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An Integrated Approach Involving Reliability Improvement and Servicing Strategy For Warranted Products

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Abstract. *An additional cost caused by the product sold with warranty is significant and the cost is reported from 2% to 10% of sales price. Reducing the warranty cost is of important to the manufacturer. There are three approaches that can be considered to reduce the warranty cost i.e. reliability improvement, preventive maintenance, and warranty servicing strategy. Most models developed in the literature (called partial models) consider reliability improvement, preventive maintenance and warranty servicing strategy separately. As these approaches interact each other to influence the warranty cost, we need to consider them as an integrated one. In this paper we develop an integrated model considering two approaches i.e. reliability improvement and servicing strategy which minimizes the expected warranty cost. A numerical example is given to illustrate the optimal solution of the model developed and compares it with that of partial models.*

Keywords: *warranty cost, integrated model, reliability improvement and servicing strategy.*

1. INTRODUCTION

Warranty offered by the manufacturer provides a protection to the consumer but it causes an additional cost as the manufacturer has to rectify all failures under warranty. The warranty cost incurred to the manufacturer is significant and the amount varies from 2% to 10% of sales price (http://www.warrantyweek.com). To find an effective way for reducing the warranty cost is of important to the manufacturer.

There are three approaches which can be considered to manufacturers for reducing the warranty cost i.e. reliability improvement (RI), preventive maintenance (PM) and servicing strategy (SS) (Yun et.al.,2008). The costs depend on the reliability of a product and the warranty policy. The reliability influences the number of failures and hence RI can reduce the number of claims and this in turn decreases the warranty cost. Thomas and Richard (2006) studied RI for reducing the warranty cost. The number of failures can be reduced by performing a proper PM over the warranty period. The study of PM for the warranted products has been developed by Richtken and Fuh (1986), Chun and Lee (1992), and Jack and Dagpunar (1994). For repairable items, SS can minimize the warranty cost and this topic has been studied by Nguyen and Murthy (1986,1989), Jack and Schouten (2000) and Jack and Murthy (2001).

The studies of reducing the warranty cost in the literature consider approaches of RI, PM and SS independently. In fact, the approaches of RI, PM and SS interact each other in reducing the warranty cost. Reliability of a product influences PM required for the product and an optimal SS that minimizes the warranty cost. PM carried out also affects reliability of the product and this in turn determining a type of SS. SS which involves replacement and imperfect repair can also improve reliability of the product. As a result, one needs an integrated approach to reduce the warranty cost.

In this paper we develop an integrated model which considers RI and SS. The outline of this paper is organized as follows. Section 2 provides the notations to formulate the model. Section 3 explains the details of the integrated model. Section 4 analyzes the model to find the optimal solution. Section 5 gives a numerical example to illustrate the performance of the model and compares the results with that of partial models. Finally, Section 6 gives a brief conclusion and discussion for future work.

2. NOTATIONS

The following notations are used to formulate the mathematical models:

τ	:	parameter of SS as a decision variable $(0 < \tau \le W)$
$\hat{\theta}$	:	target of RI as decision variable where $(\theta_t < \hat{\theta} < \theta_0)$ or $(\theta_0 < \hat{\theta} < \theta_t)$
θ	:	reliability parameter as the indicator of item reliability
θ_0	:	initial value of reliability parameter
θ_t	:	parameter value of the highest reliability can be achieved by improving the parameter
W	:	warranty period (year)
C_m	:	average cost of each minimal repair ($)
C_r	:	average cost of each replacement ($, $C_r > C_m$)
ρ	:	cost ratio of replacement cost to minimal repair cost $[= C_r / C_m]$
$F(t;\theta)$	:	distribution function for time to first item failure as a function of time t with parameter θ
$f(t;\theta)$	:	density function related to $F(t;\theta)$ $[= dF(t,\theta)/dt]$
$r(t,\theta)$	:	failure rate function related to $F(t;\theta)$ $[= f(t;\theta)/\bar{F}(t;\theta)]$
$R(t;\theta)$	:	Cumulative failure rate related to $F(t;\theta)$ $[= \int_0^t r(u;\theta)du]$
$J_P(\theta_0,\hat{\theta})$	:	RI cost per unit sold for improving the parameter from θ_0 to $\hat{\theta}$ ($/unit)
$J_S(\tau,\hat{\theta})$	:	expected warranty cost per unit sold as a function of τ and $\hat{\theta}$ ($/unit)
$J_T(\tau,\hat{\theta})$	:	expected warranty cost per unit sold as a function of τ and $\hat{\theta}$ ($/unit)

3. MODEL FORMULATION

We consider repairable items sold with the warranty period W. Under this policy, the manufacturer has to rectify all claims at no cost to the buyer. We assumed that all failures within the warranty period are valid claims and the time to repair is small and hence can be treated as being zero.

