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Cost Models for Warranty and Preventive Maintenance†

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요 약 판매되는 제품에 대한 보증비용은 소비자의 사용정도에 관계없이 일정하다고 가정한다. 하지만 현실적으로는 소비자들에 따라 사용 정도가 서로 다를 수 있다. 사용정도와 예방보수 형태는 보증비용 책정에 중요한 역할을 할 수 있다. 따라서, 본 논문에서는 소비자에 따라 사용정도가 다르고 예방보수 정책의 형태가 서로 다른 경우에 대한 제품의 기대보증 비용을 산출할 수 있는 새로운 보증비용 모형을 제시했다.

Abstract Warranty cost analysis for one-dimensional warranties assumes that the usage intensity (or rate) is the same for all buyers. In real life the usage intensity varies across the population of buyers. Also for products sold with warranty, preventive maintenance actions by manufacturers and buyers have a significant impact on the total costs for both parties. In this paper we deals with models to study the expected warranty cost for products with free repairable warranty with varying usage intensity and three types of preventive maintenance. We also review the literature which links warranty and maintenance and develops a framework to define new topics for research in the future and examines a new model formulation. It then develops a new model and carries out its analysis.]

1. Introduction

All products are unreliable in the sense that they fail. The failure can occur early due to manufacturing defects or late due to age and usage (effect of wear). Most products are sold with warranty that offers protection to buyers against early failures over the warranty period. The warranty period has been progressively getting longer. For example, in the automobile industry, the warranty period was three months in the early thirties, one year in the sixties and currently they are three to five years. With extended warranty, failures due to age and usage are covered by the warranty. The failures due to age and usage are due to degradation of the product. This degradation can be controlled by proper preventive maintenance. This implies that preventive maintenance needs to be taken into consideration in the study of warranties with long warranty period.
Preventive maintenance (by manufacturer and/or buyer) can reduce this cost. From the manufacturers perspective, the additional cost of preventive maintenance over the warranty period is worthwhile only if it less than the reduction in the warranty servicing cost with no preventive maintenance. From the buyers perspective, investment in preventive maintenance during the warranty period can have a significant impact on the maintenance cost after the warranty has expired.

One-dimensional policies are characterized by a time interval called warranty period. The cost analysis of one-dimensional policies is based on the assumption that buyers are homogeneous with respect to the usage intensity (or rate). This implies the usage rate is the same for all buyers. In contrast, two-dimensional warranty policies are characterized by a

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two-dimensional region with one axis representing time (or age) and the other usage. The product usage intensity across the buyer population can vary and is modeled as a random variable in the cost analysis. Two different approaches have been proposed and the details can be found in Blischke and Murthy (1994 and 1996).

In this paper we focus our attention on warranty cost analysis for products sold with one-dimensional free replacement warranty considering heterogeneous usage intensity and different preventive maintenance actions across the buyer population. A typical example that reflects this is the following. The usage intensity (in terms of load and frequency of usage per week) of a domestic washing machine varies depending on the size of the family. This is also true for many other domestic and industrial products. The product degradation and failure depends on the usage intensity, preventive maintenance actions and this in turn has an impact on the expected warranty cost. This needs to be taken into account in determining the sale price and reliability decisions at the design stage.

We also focus our attention on the link between warranty, preventive maintenance and usage intensity. We review the limited literature dealing with this topic and then develop a framework to define new topics for research from both manufacturer and buyer perspectives. We develop a new model and present some preliminary results

2. Product Warranties and Preventive Maintenance

In this section we give a brief overview of the literature on warranties and maintenance and discuss some of salient issues of relevance to the paper.

2.1 Product Warranty

A warranty is a contract between buyer and manufacturer that becomes effective on sale of a product. The purpose of a warranty is basically to establish liability in the event of premature failure of a product, where by failure is meant inability of the item to perform its intended function, for whatever reason. The contract specifies the product performance promised and, if this promise is not met, the compensation provided to the buyer. It also specifies the buyers responsibilities with regard to maintenance of the product as well as other provisions.

