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COST ANALYSIS OF A TWO-UNIT COLD STANDBY SYSTEM SUBJECT TO DEGRADATION, INSPECTION AND PRIORITY

ANALIZA KOSZTÓW DWU-ELEMENTOWEGO SYSTEMU Z REZERWĄ ZIMNĄ Z UWZGLĘDNIENIEM DEGRADACJI, KONTROLI STANU SYSTEMU ORAZ PRIORYTETOWOŚCI ZADAŃ

The present paper deals with a reliability model incorporating the idea of degradation, inspection and priority. The units may fail completely directly from normal mode. There is a single server who visits the system immediately when required. The original unit undergoes for repair upon failure while only replacement of the duplicate unit is made by similar new one. The original unit does not work as new after repair and so called degraded unit. The system is considered in up-state if any one of new/duplicate/degraded unit is operative. The server inspects the degraded unit at its failure to see the feasibility of repair. If repair of the degraded unit is not feasible, it is replaced by new one similar to the original unit in negligible time. The priority for operation to the new unit is given over the duplicate unit. The distribution of failure time follow negative exponential where as the distributions of inspection, repair and replacement times are assumed as arbitrary. The system is observed at suitable regenerative epochs by using regenerative point technique to evaluate mean time to system failure (MTSF), steady-state availability, busy period and expected number of visits by the server. A particular case is considered to see graphically the trend of mean time to system failure (MTSF), availability and profit with respect to different parameters.

Keywords: *degradation, inspection, priority, profit analysis.*

Niniejsza praca dotyczy modelu niezawodności uwzględniającego zagadnienia degradacji, kontroli stanu oraz priorytetowości zadań. Elementy mogą ulegać całkowitemu uszkodzeniu bezpośrednio z trybu normalnego. Istnieje jeden konserwator, który odwiedza system, gdy tylko zachodzi taka potrzeba. W przypadku uszkodzenia, element oryginalny podlega naprawie, podczas gdy element zapasowy (duplikat) podlega jedynie wymianie na nowy, podobny. Po naprawie, element oryginalny nie działa już jako element nowy lecz jako element zdegradowany. System uważa się za zdatny jeżeli pracuje którykolwiek z trzech typów elementów: nowy/rezerwowy/zdegradowany. W przypadku uszkodzenia elementu zdegradowanego, konserwator przeprowadza kontrolę stanu elementu, aby stwierdzić możliwość realizacji naprawy. Jeżeli naprawa elementu zdegradowanego jest niemożliwa, zostaje on wymieniony, w czasie pomijalnym, na element nowy, podobny do elementu oryginalnego. Nowy element uzyskuje priorytet pracy w stosunku do elementu rezerwowego. Rozkład czasu uszkodzenia jest rozkładem wykładniczym ujemnym, a rozkłady czasów kontroli stanu, naprawy i wymiany przyjmuje się jako rozkłady dowolne. System obserwuje się w odpowiednich okresach odnowy wykorzystując technikę odnowy RPT (regenerative point technique) w celu ocenienia średniego czasu do uszkodzenia systemu (MTSF), gotowości stacjonarnej, okresu zajętości oraz oczekiwanej liczby wizyt konserwatora. Przebiegi MTSF, gotowości i zysków w funkcji różnych parametrów przedstawiono w formie graficznej na podstawie studium przypadku.

Słowa kluczowe: *degradacja, kontrola stanu, priorytetowość, analiza zysków.*

Introduction

Two-unit systems have attracted the attention of many scholars and reliability engineers for their applicability in their respective fields. A bibliography of the work on the two-unit system is given by Osaki and Nakagawa [8], Kumar and Agarwal [4]. Sridharan and Mohanavadivu [9] studied the stochastic behavior of a two-unit cold standby redundant system. But no attention was paid to reliability evaluation of cold standby system due to degradation after failure. Mokaddis et al. [7] have proposed reliability model for two-unit warm standby systems subject to degradation.

Also, sometimes repair of the degraded unit is not feasible due to its excessive use and increased cost of maintenance. In such cases, the failed degraded unit may be replaced by new one in order to avoid the unnecessary expenses of repair and this can be revealed by inspection. Malik et al. [6], Malik and Chand [5] and Kadyan et al. [2] carried out the cost-benefit analysis of systems subject to degradation with inspection for feasibility of repair. Besides, it becomes necessary to give priority in operation to new one over the duplicate unit in order to increase the reliability, availability and profit of the system. The system of non-identical units with priority for operation and repair has been discussed by Chander [1].

