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Research Paper

STOCHASTIC ANALYSIS OF A RELIABILITY MODEL OF ONE-UNIT SYSTEM WITH POST INSPECTION, POST REPAIR, PREVENTIVE MAINTENANCE AND REPLACEMENT

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Profit analysis of a reliability model for one-unit system with post inspection, post repair, preventive maintenance and replacement has been presented. Expressions for reliability measures are obtained by using semi-Markov processes and regenerative point technique. Graphical study is made and cut-off points for various rates/costs to study the economic aspect have been obtained.

Keywords: Reliability engineering, Preventive maintenance, Inspection, Repair, Semi-markov processes, Regenerative point technique, Post inspection, Post repair, Failure, Measures of the system effectiveness

INTRODUCTION

One unit system under different failures and repair possibility has been extensively studied in the field of reliability by a large number of researchers under various assumptions. Gopalan and Muralidhar (1991) have discussed Cost analysis of a one unit repairable system subject to on-line preventive maintenance and/or repair. Tuteja and Taneja (1993) analysed Profit analysis of a one-server one-unit system with partial failure and subject to random inspection. Gurov and Utkin (1995) have considered Reliability and optimization of systems with periodic modifications in the probability and possibility contexts. Sehgal (2000) has analysed the study of some reliability models with partial failure, accidents and various types of repair. Tuteja *et al.* (2001) have analysed cost benefit analysis of a system where operation and sometimes repair of main-unit depends on sub-unit. Taneja *et al.* (2001) have discussed Reliability and profit analysis of a system with an ordinary and an expert repairman wherein the latter may not always be available. Naveen (2002) has discussed some problems on reliability model

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and life testing procedures. Taneja *et al.* (2004) have analysed Profit evaluation of a system wherein instructions imply perfect repair. Taneja *et al.* (2004) discussed Profit analysis of a single unit Programmable Logic Controller (PLC). Rizwan *et al.* (2005) have given the concept of accident during inspection. Said, Kh and El-Sherbeny (2005) have analysed Profit analysis of a two unit cold standby system with preventive maintenance and random change in units. But they have not consider the post repair and post inspection and preventive maintenance.

Keeping this in view, the present problem aims at studying single-unit system with post inspection, post repair and preventive maintenance.

A single repair facility is used to repair and post repair the failed unit. After the repair, the unit is sent for inspection to decide whether the repair is satisfactory. In case the repair is found unsatisfactory then unit is again sent for post inspection and post repair. The post repair is needed only when the repair of the failed unit is found unsatisfactory on inspection. Expressions for reliability measures are obtained by using semi-Markov processes and regenerative point technique.

This paper is organized as follows: briefly mentioned all sections and subsection.

A new model and transition probabilities and mean Sojourn Times has been developed and they are given below:

- Mean Time to System Failure
- Availability Analysis
- Busy Period Analysis of the Repairman (Repair and post repair time only)
- Busy Period Analysis of the Repairman (Inspection and post inspection time only)
- Expected Number of Visits by the Repairman
- Expected Number of Preventive Maintenance
- Busy Period Analysis of Replacement Time Only
- Expected Number of Replacement
- Profit Analysis
- Particular Case

The assumptions for the proposed model are given below:

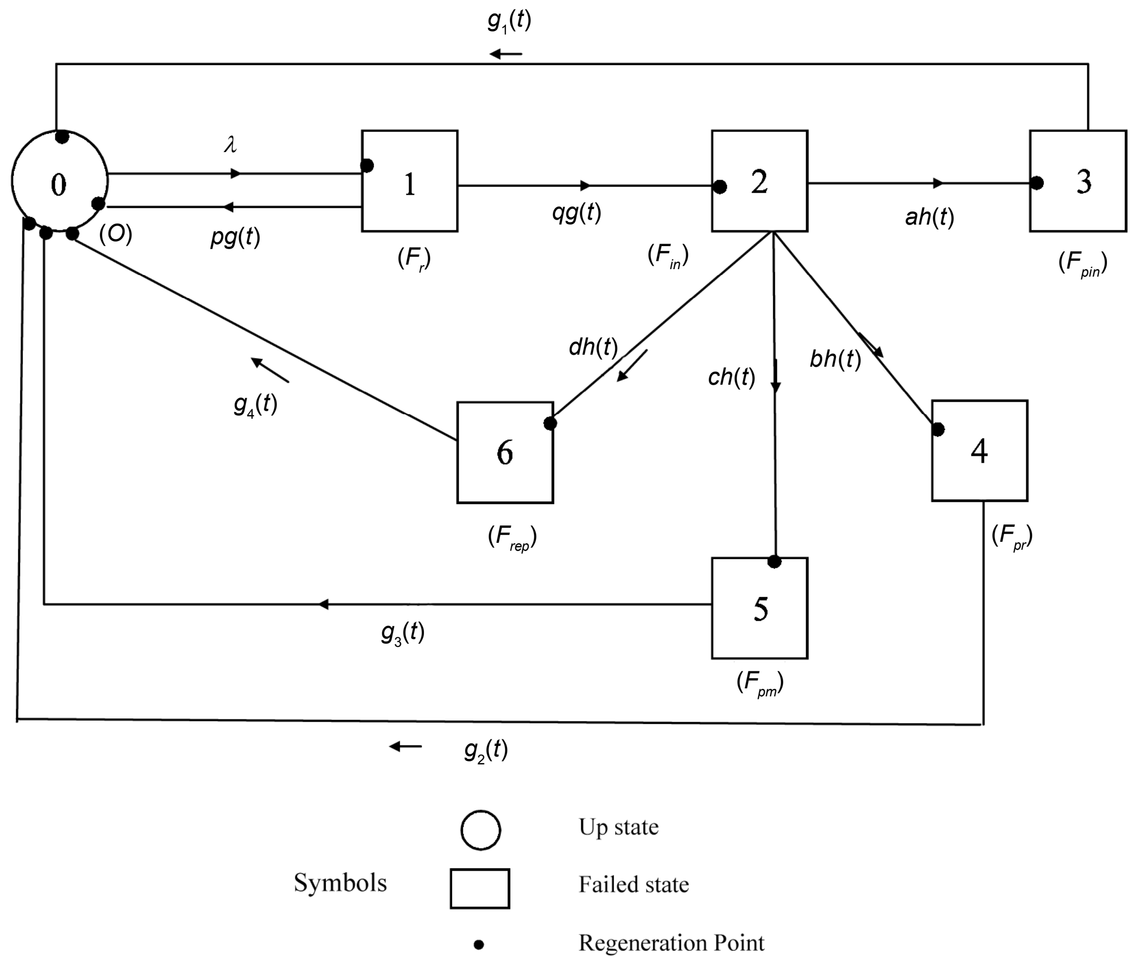
- In one-unit system, unit is operative initially.
- The system becomes inoperable on the failure of the unit in one-unit system.
- All the random variables are independent.
- The failure times are assumed to be exponentially.
- The failures are self announcing and switching is perfect and instantaneous.
- If the repair of the unit is not feasible, it is replaced by new one.

MODEL FORMULATION

Transition Probabilities and Mean Sojourn Times

The state transition diagram is shown as in Figure 1. States 1, 2, 3, 4, 5 and 6 are failed states. The epochs of entry into states 0, 1, 2, 3, 4, 5 and 6 are regeneration points and thus all the states are regenerative states.

Figure 1: Reliability Model of One Unit System with Post Inspection, Post Repair



The transition probabilities are given by

$q_{01}(t) = \lambda e^{-\lambda t}$; $q_{10}(t) = pg(t)$; $q_{12} = qg(t)$

$q_{23}(t) = ah(t)$; $q_{24}(t) = bh(t)$; $q_{25}(t) = ch(t)$;

$q_{26}(t) = dh(t)$; $q_{30}(t) = g_1(t)$; $q_{40}(t) = g_2(t)$;

$q_{50}(t) = g_3(t)$; $q_{60}(t) = g_4(t)$ ...(1-11)

The non-zero elements $p_{ij} = \lim_{s \to 0} q_{ij}^*(s)$ are:

$p_{01} = 1$, $p_{10} = p$, $p_{12} = q$, $p_{23} = a$, $p_{24} = b$, $p_{25} = c$, $p_{26} = d$, $p_{30} = 1$, $p_{40} = 1$, $p_{50} = 1$, $p_{60} = 1$ ...(12-20)

By these probabilities, it can be verified that

$p_{10} + p_{12} = 1$, $p_{23} + p_{24} + p_{25} + p_{26} = 1$ ...(21-22)

Also μ_i, the mean sojourn time in state i are:

$$\mu_0 = \frac{1}{\lambda},\ \mu_1 = \int_0^\infty \overline{G}(t)dt = g^{*\prime}(0)$$

$$\mu_2 = \int_0^\infty \overline{H}(t)dt = h^{*\prime}(0)$$

$$\mu_3 = \int_0^\infty \overline{G_1}(t)dt = g_1^{*\prime}(0)$$

$$\mu_4 = \int_0^\infty \overline{G_2}(t)dt = g_2^{*\prime}(0)$$

$$\mu_5 = \int_0^\infty \overline{G_3}(t)dt = g_3{}^{*\prime}(0)$$

$$\mu_6 = \int_0^\infty \overline{G_4}(t)dt = g_4{}^{*\prime}(0) \quad \text{...(23-29)}$$

The unconditional mean time taken by the system to transit for any state j when it has taken from epoch of entrance into regenerative state i is mathematically stated as:

$$m_{ij} = \int_0^\infty t dQ_{ij}(t) = -\left[\frac{d}{ds} q_{ij}{}^*(s)\right]_{s=0} \quad \text{...(30)}$$