3.1 Modeling Failures

The time to the first failure is modeled by a distribution function $F(t;\theta)$. The time of subsequent failures depends on the type of the rectification. If all failures are minimally repaired then the process of failures following the non-homogeneous Poisson process (NHPP) with the failure rate function $r(t;\theta)$.

3.2 Servicing Strategy

SS can be defined as a strategy to rectify each failure occurred within the warranty period. The simple SS only considers minimal repair whereas more complex SS can involve repair and replacement. The SS involving repair and replacement in the literature divides the warranty period into two intervals to three intervals for servicing the warranty. The SS with two intervals is conducted by Biedenwegs (1981) and Nguyen and Murthy (1986). The SS with three intervals has been studied by Nguyen and Murthy (1989), Jack and Schouten (2000) and Jack and Murthy (2001).

Nguyen and Murthy (1989) consider replacement in the first interval. SS where replacement is done either in early or close to the warranty period is not economical. Jack and Schouten (2000) considered minimal repairs in the first and third interval. In the second interval, the failed items are replaced by a new item depending on the age of the failed item. Although the SS yields the optimal solution but it is difficult to implement. Then Jack and Murthy (2001) have simplified it and only the first failure in the second interval results in replacement. The resulting solution is sub optimal but it is easy to implement (Jack et al.2009).

We describe the SS of Jack and Murhty (2001) as follows:

- The warranty period is divided into three intervals with parameter τ_1 and τ_2 where $0 \le \tau_1 \le \tau_2 \le W$ i.e. $[0,\tau_1]$, (τ_1,τ_2) and $[\tau_2, W]$.
- All failures in $[0,\tau_1]$ and $[\tau_2, W]$ are minimally repaired
- The first failure occurs in (τ_1,τ_2) is replaced with a new item and subsequent failures are always minimally repaired

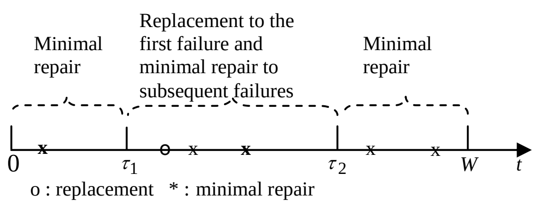

Figure 1: The SS of Jack and Murthy (2001)

Suppose that $J_s(\tau_1,\tau_2;\theta)$ is the expected warranty cost per unit sold. Jack and Murthy (2001) have derived $J_s(\tau_1,\tau_2;\theta)$ and it is given in Equation (1).

$$J_S(\tau_1,\tau_2;\theta) = C_m \cdot \left\{ R(\tau_1;\theta) + \int_{\tau_1}^{\tau_2} \left(\rho + R(W-x;\theta)\right) \frac{f(x;\theta)}{\overline{F}(\tau_1;\theta)} dx + \left[R(W;\theta) - R(\tau_2;\theta)\right] \frac{\overline{F}(\tau_2;\theta)}{\overline{F}(\tau_1;\theta)} \right\} \quad (1)$$

We consider the SS of Jack and Murthy (2001) in developing the integrated model. Furthermore, we set $\tau_1 = \tau$ and $\tau_2 = W$. Hence, the warranty period is divided into two intervals i.e. $[0,\tau]$ and $(\tau, W]$. Let $\hat{\theta}$ denote the reliability parameter. Then, the expected warranty cost is a function of τ and $\hat{\theta}$ and it is given by

$$J_S(\tau,\hat{\theta}) = C_m \left(.R(\tau,\hat{\theta}) + \int_{\tau}^{W} \left(\rho + R(W-x,\hat{\theta})\right) \frac{f(x,\hat{\theta})}{\overline{F}(\tau,\hat{\theta})} dx \right) \quad (2)$$

3.3 Reliability Improvement

RI is defined as an effort to improve the reliability of items which can minimize the warranty cost. Let θ_0 denote the initial reliability parameter. The RI can be performed by improving the reliability parameter from θ_0 to $\hat{\theta}$. The RI can be done by either increasing or decreasing of the parameter value depending on the characteristic of the reliability parameter. If failure distribution is given by Weibull distribution, $\hat{\theta} > \theta_0$ for the scale parameter and $\hat{\theta} < \theta_0$ for the shape parameter.