Keeping above facts in view, the present paper deals with a reliability model incorporating the idea of degradation, inspection and priority. The units may fail completely directly from normal mode. There is a single server who visits the system immediately when required. The original unit undergoes for repair upon failure while only replacement of the duplicate unit is made by similar new one. The original unit does not work as new after repair and so called degraded unit. The system is considered in up-state if any one of new/duplicate/degraded unit is operative. The server inspects the degraded unit at its failure to see the feasibility of repair. If repair of the degraded unit is not feasible, it is replaced by new one similar to the original unit in negligible time. The priority for operation to the new unit is given over the duplicate unit. The distribution of failure time follow negative exponential where as the distributions of inspection, repair and replacement times are assumed as arbitrary. The system is observed at suitable regenerative epochs by using regenerative point technique to evaluate mean time to system failure (MTSF), steady-state availability, busy period and expected number of visits by the server. A particular case is considered to see graphically the trend of mean time to system failure (MTSF), availability and profit with respect to different parameters.

The systems of electric transformer can be cited as a good example of the present system model.

Notation

E	:	Set of regenerative states
No	:	The unit is new and operative
NDo	:	The unit is duplicate and operative
Do	:	The unit is degraded and operative
NCs / DCs/ NDCs	:	The new/degraded/duplicate unit in cold standby
p/q	:	Probability that repair of degraded unit is feasible/not feasible
$\lambda/\lambda_1/\lambda_2$	:	Constant failure rate of new /duplicate/degraded unit
$g(t)/G(t)$, $g_1(t)/G_1(t)$	:	pdf/cdf of repair time for new/degraded unit
w(t)/W(t)	:	pdf/cdf of replacement time of the duplicate unit
h(t)/H(t)	:	pdf/cdf of inspection time of the degraded unit
$NF_{ur}/NF_{UR}/NF_{wr}$	:	New unit is failed and under repair/under continuous repair from previous state/waiting for repair.
NDF_{ure}/NDF_{URe} /NDF_{wre}/NDF_{WRe}	:	Duplicate unit is failed and under replacement/under continuous replacement from previous state/waiting for replacement/ continuously waiting for replacement from previous state.
DF_{ur}/DF_{UR}	:	Degraded unit is failed and under repair/under repair continuously from previous state.
$DF_{ui}/DF_{wi}/DF_{UI}$	:	Degraded unit is failed and under inspection /waiting for inspection/under inspection continuously from the previous state.
$q_{ij}(t),Q_{ij}(t)$	:	pdf and cdf of first passage time from regenerative state i to a regenerative state j or to a failed state j without visiting any other regenerative state in (0,t].
$q_{ij.kr}(t),Q_{ij.kr}(t)$	:	pdf and cdf of first passage time from regenerative state i to a regenerative state j or to a failed state j visiting state k,r once in (0,t].
$M_i(t)$	:	P[system up initially in state S_i ε E is up at time t without visiting any other regenerative sate]
$W_i(t)$	:	P[server is busy in the state S_i up to time t without making any transition to any other regenerative state or returning to the same via one or more non-regenerative states]
m_{ij}	:	Contribution to mean sojourn time in state $S_i \in E$ and non regenerative state if occurs before transition to $S_j \in E$.
®/©	:	Symbols for Stieltjes convolution/Laplace convolution
~|*	:	Symbols for Laplace Stieltjes Transform (LST)/Laplace Transform (LT)
'(desh)	:	Symbol for derivative of the function

The following are the possible transition states of the system model:

$S_0 = (No, NDCs)$, $S_1 = (NDo, NF_{ur})$, $S_2 = (NDF_{wre}, NF_{UR})$,
$S_3 = (NDo, DCs)$, $S_4 = (Do, NDF_{ure})$, $S_5 = (DF_{wi}, NDF_{URe})$,
$S_6 = (Do, NDCs)$, $S_7 = (NDo, DF_{ui})$, $S_8 = (NDo, DF_{ur})$, (1)
$S_9 = (NDF_{wre}, DF_{UI})$, $S_{10} = (NDF_{wre}, DF_{UR})$, $S_{11} = (No, NDF_{ure})$,
$S_{12} = (NDF_{WRe}, DF_{ur})$, $S_{13} = (NF_{wr}, NDF_{URe})$,

The states S_0, S_1, S_3, S_4, S_6 S_7, S_8 and S_{11} are regenerative states while S_2, S_5, S_9, S_{10}, S_{12}, and S_{13} are non-regenerative states. Thus $E = \{S_0, S_1, S_3, S_4, S_6\ S_7, S_8, S_{11}\}$.The possible transition between states along with transition rates for the model is shown in figure 1.

