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PROBABILISTIC ANALYSIS OF A SYSTEM OF TWO NON-IDENTICAL PARALLEL UNITS WITH PRIORITY TO REPAIR SUBJECT TO INSPECTION

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Abstract

Two reliability models for a system of non-identical units – one is original and the other is a substandard unit (called duplicate unit) are analyzed probabilistically in detail by using regenerative point technique. There is a single server who comes immediately to do inspection and repair whenever needed. On the failure of original unit, server inspects the operative duplicate unit to see whether the unit is capable of performing the desired function well or not. If duplicate unit is not capable to do so, the operation of the system is stopped and server starts repair of the original unit immediately. However, no inspection is done at the failure of the duplicate unit as the original unit alone is capable of performing the given task well. In model 1, priority to repair the original unit is given in case system fails completely and duplicate unit is already under repair whereas in model II there is no such priority. The failure and repair times of each unit are assumed to be independent and uncorrelated random variables. The distributions of failure time of the units are taken as negative exponential while that of repair and inspection times are general. Graphs are plotted to compare some econo-reliability measures of the models such as MTSF, availability and profit for a particular case.

Keywords: Non-identical Parallel Units, Inspection, Priority to Repair, Regenerative Point and Probabilistic Analysis.

1. Introduction

Numerous reliability models for standby systems with different repair mechanism have been proposed by the researchers including Mishra and Balagurusamy [1976], Chiang and Niu [1981], Gopalan and Naidu [1982], Goel et al. [1985], Singh [1989], Gupta and Chaudhary [1994], Tuteja and Malik [1994] under the assumptions that

(i) System has identical unit(s) in cold standby.
(ii) No priority to repair a unit over the other unit is given.
(iii) Each unit is capable of performing the given task well.
(iv) Repair is done without stopping the operation of the system.

But due to high cost of identical units, the non-identical (substandard) unit(s) may be taken up for parallel working in the system. Each unit is capable of performing some set of functions but their degree of reliability and desirability may differ from unit to unit. Also, some time it becomes necessary to give priority to one of the units in repair as compared to other in order to increase the reliability and availability of the system. A good example of the situation can be cited of a system consisting of one unit of an electric transformer and the other unit as a generator. The priority to repair may be given to the transformer rather than generator due to high cost of operation of the later. Further, it is not always possible by a substandard unit to perform the given task alone under excessive load. In such a case inspection can play a key role to see whether the unit is capable of performing the desired function or not. Recently Kadyan et al. [2004] and Chander [2005] have analyzed reliability models of non-identical units with priority by keeping one unit in cold standby.

Keeping the above facts in view, an attempt is made to develop the reliability models for a system of non-identical units-one is original and the other unit as duplicate (called sub-standard unit). Repair facility is provided immediately whenever needed. On the failure of original unit, server inspects the duplicate unit to see whether the unit alone is capable of performing the given task well or not. If duplicate unit is not capable to perform the given task, the operation of the system is stopped and server starts the repair of the original unit immediately. However, system may work with full capacity when it has original unit for working at the failure of duplicate unit. The system fails completely at the failure of both units. In model 1, priority to repair the original unit is given when system fails completely and duplicate unit is already under repair whereas in model II, there is no such priority. The failure, repair and inspection times of each unit are assumed to be independent and uncorrelated random variables. The failure time distributions of units follow negative exponential with different parameters while that of repair and inspection times are general. It is assumed that switches and repairs are perfect. Regenerative point technique is adopted to derive the expressions for some measures of system effectiveness such as mean sojourn times, mean time to system failure (MTSF), availability, busy period of the server and expected number of visits by the server. Expression for profit incurred to each model is also derived by using these parameters. Graphs are plotted to make a comparison of MTSF, availability and profit of the models for a particular case.

