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ESTIMATION OF RELIABILITY FOR MULTI-COMPONENT SYSTEMS USING EXPONENTIAL, GAMMA AND LINDLEY STRESS-STRENGTH DISTRIBUTIONS

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Abstract

This paper deals with the stress vs. strength problem incorporating multi-component systems viz. standby redundancy. The models developed have been illustrated assuming that all the components in the system for both stress and strength are independent and follow different probability distributions viz. Exponential, Gamma and Lindley. Four different conditions for stress and strength have been considered for this investigation. Under these assumptions the reliabilities of the system have been obtained with the help of the particular forms of density functions of n-standby system when all stress-strengths are random variables. The expressions for the marginal reliabilities R(1), R(2), R(3) etc. have been derived based on its stress- strength models. Then the corresponding system reliabilities R_n have been computed numerically and presented in tabular forms for different stress-strength distributions with different values of their parameters. Here we consider $n \leq 3$ for estimating the system reliability R_3.

Key words: Stress-strength Model, n- Standby, Redundancy, Reliability.

1. Introduction

The strength of a system and the stresses on it may be taken as random variables and system reliability R may be defined as

$$R = \Pr(X \geq Y)$$

In a standby system, i.e. a system with standby redundancy, there are a number of components only one of which works at a time and the other remain as standbys. When an impact of stress exceeds the strength of the active component, for the first time, it fails and another from standbys, if there is any, is activated and faces the impact of stresses, not necessarily identical as faced by the preceding component. The system fails when all the components have failed.

Here we have assumed that stress-strengths of all the components in the system are independent. Sriwastav and Kakaty [7] have assumed that the components stress-strengths are similarly distributed. But in general the stress distributions will be different from the strength distributions not only in parameter values but also in forms since stresses are independent of strengths and the two are governed by different physical conditions. They have considered a cascade system with dissimilar distributions of $X's$ and $Y's$ but not for stress-strength model. So, in this paper we have considered stress-strength model for dissimilar distributions.

In Section 2 general standby stress-strength model is formulated. In subsection 2.1 to 2.4, the reliability expressions are obtained when the stress-strength of the components follow different dissimilar distributions. In Section 3, some numerical values of reliability are tabulated for some particular values of the parameters for all the cases.

2. General Model

Consider an n-standby system in which, initially, there are n components, out of which only one is working under impact of stresses and the remaining (n-1) are standbys. Whenever the working component fails, one from standbys takes its place and is subjected to impact of stresses and the system works. The system fails when all the components fail. For a detailed description of such a system one may refer to [2], [3], [6] and [7].

Symbolically, let $X_1, X_2, ..., X_n$ be a set of n independent random variables, representing the strengths of the n components arranged in order of activation in the system and let $Y_1, Y_2, ..., Y_n$, be another set of independent random variables, representing the stresses on the n components respectively, then the system reliability R_n of the system is given by,

$$R_n = R(1) + R(2) + ... + R(n) \tag{2.1}$$

where the marginal reliability $R(r)$ is the contribution to the reliability of the system by the rth component and may be defined as

$$R(r) = \Pr\left[X_1 \langle Y_1, X_2 \langle Y_2, ..., X_{r-1} \langle Y_{r-1}, X_r \geq Y_r\right]$$

Let $f_i(x)$ and $g_i(y)$ be the probability density functions (p.d.f.) of X_i and Y_i, $i = 1, 2, ..., n$ respectively then

$$R(r) = \left[\int_{-\infty}^{\infty} F_1(y) g_1(y) dy\right]\left[\int_{-\infty}^{\infty} F_2(y) g_2(y) dy\right] .. \left[\int_{-\infty}^{\infty} F_{r-1}(y) g_{r-1}(y) dy\right]\left[\int_{-\infty}^{\infty} \overline{F}_r(y) g_r(y) dy\right] \tag{2.2}$$

where $F_i(x)$ is the cumulative distribution function (c.d.f.) of X_i, i.e.

$$F_i(x) = \int_{-\infty}^{x} f_i(x) dx \quad \text{and} \quad \overline{F}_i(x) = 1 - F_i(x)$$

The following conditions for strength i.e. $f_i(x)$ and stress i.e. $g_i(y)$, have been considered for this investigation.

