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- Garg, Sambhav (2011): "Business Ethics" Paper presented at the Annual International Conference for the All India Management Association, New Delhi, India, 19–22 June.

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TWO UNIT COLD STANDBY PRIORITY SYSTEM WITH FAULT DETECTION AND PROVISION OF REST

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ABSTRACT
In the present paper a system model which consists of two dissimilar units one being main unit and another as cold standby is investigated and analyzed. The failure time distributions of both the units are assumed to be exponential with different failure rates while the repair time distributions are taken as general. The reliability analysis of this model has been carried out by using regenerative point technique.

KEYWORDS
dissimilar, exponential and general.

INTRODUCTION AND DESCRIPTION OF THE SYSTEM
The concept of inspection is widely used in literature, for describing the models, by several authors The concept of inspection is widely used in literature, for describing the models, by several authors including Agnihotri and Satsangi (1),Goel, Agnihotri and Gupta (2), Goel, Gupta and Agnihotri (3), Gupta, Bajaj and Singh (4), Malik (6), Naidu and Gopalan (7) and Pour Darvish and Joorel (8).Using the concept of inspection, we propose a reliability model which consists of two dissimilar units one being main unit and another as cold standby. Initially the main unit is in operative mode while other is kept as cold standby which becomes operative on failure of the main unit. The main unit may fail directly or becomes hot after some time of operation. The main unit on becoming hot is put under inspection to identify whether it becomes hot due to its operational behaviour or due to some partial failure and in mean time the cold standby unit becomes operative. If the main unit is found to be hot due its operational behavior it is given rest for some random time after which it works as good as new and if found to be partially failed then it is put under repair. If the cold standby unit also fails during the inspection of the main unit, the main unit which was already hot is put under operation but it works with low efficiency. The priority is given to the main unit both for operation and repair.

The failure time distributions of both the units are assumed to be exponential with different failure rates while the repair time distributions are taken as general. The system breaks down on failure of both units. All the random variables associated to different times are mutually independent. Using regenerative points in Markov renewal process, the various measures of reliability such as transient and steady state transition probabilities, distribution of time to system failure and its mean, the mean sojourn time in different states, point wise availability of system at epoch't' and its steady state availability, expected busy period in time interval (0,t] and expected number of visits of the repairman are obtained. The cost benefit analysis of the proposed models has also been carried out.

NOTATIONS
M_o : Main unit is under operation.

C_s : Cold standby unit

M_H : Main unit becomes hot.

M_{HI} : Main unit under inspection on becoming hot.

M_r : Main unit failed completely and put under repair.

M_{pr} : Main unit failed partially and under repair.

M_{HO} : Main unit under operation after becoming hot.

M_{pR} : Main unit failed partially and its repair is continued.

C_O : Cold standby unit is under operation.

C_r : Cold standby unit is under repair.

C_w : Cold standby unit is waiting for repair.

M_{FR} : Repair of main unit continued/put under repair on complete failure during hot period.

M_R : Main unit under rest.

α : Constant mean failure rate of complete failure of main unit.

β : Constant mean failure rate of cold standby unit.

γ : Constant mean failure rate of partial failure of main unit.

μ_1 : Constant mean rate of becoming hot for main unit.

δ : Constant mean rate of inspection of main unit on becoming hot.

μ_2 : Constant mean rate of entering into rest mode of main unit after becoming hot.

λ : Constant mean rate of completion of rest of main unit.

$F(.), f(.)$: c.d.f. and p.d.f. of repair time distribution of complete failure of main unit.

$G(.), g(.)$: c.d.f. and p.d.f. of repair time distribution of partial failure of main unit.

$H(.), h(.)$: c.d.f. and p.d.f. of repair time of cold standby unit.

Using these notations the various possible states of the system along with all possible transitions are presented in the Fig. 1.1. The states $S_0, S_1, S_2, S_3, S_4, S_5, S_6$ and S_9 are up states while S_7 and S_8 are failed states. Further, the states S_7 and S_8 are non regenerative states while rest of states are regenerative states.