2. Notations

E_0	State of the system at t=0
E	Set of regenerative states.
O	Original unit is operative.
$D_{(O)}/D_{OUi}$	Duplicate unit is operative/Operative but under inspection.
$O_{Fur}/O_{Fwr}/O_{FUR}$	Original unit is failed and under repair/waiting for repair/under repair continuously from previous state
D_{Fur}/D_{Fwr}	Duplicate unit failed and under repair/waiting for repair
$\overline{D}_{(O)}$	Duplicate unit is good but not working
λ/λ_1	Failure rate of original unit/duplicate unit
$g(t)/G(t)$, $g_1(t)/G_1(t)$	pdf / cdf of repair times of original and duplicate units
a/b	Probability that duplicate unit is capable of performing the given task or not operative is possible/non-possible by the server
$h(t)/H(t)$	pdf and cdf of inspection time of the server.
$q_{ij}(t)$, $Q_{ij}(t)$	pdf and cdf of first passage time for regenerative state i to a regenerative state j or to a failed state j without visiting any other regenerative state in (0, t].

$q_{ij.k}(t)$, $Q_{ij.k}(t)$	pdf and cdf of first passage time for regenerative state i to a regenerative state j or to a failed state j visiting state k once in (0,t].
$\phi_i(t)$	cdf of the first passage time from regenerative state i to a failed state.
$A_i(t)$	Probability that the system is up at instant t, given that system entered into the regenerative state i at t=0.
$B_i(t)$	Probability that the server is busy at an instant t given that system entered into the regenerative state i at t=0.
$N_i(t)$	Expected number of visits by server in $(0,t]/E_0 = S_i \in E$.
$M_i(t)$	Probability that the system, initially up in the regenerative state i, is up at time t without passing through any other regenerative state.
m_{ij}	Contribution to mean sojourn time in state S_i when the transition is to $S_j = -\tilde{Q}_{ij}(o) = -q^*_{ij}(o)$
μ_i	Mean sojourn time in state $S_i \in$ E.
LST	Laplace Stieltjes Transform
LT	Laplace Transform
~(**)	Symbol for Laplace Stieltjes Transform e.g $$\tilde{Q}_{ij}(s) = \int_0^\infty e^{-st} q_{ij}(t)dt$$
Ⓢ	Symbol for Stieltjes Convolution
©	Laplace Convolution
pdf	Probability density function.
cdf	Cumulative distribution function.

3. Analysis for Model I

Here, priority to repair the original failed unit is given when system fails completely and duplicate unit is already under repair. Transition diagram for the model is shown in Fig.1.

3.1 States of the System

The following are the possible transition states of the system:

$S_0 = (O, D_{(O)})$, $S_1 = (O_{Fwr}, D_{OUi})$, $S_2 = (O_{Fur}, D_{(O)})$

$S_3 = (O_{Fur}, \overline{D}_{(O)})$, $S_4 = (O_{Fur}, D_{Fwr})$, $S_5 = (O_{FUR}, D_{Fwr})$

$S_6 = (O, D_{Fur})$

The states S_0, S_1, S_2, S_3, S_4, S_6 are regenerative states while state S_5 is non-regenerative.

3.2 Mean Time to System Failure

$$\phi_0(t) = Q_{01}(t) Ⓢ \phi_1(t) + Q_{06}(t) Ⓢ \phi_6(t)$$

$$\phi_1(t) = Q_{12}(t) Ⓢ \phi_2(t) + Q_{13}(t) Ⓢ \phi_3(t) + Q_{14}(t)$$

$$\phi_2(t) = Q_{20}(t) Ⓢ \phi_0(t) + Q_{25}(t)$$

$$\phi_3(t) = Q_{30}(t) Ⓢ \phi_0(t)$$

$$\phi_6(t) = Q_{60}(t) Ⓢ \phi_0(t) + Q_{64}(t) \qquad (1)$$

Letting $t \to \infty$, using $Q_{ij}(\infty) = p_{ij}$, we get following transition probabilities

$$p_{01} = \frac{\lambda}{\lambda+\lambda_1},\ p_{06} = \frac{\lambda_1}{\lambda+\lambda_1},\ p_{12} = ah^*(\lambda_1),\ p_{13} = bh^*(\lambda_1)$$

$$p_{14} = 1-h^*(\lambda),\ p_{20} = g^*(\lambda_1),\ p_{25} = 1-g^*(\lambda_1) \qquad (2)$$

$$p_{26.5} = 1-g^*(\lambda_1),\ p_{30} = p_{46} = 1,\ p_{60} = g_1^*(\lambda),\ p_{64} = 1-g_1^*(\lambda)$$