(i) Stress follows two-parameter exponential and strength follows one-parameter exponential distribution.

(ii) Stress follows two-parameter gamma and strength follows one-parameter exponential distribution.

(iii) Stress follows one-parameter gamma and strength follows Lindley distribution.

(iv) Stress follows two-parameter gamma and strength follows Lindley distribution.

2.1 One-parameter exponential strength and two-parameter exponential stress

Let $f_i(x)$ be the one-parameter exponential strength with mean $\frac{1}{\lambda_i}$ and $g_i(y)$ be the two-parameter exponential [4] stress with parameter μ_i and θ_i respectively, i= 1, 2,…,n; then we have the following probability density functions

$$f_i(x,\lambda)=\begin{cases}\lambda_i e^{-\lambda_i x_i};\ x_i \geq 0,\ \lambda_i \geq 0\\ 0, \quad otherwise\end{cases} \tag{2.3}$$

and $$g_i(y;\mu,\theta)=\begin{cases}\frac{1}{\theta_i}e^{-\frac{(y_i-\mu_i)}{\theta_i}};\ y_i>\mu_i,\ \mu_i \geq 0,\ \theta_i>0\\ 0, \quad otherwise\end{cases} \tag{2.4}$$

Then from (2.2), we get,

$$R(1)=\frac{e^{-\lambda_1\mu_1}}{1+\lambda_1\theta_1}$$

$$R(2)=\left[1-\frac{e^{-\lambda_1\mu_1}}{1+\lambda_1\theta_1}\right]\frac{e^{-\lambda_2\mu_2}}{1+\lambda_2\theta_2}$$

$$R(3)=\left[1-\frac{e^{-\lambda_1\mu_1}}{1+\lambda_1\theta_1}\right]\left[1-\frac{e^{-\lambda_2\mu_2}}{1+\lambda_2\theta_2}\right]\frac{e^{-\lambda_3\mu_3}}{1+\lambda_3\theta_3}$$

Therefore in general,

$$R(r)=\left[1-\frac{e^{-\lambda_1\mu_1}}{1+\lambda_1\theta_1}\right]\left[1-\frac{e^{-\lambda_2\mu_2}}{1+\lambda_2\theta_2}\right]...\left[1-\frac{e^{-\lambda_{r-1}\mu_{r-1}}}{1+\lambda_{r-1}\theta_{r-1}}\right]\frac{e^{-\lambda_r\mu_r}}{1+\lambda_r\theta_r}$$

$$=\frac{e^{-\lambda_r\mu_r}}{1+\lambda_r\theta_r}\prod_{i=1}^{r}\left(1-\frac{e^{-\lambda_{i-1}\mu_{i-1}}}{1+\lambda_{i-1}\theta_{i-1}}\right),$$ Here, $\lambda_0=\theta_0=0$

2.2 One-parameter exponential strength and two-parameter gamma stress

Let $f_i(x)$ be one-parameter exponential strength with mean $\frac{1}{\lambda_i}$ and $g_i(y)$ be the two-parameter gamma stress with parameters μ_i *and* θ_i respectively, i=1,2,…,n, then we have the following probability density functions

$$f_i(x,\lambda)=\begin{cases}\lambda_i e^{-\lambda_i x_i};\ x_i \geq 0,\ \lambda_i \geq 0\\ 0, \quad otherwise\end{cases}$$

and $g_i(y;\mu,\theta) = \begin{cases} \dfrac{1}{\theta_i^{\mu_i}\Gamma\mu_i} y_i^{\mu_i - 1} e^{-\frac{y_i}{\theta_i}}, \; y_{i,}\mu_{i,}\theta_i > 0 \\ 0, \qquad\qquad otherwise \end{cases}$

Then, from (2.2) we get,

$$R(1) = \frac{1}{(1+\lambda_1\theta_1)^{\mu_1}}$$

$$R(2) = \left[1 - \frac{1}{(1+\lambda_1\theta_1)^{\mu_1}}\right]\left[\frac{1}{(1+\lambda_2\theta_2)^{\mu_2}}\right]$$

$$R(3) = \left[1 - \frac{1}{(1+\lambda_1\theta_1)^{\mu_1}}\right]\left[1 - \frac{1}{(1+\lambda_2\theta_2)^{\mu_2}}\right]\left[\frac{1}{(1+\lambda_3\theta_3)^{\mu_3}}\right]$$