Possible States of the System: The system, at any point of time, may be in one of the following states:

$S_0 \equiv [M_o, C_s]$ $S_1 \equiv [M_r, C_o]$ $S_2 \equiv [M_H, C_o]$

$S_3 \equiv [(M_{HO}, C_r]$ $S_4 \equiv [M_{HI}, C_o]$ $S_5 \equiv [M_{pr}, C_o]$

$S_6 \equiv [M_R, C_o]$ $S_7 \equiv [M_{FR}, C_w]$ $S_8 \equiv [M_{PR}, C_w]$

$S_9 \equiv [M_o, C_r]$

TRANSITION PROBABILITIES AND SOJOURN TIMES

The various steady state transition probabilities are as follows:

:

$$p_{01} = \frac{\alpha}{\alpha+\mu_1} \quad p_{02} = \frac{\mu_1}{\alpha+\mu_1} \quad p_{10} = \tilde{F}(\beta) \quad p_{17} = 1 - \tilde{F}(\beta)$$

$$p_{23} = \frac{\beta}{\delta+\beta} \quad p_{24} = \frac{\delta}{\delta+\beta} \quad p_{32} = \tilde{H}(\alpha) \quad p_{37} = 1 - \tilde{H}(\alpha)$$

$$p_{43} = \frac{\beta}{\beta+\gamma+\mu_2} \quad p_{45} = \frac{\gamma}{\beta+\gamma+\mu_2} \quad p_{46} = \frac{\mu_2}{\beta+\gamma+\mu_2} \quad p_{50} = \tilde{G}(\beta)$$

$$p_{58} = 1 - \tilde{G}(\beta) \quad p_{60} = \frac{\lambda}{\lambda+\beta} \quad p_{63} = \frac{\beta}{\lambda+\beta} \quad p_{79} = p_{89} = 1$$

$$p_{90} = \tilde{H}(\alpha+\mu_1) \quad p_{93} = \frac{\mu_1}{\alpha+\mu_1}\left[1 - \tilde{H}(\alpha+\mu_1)\right] \quad p_{97} = \frac{\alpha}{\alpha+\mu_1}\left[1 - \tilde{H}(\alpha+\mu_1)\right] \qquad (1)$$

