

Optimal periodic preventive maintenance policy for leased equipment

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Abstract

For leased equipment the lessor incurs penalty costs for failures occurring over the lease period and for not rectifying such failures within a specified time limit. Through preventive maintenance actions the penalty costs can be reduced but this is achieved at the expense of increased maintenance costs. The paper looks at a periodic preventive maintenance policy which achieves a tradeoff between the penalty and maintenance costs.

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1. Introduction

Businesses need a variety of equipment to produce products and services. Equipment degrades with age and usage, and ultimately fails. Through corrective maintenance (CM) failed equipment can be restored to operational state; and through preventive maintenance (PM) the rate of degradation and the likelihood of equipment failure can be controlled.

Prior to 1970, most businesses owned the equipment and maintenance (CM and PM) was carried out in-house. This began to change around 1970 and the two reasons were the following.

- (1) Increasing complexity of equipment combined with specialist skills and tools needed for carrying out maintenance actions made in-house maintenance uneconomical.
- (2) A trend towards focusing only on the activities deemed to be the core of the business and outsourcing all other activities. Most businesses viewed maintenance as a non-core activity.

As a result, maintenance outsourcing began to grow with maintenance being carried out by either the original equipment

manufacturer (OEM) or a third party. In contrast to the vast literature on maintenance [6,15,17,19] the literature on outsourcing of maintenance is very limited. Murthy and Yeung [10], Martin [7] and, Murthy and Asgharzadeh [9] deal with some of the issue in maintenance outsourcing.

Since 1990 more and more businesses started leasing equipment rather than owning them. This was mainly due to the following two reasons:

- (1) Rapid advances in technology resulting in technological obsolescence with new and better equipment appearing on the market at a faster rate.
- (2) The cost of owning the equipment becoming very high.

Nisbet and Ward [13] deal with the choice between purchase and lease in the context of radiotherapy equipment.

Leasing involves three elements: (i) lessor (who owns and maintains the equipment), (ii) lessee (who leases the equipment), and (iii) lease contract (which deals with the price and conditions of lease). The lessor offers the product (equipment) and the service (maintenance) as a bundle to the lessee. The contract usually contains penalty clauses that penalize the lessor should the leased equipment fail too often and/or the failed equipment is not restored to operational state within some specified time limit. As the level of PM effort increases the penalty costs decrease but the cost of PM actions increases. This implies that the optimal PM actions need to be decided by taking into account the penalty costs.

A number of different PM policies have been proposed in the literature. A small list of references dealing with sequential

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PM policies is [4,5,11,12,18] and with periodic PM policies is [1,2,11,14,16]. Wang [20] deals with a comprehensive survey of the maintenance policies for deteriorating systems.

Jaturonnate et al. [3] deal with a PM policy (henceforth referred to as Policy 1) which involves k PM actions carried out at times t_j , $1 \leq j \leq k$, over the lease period and the effect of PM action is to reduce the intensity function by δ_j at the j th PM action. The parameters k , $\underline{t}(\equiv t_1, t_2, \dots, t_k)$, and $\underline{\delta}(\equiv \delta_1, \delta_2, \dots, \delta_k)$ are selected optimally to achieve a tradeoff between penalty and PM costs. The two shortcomings of this PM policy are as follows:

- (1) The optimization problem involves $(2k + 1)$ parameters that need to be selected optimally.
- (2) The time intervals between successive PM actions are, in general, not constant. This implies that from an implementation point of view the PM policy is not very practical.

In this paper we look at a periodic policy (henceforth referred to as Policy 2) where the PM actions are carried out at periodic times jT , $j = 1, 2, \dots, k$ over the lease period. T is the constant time interval between two successive PM actions. The policy overcomes the second shortcoming of Policy 1. The number of PM actions over the lease period, k , depends on T and the duration of the lease. The effect of the j th PM action is to reduce the intensity function by δ_j and is a decision variable to be selected optimally. As a result, the optimization problem involves $(k + 1)$ parameters as opposed to $(2k + 1)$ in Policy 1.

The outline of this paper is as follows. We give the detail of the model formulation in Section 2. The analysis of the model is carried out in Section 3. A numerical example is presented in Section 4. We conclude with some topics for further research in Section 5.

2. Model formulation

We use the following notation:

- $F(t)$ failure distribution function
- $f(t)$ failure density function associated with $F(t)$
- $r(t)$ failure rate [hazard] function associated with $F(t)$
- $\lambda_0(t)$ failure intensity function with no PM
- $\lambda(t)$ failure intensity function with PM actions
- $A_0(t)$ cumulative failure intensity function $\left[= \int_0^t \lambda_0(x) dx \right]$ with no PM
- $A(t)$ cumulative failure intensity function $\left[= \int_0^t \lambda_0(x) dx \right]$ with PM actions
- $N(t)$ number of failures over $[0, t]$
- Y_i time to repair the i th failure
- $G(y)$ repair-time distribution function
- $g(y)$ repair-time density function $[= dG(y)/dy]$
- $k[k(T)]$ number of PM actions over the lease period
- T period of time instant to carry out PM
- t_j time instant for j th PM action
- δ_j reduction in intensity function due to j th PM action $\underline{\delta} = \{ \delta_1, \delta_2, \dots, \delta_{k(T)} \}$

- $C_p(\delta)$ cost of PM action resulting in a reduction δ in intensity function
- TC_p total cost of PM actions
- C_i cost of i th minimal repair
- C_f average cost of CM action to rectify failure
- TC_f total cost of CM actions
- τ repair time limit [parameter of lease contract]
- C_t penalty cost per unit time if repair not completed within τ [Penalty 1]
- C_n penalty cost per failure if $N(t) > 0$ [Penalty 2]
- $J(T, \underline{\delta})$ total expected cost to the lessor

2.1. Lease contract

The equipment is leased for a period L with two types of penalty associated with failures.

Penalty 1: The lessor incurs a penalty if the time to repair failure exceeds τ . Let Y denote the time to repair, then there is no penalty if $Y \leq \tau$ and a penalty $(Y - \tau)C_t$ if $Y > \tau$.

Penalty 2: The lessor incurs a penalty cost C_n for each failure that occurs over the lease period.

2.2. Modeling failures and PM actions

The time to first failure is given by a distribution function $F(x)$ and hazard function $r(x)$ an increasing function in x . Equipment failures are rectified through minimal repair and we assume that the repair times are small relative to mean time to between failures. As a result, failures can be modeled [8] by a point process with intensity function $\lambda_0(t) = r(t)$ which increases with t increasing.

The lessor carries out periodic PM with a period T . The number of PM actions carried out over the lease period, k , is the largest integer less than L/T . The time instants of PM actions are given by $\{t_j = T, 2T, \dots, kT\}$. Each PM action results in a reduction in the intensity function. The reduction resulting from the j th PM action is given by δ_j and is constrained to satisfy the following inequality

$$0 \leq \delta_j \leq \lambda_0(t_j) - \sum_{i=0}^{j-1} \delta_i \quad \text{for } 1 \leq j \leq k. \quad (1)$$

The intensity function for the occurrence of failures with periodic PM actions is given by

$$\lambda(t) = \lambda_0(t) - \sum_{i=0}^j \delta_i \quad \text{for } t_j \leq t < t_{j+1} \quad (2)$$

where $t_0 = 0$ and $\delta_0 = 0$.

2.3. Modeling costs

The cost (labor and material) for a CM action (to rectify a failure) is a random variable. The cost of a minimal repair is a random variable and let C_f denote the mean cost of repair. Let $N(L)$ denote the number of failures over the lease period

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