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SERVICING STRATEGY INVOLVING PREVENTIVE MAINTENANCE FOR PRODUCTS SOLD WITH LONGER WARRANTY PERIOD

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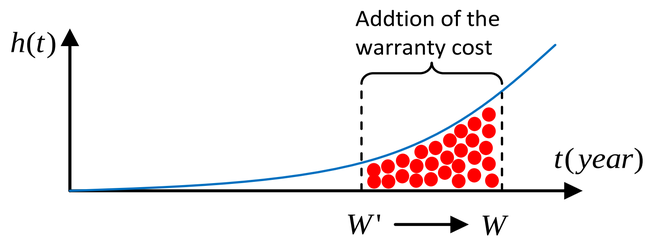
Context:

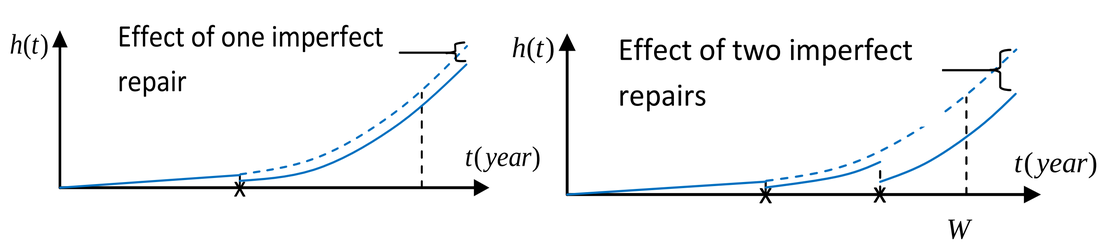
- Repairable products sold with longer warranty period in one-dimensional warranty.
- Servicing strategy involving imperfect repair and preventive maintenance to minimize the warranty cost

1. Introduction

- Nowdays, a lot of manufacturers tend to offer longer warranty period in order to increase their product competiveness.
- Lengthening the warranty period would increase the warranty cost.
- Effect of the longer warranty period from W' to W :



- Various servicing strategies have been proposed in the literature. The best servicing strategy is a servicing strategy that involves imperfect repair and this is proposed by Yun et.al. (2008). This strategy only allows one imperfect repair over the warranty period.
- For a longer warranty period, more imperfect repair would be needed in order to reduce the number of failures over the warranty period.
- Effect of imperfect repairs more than one :



- The servicing strategies which allow more than one imperfect repairs have been proposed by Varnosafaderani and Chukova (2012) for two-dimensional and Makmoen et.al. (2012) for one-dimensional but they do not involve preventive maintenance
- This research proposes a servicing strategy that allows more than imperfect repair with incoperates imperfect preventive maintenance (PM). The number of imperfect maintenances during the warranty period is at most N times, where N=2.

2. Three servicing strategies for $N=2$

Strategy 1 (Makmoen et. al., 2012)	**Strategy 2** (Strategy proposed)	**Strategy 3** (Strategy of Varnosafaderani and Chukova (2012) for one-dimensional case)
Imperfect repair with improvement level δ is done at failure (at time $t, 0 < t \le W' \le W$) if the elapsed time since the last imperfect repair (or the beginning of the operation, $t = 0$) is greater than τ (a threshold value). All other failures are fixed by minimal repair. As a result, this servicing strategy allows more than one imperfect repair.	The warranty period is divided by five intervals i.e. $(0, S_1], (S_1, W_1], (W_1, S_2], (S_2, W_2]$ and $(W_2, W]$. Each first failure in $(S_1, W_1]$ or $(S_2, W_2]$ is imperfectly repair with improvement level δ and all other failures are minimally repaired. When there is no failure in interval $(S_1, W_1]$ ($(S_2, W_2]$) then PM improvement level δ is done at W_1 (W_2).	The warranty period is divided by four intervals i.e. $(0, W_1], (W_1, W_2], (W_2, W_3]$ and $(W_3, W]$. Each first failure in interval is imperfectly repaired with improvement level δ and other failures are minimally repaired.
Total Cost $J_1(\delta,\tau,W') =$ $c_m[H(\tau)+H(W)-H(W')]\exp[H(\tau)-H(W')]+$ $\int_{W'-\tau}^{W'}\{c_{im}(\delta)+c_m[H(\tau)+H_1(W)-H_1(z_1)]\}\,h(z_1)\exp[H(\tau)-H(z_1)]dz_1+$ $\int_{\tau}^{W'-\tau}\{c_{im}(\delta)+c_m[H(\tau)+H_1(z_1+\tau)-H_1(z_1)+H_1(W)-H_1(W')]\}$ $\exp[H_1(z_1+\tau)-H(W')]h(z_1)\exp[H(\tau)-H(z_1)]dz_1+$ $\int_{\tau}^{W'-\tau}\int_{z_1+\tau}^{W'}\{2c_{im}(\delta)+c_m[H(\tau)+H_1(z_1+\tau)-H_1(z_1)+$ $H_2(W)-H_2(z_2)]\}h_1(z_2)\exp[H_1(\tau+z_1)-H_1(z_2)]$ $h(z_1)\exp[H(\tau)-H(z_1)]dz_2dz_1.$	**Total Cost** $J_2(\delta,S_1,S_2,W_1,W_2) =$ $c_mH(S_1)+\int_{S_1}^{W_1}\int_{S_2}^{W_2}\{2c_{im}(\delta)+c_m[H_1(S_2)-H_1(z_1)+H_2(W)-H_2(z_2)]\}$ $h(z_1)\exp[H(S_1)-H(z_1)]h_1(z_2)\exp[H_1(S_2)-H_1(z_2)]dz_2dz_1+$ $\int_{S_1}^{W_1}\left(c_{im}(\delta)+c_{ip}(\delta)+c_mH_1(S_2)-H_1(z_1)+H_2(W)-H_2(z_2)\right)$ $\exp[H_1(S_2)-H_1(W_2)]h(z_1)\exp[H(S_1)-H(z_1)]dz_1+$ $\int_{S_2}^{W_2}\left(c_{im}(\delta)+c_{ip}(\delta)+c_m[H_1(S_2)-H_1(W_1)+H_2(W)-H_2(z_2)]\right)$ $\exp[H(S_1)-H(W_1)h_1(z_2)\exp[H_1(S_2)-H_1(z_2)]dz_2+$ $(2c_{ip}(\delta)+c_m(H_1(S_2)-H_1(W_1)+H_2(W)-H_2(W_2)))\exp[H(S_1)-H(W_1)$ $\exp[H_1(S_2)-H_1(W_2).$	**Total Cost** $J_3(\delta,W_1,W_2,W_3) =$ $c_m[H(W_1)+H(W)-H(W_3)]\exp[H(W_1)-H(W_3)]+$ $\int_{W_2}^{W_1}\{c_1(\delta)+c_m[H(W_1)+H_1(W)-H_1(z_1)]\}h(z_1)$ $\exp[H(W_1)-H(z_1)]dz_1+$ $\int_{W_1}^{W_2}\{c_1(\delta)+c_m[H(W_1)+H_1(W_2)-H_1(z_1)+H(W)-H_1(W_3)]\}$ $\exp[H_1(W_2)-H_1(W_3)]h(z_1)\exp[H(W_1)-H(z_1)]dz_1+$ $\int_{W_1}^{W_2}\int_{W_2}^{W_3}\{2c_1(\delta)+c_m[H(W_1)+H_1(W_2)-H_1(z_1)+H_2(W)-H_2(z_2)]\}$ $h_1(z_2)\exp[H_1(W_2)-H_1(z_2)]h_1(z_1)\exp[H(W_1)-H(z_1)]dz_2dz_1$