There are many different types of warranties depending on the type of product consumer, commercial and defense acquisition. For consumer goods, the most common warranties are various versions of the free replacement and pro-rata warranties (which involve repair or replacement at no cost or pro-rated cost); cash rebates on failure of the item; and a combination free replacement/pro-rata warranty. Commercial and industrial warranties are those offered in sales by a manufacturer to another company. These warranties often are of the same basic type as those offered on consumer products, but additional features may be involved. For example, groups or lots of items may be warranted rather than individual items. Warranties of this type are called cumulative or fleet warranties. Warranties on items procured by the government include all of the above plus some special warranties, particularly in acquisition of defense products. The best known of these special warranties is the reliability improvement warranty, which includes provisions for product development and improvement. For taxonomy of different warranty policies, see Blischke and Murthy (1994). Many aspects of warranty have been studied and some of these can be found in Blischke and Murthy (1996). In this section we focus our attention on the cost analysis of warranties.

There are many issues involved in the cost analysis of a warranty. Two of these are the perspective (buyer or seller) and the basis on which the costs are to be assessed. There are a number of approaches to the costing of warranty. Costs clearly are different for buyer and seller.

2.2 Preventive Maintenance

Maintenance can be defined as actions to (i) control the deterioration process leading to failure of a system and (ii) restore the system to its operational state through corrective actions after a failure. The former is called preventive maintenance and the latter corrective maintenance.

Corrective maintenance actions are unscheduled actions intended to restore a system from a failed state into a working state. This involves either repair or replacement of failed components. In contrast, preventive maintenance actions are scheduled actions carried out to either reduce the likelihood of a failure. Preventive maintenance (PM) actions are divided into the following categories:

1. Clock-based maintenance: Here PM actions are carried out at set times. An example of this is the Block replacement policy.

2. Age-based maintenance: Here PM actions are based on the age of the component. An example of this is the Age replacement policy.

3. Usage-based maintenance: Here PM actions are based on usage of the product. This is appropriate for items such as tires, components of an aircraft, and so forth.

4 .Condition-based maintenance: Here PM actions are based on the condition of the component being maintained. This involves monitoring of one or more variables characterizing the wear process (eg, crack growth in a mechanical component). It is often difficult to measure the variable of interest directly and in this case, some other variable may be used to obtain estimates of the variable of interest. For example, the wear of bearings can be measured by dismantling the crankcase of an engine. However, measuring the vibration, noise or temperature of the bearing case provides information about wear since there is a strong correlation between these variables and bearing wear.

5. Opportunity-based maintenance: This is applicable for multi-component systems, where maintenance actions (PM or CM) for a component provide an opportunity for carrying out PM actions on one or more of the remaining components of the system.

6. Design-out maintenance: This involves carrying out modifications through re-design of the component. As a result, the new component has better reliability characteristics.

In general preventive maintenance is carried out at discrete time instants. In some cases, they are done very frequently so that they can be treated as occurring continuously over time. Man different types of model formulations have been proposed to study the effect of preventive maintenance on the degradation and failures of the product and to derive optimal preventive maintenance strategies.

Several review papers on maintenance have appeared over the last 30 years. These include McCall (1965), Pierskalla and Voelker (1976), Monahan (1982), Jardine and Buzzacot (1985), Sherif and Smith (1986), Thomas (1986), Gits (1986), Valdez-Flores and Feldman (1989), Pintelton and Gelders (1992) and Scarf (1997). Cho and Parlar (1991) and Dekker et al (1997) deal with the maintenance of mutli-component systems. Also, there are several books dealing with the topic- see, for example, Gertsbakh (1977).

3. Warranty Model Formulation

3.1 Product Warranty

The manufacturer sells a repairable product with a non-renewing free replacement warranty policy with a warranty period W. All failures in the warranty period $[0, W)$ are rectified (through corrective maintenance actions) by the manufacturer at no cost to the buyer. The product has a life L and the cost of rectifying failures (through corrective maintenance actions) in the interval $[W, L]$ subsequent to the expire of the warranty is borne by the buyer.

3.2 Item Failures

Let $F(t;\theta)$ be the failure distribution function for the product. θ is the scale parameter and is a function of the usage intensity as will be discussed later in the section. The product is sold with a free replacement warranty period that requires the manufacturer to rectify all failures over the warranty period at no cost to the buyer. The product is repairable. We assume that the failures are minimally repaired (see, Barlow and Hunter (1960)) and the time to repair is negligible so that it can be ignored. This implies that failures over the warranty period occur according to a non-homogeneous Poisson process with intensity function given by the failure rate function $r(t;\theta)$

associated with $F(t;\theta)$. This failure rate function is

given by

$$r(t;\theta) = \frac{f(t;\theta)}{1-F(t;\theta)} \qquad (1)$$

3.3 Usage Intensity

Let U denote the usage rate. This is a random variable and characterizes the different usages across the buying population. The usage rate is modeled a continuous random variable distributed over an interval $u_{\min}$ and $u_{\max}$ according to a distribution function