In general,

$$R(r) = A\prod_{i=1}^{r}\left[1 - \frac{1}{(1+\lambda_{i-1}\theta_{i-1})^{\mu_{i-1}}}\right] \quad \text{where, } A = \frac{1}{(1+\lambda_r\theta_r)^{\mu_r}};$$

Here, $\lambda_0 = \theta_0 = 0$

2.3 Lindley Strength and one-parameter gamma stress

Let $f_i(x)$ be the strength of Lindley distribution ([1], [5]) with parameter θ_i and $g_i(y)$ be one-parameter gamma stress with parameter m_i respectively, i=1,2,…,n, then we have the following probability density functions

$$f_i(x;\theta) = \begin{cases} \dfrac{\theta_i^2}{1+\theta_i}(1+x_i)e^{-\theta_i x_i}; \; x_i \rangle 0, \; \theta_i \rangle 0 \\ 0, \qquad otherwise \end{cases}$$

and $$g_i(y) = \begin{cases} \dfrac{1}{\Gamma(m_i)} e^{-y_i} y_i^{m_i - 1}; \; y_i \geq 0, \; m_i \geq 1 \\ 0, \qquad otherwise \end{cases}$$

Then from (2.2), we get,

$$R(1) = \frac{1}{(1+\theta_1)^{m_1}} + \frac{\theta_1 m_1}{(1+\theta_1)^{m_1+2}}$$

$$R(2) = \left[\frac{\theta_1^2}{(1+\theta_1)^{m_1+1}} + \frac{\theta_1^2 m_1}{(1+\theta_1)^{m_1+2}}\right]\left[\frac{1}{(1+\theta_2)^{m_2}} + \frac{\theta_2 m_2}{(1+\theta_2)^{m_2+2}}\right]$$

$$R(3)=\left[\frac{\theta_1^2}{(1+\theta_1)^{m_1+1}}+\frac{\theta_1^2 m_1}{(1+\theta_1)^{m_1+2}}\right]\left[\frac{\theta_2^2}{(1+\theta_2)^{m_2+1}}+\frac{\theta_2^2 m_2}{(1+\theta_2)^{m_2+2}}\right]\left[\frac{1}{(1+\theta_3)^{m_3}}+\frac{\theta_3 m_3}{(1+\theta_3)^{m_3+2}}\right]$$

In general,

$$R(r)=\left[\frac{\theta_1^2}{(1+\theta_1)^{m_1+1}}+\frac{\theta_1^2 m_1}{(1+\theta_1)^{m_1+2}}\right]\left[\frac{\theta_2^2}{(1+\theta_2)^{m_2+1}}+\frac{\theta_2^2 m_2}{(1+\theta_2)^{m_2+2}}\right]\cdots\cdots\left[\frac{1}{(1+\theta_r)^{m_r}}+\frac{\theta_r m_r}{(1+\theta_r)^{m_r+2}}\right]$$

2.4 Lindley Strength and two-parameter gamma distribution stress

Let $f_i(x)$ be the strength of Lindley distribution with parameter θ_i and $g_i(y)$ be two-parameter gamma stress with parameters μ_i *and* λ_i respectively, i=1,2,…,n, then we have the following probability density functions

$$f_i(x;\theta)=\begin{cases}\dfrac{\theta_i^2}{1+\theta_i}(1+x_i)e^{-\theta_i x_i}; \; x_i\rangle 0,\; \theta_i\rangle 0\\ 0, \qquad otherwise\end{cases}$$

and $$g_i(y;\mu,\lambda)=\begin{cases}\dfrac{1}{\lambda_i^{\mu_i}\Gamma(\mu_i)}y_i^{\mu_i-1}e^{-\frac{y_i}{\lambda_i}}; \; y_i,\mu_i,\lambda_i>0\\ 0, \qquad otherwise\end{cases}$$