It can be verified that

$$p_{01}+p_{06} = p_{12}+p_{13}+p_{14} = p_{20}+p_{26.5} = p_{34} = p_{46} = p_{60}+p_{64} = 1$$

The mean sojourn times μ_i in the state S_i are

$$\mu_0 = \int_0^\infty P(T>t)dt = \frac{1}{\lambda+\lambda_1},\ \mu_1 = \frac{1}{\lambda_1+\theta},\ \mu_2 = \frac{1}{\lambda_1+\alpha},\qquad \mu'_2 = \frac{1}{\alpha},$$

$$\mu_3 = \frac{1}{\alpha} = \mu_4,\ \mu_6 = \frac{1}{\lambda+\alpha_1} \qquad (3)$$

The unconditional mean time taken by the system to transit to any regenerative state $S_j \in E$ when it is counted from epoch of entrance into $S_i \in E$ is

$$m_{ij} = \int t\,dQ_{ij}(t)$$

Thus

$$\mu_0 = m_{01}+m_{06}, \mu_1 = m_{12}+m_{13}+m_{14}, \quad \mu_2 = m_{20}+m_{25}, \mu'_2 = m_{20}+m_{26.5},$$

$$\mu_3 = m_{30}, \mu_4 = m_{46}, \quad \mu_6 = m_{60}+m_{64} \qquad (4)$$

Taking LST of relations 1 and solving for $\tilde{\phi}_0(s)$ and using this we get

$$\text{MTSF } (T_1) = \lim_{s\to 0}(1-\tilde{\phi}(s))/s = N_{11}/D_{11} \qquad (5)$$

where $N_{11} = \mu_0 + \mu_1 p_{01} + \mu_2 p_{01} p_{12} + \mu_3 p_{01} p_{13} + \mu_6 p_{06}$ and
$D_{11} = 1 - p_{01}p_{12}p_{20} - p_{01}p_{13} - p_{06}p_{60}$

3.3 Availability Analysis

$$A_0(t) = M_0(t) + q_{01}(t) © A_1(t) + q_{06}(t) © A_6(t) \qquad (6)$$

$$A_1(t) = M_1(t) + q_{12}(t) © A_2(t) + q_{13}(t) © A_3(t) + q_{14}(t) © A_4(t)$$

$$A_2(t) = M_2(t) + q_{20}(t) © A_0(t) + q_{26.5}(t) © A_6(t),\ A_3(t) = q_{30}(t) © A_0(t)$$

$$A_4 t) = q_{46}(t) © A_6(t),\ A_6(t) = M_6(t) + q_{60}(t) © A_0(t) + q_{64}(t) © A_4(t)$$

where

$$M_0(t) = e^{-(\lambda+\lambda 1)t}\,dt, M_1(t) = e^{-\lambda 1t}\,\overline{H(t)}\,dt, M_2(t) = e^{-\lambda 1t}\,\overline{G(t)}\,dt, M_6(t) = e^{-\lambda t}\,\overline{G_1(t)}\,dt$$

Taking LT of relations (6) and solving for $A_0^*(s)$ and by using this, we get steady-state availability of the system as:

$$A_{10}(\infty) = \lim_{s\to 0} sA_0^*(s) = N_{12}/D_{12} \qquad (7)$$

$$N_{12} = \mu_0 p_{60} + \mu_1 p_{01} p_{60} + \mu_2 p_{01} p_{12} p_{60} + \mu_6(p_{01}p_{12}p_{26.5} + p_{01}p_{14} + p_{06})$$ and

$$D_{12} = \mu_0 p_{60} + (\mu_1 + \mu'_2 p_{12} + \mu_3 p_{13}) p_{01} p_{60} + \mu_4[p_{64}(p_{01}p_{12}p_{26.5} + p_{06} + p_{01}p_{14}) + p_{60}p_{01}p_{14}] + \mu_6(p_{01}p_{12}p_{26.5} + p_{06} + p_{01}p_{14})$$

