International Journal of Mathematics And its Applications
Volume 4, Issue 1–A (2016), 139–147.
ISSN: 2347-1557
Available Online: http://ijmaa.in/

International Journal of Mathematics And its Applications

Performance Analysis of a Cold Standby System with Fault Detection and Arrival Time of Server Subject to Imperfect Coverage

Research Article

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Abstract: The main aim of present paper is to analyse the performance measures of a standby system by using the concept of arrival time of server, repair, imperfect coverage, detection and replacement. A single repair facility is provided to the system as and when required. The repairman takes some time to conduct the repair services. Upon failure of the unit repairman first detect the failed unit to check the feasibility of repair and replacement in case fault is not completely coverage. The repair, replacement, detection and arrival time of the repairman are considered as arbitrary distributed while failure rate is taken as negative exponential distributed. The failure time of the unit is exponentially distributed while the distribution of repair times, replacement time and recovery time of the unit follows arbitrary distribution. Various recurrence relations for reliability, MTSF, availability and profit function are derived using semi-Markov process and regenerative point technique. Graphs for availability and profit function are drawn with respect to failure rate.

Keywords: Standby System; Arrival Time of Server; Imperfect Coverage; Replacement and Performance Measures.

1. Introduction

Redundancy (provision of spare unit) is a very important technique of reliability and availability improvement used in industries. During last few decades, a lot of research papers are written by researchers and scientists. A detailed list of such papers are given by [14, 16]. Under a different set of assumptions, many authors like, [2, 3, 3–8, 11–13, 18, 19] developed stochastic models for two-unit cold standby redundant systems. However, perfect coverage of failure is the common assumption considered in these papers. If, faults are not fully detected, located and covered is called imperfect coverage. According to [17] faults which are detected fully is denoted by probability a and not covered assigned the probability '$1 - a = b$'. [15] examined the reliability of a high voltage system with dependent failure and imperfect coverage. [9] used a programming parametric approach for a two-unit cold standby system by using imperfect coverage, reboot and fuzzy parameters. Barak and Malik [1] developed a reliability model for a two-unit cold standby with arrival time of server using the concept of maximum operation and repair times. Recently, [10] carried out the performance analysis of a computer system with imperfect hardware detection. But, the effect of imperfect coverage on two-unit cold standby systems has not been analyzed in the literature so far. For this purpose, in the present study a stochastic model is developed for a two-unit cold standby under the following set of assumptions:

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- Initially system has two-identical units- one operative and other as cold standby.
- A single repairman, who takes some time, is provided to the system.
- Failed unit undergoes for detection to check the feasibility of repair or replacement.
- If fault of the unit is detected by the repairman it is repaired by the repairman with some repair time otherwise unit is replaced by new one.
- The failure time of the unit is exponentially distributed while the distribution of repair times, replacement time and recovery time of the unit follows arbitrary distribution.

2. Notations

a	: Probability of complete fault coverage
b	: Probability of imperfect fault coverage
λ	: Constant failure rate of each unit of the system
H(t) / h(t)	: cdf / pdf of replacement time of failed unit when repair is not feasible
G(t) / g(t)	: cdf / pdf of repair time of failed unit when repair is feasible
M(t) / m(t)	: cdf / pdf of fault detection time of failed unit
W(t)/w(t)	: cdf / pdf of arrival time of the server
$\mu_t(t)$	: Probability that the system remains in upstate up to time t without visiting to any other regenerative state
Ⓡ/Ⓒ	: Symbol for Laplace- Stieltjes convolution/Laplace convolution

$Q_{ij}(t)/q_{ij}(t)$ is the cdf / pdf of 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]. $Q_{ij.kr}(t)/q_{ij.kr}(t)$ is the cdf/pdf of direct transition time from regenerative state i to a regenerative state j or to a failed state j visiting state k, r once in (0, t]. $W_i(t)$ is the probability that the 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 state via one or more non-regenerative states.