$G(u)$ with density function $g(u)$. These two limits denote the minimum and maximum usage rates. A form of distribution that we will consider later in the paper are:

Gamma Distribution :

$$g(u) = \frac{1}{\Gamma(\alpha)} u^{\alpha-1} e^{-u} \text{ with parameter } \alpha \geq 0$$

Note that in the second case $u_{\min} = 0$ and $u_{\max} = \infty$

whereas in the first case $u_{\min} \geq 0$ and $u_{\max} < \infty$,

given the usage rate $U = u$, θ is given by

$$\theta(u) = \delta(u)\,\theta_m \qquad (2)$$

where θ_m is design parameter and $\delta(u)$ defines the

effect of the usage rate(or load on the item) and is modelled as

$$\delta_i(u) = \sum_{j=1}^{i}\left(\frac{u}{u_{j-1}}\right)^{j-1}$$

$$u_{i-1} \leq u \leq u_i, \quad i = 1,\ 2,\ \cdots\ k \qquad (3)$$

with u_i as the additional design parameters. The design parameters depend on the design decisions and are under the control of the manufacturer. Higher values for θ_m and u_i are resulted from better design.

3.4 Effect of Maintenance Effort

Preventive maintenance actions by the buyer affect the failure rate of the item. We confine our attention to the case where preventive maintenance is carried out continuously over time. Let $m(0 \leq m \leq M)$ denote

the maintenance effort level. Let $r(t;m)$ denote the failure rate with maintenance effort level m. We consider three options for the buyer:

<u>**Option A**</u> : The buyer carries out no preventive maintenance over the life of the item. All failures are rectified through corrective maintenance actions. In this case, $m = 0$ and

$$r(t;0) = r_0(t)$$

<u>**Option B**</u> : The buyer uses a maintenance level m throughout the life of the item. In this case, we have

$$r(t;m) = r_m(t) \quad (5)$$

$[r(t;m) - r_0(t)]$ is an increasing function of m implying that the reduction in the failure rate increases with the maintenance level. $r_m(t)$ is an increasing function of t implying that even with maximum maintenance effort, the failure rate is increasing with age.

Option C : The buyer carries out no maintenance over the warranty period and the maintenance effort subsequent to the expire of the warranty is m. As a result, the failure rate is given by

$$r(t;m) = \begin{cases} r_0(t) & for \ \ 0 \le t < W \\ [r_0(W) - r_m(W)] + r_m(t) & for \ \ W \le t < L \end{cases} \quad (6)$$

4. Warranty Model Analysis

In this section we derive expressions for the expected maintenance cost to the buyer over the life of an item and the expected warranty servicing cost to the manufacturer under the three options indicated in the previous section.

4.1 Buyer's Perspective Expected Life-cycle Cost

Since failures occur according to a point process the expected number of failures over any interval is given by the integral of the failure rate function over the interval. This yields the following results:

Option A :
Let $E[N_A(W,L);\theta(u)]$ denote the number of expected failure during (W,L) under Option A, given the usage rate $U=u$

$$E[N_A(W,L);\theta(u)] = \int_W^L r_0(t;\theta(u))dt \quad (7)$$

Let $E[N_A(W,L)]$ denote the number of expected failure during (W,L) under Option A, given by

$$E[N_A(W,L)] = \int_{u_{min}}^{u_{max}} \int_W^L r_0(t;\theta(u))dtdG(u) \quad (8)$$

Then the buyer's expect life-cycle cost, $BELC_A(W,L)$, is given by

$$BELC_A(W,L) = C_R E[N_A(W,L)] \quad (9)$$

Option B :
Let $E[N_B(W,L);\theta(u)]$ denote the number of expected failure during (W,L) under Option B, given the usage rate $U=u$

$$E[N_B(W,L);\theta(u)] = \int_W^L r_m(t;\theta(u))dt \quad (10)$$

Let $E[N_B(W,L)]$ denote the number of expected failure during (W,L) under Option B, given by

$$E[N_B(W,L)] = \int_{u_{min}}^{u_{max}} \int_W^L r_m(t;\theta(u))dtdG(u) \quad (11)$$