From the obtained steady state probabilities, it can be easily verified that

$$\sum_j p_{ij} = 1, i = 0,1,\ldots,9 \qquad (2)$$

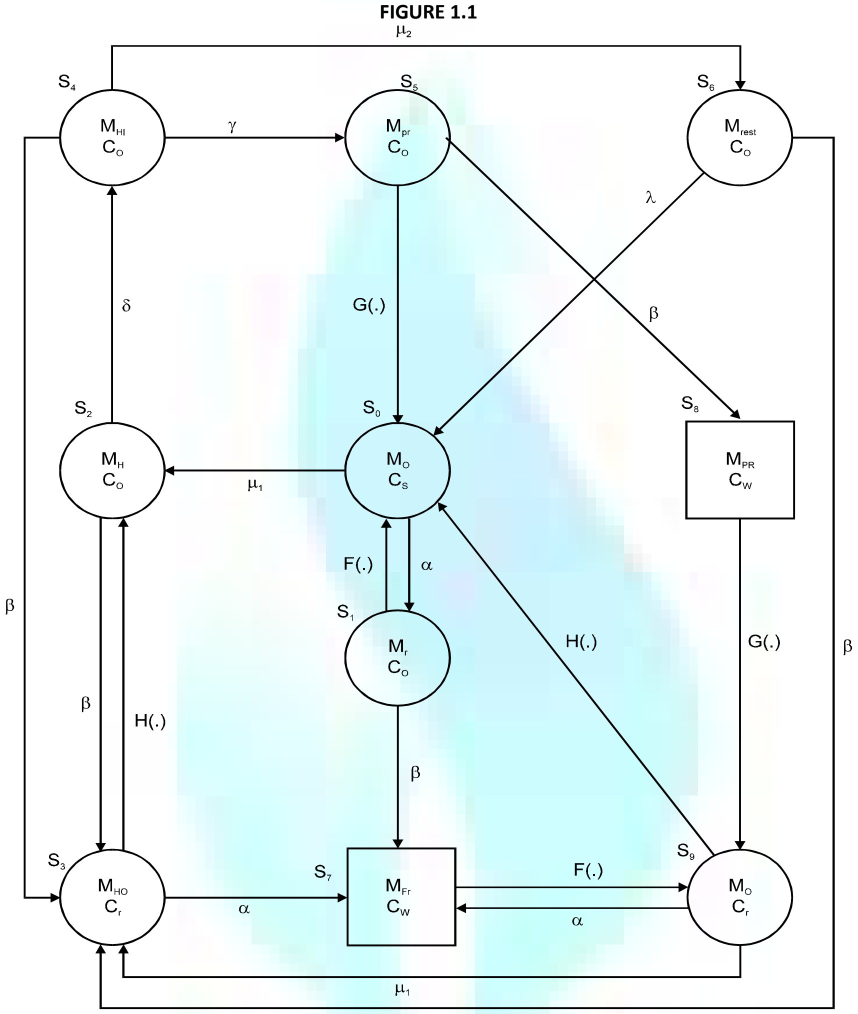
Mean Sojourn time

$$\mu_0 = \frac{1}{\alpha + \mu_1} \qquad \mu_1 = \frac{1 - \tilde{F}(\beta)}{\beta} \qquad \mu_2 = \frac{1}{\delta + \beta} \qquad \mu_3 = \frac{1 - \tilde{H}(\alpha)}{\alpha}$$

$$\mu_4 = \frac{1}{\beta + \mu_2 + \gamma} \qquad \mu_5 = \frac{1 - \tilde{G}(\beta)}{\beta} \qquad \mu_6 = \frac{1}{\lambda + \beta} \qquad \mu_9 = \frac{1 - \tilde{H}(\mu_1)}{\mu_1} \tag{3}$$

STATE TRANSITION DIAGRAM

FIGURE 1.1



MEAN TIME TO SYSTEM FAILURE

let U_i be the random variable denoting time to system failure when the system starts from state S_i, $S_i \in E$ and let $\pi_i(t) = P[U_i \le t]$ be the cdf of time to system failure for the first time when it starts operation from state S_i. To determine the distribution function, $\pi_i(t)$, we regard the failed states S_7 and S_8 as absorbing states. Using basic probabilistic arguments, the recursive relations among $\pi_i(t)$ can be easily developed and taking Laplace Stieltjes transform of the relations and solving for $\tilde{\pi}_0(s)$, we get

$$\tilde{\pi}_0(s) = \frac{N_1(s)}{D_1(s)} \tag{4}$$

where

$$N_1(s) = \tilde{Q}_{01}\tilde{Q}_{17}\left[1 - \tilde{Q}_{32}\tilde{Q}_{23} - \tilde{Q}_{24}\tilde{Q}_{32}\left(\tilde{Q}_{43} + \tilde{Q}_{46}\tilde{Q}_{63}\right)\right] + \tilde{Q}_{02}\tilde{Q}_{23}\tilde{Q}_{37} + \tilde{Q}_{02}\tilde{Q}_{24}\left[\tilde{Q}_{45}\tilde{Q}_{58} + \tilde{Q}_{37}\left(\tilde{Q}_{43} + \tilde{Q}_{46}\tilde{Q}_{63}\right)\right]$$

And

$$D_1(s) = \left(1 - \tilde{Q}_{01}\tilde{Q}_{10}\right)\left[1 - \tilde{Q}_{23}\tilde{Q}_{32} - \tilde{Q}_{24}\tilde{Q}_{32}\left(\tilde{Q}_{43} + \tilde{Q}_{46}\tilde{Q}_{63}\right)\right] - \tilde{Q}_{02}\tilde{Q}_{24}\left(\tilde{Q}_{45}\tilde{Q}_{50} + \tilde{Q}_{46}\tilde{Q}_{60}\right)$$

(for simplicity we have omitted the argument 's' from $\tilde{Q}_{ij}(s)$)

and Using $\lim_{s\to 0}\tilde{Q}_{ij}(s) \to p_{ij}$, and eq. (1) and eq. (2), we obtain the following limiting values of $N_1(s)$ and $D_1(s)$ on 's' approaches to zero

$$N_1(0) = p_{01}p_{17}[1 - p_{32}p_{23} - p_{24}p_{32}(p_{43} + p_{46}p_{63})] + p_{02}p_{23}p_{37} + p_{02}p_{24}[p_{45}p_{58} + p_{37}(p_{43} + p_{46}p_{63})]$$

$$= (1 - p_{01}p_{10})[1 - p_{23}p_{32} - p_{24}p_{32}(p_{43} + p_{46}p_{63})] - p_{02}p_{24}(p_{45}p_{50} + p_{46}p_{60})$$

and

$$D_1(0) = (1 - p_{01}p_{10})[1 - p_{23}p_{32} - p_{24}p_{32}(p_{43} + p_{46}p_{63})] - p_{02}p_{24}(p_{45}p_{50} + p_{46}p_{60}) \quad (5)$$

On comparing the above expressions of $N_1(0)$ and $D_1(0)$, we observe that $N_1(0) = D_1(0)$ and thus $\tilde{\pi}_0(s) = 1$ as $s \to 0$, which implies that $\pi_0(t)$ is a proper cumulative distribution function.