3. Transition Probabilities and Mean Sojourn Times

Simple probabilistic considerations yield the following expressions for the non-zero elements

$$p_{ij} = Q_{ij}(\infty) = \int_0^\infty q_{ij}(t)dt \text{ as} \tag{1}$$

$$\begin{aligned}
&p_{01} = 1, p_{12} = w^*(\lambda),\ p_{12} = 1 - w^*(\lambda),\ p_{23} = bm^*(\lambda),\ p_{24} = m^*(\lambda),\ p_{25} = 1 - m^*(\lambda),\ p_{30} = h^*(\lambda),\ p_{3.13} = 1 - h^*(\lambda),\\
&p_{40} = g^*(\lambda),\ p_{4.12} = 1 - g^*(\lambda),\ p_{56} = am^*(0),\ p_{57} = bm^*(0),\ p_{62} = g^*(0),\ p_{72} = h^*(0),\ p_{89} = w^*(0),\ p_{9.10} = am^*(0),\\
&p_{9.11} = bm^*(0),\ p_{10.2} = g^*(0),\ p_{11.2} = h^*(0),\ p_{12.2} = g^*(0),\ p_{13.2} = h^*(0),\ p_{12.8,9,10} = aw^*(0)m^*(0)g^*(0)[1 - w^*(\lambda)],\\
&p_{12.8,9,11} = aw^*(0)m^*(0)h^*(0)[1 - w^*(\lambda)],\ p_{22.5,6} = am^*(0)g^*(0)[1 - m^*(\lambda)],\\
&p_{22.5,7} = bm^*(0)h^*(0)[1 - m^*(\lambda)],\ p_{32.13} = h^*(0)[1 - h^*(\lambda)],\ p_{42.12} = m^*(0)[1 - g^*(\lambda)]
\end{aligned} \tag{2}$$

The sum of all transition probabilities from each state is equal to one. Mean sojourn times (μ_i) at each regenerative state S_i is as follows:

$$\mu_0 = \frac{1}{\lambda},\ \mu_1 = \frac{1}{\alpha + \lambda},\ \mu_2 = \frac{1}{\beta + \lambda},\ \mu_3 = \frac{1}{\theta + \lambda},\ \mu_4 = \frac{1}{\gamma + \lambda},\ \mu_1^{'} = \frac{1}{\alpha}, \mu_3^{'} = \frac{1}{\theta},\ \mu_2^{'} = \frac{1}{\beta} \text{ and } \mu_4^{'} = \frac{1}{\gamma}$$

4. System Description

Under the above stated assumptions, stochastic model is developed for a two-unit cold standby using the concept of repair and detection and imperfect coverage. The states of the system are follows:

Program : TEX

$S_0(N_0, Cs)$: The system is in working conditions having one unit operative and other in cold standby.

$S_1(N_0, WFd)$: The system is in working conditions having one unit operative and other in waiting for fault detection.

$S_2(N_0, Fud)$: The system is in working conditions having one unit operative and other unit is under fault detection.

$S_3(N_0, Furp)$: The system is in working conditions having one unit operative and other unit under replacement due to imperfect fault coverage.

$S_4(N_0, Fur)$: The system is in working conditions having one unit operative and other unit under repair after perfect fault coverage.

$S_5(FUD, Fwd)$: The system is in down state. One failed unit continuous under fault detection and other waiting for fault detection.

$S_6(Fur, FWD)$: The system is in down state. One failed unit is under repair and other continuously waiting for fault detection.

$S_7(Furp, FWD)$: The system is in down state. One failed unit is under replacement and other continuously waiting for fault detection.

$S_8(FWD, Fwd)$: The system is in down state. One failed unit continuous waiting for fault detection and other also waiting for fault detection.

$S_9(Fud, FWD)$: The system is in down state. One failed unit under fault detection and other continuously waiting for fault detection.

$S_{10}(Fur, FWD)$: The system is in down state. One failed unit under repair and other continuously waiting for fault detection.

$S_{11}(Furp, FWD)$: The system is in down state. One unit under replacement and other continuously waiting for fault detection.

$S_{12}(FUR, Fwd)$: The system is in down state. One failed unit continuously under repair and other waiting for fault detection.

$S_{13}(FURP, Fwd)$: The system is in down state. One failed unit continuously under replacement and other waiting for fault detection.

The set E = {S0, S1, S2, S3, S4} represents all regenerative states.