Then from (2.2), we get,

$$R(1)=\frac{1}{(1+\lambda_1\theta_1)^{\mu_1}}+\frac{\lambda_1\theta_1\mu_1}{(1+\theta_1)(1+\lambda_1\theta_1)^{\mu_1+1}}$$

$$R(2)=\left[\frac{\theta_1^2}{(1+\theta_1)(1+\lambda_1\theta_1)^{\mu_1}}+\frac{\lambda_1\theta_1^2\mu_1}{(1+\theta_1)(1+\lambda_1\theta_1)^{\mu_1+1}}\right]\left[\frac{1}{(1+\lambda_2\theta_2)^{\mu_2}}+\frac{\lambda_2\theta_2\mu_2}{(1+\theta_2)(1+\lambda_2\theta_2)^{\mu_2+1}}\right]$$

$$R(3)=\left[\frac{\theta_1^2}{(1+\theta_1)(1+\lambda_1\theta_1)^{\mu_1}}+\frac{\lambda_1\theta_1^2\mu_1}{(1+\theta_1)(1+\lambda_1\theta_1)^{\mu_1+1}}\right]\left[\frac{\theta_2^2}{(1+\theta_2)(1+\lambda_2\theta_2)^{\mu_2}}+\frac{\lambda_2\theta_2^2\mu_2}{(1+\theta_2)(1+\lambda_2\theta_2)^{\mu_2+1}}\right]$$
$$\left[\frac{1}{(1+\lambda_3\theta_3)^{\mu_3}}+\frac{\lambda_3\theta_3\mu_3}{(1+\theta_3)(1+\lambda_3\theta_3)^{\mu_3+1}}\right]$$

In general,

$$R(r)=\left[\frac{\theta_1^2}{(1+\theta_1)(1+\lambda_1\theta_1)^{\mu_1}}+\frac{\lambda_1\theta_1^2\mu_1}{(1+\theta_1)(1+\lambda_1\theta_1)^{\mu_1+1}}\right]\left[\frac{\theta_2^2}{(1+\theta_2)(1+\lambda_2\theta_2)^{\mu_2}}+\frac{\lambda_2\theta_2^2\mu_2}{(1+\theta_2)(1+\lambda_2\theta_2)^{\mu_2+1}}\right]$$
$$\cdots\left[\frac{1}{(1+\lambda_r\theta_r)^{\mu_r}}+\frac{\lambda_r\theta_r\mu_r}{(1+\theta_r)(1+\lambda_r\theta_r)^{\mu_r+1}}\right]$$

3. Numerical Evaluation

For some specific values of the parameters involved in the expressions of $R(r),\ r=1,2,3$, we have evaluated the marginal reliabilities $R(1)$, $R(2)$, $R(3)$ and the system reliability R_3 for different cases of Exponential, Gamma and Lindley distributions from their expressions obtained in section 2.

λ_1	λ_2	λ_3	μ_1	μ_2	μ_3	θ_1	θ_2	θ_3	$R(1)$	$R(2)$	$R(3)$	R_3
1	1	1	.1	.1	.1	.2	.2	.2	.7540	.1855	.0456	.9851
1	1	1	.2	.2	.2	.3	.3	.3	.6298	.2332	.0863	.9493
1	1	1	.3	.3	.3	.4	.4	.4	.5292	.2491	.1173	.8956
2	2	2	.1	.1	.1	.2	.2	.2	.5848	.2428	.1008	.9284
2	2	2	.2	.2	.2	.3	.3	.3	.4190	.2434	.1414	.8038
2	2	2	.3	.3	.3	.4	.4	.4	.3049	.2119	.1473	.6641
3	3	3	.1	.1	.1	.2	.2	.2	.4630	.2486	.1335	.8452
3	3	3	.2	.2	.2	.3	.3	.3	.2888	.2054	.1461	.6403
3	3	3	.3	.3	.3	.4	.4	.4	.1848	.1507	.1228	.4583
1	1	1	.1	.1	.1	.1	.1	.1	.8226	.1459	.0259	.9944
2	2	2	.1	.1	.1	.1	.1	.1	.6823	.2168	.0689	.9679
3	3	3	.1	.1	.1	.1	.1	.1	.5699	.2451	.1054	.9204
4	4	4	.1	.1	.1	.1	.1	.1	.4788	.2496	.1301	.8584
.1	.1	.1	.2	.2	.2	1	1	1	.8911	.0970	.0106	.9987
.1	.1	.1	.2	.2	.2	2	2	2	.8168	.1496	.0274	.9939
.1	.1	.1	.2	.2	.2	3	3	3	.7540	.1855	.0456	.9851
.1	.1	.1	.2	.2	.2	4	4	4	.7001	.2099	.0630	.9730
.1	.1	.1	1	1	1	.1	.1	.1	.8959	.0933	.0097	.9989
.1	.1	.1	2	2	2	.1	.1	.1	.8106	.1535	.0291	.9932
.1	.1	.1	3	3	3	.1	.1	.1	.7335	.1995	.0521	.9811
.1	.1	.1	4	4	4	.1	.1	.1	.6637	.2232	.0751	.9620