Thus, Mean Time to System Failure (MTSF) when system starts operation with the entrance into S_0 is obtained as

$$E(T) = -\frac{d}{ds}\tilde{\pi}_0(o) = \frac{D_1'(0) - N_1'(0)}{D_1(0)} \quad (6)$$

where $N_1'(0)$ and $D_1'(0)$ are the derivatives of the numerator and denominator of $\tilde{\pi}_0(s)$ at $s \to 0$.

To obtain the numerator of MTSF defined by (5),

$$m_{ij} = -\tilde{Q}_{ij}'(s)_{/s=0} = \frac{d}{ds}\int_0^\infty e^{-st}dQ_{ij}(t)/_{s=0} \quad \text{and} \quad \sum_j m_{ij} = \mu_i$$

where m_{ij} is the mean elapsed time of the system in state S_i before transiting to state S_j.

Therefore, on arranging the coefficients of m_{ij}'s and also by using the above relations, the expression for $D_1'(0) - N_1'(0)$ can be written as:

$$D_1'(0) - N_1'(0) = (\mu_0 + \mu_1 p_{01})[1 - p_{23}p_{32} - p_{24}p_{32}(p_{43} + p_{46}p_{63})] + \mu_2(1 - p_{01}) + \mu_3 p_{02}[p_{23} + p_{24}(p_{43} + p_{46}p_{63})] + p_{02}p_{24}(\mu_4 + \mu_5 p_{45} + \mu_6 p_{46}) \quad (7)$$

Therefore, using (5) and (7) in (6), the mean time to system failure (MTSF) becomes

$$E(T) = \frac{(\mu_0 + \mu_1 p_{01})[1 - p_{23}p_{32} - p_{24}p_{32}(p_{43} + p_{46}p_{63})] + \mu_2(1 - p_{01}) + \mu_3 p_{02}[p_{23} + p_{24}(p_{43} + p_{46}p_{63})] + p_{02}p_{24}(\mu_4 + \mu_5 p_{45} + \mu_6 p_{46})}{(1 - p_{01}p_{10})[1 - p_{23}p_{32} - p_{24}p_{32}(p_{43} + p_{46}p_{63})] - p_{02}p_{24}(p_{45}p_{50} + p_{46}p_{60})}$$

AVAILABILITY ANALYSIS

$A_i(t)$ is the probability that the system is up at epoch 't' given that initially it was in up state S_i. Using the definition of $A_i(t)$, the recursive relations among $A_i(t)$ can be easily developed, taking their Laplace transform and solving $A_0^*(s)$, we can write the expression of steady-state availability of the system in the following form:

$$A_0 = \lim_{t\to\infty} A_0(t) = \lim_{s\to 0} sA_0^*(s) = \lim_{s\to 0} s\frac{N_2(s)}{D_2(s)} \quad (8)$$

which is an indeterminate form since the denominator of (8) becomes zero as $s \to 0$, which can easily be verified.

Therefore, on using L' Hospital's rule, the steady state availability, A_0 becomes

$$A_0 = \lim_{s\to 0}\frac{sN_2'(s) + N_2(s)}{D_2'(s)} = \frac{N_2(0)}{D'_2(0)} \quad (9)$$

Further on using the following relations:

$$\lim_{s\to 0} q_{ij}^*(s) = q_{ij}^*(0) = p_{ij} \quad \text{and} \quad -q_{ij}^{*\prime}(0) = m_{ij}$$

also $Z_i^*(0) = \mu_i,\ i = 0, 1, 2, 3, 4, 5, 6, 9$

The numerator and denominator of steady state availability of the system starting from state S_0, $S_0 \in E$, is thus becomes