Transition Probabilities and Mean Sojourn Times

Simple probabilistic considerations yield the following expressions for the non-zero elements $p_{ij} = Q_{ij}(\infty) = \int q_{ij}(t)\,dt$ as:

$$\begin{array}{lll} p_{01} = p_{34} = p_{67}, & p_{12} = 1-g^*(\lambda_1) = p_{14.2}, & p_{13} = g^*(\lambda_1), \\ p_{46} = w^*(\lambda_2), & p_{47.5} = 1-w^*(\lambda_2) = p_{45}, & p_{7,0} = q\,h^*(\lambda_1), \\ p_{7,8} = p\,h^*(\lambda_1), & p_{7,9} = 1-h^*(\lambda_1), & p_{7,11.9} = [1-h^*(\lambda_1)]q, \\ p_{7,4.9,12} = p[1-h^*(\lambda_1)], & p_{8,3} = g_1^*(\lambda_1), & p_{8,10} = 1-g_1^*(\lambda_1) = p_{8,4.10,} \\ p_{11,0} = w^*(\lambda), & p_{11,13} = 1-w^*(\lambda) = p_{11,1.13} & \end{array} \tag{2}$$

For these transition probabilities, it can be verified that

$$p_{01}=p_{34}=p_{67}=p_{12}+p_{13}=p_{14.2}+p_{13}=p_{45}+p_{46}=p_{46}+p_{47.5}=p_{7,0}+p_{7,8}+p_{7,9}=p_{7,0}+p_{7,8}+p_{7,11.9}+p_{7,4.9,12}=p_{83}+p_{8,10}=p_{83}+p_{8,4.10}=p_{11,0}+p_{11,13}=p_{11,0}+p_{11,1.13}=1 \tag{3}$$