The RI requires cost which is called the RI cost. For the manufacturer, the RI is considered only if the reduction of the warranty cost exceeds the RI cost. Various models of the cost function of RI have been proposed by Vintr (1999), Murthy and Khumar (2000), Kleyner et. al. (2004) and Huang et al.(2007). We consider the cost model of Huang et.al.(2007). The RI cost increases exponentially as the improvement of reliability increases. Suppose that the RI cost is $J_p(\theta_o,\hat{\theta})$ given by:

$$J_P(\theta_0,\hat{\theta}) = \begin{cases} a + b\exp\left(k \dfrac{\theta_0 - \hat{\theta}}{\hat{\theta} - \theta_t}\right) & for \quad \theta_t < \hat{\theta} < \theta_0 \\ a + b\exp\left(k \dfrac{\hat{\theta} - \theta_0}{\theta_t - \hat{\theta}}\right) & for \quad \theta_0 < \hat{\theta} < \theta_t \end{cases} \quad (3)$$

where a is a fixed cost per unit, b is a coefficient cost of changing the parameter value per unit and k is a technology factor, $a,b,k > 0$.

3.4 Integrating RI and SS

We describe an integrated model involving RI and SS as follows. The performance measure of the integrated model is the total cost which is defined as sum of the warranty cost and the RI cost. Suppose that the total cost per unit sold is $J_T(\tau,\hat{\theta})$ given by:

$$J_T(\tau,\hat{\theta}) = J_S(\tau,\hat{\theta}) + J_p(\theta_o,\hat{\theta}) \quad (4)$$

where $J_S(\tau,\hat{\theta})$ is given by Equation (2) and $J_p(\theta_o,\hat{\theta})$ is given by Equation (3). The decision variables of the model are τ and $\hat{\theta}$.

4. MODEL ANALYSIS

We obtain τ^* and $\hat{\theta}^*$ which minimize $J_T(\tau,\hat{\theta})$ subject to $0 < \tau \le W$ and $\theta_t < \hat{\theta} < \theta_0$. Theorem 1 and 2 give the characteristics of τ^* and $\hat{\theta}^*$. Theorem 1 is adopted from the theorem of Jack and Murthy (2001).

Theorem 1

If a repairable item has the increasing failure rate with t then:

i. If $1 < \rho < 1 + R(W,\hat{\theta}) - 2R(W/2,\hat{\theta})$ then there is $\tau^* = d$ where $d \in [0, W/2)$ hence $J_s(d,\hat{\theta}) < C_m R(W,\hat{\theta})$

ii. If $\rho > 1 + R(W,\hat{\theta}) - 2R(W/2,\hat{\theta})$ then $\tau^* = W$ and the optimal servicing strategy is always minimally repaired for all failures and hence $J_s(W,\hat{\theta}) = C_m R(W,\hat{\theta})$.

The proof of the Theorem 1 is given in Jack and Murthy (2001).

We will show that $J_T(\tau,\hat{\theta})$ is a convex function of $\hat{\theta}$. By differentiating $J_T(\tau,\hat{\theta})$ with respect to $\hat{\theta}$, we have

$$\frac{\partial J_T(\tau,\hat{\theta})}{\partial\hat{\theta}} = C_m \left(\frac{\partial}{\partial\hat{\theta}} \left(J_s(\tau,\hat{\theta})\right) - \eta\phi(\hat{\theta}) \right) \quad (5)$$

and

$$\frac{\partial^2 J_T(\tau,\hat{\theta})}{\partial\hat{\theta}^2} = C_m \left(\frac{\partial^2}{\partial\hat{\theta}^2} \left(J_s(\tau,\hat{\theta})\right) + \eta\psi(\hat{\theta})\phi(\hat{\theta}) \right) \quad (6)$$

where $\eta = b / C_m$, $\phi(\hat{\theta}) = k \dfrac{\theta_0 - \theta_t}{\left(\hat{\theta} - \theta_t\right)^2} \exp\left(k \dfrac{\theta_0 - \hat{\theta}}{\hat{\theta} - \theta_t}\right)$

and $\psi(\hat{\theta}) = \dfrac{1}{\left(\hat{\theta} - \theta_a\right)} \left(2 + k \dfrac{\theta_0 - \hat{\theta}}{\left(\hat{\theta} - \theta_t\right)}\right)$.