Thus,

$m_{01} = \mu_0$, $m_{10} + m_{12} = \mu_1$, $m_{23} + m_{24} + m_{25} + m_{26} = \mu_2$

$m_{30} = \mu_3$, $m_{40} = \mu_4$, $m_{50} = \mu_5$, $m_{60} = \mu_6$ ...(31-37)

Mean Time to System Failure

By probabilistic arguments, we obtain the following recursive relation for $\phi_i(t)$:

$\phi_0(t) = Q_{01}(t)$ ...(38)

Taking Laplace-Stieltjes Transforms (L.S.T.) of above relation and solving for $\phi_0{}^{**}(s)$, the mean time to system failure when the system starts from the state '0' is given by

$$T_0 = \lim_{s \to 0} \frac{1 - \phi_0{}^{**}(s)}{s} = \mu_0 \quad \text{...(39)}$$

Availability Analysis

Using the arguments of the theory of regenerative processes, the availability $A_i(t)$ is seen to satisfy the following recursive relations:

$A_0(t) = M_0(t) + q_{01}(t) \copyright A_1(t)$

$A_1(t) = q_{10}(t) \copyright A_0(t) + q_{12}(t) \copyright A_2(t)$

$A_2(t) = q_{23}(t) \copyright A_3(t) + q_{24}(t) \copyright A_4(t) + q_{25}(t) \copyright A_5(t)$

$A_3(t) = q_{30}(t) \copyright A_0(t)$

$A_4(t) = q_{40}(t) \copyright A_0(t)$

$A_5(t) = q_{50}(t) \copyright A_0(t)$

$A_6(t) = q_{60}(t) \copyright A_0(t)$ ...(40-46)

where,

$M_0(t) = e^{-\lambda t}$ ...(47)

Taking Laplace Transforms (L.T.) of the above equations and solving for $A_0{}^*(s)$, we get

$$A_0{}^*(s) = \frac{N_1(s)}{D_1(s)} \quad \text{...(48)}$$

where, $N_1(s) = M_0{}^*(s)$

$D_1(s) = 1 - q_{01}{}^*(s)\ [q_{10}{}^*(s) + q_{12}{}^*(s)\ \{q_{23}{}^*(s)q_{30}{}^*(s) + q_{24}{}^*(s)_{q40}{}^*(s) + q_{25}{}^*(s)\ q_{50}{}^*(s) + q_{26}{}^*(s)q_{60}{}^*(s)\}]$ ...(49-50)

In steady state, the availability of the system is given by

$$A_0 = \lim_{s \to 0} sA_0{}^*(s) = N_1 / D_1 \quad \text{...(51)}$$

where, $N_1 = \mu_0$

and $D_1 = \mu_0 + \mu_1 + q(\mu_2 + a\mu_3 + b\mu_4 + c\mu_5 + d\mu_6)$ ...(52-53)

Busy Period Analysis of the Repairman (Repair and Post Repair Time Only)

By probabilistic arguments, we have the following recursive relation for $B_i(t)$:

$B_0(t) = q_{01}(t) \copyright B_1(t)$

$B_1(t) = W_1(t) + q_{10}(t) \copyright B_0(t) + q_{12}(t) \copyright B_2(t)$

$B_2(t) = q_{23}(t) \copyright B_3(t) + q_{24}(t) \copyright B_4(t) + q_{25}(t) \copyright B_5(t)$

$B_3(t) = q_{30}(t) \copyright B_0(t)$

$B_4(t) = q_{40}(t) \copyright B_0(t)$

$B_5(t) = q_{50}(t) © B_0(t)$

$B_6(t) = q_{60}(t) © B_0(t)$ ...(54-60)

where $W_1(t) = \bar{G}(t)$ ...(61)

Taking Laplace Transforms of the above equations and solving them for $B_0^*(s)$, we get

$$B_0^*(s) = \frac{N_2(s)}{D_1(s)} \quad ...(62)$$

where, $N_2(s) = W_1^*(s)q_{01}^*(s)$ ...(63)

In steady-state, the total fraction of time which the system is under repair of the repairman, is given by

$$B_0 = \lim_{s \to 0} sB_0^*(s) = N_2 / D_1 \quad ...(64)$$

where, $N_2 = \mu_1$ ...(65)

and D_1 is already specified.