$$N_2(0) = [(1-p_{97})(\mu_0 + p_{01}\mu_1) + p_{01}p_{17}\mu_9]\begin{bmatrix}(1-p_{97})(1-p_{23}p_{32} - p_{24}p_{32}p_{43} - p_{24}p_{46}p_{32}p_{63}) \\ -p_{37}p_{93}(p_{23}+p_{24}p_{43}) - p_{24}p_{93}(p_{45}p_{58}+p_{46}p_{37}p_{63})\end{bmatrix}$$

$$+[p_{01}p_{17}p_{93} + p_{02}(1-p_{97})]\begin{bmatrix}\begin{pmatrix}\mu_2 + \mu_3 p_{23} + \mu_4 p_{24} + \mu_3 p_{24}p_{43} + \mu_5 p_{24}p_{45} \\ +\mu_6 p_{24}p_{46} + \mu_3 p_{24}p_{46}p_{63}\end{pmatrix}(1-p_{97}) \\ +(p_{23}p_{37} + p_{24}p_{45}p_{58} + p_{24}p_{37}p_{46}p_{63} + p_{24}p_{37}p_{43})\mu_9\end{bmatrix}$$

$$D_2'(0) = \mu_0(1-p_{97})\begin{bmatrix}p_{23}p_{37}p_{90} + p_{24}p_{43}p_{37}p_{90} + p_{24}p_{45}p_{90} + p_{24}p_{45}p_{50}p_{93} \\ +p_{24}p_{46}p_{90} + p_{24}p_{46}p_{60}p_{93}\end{bmatrix}$$

$$+\mu_1 p_{01}(1-p_{97})\begin{bmatrix}1-p_{97}-p_{23}p_{32}p_{90}-p_{23}p_{93}-p_{24}p_{45}p_{58}p_{93}-p_{24}p_{32}p_{43}p_{90} \\ -p_{24}p_{43}p_{93}-p_{24}p_{46}p_{32}p_{63}p_{90}-p_{24}p_{46}p_{63}p_{93}\end{bmatrix}$$

$$+\mu_2(1-p_{97})(1-p_{97}-p_{01}p_{10}+p_{01}p_{10}p_{97}-p_{01}p_{17}p_{90})$$

$$+\mu_3(1-p_{97}-p_{01}p_{10}+p_{01}p_{10}p_{97}-p_{01}p_{17}p_{90})[(p_{23}+p_{24}p_{43}+p_{24}p_{46}p_{63})(1-p_{97})]$$

$$+\mu_4 p_{24}(1-p_{97})(1-p_{01}p_{10}-p_{01}p_{17}p_{90})(1-p_{97})$$

$$+\mu_5 p_{24}p_{45}(1-p_{97})(1-p_{97}-p_{01}p_{10}+p_{01}p_{10}p_{97}-p_{01}p_{17}p_{90})$$

$$+\mu_6 p_{24}p_{46}(1-p_{97})(1-p_{97}-p_{01}p_{10}+p_{01}p_{10}p_{97}-p_{01}p_{17}p_{90})$$

$$+\mu_7 p_{97}\left[(1-p_{01}p_{10})\begin{pmatrix}1-p_{97}-p_{23}p_{32}p_{97}+p_{23}p_{37}p_{93}-p_{24}p_{43}p_{32}p_{97} \\ +p_{24}p_{43}p_{37}p_{93}-p_{24}p_{46}p_{32}p_{63}p_{97}+p_{24}p_{46}p_{37}p_{63}p_{93}\end{pmatrix}\right]$$

$$+\mu_7 p_{97}[(1-p_{01}p_{10})p_{24}p_{43}p_{37}p_{90}]$$

$$+\mu_7 p_{97}(p_{23}p_{37}p_{90}-p_{24}p_{45}p_{50}p_{97}-p_{24}p_{46}p_{60}p_{97}+p_{24}p_{46}p_{37}p_{63}p_{90})$$

BUSY PERIOD ANALYSIS

$B_i(t)$ is the probability that the system having started from regenerative state $S_i, S_i \in E$ at time $t = 0$ is under repair i.e. the repairman is busy. Using the definition of $B_i(t)$, the recursive relations among $B_i(t)$ can be easily developed, taking their Laplace transform and solving them for $B_0^*(s)$, the steady state probability that the system is under repair with repairman starting from state S_0, i.e. in the long-run the repairman is busy is given by

$$B_0 = \lim_{t\to\infty} B_0(t) = \lim_{s\to 0} s B_0^*(s) == \lim_{s\to 0} s\frac{N_3(s)}{D_3(s)} \qquad (10)$$