5. Reliability and MTSF

The mean time to system failure and reliability of a cold standby system is analyzed in this section with arrival time of the server and fault detection subject to imperfect coverage. The cumulative density function of first passage time is denoted by $R_i(t)$ betweenS_i, $S_j \in F$. On the basis of system description, we derived following recurrence relation for $R_i(t)$ by assuming the down state S_j as an absorbing state.

$$R_i\left(t\right) = \sum_j Q_{i,j}\left(t\right) Ⓡ R_j\left(t\right) + \sum_k Q_{i,k}\left(t\right) \tag{3}$$

Where $S_j \in F$ to $S_i \in F$ can transit and S_k is a down state to which the state S_i can transit. We simplify the recurrence relation (3) by taking LST for $R_0^{**}(s)$. We have

$$R*(s) = \frac{1 - R_0^{**}(s)}{s} \tag{4}$$

By taking the inverse LT of equation (4), we can obtain the reliability of the system. Now, the mean time to system failure (MTSF) is given by

$$\text{Mean time to system failure} = \lim_{s \to o} \frac{1 - R_0^{**}(s)}{s} = \lim_{s \to o} \frac{D^{'}(0) - N^{'}(0)}{D(0)} \tag{5}$$

Where

$$D(s) = \begin{vmatrix} 1 & -Q_{01}^{**}(s) & 0 & 0 & 0 \\ 0 & 1 & -Q_{12}^{**}(s) & 0 & 0 \\ 0 & 0 & 1 & -Q_{23}^{**}(s) & -Q_{24}^{**}(s) \\ -Q_{30}^{**}(s) & 0 & 0 & 1 & 0 \\ -Q_{40}^{**}(s) & 0 & 0 & 0 & 1 \end{vmatrix} \text{ and } N(s) = \begin{vmatrix} 0 & -Q_{01}^{**}(s) & 0 & 0 & 0 \\ Q_{18}^{**}(s) & 1 & -Q_{12}^{**}(s) & 0 & 0 \\ Q_{25}^{**}(s) & 0 & 1 & -Q_{23}^{**}(s) & -Q_{24}^{**}(s) \\ Q_{3.13}^{**}(s) & 0 & 0 & 1 & 0 \\ Q_{4.12}^{**}(s) & 0 & 0 & 0 & 1 \end{vmatrix}$$

6. Steady State Availability

By probabilistic arguments

$$M_0(t) = e^{-(a\lambda_1 + b\lambda_2)t},\ M_1(t) = e^{-(a\lambda_1 + b\lambda_2)t\overline{F(t)}},\ M_2(t) = e^{-(a\lambda_1 + b\lambda_2)t\overline{H(t)}} \text{ and } M_3(t) = e^{-(a\lambda_1 + b\lambda_2)t\overline{G(t)}}$$

From the arguments used in the theory of regenerative processes, the point wise availabilities $A_i(t)$ are seen to satisfy the following recurrence relation

$$A_i(t) = M_i(t) + \sum_j q_{i,j}^{(n)} \copyright A_j(t) \tag{6}$$

Where S_j, $S_i \in E$ and state S_i can transit to the successive state S_j through n transitions. Taking Laplace transformation of equation (6) and solving for $A_0^*(s)$ we get

$$A_0(\infty) = \lim_{s \to 0} s\, A_0^*(s) = \frac{N_1(0)}{D_1'(0)}$$

Where

$$D_1(s) = \begin{vmatrix} 1 & -q_{01}^*(s) & 0 & 0 & 0 \\ 0 & 1 & \begin{matrix} -q_{12}^*(s) - q_{12.8,9,10}^*(s) \\ -q_{12.8,9,11}^*(s) \end{matrix} & 0 & 0 \\ 0 & 0 & \begin{matrix} 1 - q_{22.5,6}^*(s) \\ -q_{22.5,7}^*(s) \end{matrix} & -q_{23}^*(s) & -q_{24}^*(s) \\ -q_{30}^*(s) & 0 & -q_{32.13}^*(s) & 1 & 0 \\ -q_{40}^*(s) & 0 & -q_{42.12}^*(s) & 0 & 1 \end{vmatrix} \text{ and}$$