Busy Period Analysis of the Repairman (Inspection and Post Inspection Time Only)

By probabilistic arguments, we have the following recursive relations for $IT_i(t)$:

$IT_0(t) = q_{01}(t) © IT_1(t)$

$IT_1(t) = q_{10}(t) © IT_0(t) + q_{12}(t) © IT_2(t)$

$DT_2(t) = W_2(t) + q_{23}(t) © IT_3(t) + q_{24}(t) © IT_4(t) + q_{25}(t) © IT_5(t) + q_{26}(t) © IT_6(t)$

$IT_3(t) = q_{30}(t) © IT_0(t)$

$IT_4(t) = q_{40}(t) © IT_0(t)$

$IT_5(t) = q_{50}(t) © IT_0(t)$

$IT_6(t) = q_{60}(t) © IT_0(t)$ ...(81-87)

where, $W_2(t) = \bar{H}(t)$ ...(88)

Taking Laplace Transforms (L.T.) of the above equations and solving them for $IT_0^*(s)$, we get

$$IT_0^*(s) = \frac{N_3(s)}{D_1(s)} \quad ...(89)$$

where $N_3(s) = W_2^*(s)q_{10}^*(s)q_{12}^*(s)$ ...(90)

In steady state, the total fraction of the discussion time of the expert repairman, is given by

$$IT_0 = \lim_{s \to \infty} sIT_0^*(s) = \frac{N_3}{D_1} \quad ...(91)$$

where, $N_3 = \mu_2 q$ ...(92)

and D_1 is already specified.

Expected Number of Visits by the Repairman

By probabilistic arguments, we have the following recursive relations:

$V_0(t) = Q_{01}(t) Ⓢ [1 + V_1(t)]$

$V_1(t) = Q_{10}(t) Ⓢ V_0(t) + Q_{12}(t) Ⓢ V_2(t)$

$V_2(t) = Q_{23}(t) Ⓢ V_3(t) + Q_{24}(t) Ⓢ V_4(t) + Q_{25}(t) Ⓢ V_5(t) + Q_{26}(t) Ⓢ V_6(t)$

$V_3(t) = Q_{30}(t) Ⓢ V_0(t)$

$V_4(t) = Q_{40}(t) Ⓢ V_0(t)$

$V_5(t) = Q_{50}(t) Ⓢ V_0(t)$

$V_6(t) = Q_{60}(t) Ⓢ V_0(t)$ ...(93-99)

Taking L.S.T. of the above equations and solving them for $V_0^{**}(s)$, we get

$$V_0^{**}(s) = \frac{N_4(s)}{D_1(s)} \quad ...(100)$$

where, $N_4(s) = Q_{01}^{**}(s)$ ...(101)

In steady-state, the total number of visits by the ordinary repairman per unit time is given by:

$$V_0 = \lim_{t \to \infty}[V_0(t)/t] = \lim_{s \to 0}[sV_0^{**}(s)] = N_4 / D_1$$

...(102)

where, $N_4 = 1$ ...(103)

and D_1 is already specified.

Expected Number of Preventive Maintenance

By probabilistic arguments, we have the following recursive relations:

$PM_0(t) = Q_{01}(t)$ Ⓢ $PM_1(t)$

$PM_1(t) = Q_{10}(t)$ Ⓢ $PM_0(t) + Q_{12}(t)$ Ⓢ $[1 + PM_2(t)]$

$PM_2(t) = Q_{23}(t)$ Ⓢ $PM_3(t) + Q_{24}(t)$ Ⓢ $PM_4(t) + Q_{25}(t)$ Ⓢ $PM_5(t) + Q_{26}(t)$ Ⓢ $PM_6(t)$

$PM_3(t) = Q_{30}(t)$ Ⓢ $PM_0(t)$

$PM_4(t) = Q_{40}(t)$ Ⓢ $PM_0(t)$

$PM_5(t) = Q_{50}(t)$ Ⓢ $PM_0(t)$

$PM_6(t) = Q_{60}(t)$ Ⓢ $PM_0(t)$ ...(104-110)

Taking L.S.T.of the above equations and solving them for $PM_0^{**}(s)$, we get:

$$PM_0^{**}(s) = \frac{N_5(s)}{D_1(s)}$$ ...(111)

where, $N_5(s) = Q_{01}^{**}(s)Q_{12}^{*}(s)$ ...(112)

In steady-state, the total number of preventive maintenance per unit time is given by:

$$PM_0 = \lim_{t\to\infty}[PM_0(t)/t] = \lim_{s\to 0}[sPM_0^{**}(s)] = N_5 / D_1$$ ...(113)

where, $N_5 = q$ ...(114)

and D_1 is already specified.

Busy Period Analysis of Replacement Time Only

By probabilistic arguments, we have the following recursive relations:

$B_0^R(t) = q_{01}(t)$ © $B_1^R(t)$

$B_1^R(t) = q_{10}(t)$ © $B_0^R(t) + q_{12}(t)$ © $B_2^R(t)$

$B_2^R(t) = q_{23}(t)$ © $B_3^R(t) + q_{24}(t)$ © $B_4^R(t) + q_{25}(t)$ © $B_5^R(t) + q_{26}(t)$ © $B_6^R(t)$

$B_3^R(t) = q_{30}(t)$ © $B_0^R(t)$

$B_4^R(t) = q_{40}(t)$ © $B_0^R(t)$

$B_5^R(t) = q_{50}(t)$ © $B_0^R(t)$

$B_6^R(t) = q_{60}(t)$ © $B_0^R(t)$ ...(115-121)

Taking Laplace Transforms of the above equations and solving them for $B_0^{R*}(s)$, we get

$$B_0^{R*}(s) = \frac{N_6(s)}{D_1(s)}$$ ...(122)

where, $N_6(s) = \mu_6 d$ ...(123)

and D_1 is already specified.

