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Optimal maintenance strategy under renewable warranty with repair time threshold

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ABSTRACT

In this paper, we consider a periodic preventive maintenance model, from the manufacturer's perspective, which can be implemented to reduce the maintenance cost of a repairable product during a given warranty period. The product is assumed to deteriorate with age and the warranty policy we adopt in this paper takes into account the two factors of failure time and repair time of the product when the product failure occurs. Under the proposed two-factor warranty, a repair time threshold is pre-determined and if the repair takes more time than that of the threshold, the failed product is replaced with a renewed warranty policy. Otherwise, the product is only minimally repaired to return to the operating state. During such a renewable warranty period, preventive maintenance is conducted to reduce the rate of degradation periodically while the product is in operation. By assuming certain cost structures, we formulate the expected warranty cost during the warranty period from the manufacturer's perspective when a periodic preventive maintenance strategy is adapted. Although more frequent preventive maintenance increases the warranty cost, the chance of product failures would be reduced. The main aim of this paper is to accomplish the optimal trade-off between the warranty cost and the preventive maintenance period by determining the optimal preventive maintenance period that minimizes the total expected warranty cost during the warranty period. Assuming the power law process for the product failures, we illustrate our proposed maintenance model numerically and study the impact of relevant parameters on the optimal preventive maintenance policy.

1. Introduction

The effectiveness of a maintenance policy for a repairable product may depend on the nature of the warranty policy from the manufacturer's perspective. One of the main purposes of an effective maintenance policy is to minimize the maintenance cost incurred during the life cycle of the product, while keeping the product at maximum availability. Regarding this, many studies have been conducted on the subject of optimal maintenance policy incorporated with various types of warranty policies in the literature. Park and Pham [1] and Shafiee and Chukova [2] discuss various maintenance models along with warranty policies and give a useful literature review on this subject.

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Nomenclature

pdf	probability density function
cdf	cumulative distribution function
i.i.d.	independent and identically distributed
r.v.	random variable
ROCOF	rate of occurrence of failures
T, Y	random variables representing failure time and repair time, respectively
$f(t)$, $h(t)$, $F(t)$	*pdf*, failure rate function, distribution function of T, without PM
$f_{PM}(t)$, $h_{PM}(t)$, $F_{PM}(t)$	*pdf*, failure rate function, distribution function of T, with PM
$g(y)$, $G(y)$	*pdf*, *cdf* of Y
ω, ω_0	length of original warranty period and extended warranty period, respectively
y_0	repair time threshold
δ	PM interval
α	PM restoration level
C_r,C_m, C_{pm}, C_f	cost of replacement, minimal repair, PM, failure during the warranty period, respectively
c_r,c_m, c_{pm}, c_f	unit cost of replacement, minimal repair, PM, failure during the warranty period, respectively
EC(ω, δ)	expected total warranty cost when the original warranty period and the PM interval are equal to ω and δ, respectively
N_R	number of replacements conducted during the warranty period
N_M	number of minimal repairs conducted during the warranty period
I_j	inter-replacement time interval between the (j-1)$^{\text{th}}$ replacement and the j^{th} replacement during the warranty period for $j=1, 2, \ldots, N_R$.
$m(\omega, y_0)$	expected length of I_j for $j=1, 2, \ldots, N_R$.
$\lfloor\ \rfloor$	integer part of number

Assumptions

- All the warranty claims are valid and accepted.
- The length of time required to repair the product is excluded from the warranty period.
- The length of time required to replace the product is negligible.
- The product is assumed to have an increasing failure rate.

In most of the transactions, the manufacturer provides certain types of warranty policy, and the warranty cost analysis in conjunction with a maintenance policy has thus become an important issue to reduce the total expected maintenance cost for a repairable product. Park and Pham [3] carry out the warranty cost analysis in terms of the expected cost for *k-out-of-n* systems. They optimize the warranty period, warranty service time limit, and periodic preventive maintenance cycle to minimize the long-run expected cost from the customers' perspective. Bai and Pham [4] consider the repair-limit warranty policy from the manufacturer's perspective and control the number of repair services to avoid the risk of providing too many repair services during the warranty period. Park and Pham [5] investigate a cost model where the warranty servicing time and the failure time are statistically correlated by the bivariate exponential distribution suggested by Marshall and Olkin [6].

The preventive maintenance (PM), which is an action taken on a product while it is still operating, upgrades the product and so improves its reliability by slowing the degradation process of the product. Although more frequent PM actions increase the maintenance cost of the product, such actions can result in reducing the chance of product failures. In this respect, the optimal trade-off between the number of PM actions and the maintenance cost becomes necessary in order to obtain an efficient maintenance strategy for both the manufacturer and the user. Canfield [7] proposed a periodic PM model, under which the failure rate of the product is reduced at each preventive maintenance action. Later, Shafiee et al. [8] discussed several optimal PM warranty strategies by determining several relevant decision variables regarding the maintenance policy. Other references for optimal PM models can be found therein.

The main aim of this paper is to acquire an optimal periodic PM policy during the warranty period by determining the optimal length of inter-PM time (which is referred to as a PM interval throughout this study), minimizing the expected total warranty cost that would incur during the warranty period from the manufacturer's perspective. At each PM action, we adopt the Canfield's [7] periodic PM, under which the product's failure rate is somewhat slowed down each time the PM is conducted by the manufacturer. We also adopt a renewable minimal repair-replacement warranty with a pre-determined repair time threshold as a warranty policy. The renewable minimal repair-replacement warranty was first suggested by Park et al. [9] and works as follows. When a product fails during the warranty period, the failed product is initially minimally repaired. If the repair can be completed within the repair time threshold, the repaired product is returned to the bad-as-old condition with no changes in its failure rate. However, if the repair exceeds the threshold, the failed product is replaced with