3.4 Busy Period Analysis

$$B_0(t) = q_{01}(t) © B_1(t) + q_{06}(t) © B_6(t)$$
$$B_1(t) = W_1(t)+q_{12}(t) © B_2(t)+q_{13}(t) © B_3(t)+q_{14}(t) © B_4(t)$$
$$B_2(t) = W_2(t)+q_{20}(t) © B_0 (t)+q_{26.5}(t) © B_6(t)$$
$$B_3(t) = W_3(t)+q_{30}(t) © B_0 (t)$$
$$B_4(t) = W_4(t)+q_{46}(t) © B_6 (t)$$
$$B_6(t) = W_6(t)+q_{60}(t) © B_0 (t)+q_{64}(t) © B_4(t) \quad (8)$$

where

$W_1(t) = e^{-\lambda 1t}\,\overline{H}(t)$,$W_2(t) = e^{-\lambda 1t}\,\overline{G}(t) + (\lambda_1 e^{-\lambda 1t} ©1)\,\overline{G}(t)$

$W_3(t) = G(t)$, $\quad W_4(t) = \overline{G}(t)$, $W_6(t) = e^{-\lambda t}\,\overline{G_1}(t)$

Taking LT of relations (8) and solving for $B_0^*(s)$ and by using this, we get in the long run the time for which the system is under repair as

$$B_{10} = \lim_{s\to 0} sB_0^*(s) = N_{13} / D_{12} \quad (9)$$

where $N_{13} = (W_1+W_2p_{12}+W_3p_{13})p_{01}p_{60} +W_4[p_{64}(p_{01}p_{12}p_{26.5}+p_{06})+ p_{01}p_{14}]+W_6(p_{01}p_{12}p_{26.5}+p_{01}p_{14}+p_{06})$ and D_{12} is already specified.

3.5 Expected Number of Visits by the Server

$$N_0(t) = Q_{01}(t)Ⓢ[1+N_1(t)] +Q_{06}(t)\, Ⓢ[1+N_6(t)] \quad (10)$$
$$N_1(t) = Q_{12}(t)ⓈN_2(t)+Q_{13}(t)\, ⓈN_3(t)+ Q_{14}(t)\, Ⓢ\, N_4(t)$$
$$N_2(t) = Q_{20}(t)\, ⓈN_0(t)+Q_{26.5}(t)\, ⓈN_6(t),\ \ N_3(t) = Q_{30}(t)ⓈN_0(t)$$
$$N_4(t) = Q_{46}(t)ⓈN_6(t),\ N_6(t) = Q_{60}(t)ⓈN_0(t)+Q_{64}(t)ⓈN_4(t)$$

Taking LST of relations (10) and solving for $\tilde{N}o$ (s) and by using this, we get expected number of visits per unit time as:

$$N_{10}= \lim_{s\to 0} s\tilde{N}_0(s) = N_{14} / D_{12} \quad (11)$$

where $N_{14} = p_{60}$ and D_{12} is already specified.

4. Analysis for Model II

Here no priority to repair the original unit is given. Transition diagram for the model is shown in figure 2.

4.1 States of the system

The states S_0, S_1, S_2, S_3, S_4, S_5, S_6 are same as defined for model I while the remaining state $S_7 = (O_{Fwr}, D_{FUR})$.

The states S_0, S_1, S_2, S_3, S_4, S_6 are regenerative states while S_5 and S_7 are non-regenerative states.

4.2 Mean Time to System Failure (MTSF)

The MTSF of this model is the same as that of model I.

4.3 Transition Probabilities and Mean Sojourn Times

The expression for some of the transition probabilities and mean sojourn times are same as derived for model I while the remaining are

$$p_{67} = \frac{\lambda}{\lambda+\lambda_1} = p_{62.7} \quad \text{with} \quad p_{60}+p_{62.7} = 1$$

and $\mu'_2 = \frac{1}{\alpha} = \mu_5$, $\mu'_6 = \frac{1}{\alpha_1}$, where $\mu_6 = m_{60} + m_{65}$

4.4 Availability Analysis

The expressions for $A_0(t)$, $A_1(t)$, $A_2(t)$ $A_3(t)$, $A_4(t)$ are same as defined in model I while the remaining is

$A_6(t) = M_6(t) + q_{60}(t) © A_0(t) + q_{62.7}(t) © A_2(t)$

Steady-state availability is given by

$$A_{20}(\infty) = \lim_{s\to 0} sA_0^*(s) = N_{22}/D_{22} \tag{12}$$

$N_{22} = \mu_0 p_{60}+\mu_1 p_{01}p_{60} + \mu_2 p_{01}p_{12}p_{60} + \mu_6(p_{01}p_{12}p_{26.5} + p_{01}p_{14}+p_{06})$ and