Since $\phi(\hat{\theta}) > 0$ and $\psi(\hat{\theta}) > 0$ for $\hat{\theta} \in (\theta_t, \hat{\theta}_0)$ then the parameter $\hat{\theta}^*$ is obtained if and only if $\frac{\partial J_T(\tau,\hat{\theta})}{\partial\hat{\theta}}=0$ or $\frac{\partial}{\partial\hat{\theta}}J_S(\tau,\hat{\theta})>0$. We find $\hat{\theta}^*$ by using Theorem 2 as follows:

Theorem 2
If the larger (smaller) of $\hat{\theta}$ produces the worse (better) reliability of an item then:
If $\hat{\theta}_2>\hat{\theta}_1 \Leftrightarrow f(x,\theta_2)>f(x,\theta_1)$ then $J_s(\tau,\hat{\theta}_2)>J_s(\tau,\hat{\theta}_1)$ and hence $\frac{\partial}{\partial\hat{\theta}}J_S(\tau,\hat{\theta})>0$. As a result, there exists $\hat{\theta}\in(\theta_t,\theta_0)$ hence $J_s(\tau,\hat{\theta})$ is a convex function of $\hat{\theta}$.

Proof:

If $\hat{\theta}_2>\hat{\theta}_1$ then from Equation (2) we have

$$R(\tau,\hat{\theta}_2)+\int_\tau^W\left(\rho+R(W-x,\hat{\theta}_2)\right)\frac{f(x,\hat{\theta}_2)}{\bar{F}(\tau,\hat{\theta}_2)}dx>R(\tau,\hat{\theta}_1)+\int_\tau^W\left(\rho+R(W-x,\hat{\theta}_1)\right)\frac{f(x,\hat{\theta}_1)}{\bar{F}(\tau,\hat{\theta}_1)}dx \quad (7)$$

Equation (7) can be rewritten as (8).

$$R(\tau,\hat{\theta}_2)-R(\tau,\hat{\theta}_1)+\int_\tau^W\left(\rho+R(W-x,\hat{\theta}_2)\right)\frac{f(x,\hat{\theta}_2)}{\bar{F}(\tau,\hat{\theta}_2)}dx-\int_\tau^W\left(\rho+R(W-x,\hat{\theta}_1)\right)\frac{f(x,\hat{\theta}_1)}{\bar{F}(\tau,\hat{\theta}_1)}dx>0 \quad (8)$$

Since $R(\tau,\hat{\theta}_2)-R(\tau,\hat{\theta}_1)>0$ then Equation (8) is satisfied by

$$\int_\tau^W\left(\rho+R(W-x,\hat{\theta}_2)\right)\frac{f(x,\hat{\theta}_2)}{\bar{F}(\tau,\hat{\theta}_2)}dx-\int_\tau^W\left(\rho+R(W-x,\hat{\theta}_1)\right)\frac{f(x,\hat{\theta}_1)}{\bar{F}(\tau,\hat{\theta}_1)}dx>0 \quad (9)$$

Equation (9) holds when $x=c$, c is a constant and $c\in[\tau,W]$. Then we have

$$\left(\rho+R(W-c,\hat{\theta}_2)\right)\frac{f(c,\hat{\theta}_2)}{\bar{F}(c,\hat{\theta}_2)}-\left(\rho+R(W-c,\hat{\theta}_1)\right)\frac{f(c,\hat{\theta}_1)}{\bar{F}(c,\hat{\theta}_1)}>0 \quad (10)$$

or

$$\left(\frac{\rho+R(W-c,\hat{\theta}_2)}{\rho+R(W-c,\hat{\theta}_1)}\right)\left(\frac{\bar{F}(\tau,\hat{\theta}_1)}{\bar{F}(\tau,\hat{\theta}_2)}\right)\left(\frac{f(c,\hat{\theta}_2)}{f(c,\hat{\theta}_1)}\right)>1 \quad (11)$$

Since $R(W-c,\hat{\theta}_2)>R(W-c,\hat{\theta}_1)$ and $\bar{F}(\tau,\hat{\theta}_1)>\bar{F}(\tau,\hat{\theta}_2)$ then Equation (11) is satisfied if and only if $f(c,\hat{\theta}_2)>f(c,\hat{\theta}_1)$.