$$N_1(s) = \begin{vmatrix} M_0^*(s) & -q_{01}^*(s) & 0 & 0 & 0 \\ M_1^*(s) & 1 & \begin{matrix} -q_{12}^*(s) - q_{12.8,9,10}^*(s) \\ -q_{12.8,9,11}^*(s) \end{matrix} & 0 & 0 \\ M_2^*(s) & 0 & \begin{matrix} 1 - q_{22.5,6}^*(s) \\ -q_{22.5,7}^*(s) \end{matrix} & -q_{23}^*(s) & -q_{24}^*(s) \\ M_3^*(s) & 0 & -q_{32.13}^*(s) & 1 & 0 \\ M_4^*(s) & 0 & -q_{42.12}^*(s) & 0 & 1 \end{vmatrix}$$

7. Busy Period Analysis of Repairman due to Fault Detection, Repair and Replacement

By probabilistic arguments, we get the following recurrence relations for $B_i(t)$

$$\begin{aligned} B_i^d(t) &= K_i(t) + \textstyle\sum_j q_{i,j}^{(n)}(t) © B_j^d(t) \\ B_i^r(t) &= K_i(t) + \textstyle\sum_j q_{i,j}^{(n)}(t) © B_j^r(t) \\ B_i^{rp}(t) &= K_i(t) + \textstyle\sum_j q_{i,j}^{(n)}(t) © B_j^{rp}(t) \end{aligned} \tag{7}$$

Where $S_j,\ S_i \in E$ and stateS_i can transit to the successive stateS_j through n transitions. The probability that the repairman remains busy in any state S_i due to fault detecting, repairing and replacement of the unit 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 is denoted by $K_i(t)$ and so

$$K_1(s) = e^{-\lambda t)}\overline{M}(t),\ K_3(s) = e^{-\lambda t}\overline{H}(t),\ K_4(s) = e^{-\lambda t}\overline{G}(t)$$

The time for which repairman is busy in various repair and fault detection activities is given by

$$B_0^d(\infty) = \lim_{s\to 0} sB_0^{*d}(s) = \frac{N_2(0)}{D_2'(0)},\quad B_0^r(\infty) = \lim_{s\to 0} sB_0^{*r}(s) = \frac{N_3(0)}{D_2'(0)} \text{ and } B_0^{rp}(\infty) = \lim_{s\to 0} sB_0^{*rp}(s) = \frac{N_4(0)}{D_2'(0)}$$

Where the values of $B_0^{*^d}(s)$, $B_0^{*^r}(s)$ and $B_0^{*^{rp}}(s)$ are obtained by taking Laplace transformation of equation (7). And

$$N_2(s) = \begin{vmatrix} 0 & -q_{01}^*(s) & 0 & 0 & 0 \\ 0 & 1 & \begin{matrix} -q_{12}^*(s) - q_{12.8,9,10}^*(s) \\ -q_{12.8,9,11}^*(s) \end{matrix} & 0 & 0 \\ W_2^*(s) & 0 & \begin{matrix} 1 - q_{22.5,6}^*(s) \\ -q_{22.5,7}^*(s) \end{matrix} & -q_{23}^*(s) & -q_{24}^*(s) \\ 0 & 0 & -q_{32.13}^*(s) & 1 & 0 \\ 0 & 0 & -q_{42.12}^*(s) & 0 & 1 \end{vmatrix},$$

$$N_3(s) = \begin{vmatrix} 0 & -q_{01}^*(s) & 0 & 0 & 0 \\ 0 & 1 & \begin{matrix} -q_{12}^*(s) - q_{12.8,9,10}^*(s) \\ -q_{12.8,9,11}^*(s) \end{matrix} & 0 & 0 \\ 0 & 0 & \begin{matrix} 1 - q_{22.5,6}^*(s) \\ -q_{22.5,7}^*(s) \end{matrix} & -q_{23}^*(s) & -q_{24}^*(s) \\ 0 & 0 & -q_{32.13}^*(s) & 1 & 0 \\ W_4^*(s) & 0 & -q_{42.12}^*(s) & 0 & 1 \end{vmatrix} \text{ and}$$