Then the buyer's expect life-cycle cost, $BELC_A(W,L)$, is given by

$$BELC_B(W,L) = C_R E[N_B(W,L)] + C_M(m)L \quad (12)$$

Option C :
Let $E[N_C(W,L);\theta(u)]$ denote the number of expected failure during (W,L) under Option C, given the usage rate $U=u$

$$E[N_C(W,L);\theta(u)] = \int_W^L [r_0(W;\theta(u)) - r_m(W;\theta(u)) + r_m(t;\theta(u))]dt$$

(13)

Let $E[N_C(W,L)]$ denote the number of expected failure during (W,L) under Option C, given by

$$E[N_C(W,L)] = \int_{u_{min}}^{u_{max}} \int_W^L [r_0(W;\theta(u)) - r_m(W;\theta(u)) - r_m(t;\theta(u))]\,dt\,dG(u) \quad (14)$$

Then the buyer's expect life-cycle cost, $BELC_C(W,L)$, is given by

$$BELC_C(W,L) = C_R E[N_C(W,L)] + C_M(m)(L-W) \quad (15)$$

Optimal Decision

Property 1: For a given maintenance level m $(0 \le m \le M)$, the optimal choice between the three options is determined by a relative comparison of the expected life-cycle costs. The one that yields the lowest cost is the optimal strategy.

Property 2: The optimal maintenance level for Options B and C are obtained by minimizing the expected life-cycle costs. The optimal maintenance level achieves an optimal trade-off between the preventive and corrective maintenance costs incurred by the buyer.

One can derive various relationships for comparing the options. One of them (comparing Options A and B) is as follows.

Property 3:

Define $\Delta(m) = C_R(m) \int_W^L [r_0(t) - r_m(t)]dt.$

This is the saving in corrective maintenance cost by using preventive maintenance at level m. Option B is better than Option A if $\Delta(m) > C_m L$ for some m.

4.2 Manufacturers Perspective Expected Warranty Cost per Unit

The cost to the manufacturer is the warranty servicing cost (the cost of rectifying failures under warranty). Under Options A and C, the expected warranty cost per unit is given by

$$MEWC_A = MEWC_C = C_R(m) \int_0^W r_0(t)dt \quad (16)$$

Under Option B, it is given by

$$MEWC_B = C_R(m) \int_0^W r_m(t)dt \quad (17)$$

Since $r_m(t) < r_0(t)$, the expected warranty cost per unit to the manufacturer under Option B is smaller than that under Options A and C.

Optimal Decision

The optimal strategy for the manufacturer is to ensure that the buyer chooses Option B. One way of ensuring this is through proper pricing (assuming that the corrective repairs outside the warranty period are carried out by the manufacturer or his/her agent). Another option is to offer some incentive that will make it attractive for the buyer to choose Option B. One such approach is a longer warranty period. However, this can raise several other issues for example, the resulting moral hazard if the manufacturer cannot monitor the maintenance effort expended by buyers.

5. Numerical Example

The usage population can be clustered into several groups. The general case is to cluster them into k groups. In this example, the simplest case is to cluster them into 3 groups, i. e., the light users, medium users and heavy users. The usage rate is given by a Gamma distribution with parameter α, therefore $g(x) = \frac{1}{\Gamma(\alpha)} x^{\alpha-1} e^{-x}$, $x \ge 0$. Also, let $F_0(t)$

be a Weibull distribution with shape parameter β and scale parameter $\theta(u)$. We model the effect of preventive maintenance on the failure distribution through a change in the scale parameter. As a result, if a constant maintenance effort m is used over the life of the item, then the failure distribution is given by a Weibull distribution with shape parameter β and scale parameter θ_m.. The relationship between θ_m and θ_0 is assumed to be of the form

$$\theta_m = \theta_0\left(\frac{10}{10-m}\right)^{\gamma} \tag{18}$$

with $0 \leq m \leq 10$ and $\gamma > 0$. This implies that the expected number of failures in any interval decreases as the maintenance level increases. The expected lifecycle cost to the buyer over the life of an item and the expected warranty cost per unit to the manufacturer under the three options are as follows;

5.1 Buyer's Perspective

Let $W=2$, $L=5$, $\beta=3$, $\gamma=1$ and $\theta_0=0.5$. This implies that the mean time to first failure is 1.8 years. Also let $u_{\min}=0$, $u_1=0.5$, $u_2=2$, $u_{\max}=5$ and $\alpha=2$. We assume that m takes on only discrete values and W is in years and the unit for usage rate is 10^4㎞/*year*.