Table 1: **One-parameter exponential strength and two-parameter exponential stress**

From Table 1, it may be observed that the system reliability R_3 decreases when the strength parameter is constant with increasing stress parameter. For instance, if the strength parameters $\lambda_1=\lambda_2=\lambda_3=1$ are fixed and the stress parameters μ_i and θ_i; i=1,2,3 increase from 0.1 upto 0.3, then the system reliabilities R_3 decrease from 0.9851 upto 0.8956. Increasing stress and strength parameters decrease the system reliability. Similarly, when strength parameter increases with some fixed stress parameter, the system reliability decreases. For example, if strength parameters λ_i; i=1,2,3 increase from 1 upto 4 with fixed stress parameters $\mu_1 = \mu_2 = \mu_3 = \theta_1 = \theta_2 = \theta_3 = .1$, the system reliabilities R_3 decrease from 0.9944 upto 0.8584.

θ_1	θ_2	θ_3	λ_1	λ_2	λ_3	μ_1	μ_2	μ_3	$R(1)$	$R(2)$	$R(3)$	R_3
1	1	1	.1	.1	.1	2	2	2	.8264	.1434	.0249	.9948
1	1	1	.2	.2	.2	3	3	3	.5787	.2438	.1027	.9252
1	1	1	.3	.3	.3	4	4	4	.3501	.2275	.1479	.7255
2	2	2	.1	.1	.1	2	2	2	.6944	.2122	.0648	.9715
2	2	2	.2	.2	.2	3	3	3	.3644	.2316	.1472	.7433
2	2	2	.3	.3	.3	4	4	4	.1526	.1293	.1096	.3915
3	3	3	.1	.1	.1	2	2	2	.5917	.2416	.0986	.9319
3	3	3	.2	.2	.2	3	3	3	.2441	.1845	.1395	.5682
3	3	3	.3	.3	.3	4	4	4	.0767	.0708	.0654	.2130
4	4	4	.1	.1	.1	2	2	2	.5102	.2499	.1224	.8825
4	4	4	.2	.2	.2	3	3	3	.1715	.1421	.1177	.4312
4	4	4	.3	.3	.3	4	4	4	.0427	.0409	.0391	.1227
5	5	5	.1	.1	.1	2	2	2	.4444	.2469	.1372	.8285
5	5	5	.2	.2	.2	3	3	3	.1250	.1094	.0957	.3301
5	5	5	.3	.3	.3	4	4	4	.0256	.0249	.0243	.0749

Table 2: **One-parameter exponential strength and two-parameter gamma stress**

Table 2 reveals that for fixed values of $\theta_1, \theta_2, \theta_3$ and increasing values of $\lambda_1, \lambda_2, \lambda_3, \mu_1, \mu_2, \mu_3$, the system reliability R_3 decreases. For example, for fixed values 1 of $\theta_1, \theta_2, \theta_3$ and increasing values from 0.1 to 0.3 of λ_1, λ_2, λ_3 and θ_1, θ_2 and θ_3, the system reliability R_3 decreases from 0.9948 upto 0.7433.