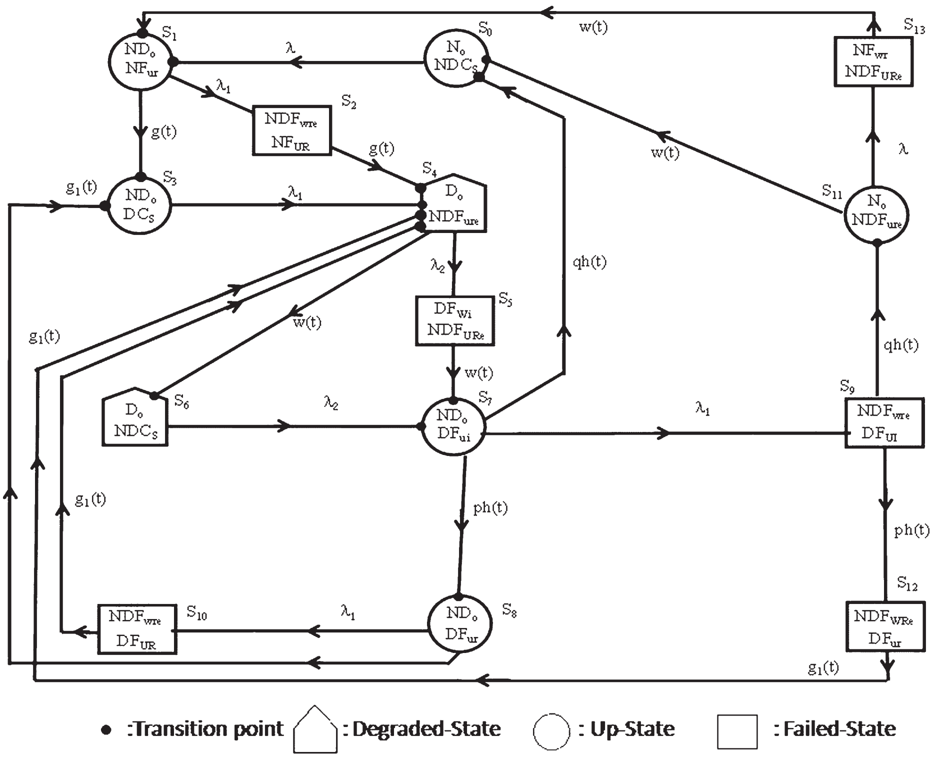


Fig. 1. State transition diagram

The mean sojourn times μ_i in state S_i are given by

$$\begin{array}{llll} \mu_0 = \dfrac{1}{\lambda}, & \mu_1 = \dfrac{1}{\lambda_1}[1-g^*(\lambda)], & \mu_3 = \dfrac{1}{\lambda_1}, & \mu_4 = \dfrac{1}{\lambda_2}[1-w^*(\lambda_2)], \\ \mu_6 = \dfrac{1}{\lambda_2}, & \mu_7 = \dfrac{1}{\lambda_2}[1-h^*(\lambda_1)], & \mu_8 = \dfrac{1}{\lambda_1}[1-g_1^*(\lambda_1)], & \mu_{11} = \dfrac{1}{\lambda}[1-w^*(\lambda)] \end{array} \tag{4}$$

The unconditional mean time taken by the system to transit from any state S_i when time is counted from epoch at entrance into state S_j is stated as:

$$m_{ij} = \int t\,dQ_{ij}(t) = -q_{ij}^{*\prime}(0) \text{ and } \mu_i = E(T) = \int_0^\infty P(T>t)dt = \sum_j m_{ij} \tag{5}$$

where T denotes the time to system failure.

Relationship Between Unconditional Mean and Mean Sojourn Times

$$\begin{array}{lll} m_{01}=\mu_0, & m_{12}+m_{13}=\mu_1, & m_{13}+m_{14.2}=\mu^1_1 \text{ (say)}, \\ m_{34}=\mu_3, & m_{45}+m_{46}=\mu_4, & m_{46}+m_{47.5}=\mu^1_4 \text{ (say)}, \\ m_{67}=\mu_6, & m_{7,8}+m_{7,10}+m_{7,9}=\mu_7, & m_{7,8}+m_{7,0}+m_{7,11.9}+m_{7,4.9,12}=\mu^1_7 \text{(say)}, \\ m_{83}+m_{8,10}=\mu_8, & m_{83}+m_{8,4.10}=\mu^1_8 \text{ (say)}, & m_{11,13}+m_{11,0}=\mu_{11,} \\ m_{11,0}+m_{11,1.13}=\mu^1_{11} \text{(say)} & & \end{array} \tag{6}$$

Mean Time to System Failure

Let $\phi_i(t)$ be the cdf of the first passage time from regenerative state i to a failed state. Regarding the failed state as absorbing state, we have the following recursive relations for $\phi_i(t)$:

$$\varphi_i(t)=\sum_j Q_{i,j}(t)®\varphi_j(t)+\sum_k Q_{i,k}(t) \tag{7}$$

where j is an operative regenerative state to which the given regenerative state i can transit and k is a failed state to which the state i can transit directly.

Taking L.S.T. of relations (7) and solving for $\tilde{\varphi}_0(s)$.

Using this, we have

$$R^*(s) = (1-\tilde{\varphi}_0(s))/s \tag{8}$$

The reliability R(t) can be obtained by taking Laplace inverse transform of (8).

The mean time to system failure can be given by

$$\mathrm{MTSF}(T_1) = \lim_{s\to 0} R^*(s)=\frac{N_{11}}{D_{11}} \tag{9}$$

where

$N_{11}=(1-p_{78}p_{83}p_{46})(\mu_0+\mu_1)+\mu_3[p_{13}+p_{46}(p_{83}+p_{78}p_{8,10})]+p_{13}(\mu_4+p_{46}(\mu_6+\mu_7+\mu_8 p_{78}))$

and

$D_{11}=1-p_{46}(p_{78}p_{83}+p_{13}p_{70})$

Availability Analysis

Let $A_i(t)$ be the probability that the system is in up state at instant t given that the system entered regenerative state i at $t=0$. The recursive relations for $A_i(t)$ are given by:

$$A_i(t)=M_i(t)+\sum_j q_{i,j}^{(n)}(t)©A_j(t) \tag{10}$$

where j is any successive regenerative state to which the regenerative state i can transit through $n\geq 1$ (natural number) transitions.