Expected Number of Replacement

By probabilistic arguments, we have the following recursive relations:

$RP_0(t) = Q_{01}(t)$ Ⓢ $RP_1(t)$

$RP_1(t) = Q_{10}(t)$ Ⓢ $RP_0(t) + Q_{12}(t)$ Ⓢ $RP_2(t)$

$RP_2(t) = Q_{23}(t)$ Ⓢ $RP_3(t) + Q_{24}(t)$ Ⓢ $RP_4(t) + Q_{25}(t)$ Ⓢ $RP_5(t) + Q_{26}(t)$ Ⓢ $RP_6(t)$

$RP_3(t) = Q_{30}(t)$ Ⓢ $RP_0(t)$

$RP_4(t) = Q_{40}(t)$ Ⓢ $RP_0(t)$

$RP_5(t) = Q_{50}(t)$ Ⓢ $RP_0(t)$

$RP_6(t) = Q_{60}(t)$ Ⓢ $RP_0(t)$ ...(124-130)

Taking L.S.T. of the above equations and solving them for $RP_0^{**}(s)$, we get:

$$RP_0^{**}(s) = \frac{N_7(s)}{D_1(s)}$$ ...(131)

where, $N_7(s) = Q_{01}^{**}(s)Q_{12}^{**}(s)$ ...(132)

In steady-state, the total number of expected replacement per unit time is given by

$$RP_0 = \lim_{t\to\infty}\left[RP_0 **(t)/t\right] = \lim_{s\to 0}\left[sRP_0 **(s)\right] = N_7 / D_1 \quad ...(133)$$

where, $N_7 = d$ ...(134)

and D_1 is already specified.

Profit Analysis

The expected total profit incurred to the system in steady-state is given by

$$P = C_0A_0 - C_1B_0 - C_2IT_0 - C_3V_0$$

$$- C_4PM_0 - C_5B_0^R - C_6RP_0 \quad ...(135)$$

where,

C_0 = Revenue per unit up time of the system

C_1 = Cost per unit time for which the repairman is busy in repair

C_2 = Cost per unit time for which the repairman is busy in inspection

C_3 = Cost per visit of the repairman

C_4 = Cost per preventive maintenance

C_5 = Cost per unit time for replacement

C_6 = Cost per visit of the repairman for replacement

Particular Case

For graphical interpretation, the following particular case is considered:

$$g(t) = \alpha e^{-\alpha t}, g_1(t) = \alpha_1 e^{-\alpha_1 t}, g_2(t) = \alpha_2 e^{-\alpha_2 t},$$

$$g_3(t) = \alpha_3 e^{-\alpha_3 t}, g_4(t) = \alpha_4 e^{-\alpha_2 t}, h(t) = \beta e^{-\beta t}$$

Thus, we can easily obtain the following:

$p_{01} = p_{30} = p_{40} = p_{50} = p_{60} = 1$, $p_{10} = p$, $p_{12} = q$, $p_{23} = a$, $p_{24} = b$, $p_{25} = c$, $p_{25} = d$

$$\mu_0 = \frac{1}{\lambda}, \mu_1 = \frac{1}{\alpha}, \mu_2 = \frac{1}{\beta}, \mu_3 = \frac{1}{\alpha_1}$$

$$\mu_4 = \frac{1}{\alpha_2}, \mu_5 = \frac{1}{\alpha_3}, \mu_6 = \frac{1}{\alpha_4}$$

Using the above equations and Equations (39), (51) and (135), we can have the expressions for M.T.S.F., availability and profit for this particular case. On the basis of the numerical values taken as:

$p = 0.5$, $q = 0.5$, $a = 0.2$, $b = 0.7$, $c = 0.1$, $d = 0.2$, $\beta = 10$, $\alpha = 0.25$, $\alpha_1 = 0.4$, $\alpha_2 = 0.35$, $\alpha_3 = 0.2$, $\alpha_4 = 0.1$, $\lambda = 0.005$, $C_o = 300$, $C_1 = 500$, $C_2 = 200$, $C_3 = 400$, $C_4 = 500$, $C_5 = 500$, $C_6 = 300$.

The values of various measures of system effectiveness are obtained as:

Mean Time to System Failure (MTSF) = 200

Availability (A_0) = 0.968289

Busy period of ordinary repairman (B_0) = 0.019366

Expected inspection time (IT_0) = 0.000242

Expected number of visits by the repairman (V_0) = 0.004841

Expected number of preventive maintenance (PM_0) = 0.002421

Busy period of replacement $\left(B_0^R\right)$ = 0.009683

Expected number of replacements (RP_0) = 0.000968

RESULT AND DISCUSSION

For the graphical interpretation, the mentioned particular case is considered.