3. Numerical Example

- The failure distribution following Weibull distribution with two parameters - α and β
- The nominal parameter values : $\alpha = 1$ (year), $\beta = 2$, $c_m = 1$ and $W = 7$ years
- The cost of imperfect repair : $c_{im}(\delta) = c_m + (c_p - c_m)\delta^4$ (Yun et. al., 2008)

Results

- Effect of the value of $r = c_{ip}(\delta)/c_{im}(\delta)$ to the optimal solutions for Strategy 2

TABLE 1. THE OPTIMAL SOLUTIONS FOR STRATEGY 2 , $r = \{0.9, 0.7, 0.5\}$

r	$c_{ip}(\delta^*)$	$c_{im}(\delta^*)$	δ^*	S_1^*	W_1^*	S_2^*	W_2^*	J_2^*
0.9	3.18	3.53	0.84	2.27	3.48	4.35	5.54	25.111
0.7	3.36	4.80	0.93	2.39	2.39	4.61	4.61	24.530
0.5	3.00	6.00	1.00	2.33	2.33	4.67	4.67	22.333

$J_2^* = J_2^*(\delta^*, S_1^*, S_2^*, W_1^*, W_2^*)$

Remarks:
J_2^* decreases as r decreases. Decreasing r shows the cost of imperfect PM is getting smaller.
$S_1(S_2)$ approaches $W_1(W_2)$ when r decreases. This is so as imperfect PM cost is cheaper than that of imperfect repair.

- We compare the performances of all servicing strategies for a various of α (= representing the reliability of product) at $r = 0.5$

TABLE 2. RESULTS OF STRATEGY 1, 2 AND 3

α	MTTF	J_1^*	J_2^*	J_3^*
1.0	0.89	25.176	22.333	25.111
2.0	1.77	8.201	8.055	8.147
3.0	2.66	4.175	4.189	4.205
4.0	3.54	2.559	2.752	2.596

$J_1^* = J_1^*(\delta^*, \tau^*, W'^*)$, $J_3^* = J_3^*(\delta^*, W_1^*, W_2^*, W_3^*)$

Remarks :
- $\alpha = 1$ and $\alpha = 4$ represents the lowest and highest product reliability, respectively.
- Strategy 1 is the best for the high reliability ($\alpha = 3$ and $\alpha = 4$)
- Strategy 2 (proposed strategy) is the best strategy for the product with low reliability ($\alpha = 1$ and $\alpha = 2$) This strategy becomes the best strategy if the cost of PM is relatively small and the reliability of the product is low.
- When PM has not been considered, Strategy 3 is the best strategy for products with low reliability.

4. Conclusion

- We have studied a servicing strategy which incorporates PM for products sold with a long warranty period.
- The servicing strategy proposed is suitable to be used if the cost of PM is relatively small and the reliability of the product is low.
- The strategy can be extend to two dimensional warranty case and this topic is currently under investigation.

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