$$\begin{aligned}
&M_0(t)=e^{-\lambda t} \quad M_1(t)=e^{-\lambda_1 t}\,\bar{G}(t), \quad M_3(t)=e^{-\lambda_1 t}, \quad M_4(t)=e^{-\lambda_2 t}\,\overline{W}(t),\\
&M_6(t)=e^{-\lambda_2 t}, \quad M_7(t)=e^{-\lambda_1 t}\,\overline{H}(t), \quad M_8(t)=e^{-\lambda_1 t}\,\bar{G}_1(t), \quad M_{11}(t)=e^{-\lambda t}\,\overline{W}(t),
\end{aligned} \tag{11}$$

We have,

Taking LT of relations (10) and solving for $A_0^*(s)$.

The steady-state availability of the system can be given by

$$A_0(\infty)=\lim_{s\to 0} s\,A_0^*(s)=\frac{N_{12}}{D_{12}} \tag{12}$$

where

$N_{12}=[p_{11.9}+p_{70}]\,(\mu_0+\mu_1+p_{13}\mu_3)+\mu_4+p_{46}\mu_6+\mu_7+p_{78}(\mu_3p_{83}+\mu_8)+p_{7,11.9}\mu_{11}$

$D_{12}=[p_{70}(\mu_0+\mu^1_1+\mu_3)+\mu^1_4+\mu_6p_{46}+\mu^1_7+p_{78}(p_{83}\mu_3+\mu^1_8)+p_{7,11.9}(p_{11,0}\mu_0+\mu^1_1+\mu_3+\mu^1_{11})$

Busy Period Analysis for Server

Let $B_i(t)$ be the probability that the server is busy at an instant t given that the system entered regenerative state i at $t = 0$. The following are the recursive relations for $B_i(t)$

$$B_i(t)=W_i(t)+\sum_j q_{i,j}^{(n)}(t)©B_j(t) \tag{13}$$

where j is a subsequent regenerative state to which state i transits through $n\geq 1$ (natural number) transitions.

We have,

$$\begin{aligned}
&W_1(t)=[e^{-\lambda_1 t}+(\lambda_1e^{-\lambda_1 t}©1)]\,\bar{G}(t), \quad W_4(t)=[e^{-\lambda_2 t}+(\lambda_2e^{-\lambda_2 t}©1)]\,\overline{W}(t)\\
&W_7(t)=[e^{-\lambda_1 t}+(\lambda_1e^{-\lambda_1 t}©1)]\,\overline{H}(t)+(\lambda_1e^{-\lambda_1 t}©ph(t)©1)\,\bar{G}_1(t),\\
&W_8(t)=[e^{-\lambda_1 t}+(\lambda_1e^{-\lambda_1 t}©1)]\,\bar{G}_1(t), \quad W_{11}(t)=[e^{-\lambda t}+[(\lambda e^{-\lambda t}©1)]\,\overline{W}(t)
\end{aligned} \tag{14}$$

Taking LT of relations (13) and solving for $B_0^*(s)$ and using this, we can obtain the fraction of time for which the repairman is busy in steady state

$$B_0=\lim_{s\to 0} s\,B_0^*(s)=\frac{N_{13}}{D_{12}} \tag{15}$$

$N_{13}=[p_{11.9}+p_{70}]\,W_1^*(0)+W_4^*(0)+W_7^*(0)+p_{78}W_8^*(0)+p_{7,11.9}W_{11}^*(0)$

and D_{12} is already mentioned**.**

Expected Number of Visits

Let $N_i(t)$ be the expected number of visits by the server in (0,t] given that the system entered the regenerative state i at $t=0$. We have the following recursive relations for $N_i(t)$:

$$N_i(t)=\sum_j Q_{i,j}(t)®\left[\delta_j+N_j(t)\right] \tag{16}$$

where j is any regenerative state to which the given regenerative state i transits and $\delta_i=1$, if j is the regenerative state where the server does job afresh otherwise $\delta_i=0$.

Taking LST of relations (16) and solving for $\tilde{N}_0(s)$.

The expected number of visits per unit time are given by,

$$N_0=\mathop{Lt}_{s\to 0} s\,\tilde{N}_0(s)=\frac{N_{14}}{D_{12}} \tag{17}$$

where

$N_{14}=[p_{11.9}+p_{70}](1+p_{13})+p_{46}+p_{78}p_{83}$

and D12 is already specified.