θ_1	θ_2	θ_3	m_1	m_2	m_3	$R(1)$	$R(2)$	$R(3)$	R_3
.1	.2	.3	1	1	1	.9842	.0150	.0007	.9999
.1	.2	.3	2	2	2	.9630	.0188	.0010	.9829
.1	.2	.3	3	3	3	.9376	.0209	.0012	.9597
.1	.2	.3	4	4	4	.9088	.0216	.0012	.9316
.4	.5	.6	1	1	1	.8601	.1140	.0200	.9941
.4	.5	.6	2	2	2	.7185	.0909	.0140	.8234
.4	.5	.6	3	3	3	.5876	.0646	.0081	.6603
.4	.5	.6	4	4	4	.4728	.0428	.0041	.5197
.7	.8	.9	1	1	1	.7307	.1865	.0544	.9717
.7	.8	.9	2	2	2	.5136	.1001	.0209	.6346
.7	.8	.9	3	3	3	.3514	.0484	.0067	.4066
.7	.8	.9	4	4	4	.2357	.0219	.0019	.2596

Table 3: **Lindley Strength and one-parameter gamma stress**

From Table 3, it can be seen that for fixed but different values of strength parameters $\theta_1, \theta_2, \theta_3$ and increasing but equal values of stress parameters m_1, m_2, m_3, the system reliability R_3 decreases. For example, corresponding to the values $\theta_1 = .1,\ \theta_2 = .2,\ \theta_3 = .3,\ m_1 = m_2 = m_3 = 1$, the system reliability $R_3 = .9999$ but for $\theta_1 = .1,\ \theta_2 = .2,\ \theta_3 = .3,\ m_1 = m_2 = m_3 = 4$, $R_3 = .9316$. Thus, by proper choice of the different parameters, very high system reliability $R_3 = .9999$ can be achieved.

λ_1	λ_2	λ_3	μ_1	μ_2	μ_3	θ_1	θ_2	θ_3	$R(1)$	$R(2)$	$R(3)$	R_3
1	1	1	2	2	2	.1	.1	.1	.9630	.0204	.0004	.9839
1	1	1	2	2	2	.2	.2	.2	.8873	.0548	.0034	.9455
1	1	1	2	2	2	.3	.3	.3	.8018	.0834	.0087	.8938
1	1	1	2	2	2	.4	.4	.4	.7185	.1017	.0144	.8346
1	1	1	2	2	2	.5	.5	.5	.6420	.1110	.0192	.7721
2	2	2	3	3	3	.1	.1	.1	.8418	.0266	.0008	.8692
2	2	2	3	3	3	.2	.2	.2	.6247	.0401	.0026	.6674
2	2	2	3	3	3	.3	.3	.3	.4554	.0366	.0029	.4949
2	2	2	3	3	3	.4	.4	.4	.3348	.0284	.0024	.3656
2	2	2	3	3	3	.5	.5	.5	.2500	.0208	.0017	.2726
3	3	3	4	4	4	.1	.1	.1	.6439	.0210	.0006	.6656
3	3	3	4	4	4	.2	.2	.2	.3433	.0148	.0006	.3588
3	3	3	4	4	4	.3	.3	.3	.1886	.0073	.0002	.1962
3	3	3	4	4	4	.4	.4	.4	.1092	.0034	.0001	.1128
3	3	3	4	4	4	.5	.5	.5	.0666	.0016	.0004	.0682

Table 4: **Lindley Strength and two-parameter gamma distribution stress**

Table 4 exhibits the values of marginal reliabililities $R(1), R(2), R(3)$ and system reliability R_3 for a system with Lindley Strength and two-parameter gamma distribution stress corresponding to different values of stress-strength parameters. It is observed that system reliability R_3 decreases with increasing stress-strength parameters. Also, for some fixed values of the stress parameters $\lambda_1,\ \lambda_2,\ \lambda_3,\ \mu_1,\ \mu_2,\ \mu_3$ and increasing values of the strength parameters $\theta_1,\ \theta_2,\ \theta_3$, the system reliability R_3 decreases. For instance, for $\lambda_1 = \lambda_2 = \lambda_3 = 1,\ \mu_1 = \mu_2 = \mu_3 = 2,\ \theta_1 = \theta_2 = \theta_3 = .1$, $R_3 = .9839$ and for $\lambda_1 = \lambda_2 = \lambda_3 = 1,\ \mu_1 = \mu_2 = \mu_3 = 2,\ \theta_1 = \theta_2 = \theta_3 = .2$ $R_3 = .9455$.

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