$D_{22} = \mu_0 p_{60}+(\mu_1+\mu'_2 p_{12}+\mu_3 p_{13})p_{01}p_{60}+\mu_4[p_{64}(p_{01}p_{12}p_{26.5}+p_{06}+p_{01}p_{14}) +p_{60}p_{01}p_{14}]+ \mu_6(p_{01}p_{12}p_{26.5} + p_{06} +p_{01}p_{14})$

4.5 Busy Period Analysis

The expressions for $B_0(t)$, $B_1(t)$, $B_2(t)$, $B_3(t)$, $B_4(t)$ are same as defined in model I and the remaining is

$B_6(t) = W_6(t)+q_{60}(t) © B_0(t)+q_{62.7}(t) © B_2(t)$, where

$W_6(t) = e^{-\lambda t}\,\overline{G_1}(t) + (\lambda e^{-\lambda t} © 1)\,\overline{G_1}(t)$

Now proceeding in similar way as in model I, the time for which the system is under repair to given by

$$B_{20} = \lim_{s\to 0} sB_0^*(s) = N_{23}/D_{22} \tag{13}$$

where $N_{23} = (W_1+W_2p_{12}+W_3p_{13})p_{01}p_{60} +W_4[p_{64}(p_{01}p_{12}p_{26.5}+p_{06})+ p_{01}p_{14}] +W_6(p_{01}p_{12}p_{26.5}+p_{01}p_{14}+p_{06})$

and D_{12} is already specified.

4.6 Expected number of visits by the server

The expressions for $N_0(t)$, $N_1(t)$, $N_2(t)$, $N_3(t)$, $N_4(t)$ are same as defined in model I while the remaining equation is:

$N_6(t) = Q_{60}(t)Ⓢ N_0(t)+Q_{62.7}(t) Ⓢ N_2(t)$

The expected number of visits per unit time is given by

$$N_{20} = \lim_{s\to 0} s\tilde{N}_0(s) = N_{24}/D_{22} \tag{14}$$

where $N_{24} = (1-p_{26.5}\, p_{62.7})$ and D_{22} is already specified.

5. Profit Analysis

The expected profit incurred to the system models in (0,t] are given by:

$P_1 = K_0A_{10} – K_1B_{10} – K_2N_{10}$

$P_2 = K_0A_{20} – K_1B_{20} – K_2N_{20}$ (15)

where K_0 = Fixed revenue per unit up time of the system

K_1 = Fixed cost per unit up time for which server is busy

K_2 = Fixed cost per unit visit by the server

Particular Case

Suppose that $g(t) = \alpha e^{-\alpha t}$, $g_1(t) = \alpha_1 e^{-\alpha_1 t}$, $h(t) = \theta e^{-\theta t}$

By using the non-zero element p_{ij}, we get the following results

For model I

MTSF $(T_1) = \dfrac{N_{11}}{D_{11}}$, Availability $(A_{10}) = \dfrac{N_{12}}{D_{12}}$,

Busy Period $(B_{10}) = \dfrac{N_{13}}{D_{12}}$, Expected no. of visits $(N_{10}) = \dfrac{N_{14}}{D_{12}}$

For model II

MTSF of this model is same as that of model I.

Availability $(A_{20}) = \dfrac{N_{22}}{D_{22}}$, Busy Period $(B_{20}) = \dfrac{N_{23}}{D_{22}}$,

Expected no. of visits $(N_{20}) = \dfrac{N_{24}}{D_{22}}$, where

$N_{11} = (\lambda+\alpha_1)[(\lambda_1+\alpha)(\lambda+\lambda_1+\theta+b\theta)+a\theta\lambda]+\lambda_1(\lambda_1+\theta)(\lambda_1+\alpha)$

$D_{11} = (\lambda_1+\theta)(\lambda_1+\alpha)[(\lambda+\lambda_1)(\lambda+\alpha_1)-\lambda_1\alpha_1]-\theta\lambda(\lambda+\alpha_1)[a\alpha-b(\lambda_1+\alpha)]$