$$N_4(s) = \begin{vmatrix} 0 & -q_{01}^*(s) & 0 & 0 & 0 \\ 0 & 1 & -q_{12}^*(s) - q_{12.8,9,10}^*(s) - q_{12.8,9,11}^*(s) & 0 & 0 \\ 0 & 0 & 1 - q_{22.5,6}^*(s) - q_{22.5,7}^*(s) & -q_{23}^*(s) & -q_{24}^*(s) \\ W_3^*(s) & 0 & -q_{32.13}^*(s) & 1 & 0 \\ 0 & 0 & -q_{42.12}^*(s) & 0 & 1 \end{vmatrix}$$

And $D_2(s)$ is obtained already.

8. Expected Number of Repairs by the Server

By probabilistic arguments, we have following recursive relations for $N_i(t)$

$$R_i\left(t\right)=\sum_j Q_{i,j}^{(n)}\left(t\right) ® \left[\delta_j+R_j\left(t\right)\right] \tag{8}$$

Where $S_j,\ S_i\ \in\ E$ and stateS_i can transit to state S_j while $\delta j=\begin{cases}1 & if\, S_j\in E\\ 0 & otherwise\end{cases}$, where repairman starts a new job. The anticipated number of repairs per unit time by the repairman is given by

$$R_0(\infty)=\lim_{s\to 0}\ s\,R_0^{**}(s)=\frac{N_5(s)}{D_2'(s)} \tag{9}$$

Where the value of $N_0^{**}(s)$ is obtained by taking the Laplace Steiltjes Transform of equation

$$N_5(s)=\begin{vmatrix} 0 & -Q_{01}^*(s) & 0 & 0 & 0\\ 0 & 1 & -Q_{12}^*(s)-Q_{12.8,9,10}^*(s)-Q_{12.8,9,11}^*(s) & 0 & 0\\ 0 & 0 & 1-Q_{22.5,6}^*(s)-Q_{22.5,7}^*(s) & -Q_{23}^*(s) & -Q_{24}^*(s)\\ 0 & 0 & -Q_{32.13}^*(s) & 1 & 0\\ Q_{40}^*(s)+Q_{42.12}^*(s) & 0 & -Q_{42.12}^*(s) & 0 & 1 \end{vmatrix}$$

And D$_2$(s) is obtained already.

9. Anticipated Number of Arrivals by the Repairman

By probabilistic arguments, we have following recursive relations for $N_i(t)$

$$N_i\left(t\right)=\sum_j Q_{i,j}^{(n)}\left(t\right) ® \left[\delta_j+N_j\left(t\right)\right] \tag{10}$$

Where $S_j,\ S_i\ \in\ E$ and stateS_i can transit to stateS_j while $\delta j=\begin{cases}1 & if\, S_j\in E\\ 0 & otherwise\end{cases}$, where repairman starts a new job. The anticipated number of arrivals per unit time by the repairman is given by

$$N_0(\infty)=\lim_{s\to 0}\ s\,\tilde{N}_0(s)=\frac{N_4(s)}{D_2'(s)} \tag{11}$$

Where the value of $\tilde{N}_0(s)$ is obtained by taking the Laplace Steiltjes Transform of equation (8). And

$$N_6(s)=\begin{vmatrix} Q_{12}^*(s)+Q_{12.8,9,10}^*(s)+Q_{12.8,9,11}^*(s) & -Q_{01}^*(s) & 0 & 0 & 0\\ 0 & 1 & -Q_{12}^*(s)-Q_{12.8,9,10}^*(s)-Q_{12.8,9,11}^*(s) & 0 & 0\\ 0 & 0 & 1-Q_{22.5,6}^*(s)-Q_{22.5,7}^*(s) & -Q_{23}^*(s) & -Q_{24}^*(s)\\ 0 & 0 & -Q_{32.13}^*(s) & 1 & 0\\ 0 & 0 & -Q_{42.12}^*(s) & 0 & 1 \end{vmatrix}$$

and D$_2$(s) is already obtained.