5. NUMERICAL EXAMPLES

We consider that $F(t;\cdot)$ is Weibull with scale and shape parameter, α and β respectively. We consider the shape parameter for improving the reliability with $\theta=\beta$ at $\theta_0=2$ and $\alpha=1$ and hence the distribution function is given by $F(t;2,1)=1-\exp(-t^2)$. We assume that $C_m=\$100$, $\theta_{\min}=1.5$, $\hat{a}=0.05$ and $k=1.1$. To show the performance of the integrated model we consider four strategies for reducing the warranty cost.

Strategy 0: All failures under warranty are minimally repaired

In this strategy, the value of the reliability parameter is equal to the initial value $\hat{\theta}=\theta_0$ and $\tau=W$. The total cost of this strategy is given by

$$J_T(\tau,\hat{\theta})=C_m.R(W,\theta_0) \quad (12)$$

Strategy 1: Using the SS of Jack and Murthy (2001)

In this strategy, we use the SS of Jack and Murthy (2001) as we discussed it in Section 3.2. The total cost is a function of variable τ at $\hat{\theta}=\theta_0$ and it is given by Equation (2).

Strategy 2: Improving the reliability and All failures under warranty are minimally repaired

In this strategy, we use the approach of RI by decreasing the parameter from θ_0 to $\hat{\theta}$. The total cost is a function of $\hat{\theta}$ at $\tau=W$ and it is given by

$$J_T(W,\hat{\theta})=C_m\left[\hat{a}+\eta\exp\left(k\frac{\theta_0-\hat{\theta}}{\hat{\theta}-\theta_t}\right)+R(W,\hat{\theta})\right] \quad (13)$$

where $\hat{a}=a/C_m$.

Strategy 3 : Integrating the RI and the SS of Jack and Murthy (2001)

In this strategy, RI and SS are considered simultaneously as discussed in Section 3.4. The total cost is a function of variables τ and $\hat{\theta}$ and it is given by Equation (4).

Table 1 shows the total cost of the Strategy 0,1,2 and 3 for $\rho=2$, $\eta=0.1$.

Table 1: The total cost of Strategy 0,1,2 and 3 for $\rho=2$, $\eta=0.1$, $\theta_0=2$ and $W=3$

Strategy	τ^*(year)	$\hat{\theta}^*$	$J_T(\tau^*,\hat{\theta}^*)$
0	3	2	900
1	1.212	2	566.6
2	3	1.70	704.4
3	1.146	1.78	556.2*

In Table 1, the Strategy 3 yields the least total cost. The integrated model (Strategy 3) is the best compared to those of other strategies in reducing the warranty cost. Table 2 gives the total cost of the Strategy 3 for various values of the ρ and η i.e. $\rho = \{2,3,5\}$ and $\eta = \{0.1,0.3\}$.

Table 2: The total cost of the Strategy 3 for $\rho = \{2,3,5\}$, $\eta = \{0.1,0.3\}$ $\theta_0 = 2$ an $W = 3$

η	ρ	τ^* (year)	$\hat{\theta}^*$	$J_T(\tau^*, \hat{\theta}^*)$
	2	1.146	1.778	556.2
0.1	3	1.149	1.776	655.8
	5	3	1.700	704.4
	2	1.175	1.870	592.3
0.5	3	1.178	1.870	692.2
	5	3	1.753	778.9

Table 2 indicates that the optimal value of parameters of τ and $\hat{\theta}$ are affected by the values of ρ and η. The total cost increases as the value of ρ or η increases.

6. CONCLUSION

In this paper, we have studied an integrated strategy involving reliability improvement and servicing strategy which minimizes the total cost i.e. the sum of the RI cost and SS cost (warranty cost). From the numerical examples, the integrated model provides the least total cost than those of other models.

An integrated model which considers preventive maintenance actions is interesting to research and this topic is under investigating.

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