$N_{12} = \alpha(\alpha_1+\lambda_1)[(\lambda_1+\theta)(\lambda_1+\alpha)+\lambda(\lambda_1+\alpha+a\theta)]$

$D_{12} = \alpha_1(\lambda_1+\alpha)[\alpha(\lambda+\lambda_1+\theta)+\lambda(\theta+\lambda_1)]+\lambda_1(\lambda+\alpha)[\lambda(a\theta+\lambda_1+\alpha)+(\lambda_1+\theta)(\lambda_1+\alpha)]$

$N_{13} = \lambda\alpha_1(\lambda_1+\alpha)(\alpha+\theta)+(\lambda_1+\theta)(\lambda_1+\alpha)(\lambda+\lambda_1\alpha)+(\lambda_1+\alpha)[\lambda\lambda_1(\lambda+\alpha_1)+\alpha]+a\theta\lambda\lambda_1(\lambda+\alpha)$

$N_{14} = \alpha\alpha_1(\lambda+\alpha_1)(\lambda+\lambda_1)(\lambda_1+\theta)(\lambda_1+\alpha)$

$N_{22} = \alpha\alpha_1[(\lambda_1\alpha_1+\lambda\alpha_1+\alpha\alpha_1)(\lambda+\lambda_1+\theta)+\lambda\{a\theta(\lambda+\lambda_1)+\lambda\lambda_1+\lambda_1(\lambda_1+\theta)\}$
$\quad +\lambda_1\{a\theta+\lambda_1+\alpha+(\lambda_1+\theta)(\lambda_1+\alpha)\}]$

$D_{22}=\alpha\alpha_1(\lambda_1+\theta)[\alpha\lambda_1+\alpha_1(\lambda_1+\alpha)]+\alpha\alpha_1[\alpha\lambda(\lambda+\lambda_1)+(\lambda_1+\alpha)\{\lambda^2+\alpha_1(\lambda+\lambda_1)\}]$
$\quad +\lambda\alpha_1(\lambda_1+\alpha)[a\theta(\lambda+\alpha_1)+\lambda\lambda_1(\lambda_1+\theta+1)]+\lambda\alpha_1(\lambda_1+b\theta)[\alpha\lambda+\alpha_1(\lambda_1$
$\quad \alpha)]+\alpha\lambda_1(\lambda+\alpha_1)[(\lambda_1+\alpha)(\lambda+\lambda_1+\theta)+\alpha\theta\lambda]$

$N_{23} = \lambda\alpha_1(\alpha+\lambda+b\theta)[\lambda\alpha+\alpha_1(\alpha+\lambda_1)]+\lambda\alpha_1(\lambda_1+\alpha)[\lambda_1(\lambda_1+\theta+\lambda)+a\theta(\lambda+\alpha_1)]$
$\quad +\lambda_1\alpha(\lambda+\alpha_1)[(\lambda_1+\alpha)(\lambda+\lambda_1+\theta)+a\theta\lambda]$

and

$N_{24} = (\alpha\alpha_1)(\lambda+\lambda_1)(\lambda_1+\theta)[\alpha\lambda+\alpha_1(\alpha+\lambda_1)]$

6. Conclusion

The mean time to system failure of both the models is same as shown graphically in figure 3. It is analyzed that MTSF decreases with the increase of failure rates λ and λ_1 for fixed values of other parameters α, α_1, θ, a and b. Figures 4 and 5 depict the behavior of availability of models w.r.t. failure rate λ. The availability of the model I is more than that of the model II but it decreases with the increase of failure rates λ and λ_1. Further if repair rate α increases, the availability of the models increases rapidly. The numerical results obtained for a particular case also reveal that profit difference (P_2-P_1) keeps on decreasing with the increase of failure rate λ for $\alpha_1 = 0.04$, $\lambda_1 = 0.1$, $\alpha = 0.2$, $\theta = 0.6$, a = 0.3 and b = 0.7. Again, if repair rate α increases, model II becomes more profitable. Hence, finally we conclude that system models become less profitable when probability of performing given task by the duplicate unit is very small and priority to repair the original unit is given.