Since the denominator of (10) becomes zero as $s \to 0$, thus on using L' Hospital's Rule and the results $\lim_{s\to 0} q_{ij}^*(s) = q_{ij}^*(0) = p_{ij}$ and $-q_{ij}^{*\prime}(0) = m_{ij}$ also

the expression for B_0 becomes

$$B_0 = \lim_{s\to 0}\frac{N_3(s)}{D_3'(s)} = \frac{N_3(0)}{D_3'(0)} \qquad (11)$$

where

$$N_3(0) = (1-p_{97}-p_{23}p_{37}p_{93}-p_{24}p_{43}p_{37}p_{93}-p_{24}p_{45}p_{58}p_{93}-p_{24}p_{37}p_{46}p_{63}p_{93})$$

$$[\mu_1 p_{01}(1-p_{97}) + p_{01}p_{17}\mu_9 + p_{01}p_{17}\mu_7]$$

$$+(p_{23}p_{37}+p_{24}p_{43}p_{37}+p_{24}p_{45}p_{58}+p_{24}p_{46}p_{37}p_{63})\mu_9$$

$$+(1-p_{97})(p_{23}\mu_3+p_{24}\mu_4+p_{24}p_{43}\mu_3+p_{24}p_{45}\mu_5+p_{24}p_{46}p_{63}\mu_3)$$

$$+(p_{23}p_{37}+p_{24}p_{43}p_{37}+p_{24}p_{45}p_{58}p_{97}+p_{24}p_{46}p_{37}p_{63})\mu_7$$

and the expression of $D_3'(0)$ is equivalent to $D_2'(0)$,

EXPECTED NUMBER OF VISITS

$V_i(t)$ is the expected number of visits by the repairman during time (0, t], given that the system initially starts from the regenerative state $S_i, S_i \in E$ at time $t=0$. Thus, the expressions for various $V_i(t), i=0,1,2,3,4,5,6,7,9$ can be obtained and taking Laplace Stieltjes transform , we get a system of linear equations in $\tilde{V}_i(s)$ and solving them for $\tilde{V}_0(s)$ we get the expected number of visits per unit of time, in steady state

$$V_0 = \lim_{t\to\infty}\left[\frac{V_0(t)}{t}\right] = \lim_{s\to 0} s\,\tilde{V}_0(s) = \lim_{s\to 0} s\,\frac{N_4(s)}{D_4(s)} = \frac{N_4(0)}{D_4'(0)} \tag{12}$$

(since $D_4(s)$ tends to zero as s→0 and on using L' Hospital's rule)

where

$$N_4(0) = p_{01}(1-p_{97})(1-p_{97})(1-p_{23}p_{32}-p_{24}p_{43}p_{32}-p_{24}p_{46}p_{32}p_{63})$$
$$+p_{01}(1-p_{97})[p_{23}p_{37}p_{93}+p_{24}p_{43}p_{37}p_{93}+p_{24}p_{45}p_{58}p_{93}-p_{24}p_{46}p_{37}p_{63}p_{93}]$$
$$+(1-p_{97})[p_{01}p_{17}p_{93}+p_{02}(1-p_{97})]$$

and the expression of $D_4'(0)$ is equivalent to $D_2'(0)$,

COST BENEFIT ANALYSIS

For obtaining, the total expected cost incurred in time $(0,t]$, we consider the expected time for which the system is under repair and the number of times the repairman becomes available.

Let $C(t)$ denotes the expected total cost incurred in time $(0,t]$, which is given as

$$C(t) = C_1\mu_R(t) + C_2V_0(t) \tag{13}$$

where

C_1 = Cost per unit time for the system to be repaired by repairman

C_2 = Cost per visit by the repairman

Further, let the expected total revenue in time (0, t] is denoted by $R(t)$ and is defined as (14)

$$R(t) = C_0\mu_{up}(t)$$

where

C_0 is revenue per unit up time of the system.