Profit Analysis

Profit incurred to the system model in steady state is given by

$$P_1=K_1A_0-K_2B_0-K_3N_0$$

Where: K_1 = Revenue per unit up time of the system

K_2 = Cost per unit time for which server is busy

K_3 = Cost per visit by the server

Particular Case

Let us take $g(t)=\theta e^{-\theta t}$, $g_1(t)=\theta_1 e^{-\theta_1 t}$, $h(t)=\alpha e^{-\alpha t}$ and $w(t)=\beta e^{-\beta t}$

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

$MTSF(T_1)=N_{11}/D_{11}$, Availability$(A_0)=N_{12}/D_{12}$

Busy Period$(B_0)=N_{13}/D_{12}$, Expected no. of visits$(N_0)=N_{14}/D_{12}$

where

$$D_{11}=[(\theta+\lambda_1)(\alpha+\lambda_1)(\lambda_1+\theta_1)(\beta+\lambda_2)-\alpha[p\theta_1(\theta+\lambda_1)+q\theta(\lambda_1+\theta_1)]]/(\theta+\lambda_1)(\alpha+\lambda_1)(\lambda_1+\theta_1)(\beta+\lambda_2)$$

$$N_{11}=[\lambda_2\lambda_1[(\alpha+\lambda_1)(\lambda_1+\theta_1)(\beta+\lambda_2)-\beta\alpha p\theta_1]][(\lambda+\theta+\lambda_1)+\lambda_2\lambda[\theta(\alpha+\lambda_1)(\lambda_1+\theta_1)(\beta+\lambda_2)$$

$$+\beta(\theta+\lambda_1)(\theta_1(\alpha+\lambda_1)+p\alpha\lambda_1)]+\lambda\lambda_1[\lambda_2(\alpha+\lambda_1)(\lambda_1+\theta)+\beta\{(\lambda_1+\theta_1)(\alpha+2\lambda_1)+p\alpha\lambda_2\}]] \quad /[\lambda\lambda_1\lambda_2(\theta+\lambda_1)(\alpha+\lambda_1)(\lambda_1+\theta_1)(\beta+\lambda_2)]$$

$$D_{12}=[q\lambda_2\theta_1\beta\alpha(\beta+\lambda_2)(\lambda_1+\theta_1)(\beta+\lambda)(\lambda_1(\theta+\lambda)+\theta\lambda)+\theta\lambda\theta_1\lambda_1(\alpha+\lambda_1)(\lambda_1+\theta_1)(\beta+\lambda)$$

$$(\lambda_2(1+\beta A)(\beta+\lambda_2)+\beta^2)+p\lambda_2\beta\theta\lambda\alpha(\beta+\lambda)(\beta+\lambda_2)(\theta_1^2+\lambda_1(\theta_1+\lambda_1))+q\theta_1\lambda_2\lambda_1(\beta+\lambda_2)$$

$$(\lambda_1+\theta_1)(\beta^2\lambda_1\theta+(\theta+\lambda_1)\lambda\beta(\beta+\lambda)+\lambda\theta\lambda_1(\beta+\lambda))]/[\theta_1\lambda_1\theta\lambda\beta\lambda_2(\beta+\lambda_2)(\lambda_1+\theta_1)(\beta+\lambda)(\alpha+\lambda_1)]$$

$$N_{12}=[(\beta+\lambda)\{q\lambda_2(\alpha+\lambda_1)(\lambda+\lambda_1)+\lambda\lambda_1(\alpha+\lambda_1+\lambda_2)\}+\lambda_2\lambda(p\alpha(\beta+\lambda)+\lambda_1^2q)]$$