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State Transition Diagrams

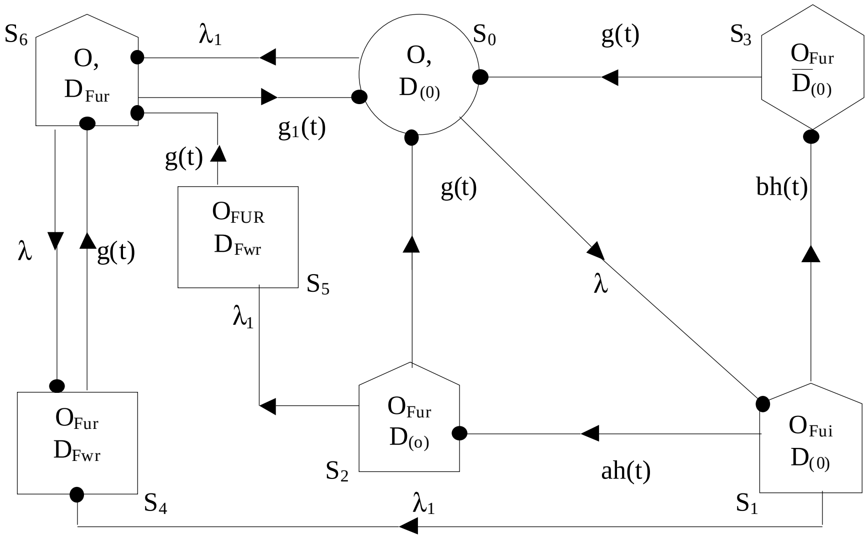

Fig. 1: Model I

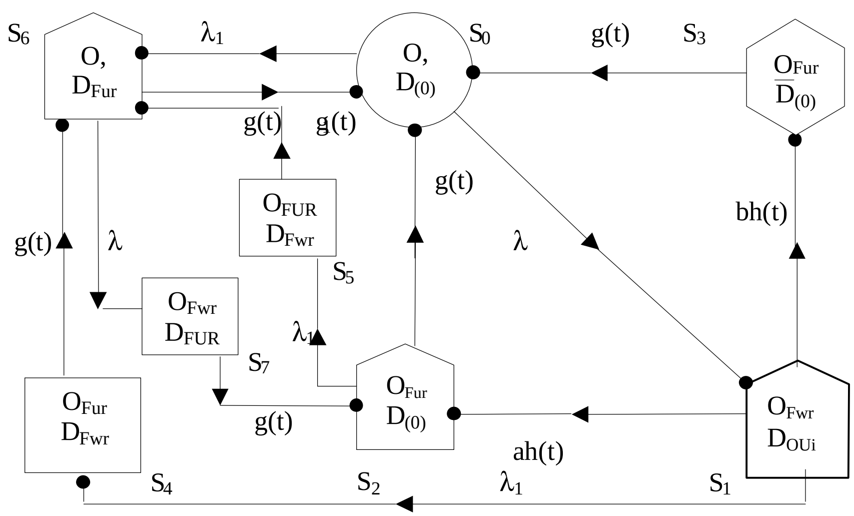

Fig. 2: Model II

● Regenerative point ○ Up-state ⌂ Single unit working state