10. Performance Analysis

The performance of the system is analyzed by net profit incurred in steady-state. The profit earned by the system can be obtained as

$$P = X_0 A_0 - X_1 B_0^d - X_2 B_0^r - X_3 B_0^{rp} - X_4 N_1 - X_5 N_2 \tag{12}$$

X_0 = Income by the availability of the system per unit up-time

X_1 = Expenditure per unit time for which repairman is engaged in fault detection

X_2 = Expenditure per unit time for which repairman is engaged in repair

X_3 = Expenditure per unit time for which repairman is engaged in replacement

X_4 = Expenditure per unit time for expected number of repairs

X_5 = Expenditure per unit time for expected number of visits by the server

11. Numerical Results

The numerical results for different reliability measures of a cold standby system with fault detection and arrival time of server are derived in tables 1-2 for a particular case by considering all random variables as exponentially distributed, i.e., $h(t) = \theta e^{-\theta t}$, $g(t) = \gamma e^{-\gamma t}$, $m(t) = \beta e^{-\beta t}$ and $w(t) = \alpha e^{-\alpha t}$.

Λ	$\theta = 1.5$, $\beta = .27$, $\alpha = 1.2$, $\gamma = 4$, $a = 0.6$, $b = 0.4$	$\theta = 1.5$, $\beta = .27$, $\alpha = 1.2$, $\gamma = 2$, $a = 0.6$, $b = 0.4$	$\theta = 1.5$, $\beta = .93$, $\alpha = 1.2$, $\gamma = 4$, $a = 0.6$, $b = 0.4$	$\theta = 1.5$, $\beta = .27$, $\alpha = 2.3$, $\gamma = 4$, $a = 0.6$, $b = 0.4$
0.10	0.8443	0.8432	0.9401	0.8437
0.11	0.8316	0.8304	0.9345	0.8309
0.12	0.8193	0.8181	0.9290	0.8185
0.13	0.8074	0.8061	0.9236	0.8065
0.14	0.7959	0.7945	0.9182	0.7949
0.15	0.7847	0.7833	0.9128	0.7837
0.16	0.7739	0.7724	0.9076	0.7728
0.17	0.7634	0.7619	0.9024	0.7622
0.18	0.7532	0.7517	0.8972	0.7520
0.19	0.7433	0.7417	0.8921	0.7420
0.20	0.7337	0.7321	0.8871	0.7323

Table 1. **Availability vs. Failure rate of the system**

λ	$\theta = 1.5$, $\beta = .27$, $\alpha = 1.2$, $\gamma = 4$, $a = 0.6$, $b = 0.4$	$\theta = 1.5$, $\beta = .27$, $\alpha = 1.2$, $\gamma = 2$, $a = 0.6$, $b = 0.4$	$\theta = 1.5$, $\beta = .93$, $\alpha = 1.2$, $\gamma = 4$, $a = 0.6$, $b = 0.4$	$\theta = 1.5$, $\beta = .27$, $\alpha = 2.3$, $\gamma = 4$, $a = 0.6$, $b = 0.4$
0.10	4005.3	3996.3	4406.0	3999.1
0.11	3939.8	3930.6	4377.8	3.932.9
0.12	3876.4	3867.0	4.350.0	3868.8
0.13	3815.1	3805.5	422.4	3806.8
0.14	3755.7	3745.9	4295.2	3746.7
0.15	3698.2	3688.2	4268.3	3688.5
0.16	3642.4	3632.2	42418	3632.1
0.17	3588.3	3578.0	4215.5	3577.3
0.18	3535.7	3525.3	4189.5	3524.1
0.19	3484.7	3474.2	4163.8	3472.5
0.20	3335.2	3424.5	4138.4	3422.3

Table 2. **Profit vs. Failure rate of the system**

12. Conclusion

Tables -1 & 2 shows the behavior of the system's availability and profit with respect to failure rate of the system. From, it we find that the system's availability and profit decreases with the increase of failure rate (λ) and arrival time of server (α) while availability and profit increases with the increase of replacement rate (θ), repair rate (γ) and detection rate (β). Thus, we finally conclude that a cold standby system can be made more profitable by increasing the detection rate, replacement rate and repair rate of the failed unit.

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