Figure 2: MTSF vs. Failure Rate

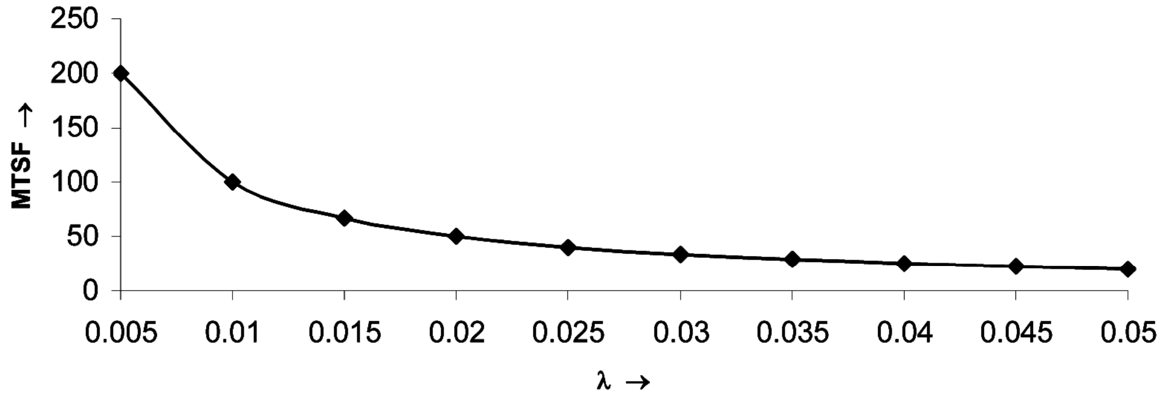


Figure 3: Availability vs. Failure Rate for Different Repair Rate

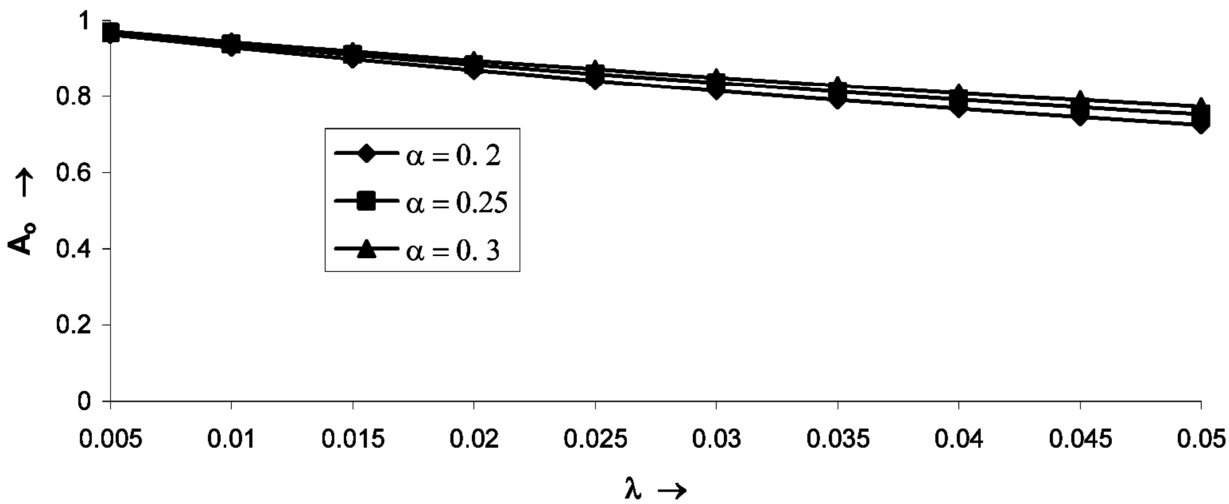
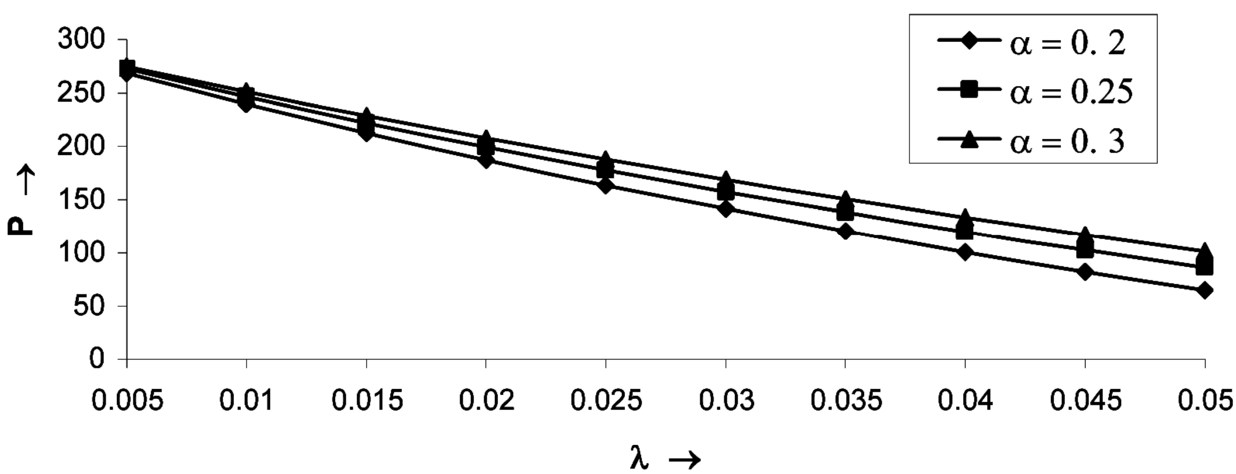