Therefore, the total expected profit of the system in time $(0,t]$, is given by

$$P(t) = R(t) - C(t) = p_0\mu(t) - C_1\mu(t) + C_2V_0(t)$$

The expected total profit per unit is given by

$$P = \frac{P(t)}{t}$$

And, in the long- run, this profit is becomes

$$P = \lim_{t\to\infty}\frac{P(t)}{t} = \lim_{s\to 0}\left[s^2.P^*(s)\right] = C_0A_0 - C_1B_0 - C_2V_0 \tag{15}$$

GRAPHICAL REPRESENTATIONS OF MTSF AND AVAILABILITY

The repair time distributions of the complete failure of main unit, partial failure of main unit and cold standby unit of the system were assumed arbitrary while describing the system description and all other times assumed exponentially distributed with different parameters. To study the behavior of its MTSF and availability through graphical presentation, we assume that the repair time distributions of these three failures are also exponential with constant failure rate θ_1, θ_2 and θ_3, respectively. To plot the graphs of MTSF and availability of the system, we consider three different cases for the various values of the failure and repair rates. In the first case, we fixed the values of $\beta=\gamma=\delta=\mu_1=\mu_2=\lambda=\theta_1=\theta_2=\theta_3=0.30$ and different values of $\alpha,\ 0<\alpha\le 1$. In the second case, $\beta=\gamma=\delta=\mu_1=\mu_2=\lambda=\theta_1=\theta_2=\theta_3=0.50$ and different values of $\alpha,\ 0<\alpha\le 1$, while in the third case, $\beta=\gamma=\delta=\mu_1=\mu_2=\lambda=\theta_1=\theta_2=\theta_3=0.80$ and different values of $\alpha,\ 0<\alpha\le 1$. The three sets of graphs of MTSF and availability have been plotted and presented through Figure 1.2 and Figure 1.3, respectively. From, these figures we observed that, in all cases, both MTSF and availability of the system decreases with increasing failure rate of complete failure of main unit.

FIGURE 1.2

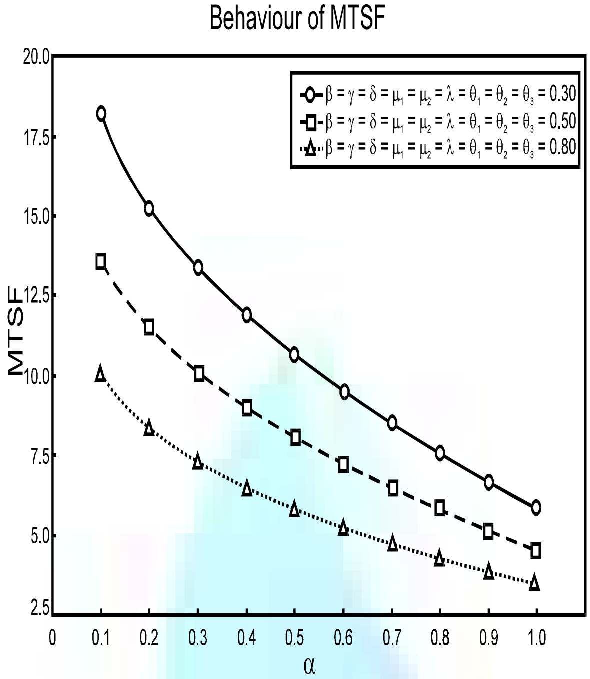
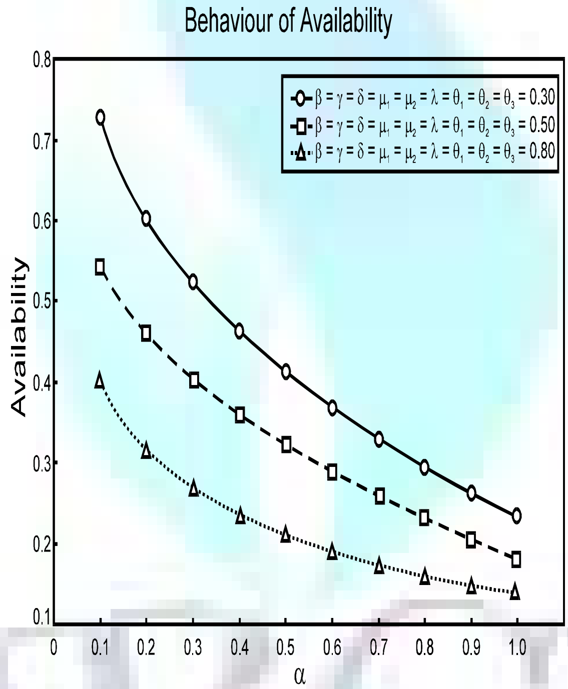


FIGURE 1.3



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