□ Failed state ⬡ Non-working state

Graphical Study

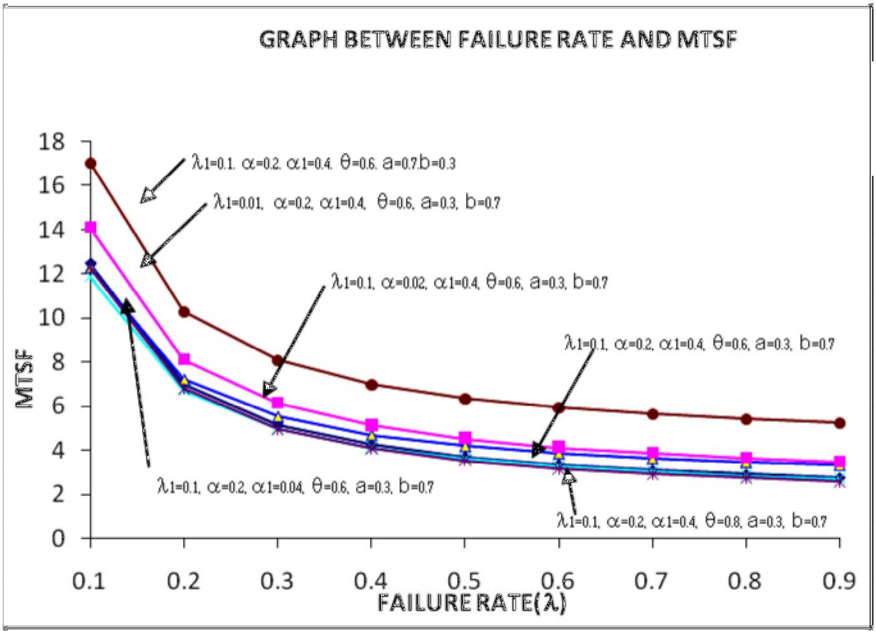

Fig. 3

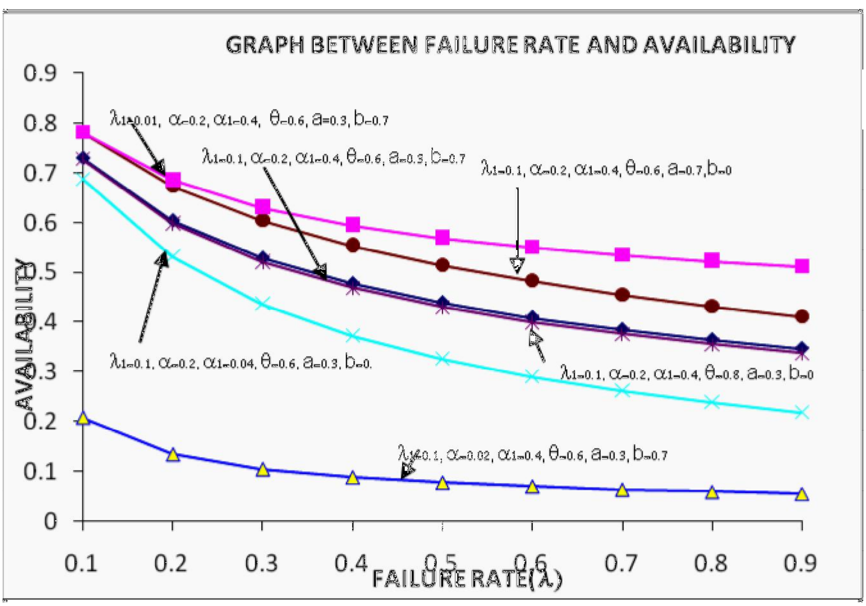

Fig. 4 (for Model-I)

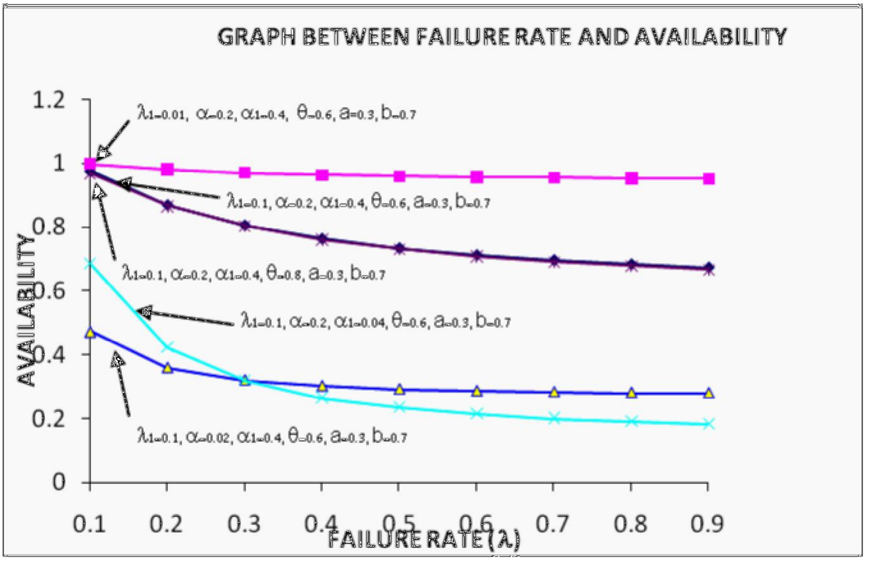

Fig. 5 (for Model-II)