1. **Option A** : The number of expected failure during (W, L) under Option A

$$E[N_A(W,L)] = \theta_0\left(L^\beta - W^\beta\right) \times \sum_{i=1}^{k}\prod_{j=1}^{i}\left(\frac{1}{u_{j-1}}\right)^{(j-1)\beta}\frac{\Gamma(\alpha+i(i-1)\beta/2)}{\Gamma(\alpha)}\left[G\left(u_i;\alpha+\frac{i(i-1)\beta}{2}\right)-G\left(u_{i-1};\alpha+\frac{i(i-1)\beta}{2}\right)\right] \tag{19}$$

Then the buyer's expected life-cycle cost, $BELC_A(W, L)$ under Option A is given by equation(9) and equation(19).

2. **Option B** : The number of expected failure during (W, L) under Option B

$$E[N_B(W,L)] = \theta_m\left(L^\beta - W^\beta\right) \times \sum_{i=1}^{k}\prod_{j=1}^{i}\left(\frac{1}{u_{j-1}}\right)^{(j-1)\beta}\frac{\Gamma(\alpha+i(i-1)\beta/2)}{\Gamma(\alpha)}\left[G\left(u_i;\alpha+\frac{i(i-1)\beta}{2}\right)-G\left(u_{i-1};\alpha+\frac{i(i-1)\beta}{2}\right)\right] \tag{20}$$

Then the buyer's expected lifecycle cost, $BELC_B(W, L)$ under Option B is given by equation(12) and equation(20).

3. **Option C** : The number of expected failure during (W, L) under Option B

$$E[N_C(W,L)] = \left[\beta W^{\beta-1}\left(\theta_0{}^\beta - \theta_m{}^\beta\right)(L-W) + \theta_m{}^\beta\left(L^\beta - W^\beta\right)\right] \times \sum_{i=1}^{k}\prod_{j=1}^{i}\left(\frac{1}{u_{j-1}}\right)^{(j-1)\beta}\frac{\Gamma(\alpha+i(i-1)\beta/2)}{\Gamma(\alpha)}\left[G\left(u_i;\alpha+\frac{i(i-1)\beta}{2}\right)-G\left(u_{i-1};\alpha+\frac{i(i-1)\beta}{2}\right)\right] \tag{21}$$

Then the buyer's expected life-cycle cost, $BELC_C(W, L)$ under Option C is given by equation(15) and equation(21).

The results guess that for a low repair cost, the optimal decision is to choose no maintenance during the life of the item(Option A). For a medium repair cost, the optimal decision is to choose maintenance after the warranty period expired(Option C). For a higher repair cost, the optimal decision is to choose full maintenance(Option B). The decision which level of maintenance should be taken depend on the cost of the maintenance. But, in general, it is not possible to derive analytical expressions for the expected warranty costs. In this case, one needs to use some computational schemes to obtain cost estimates. Therefore, in this section, we discuss some special cases for which it is possible to derive analytical expressions.

5.2 Manufacturer's Perspective

Given that the failure distribution of the item is Weibull, then equation(16) for Options A and C becomes,

$$MEWC_A(W) = MEWC_C(W) = C_R(m)\theta_c W^{\beta} \times \sum_{i=1}^{k} \prod_{j=1}^{i} \left(\frac{1}{u_{j-1}}\right)^{(j-1)\beta} \frac{\Gamma(\alpha + i(i-1)\beta/2)}{\Gamma(\alpha)} \left[G\left(u_i; \alpha + \frac{i(i-1)\beta}{2}\right) - G\left(u_{i-1}; \alpha + \frac{i(i-1)\beta}{2}\right)\right] \tag{22}$$

and equation(17) for Option B becomes,

$$MEWC_B(W) = C_R(m)\theta_m W^{\beta} \times \sum_{i=1}^{k} \prod_{j=1}^{i} \left(\frac{1}{u_{j-1}}\right)^{(j-1)\beta} \frac{\Gamma(\alpha + i(i-1)\beta/2)}{\Gamma(\alpha)} \left[G\left(u_i; \alpha + \frac{i(i-1)\beta}{2}\right) - G\left(u_{i-1}; \alpha + \frac{i(i-1)\beta}{2}\right)\right] \tag{23}$$

The result guess that as the repair cost increases, the expected warranty cost per unit to the manufacturer increases and as the maintenance level increases, the expected warranty cost per unit decreases.