$$/[\lambda\lambda_1\lambda_2(\alpha+\lambda_1)(\beta+\lambda)$$

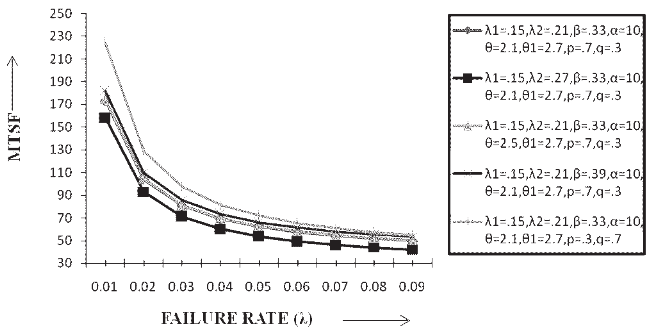
$$N_{13}=[(\beta q+\theta+B\beta\theta)(\alpha+\lambda_1)\theta_1+p\theta\beta\alpha+q\lambda_1\theta_1\theta]/[\theta\theta_1\beta(\alpha+\lambda_1)]$$

$$N_{14}=[(\alpha+\lambda_1)(\theta_1+\lambda_1)[q(2\theta+\lambda_1)(\beta+\lambda_2)+\beta(\theta+\lambda_1)]+p\alpha\theta_1(\theta+\lambda_1)(\beta+\lambda_2)]/$$

$$(\beta+\lambda_2)(\lambda_1+\theta_1)(\alpha+\lambda_1)(\theta+\lambda_1)$$

$$A=[q(\alpha+\lambda_1)^2+\alpha^2p]\theta_1\alpha+q\alpha[(\alpha+\theta_1)(\alpha+\lambda_1)^2-\alpha^2(\alpha+\theta_1+\lambda_1)]/[(\theta_1\alpha^2(\alpha+\lambda_1)^2]$$

$$B=[\theta_1(\alpha+\theta_1)(\theta_1+\lambda_1)+\alpha^2p\lambda_1]/[(\theta_1\alpha(\alpha+\theta_1)(\theta_1+\lambda_1)].$$

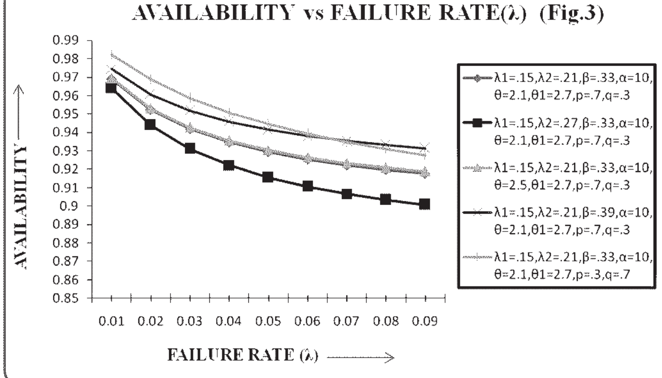


MTSF vs FAILURE RATE(λ) (Fig.2)

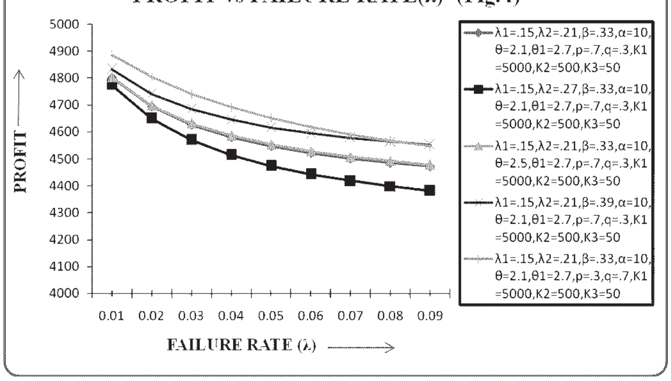
Conclusion

The mean time to system failure (MTSF) of the model is shown in figure 2. This figure indicates that MTSF decreases with the increase of failure rates λ and λ_2 for fixed values of other parameters. But, MTSF increase as repair rate θ and replacement rate β increase. Figure 3 and 4 depict the behaviour of availability and profit of the model. From these figures it can be seen that their values go on decreasing as failure rates λ and λ_2 increase. However, their values increase if repair rate θ and replacement rate β increase for fixed values of other parameters including $K_1=5000$, $K_2=500$ and $K_3=50$. Further, if we interchange p and q, the availability and the profit of the system increase for $\lambda\leq0.07$.

Hence, on the basis of the results obtained for a particular case it is concluded that the concepts of priority for operation to new unit over the duplicate unit and replacement of the degraded unit at its failure are economically beneficial to use.



AVAILABILITY vs FAILURE RATE(λ) (Fig.3)



PROFIT vs FAILURE RATE(λ) (Fig.4)

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