Figure 4: Profit vs. Failure Rate for Different Repair Rate



Figures 2 and 3 show the behavior of MTSF and availability respectively with respect to failure rate (λ). It is clear from the graphs that the MTSF and the availability both get decrease with increase in the values of failure rate. The availability increases with increase in the values of repair rate.

Reveals the pattern of the profit with respect to failure rate (λ) for different values of repair rate (α). The profit decreases with the increase in the values of failure rate (λ) and is higher for higher values of repair rate (α) (Figure 4).

Depicts the pattern of profit with respect to cost (C_6) for different values of discussion rate (β). The profit decreases with increase in the values of (C_6) and is higher for higher values of discussion rate (β) (Figure 5).

Figure 6 shows that the profit increases with the increase in values of probability (p) and lower for higher value of probability (a).

Figure 5: Profit vs. Cost C_6 for Different Discussion Rate (β)

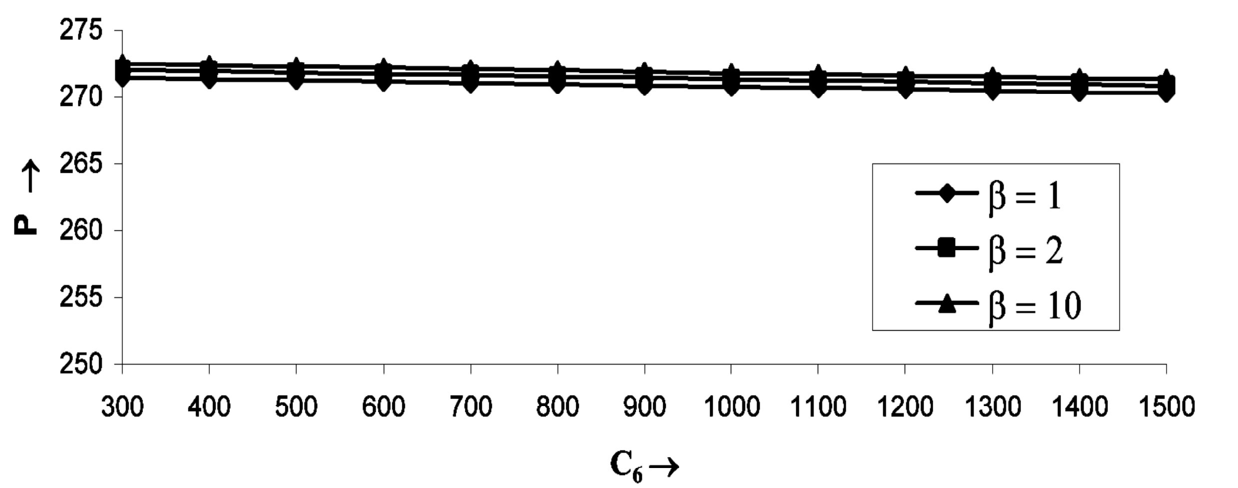


Figure 6: Profit vs. Probability (p) for Different Values of Probability (a)