6. Conclusions

Products which are sold with warranty, preventive maintenance actions by manufacturers and buyers have a significant impact on the total costs for both parties. Also the product usage intensity across the buyer population varies and can model as a random variable in the cost analysis.

As mentioned earlier, the optimal decision of the buyer with regards to preventive maintenance depends on the parameter values of the model. A non-myopic buyer would choose between all three options whereas a myopic buyer would only choose between Options A and C. For a non-myopic buyer if Option B is the optimal strategy, then the buyer carries out preventive maintenance effort over the life of the item. This not only yields the lowest life cycle cost to the buyer but also results in a saving to the manufacturer. In contrast, a myopic buyer would choose Option C that does not result in a reduction in the cost to the manufacturer. In this case, the manufacturer might like to explore some incentive scheme (for example, monetary compensation) to induce the buyer to carry out preventive maintenance over the warranty period. As long as the cost of this is less than the savings in the manufacturers cost, it results in a win-win situation for both. However, the manufacturer needs to be aware of the resulting moral hazard problem the buyer might collect the compensation and not carry out the preventive maintenance actions over the warranty period when there is no way for the manufacturer to observe the actions of the buyer. With modern technology, in some cases it is possible for the manufacturer to observe the maintenance effort during warranty period by building in proper tamper proof data logging sensors and recorders. In this case, the manufacturer can modify the warranty policy so that the warranty period is extended from w to w_1 should the buyer carry out preventive maintenance during warranty period. This implies that non-myopic buyers are rewarded and myopic buyers tempted to carry out preventive maintenance over the warranty period through this inducement.

In this paper we develop warranty cost models for products sold with one-dimensional free replacement warranty considering heterogeneous usage intensity and different preventive maintenance actions across the buyer population.

References

[1] Blischke, W.R. and Murthy, D.N.P., (1994), Warranty Cost Analysis, Marcel Dekker, New York.

[2] Chun, Y.H., (1992), Optimal number of periodic preventive maintenance operations under warranty, Reliability Engineering and System Safety, 37, 223-225.

[3] Dekker, R., (1996), Applications of maintenance optimization models: A review and analysis.Reliability-Engineering-and-System-Safety, 51, 229-240.

[4] Dekker, R., Wildeman, R.E. and van der Duyn Schouten, F.A., (1997), A review of multi-component maintenance models with economic dependence, Mathematical Methods of Operations Research, 45, 411-35.

[5] Kim, C. S., I. Djamaludin and Murthy, D.N.P.,(2001), Warranty and Preventive Maintenance, International Journal of Reliability, Quality and Safety Engineering, Vol.8, No.2, 89-107

[6] Kim, C. S. and J.S, Kim(2001), Warranties for Products with Varying Usage Intensity, Journal of Industrial and Systems Engineering, Vol. 24, No. 64, 29-37

[7] Kim, C. S., I. Djamaludin and Murthy, D.N.P.,(2001), Warranty Cost Analysis with Heterogeneous Usage Intensity, International Transactions in Operational Research, Vol.8, No.3, 337-347

[8] Monga, A. & Zuo, M.J., (1998), Optimal system design considering maintenance and warranty, Computers Operations Research, 9, 691-705.

[9] Murthy, D.N.P., (1984), Optimal maintenance and sale date of a machine, International J. Systems Science 15, 277-292.

[10] Murthy, D.N.P. and Hwang, M.C., (1996), Optimal discrete and continuous maintenance policy for a complex unreliable machine, International Journal of System Science, v27, 483-495.

[11] Murthy, D.N.P. & Padmanabhan, V., (1999), A dynamic model of product warranty with consumer moral hazard, under preparation.

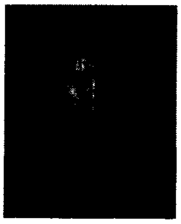
[12] Padmanabhan, V., (1995), Usage heterogeneity and extended warranty, Journal of Economics and Management Strategy, 4, 33-53.

[13] Pham, H. and Wang, H., (1996), Imperfect maintenance, European J. Operations Research 94, 425-438.

[14] Pintelon, L.M. and Gelders, L.F. (1992), Maintenance Management Decision Making, European Journal of Operational Research, 58, 301-317.

[15] Sahin, I. and Polatoglu, H., (1996), Maintenance strategies following the expiration of warranty, IEEE Transactions on Reliability, 45, 220-228.

[16] Sahin, I. and Polatoglu, H., (1996), Manufacturing Quality, Reliability and preventive maintenance, Production and Operations Management, 5, 132-147.



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