surpasses others seen in the literature since it considers at the same time the warranty negotiation situation and the optimal life-cycle duration under imperfect preventive actions. We also propose a simplified approach that facilitates the task of implementing the method in standard solvers.
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Keywords: Imperfect maintenance; Warranty; Management; Life-cycle cost

1. Introduction

Many systems are sold with a warranty that offers protection to the buyers against early failures during the infancy of the equipment and as a medium of promotion to the vendor. When the warranty period tends to be large, degradation also appears during it and in this case preventive maintenance plays an important role in order to reduce the failure rate, and its evolution in time.

Offering periods of warranty implies extra costs for the vendor. There exist repair costs (corrective maintenance) and possibly penalty costs to be paid, which are associated to downtime. A preventive maintenance program may reduce such corrective costs. Given that the buyer does not pay repairs during the warranty period, there exist no incentives for him to expense in preventive actions (in the case that the warranty also covers for the downtime costs). For the vendor, it is convenient to perform preventive actions only if they cost less than the expected corrective costs.

From the buyers' point of view, investing in preventive maintenance during and after the warranty period may have significant effects on the life-cycle costs. Consequently, it may be convenient to define preventive policies all along the life-cycle T_l. The aim of this work is to present a general framework for this situation from the point of view of the buyer.

We consider three kind of maintenance actions: minimal repair (as good as before the failure), imperfect overhaul (between as good as after the previous overhaul and as good as before the overhaul) or replaced (as good as new). Each action has its own costs and may depend on variables such as age and/or quality. We will consider a single component analysis, neglecting scale economies that may appear from negotiating for multi-component systems. We also discard revenue-sharing contracts as studied in Cachon and Lariviere [1]. A cost analysis for systems in series, in parallel and a combination of both may be found in Bai and Pham [2].

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Modelling of the system improvement due to imperfect maintenance is crucial to establish the cost model to be optimized. Malik [3] introduced the concept of virtual age, which essentially says that the system is younger than before the action by some interval T_y. A similar formulation is offered by Kijima [4]. A limitation of the virtual age model is that it does not alter the reference failure rate function. Nakagawa [5] assumed that the action is minimal with probability a and perfect with probability $(1-a)$. As it is referred to minimal and perfect actions, this model implies that as time passes the quality of the overhauls must be improved in order to keep a constant. This has some consequences: if the original failure rate without overhauls of the system is a power function of time, the failure rate is always bounded. Zhang and Jardine [6] propose a failure rate model where after an overhaul, it is between as good as before and as good as after previous overhaul. This model does not bound the failure rate as Nakagawa's, but due to the discontinuities in the failure rate function, it may be difficult to evaluate the number of expected failures during the warranty period, which is variable in our model. Djamaludin et al. [7], propose to use a continuous failure rate function λ whose time-dependency parameter is associated to the quality (cost) σ of the maintenance policy, that is

$$\lambda(t,\sigma) = \frac{\beta}{\eta_\sigma}\left(\frac{t}{\eta_\sigma}\right)^{\beta-1}$$

with

$$\eta_\sigma = \eta_0\left(\frac{1}{1-\sigma}\right)^{\kappa}$$

for $t \in [0,T_l]$ and $\sigma \in [0,1)$. We observe that they use a time non-homogeneous Poisson process. For maximum quality, the failure rate tends to be constant, for minimum quality, the failure rate corresponds to the original failure rate when minimal repairs are performed. A serious limitation of this approach is how to model the relationship between the quality of the preventive policy and the failure rate. A summary of research on imperfect maintenance is offered in Pham and Wang [8].

Considering warranty, Djamaludin et al. [7] develop a framework to study preventive policies when the vendor offers an initial period of warranty T_w where he pays labor, materials and downtime costs if a failure occurs. Under this premise, the buyer is not necessarily committed with preventive maintenance. With that agreement, the costs to the buyer (if he decides to perform preventive maintenance during $[0,T_l]$ are

$$C_r + c_p T_l + C_m \int_{T_w}^{T_l} \lambda(t,\sigma)\mathrm{d}t$$

where C_r corresponds to the overall cost of a replacement (investment, labor, material, downtime costs); c_p is the expected overall cost of preventive maintenance per unit time and C_m is the overall cost per failure. In this model, T_l and T_w are considered as fixed parameters.

Jack and Dagpunar [9] use a virtual age model to determine the quality and the period between overhauls. In their model, the optimal solution is complete renewal at each overhaul (age 0). Jung and Park [10] study the optimal periodic preventive policies following the expiration of warranty. They use the expected maintenance cost rate per unit time from the buyer's perspective. They also use a virtual age model for the failure rate and consider that preventive activities start just after the end of the warranty. This limits the optimality of the preventive maintenance since early preventive actions may reduce even further the life-cycle costs [7]. Warranties may also be defined by several criteria and not only age. Concerning warranties that are limited by age and usage, Chen and Popova [11] propose a simulation-based approach to determine minimal repair and replacement policies. Product design and warranty interaction has been studied, i.e. in Kimura et al. [12]. They derive optimal release policies when the designer (which also acts as the vendor) has to pay the cost for fixing any faults detected during the warranty period. More recently, Kim et al. [13], following Kijima's virtual age model [4], develop a strategy to determine maintenance policies in a similar way as in the article by Djamaludin et al. [7], but considering discrete overhaul actions, as we do in this work. In the model by Kim et al., life-cycle duration as well as warranty interval are known a priori. Huang and Zhuo [14] study the selection of the type of warranty to be offered by the vendor. The criterion is the maximization of the vendors profit. They use a fixed continuous failure rate function and, therefore, the model does not reflect explicitly the dependency of the warranty strategy on the maintenance policy. Research dealing on warranty cost analysis has been summarized in Blischke and Murthy [15] and Murthy and Djamaludin [16].

The model that is presented here considers that preventive policies are taken from the beginning of the life-cycle. In this way, the failure rate is reduced and costs associated to corrective maintenance are reduced.

We shall propose a failure rate model that takes the advantages of both the model of Zhang and Jardine and the one by Djamaludin et al. Based on the proposed model we minimize the expected cost per unit-time. It allows an optimal decision on life-cycle duration and the number of periodic overhauls to perform during it. It also permits a negotiation of the warranty period with the vendor. We show results for the case when the reference failure rate function is growing exponentially with time. We illustrate the methodology through a numerical example and we obtain optimal values for the number of overhauls and the life-cycle duration.

The improvements made over the reference models are:

- Life-cycle T_l is a decision variable;
- We obtain an optimal value for the warranty period T_w to be negotiated with the vendor;

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