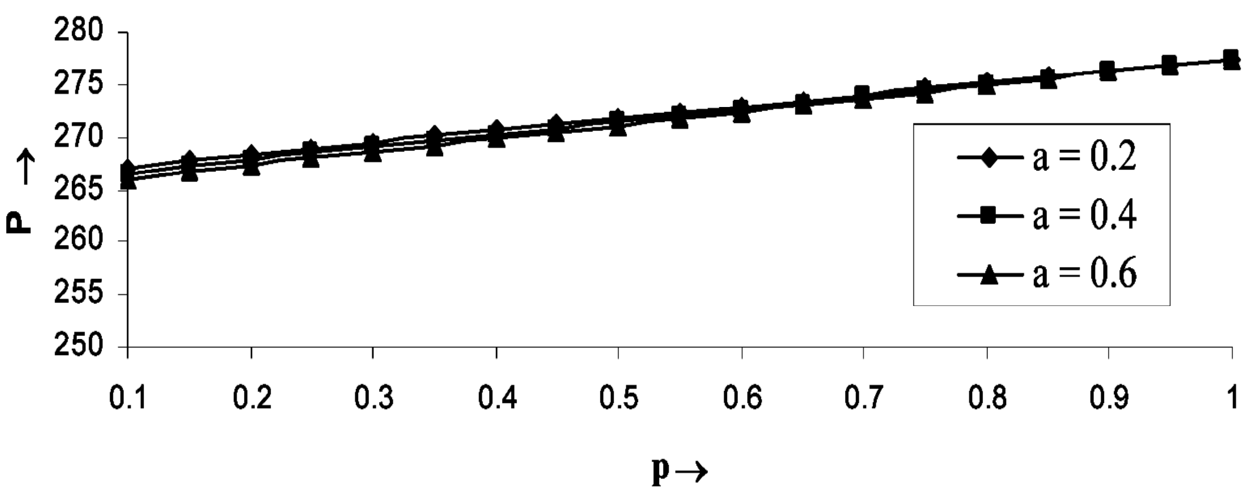
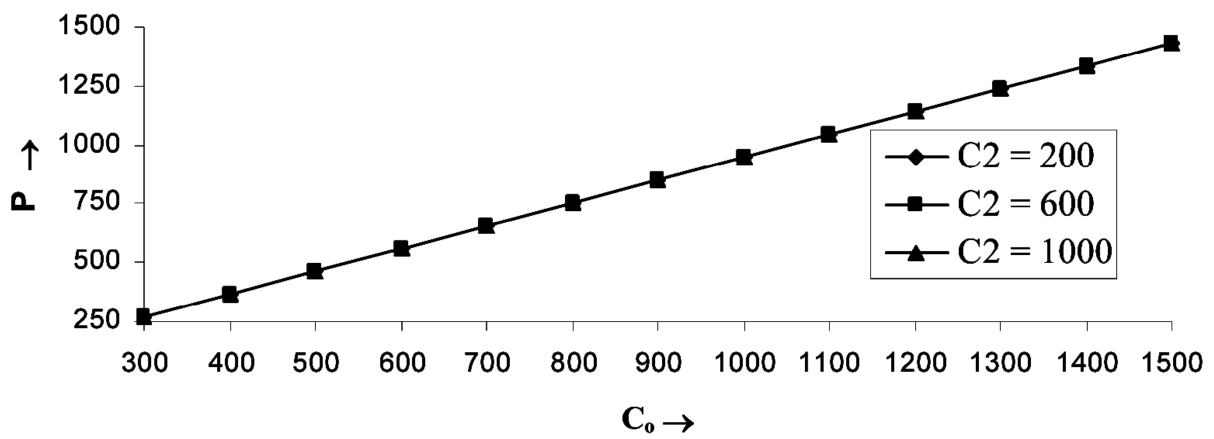


Figure 7 shows the behavior of profit with respect to revenue per unit time (C_o) for different values of cost (C_2). The profit increases with the increase in values of revenue (C_o) and becomes lower for higher values of cost (C_2).

Figure 7: Profit vs. Revenue (C_o) for Different Values of Cost (C_2)



CONCLUSION

In this paper, we developed the explicit expressions for the Mean Time to System Failure (MTSF), system availability, busy period and profit analysis for the system and performed graphical study to see the behavior of the failure rates and repair rates parameters on system performance. It is observed that from graphical study system performance increases with repair rates and decreases with failure rates.

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APPENDIX

Notations		
λ	:	Constant failure rate of the unit
p	:	Probability that repairman is able to repair the failed unit
q	:	$1 - p$, i.e., the probability that the repairman is unable to repair the failed unit
a	:	Probability of post inspection
b	:	Probability of post repair
c	:	Probability of preventive maintenance
d	:	Probability of replacement
$h(t)$, $H(t)$	:	p.d.f., c.d.f. of the inspection time
$g(t)$, $G(t)$	:	p.d.f., c.d.f. of repair time of the repairman
$g_1(t)$, $G_1(t)$	:	p.d.f., c.d.f. of the post inspection time
$g_2(t)$, $G_2(t)$	:	p.d.f., c.d.f. of the post repair time
$g_3(t)$, $G_3(t)$	:	p.d.f., c.d.f. of the preventive maintenance time
$g_4(t)$, $G_4(t)$	:	p.d.f., c.d.f. of the replacement time
Symbols for the State of the System		
o	:	Operative
F_r	:	Failed unit under repair of the repairman
F_{in}	:	Failed unit under inspection
F_{pin}	:	Failed unit under post inspection
F_{pr}	:	Failed unit under post repair
F_{pm}	:	Failed unit under preventive maintenance
F_{rep}	:	Failed unit under replacement