Tabular Comparison of Two similar Dual-unit Systems with single server

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Abstract — In this paper, reliability measures of two dual-unit systems having non-identical units are compared under different weather conditions namely normal & abnormal in steady state using semi-Markov process and regenerative point technique. In both the models, initially original unit (called as main unit) is operative while the other substandard unit (called as duplicate unit) is kept at cold standby mode. Two units either have normal mode of operation or failed. There is a single server who performs the repair activities of both units in normal weather conditions only. Server leaves the system in abnormal weather conditions. In model I, neither operation nor repair activities are allowed in abnormal weather conditions but in model II, operation of both units are allowed in different weather conditions. The distribution for failure times of the units and time to change of weather conditions are taken as negative exponential while that of repair time of the units are arbitrary. All random variables are statistically independent. The results for some important reliability measures such as MTSF, availability, busy period of server, expected number of visits by the server have been analyzed for arbitrary values of various parameters and costs. Reliability comparisons and profit comparisons are made between the two systems.

Index Terms — Dual-unit system, Semi-Markov process, Regenerative point technique

I. INTRODUCTION

In view of their frequent and vital use in management and industrial sectors, the repairable systems of two or more identical units have catered great attentiveness among researcher and scientists. These systems are investigated stochastically in detail by the scholars including Gopalan and Naidu (1982), Goyal and Murari (1984), and Singh (1989) under strict control of environment conditions. The weather environment has a significant impact on the performance of the operating systems. The physical stresses created by adverse weather conditions deteriorate performance and efficiency of these systems. Besides, scientists and engineers have tried a lot to develop systems which can work in varying environmental conditions but when cost of unit is higher than the non-identical unit (may be a substandard unit) might be kept as spare in cold standby not only to improve the reliability of the system but also to maintain performance of the system in emergency. Chander et al. (2007) discussed standby systems of non-identical units with different failure and repair policies. Each unit is capable of performing the same kind of functions but their degree of reliability and desirability may differ from unit to unit. The weather environment has a significant impact on the performance of the operating systems. The physical stresses created by adverse weather conditions deteriorate performance and efficiency of these systems. Also, sometimes it becomes very difficult to keep the environmental conditions under control which may fluctuate due changing climate and other natural catastrophic. While considering this fact in mind, Malik and Barak (2009), Malik et al. (2012) and Deswal. S (2015) obtained reliability and economic measures of a non-identical units with no operation and repair activities in abnormal weather.

This Paper concentrates on two repairable systems of two non-identical units. Both systems contain two units—one is original (called main unit) and other is a substandard unit (called duplicate unit) under two weather conditions – normal and abnormal. The environmental conditions when satisfied to the system correspond to normal weather; otherwise, it is supposed that the system is in abnormal weather. Initially, the system is operative with main unit and duplicate unit is kept a spare in cold standby. Both units have direct complete failure from normal mode. Each unit is capable of performing the same set of functions with different degree of reliability and desirability. There is a single server who visits the system immediately whenever needed to do repair of the failed unit in normal weather only. The operation and repair of the units are not allowed in abnormal weather as a precautionary measure to avoid excessive damage to the system in Model I. But sometimes we may have emergency situations in which operation of the system becomes necessary irrespective of weather conditions. Dhillon and Nateoson (1983), Pawar et al. (2010, 2013), Promila et al. (2010) have determined reliability measures of a single unit system subject to weather conditions allowing operation in abnormal weather So, operation of both units is allowed in Model II. The repair of the units are as usual in normal weather. The units work as new after repair. In these Models repair activities are not allowed in abnormal
weather. The distribution of failure times of units and change of weather conditions are taken as negative exponential while that of repair times of the units follow arbitrary distributions. All random variables are statistically independent. The semi-Markov and regenerative point technique are adopted to drive the expressions for the reliability measures such as mean time to system failure (MTSF), availability, busy period of the server, expected number of visits by the server and profit function. The results are analyzed through graphs for particular values of various parameters and costs. The mean time to system failure (MTSF) and profit of these Models are compared. The application of the present work can be visualized in a software industry where application software is run through two different databases-one is initially operative and other is kept in cold standby

II. NOTATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>The set of regenerative states</td>
</tr>
<tr>
<td>MO/DO</td>
<td>Main/Duplicate unit is good and operative</td>
</tr>
<tr>
<td>MWO / DWO</td>
<td>Main/Duplicate unit is good and waiting for operation in abnormal weather</td>
</tr>
<tr>
<td>MO / DO</td>
<td>Main/Duplicate unit is good and operating in abnormal weather</td>
</tr>
<tr>
<td>MCs/DCs</td>
<td>Main/Duplicate unit is in cold standby mode</td>
</tr>
<tr>
<td>MCs / DCs</td>
<td>Main/Duplicate unit is in cold standby mode in abnormal weather</td>
</tr>
<tr>
<td>λ / λ 1</td>
<td>Constant failure rate of Main /Duplicate unit</td>
</tr>
<tr>
<td>β / β 1</td>
<td>Constant rate of change of weather from normal to abnormal/abnormal to normal weather</td>
</tr>
<tr>
<td>MFur/DFur</td>
<td>Main/duplicate unit failed and under repair</td>
</tr>
<tr>
<td>MFUR/DFUR</td>
<td>Main/duplicate unit failed and under repair continuously from previous state</td>
</tr>
<tr>
<td>MFwr/DFwr</td>
<td>Main/duplicate unit failed and waiting for repair</td>
</tr>
<tr>
<td>MFWR/DFWR</td>
<td>Main/duplicate unit failed and waiting for repair continuously from previous state</td>
</tr>
<tr>
<td>MFWR / DFwr</td>
<td>Main/Duplicate unit failed and waiting for repair due to abnormal weather</td>
</tr>
<tr>
<td>g(t)/G(t)</td>
<td>pdf/cdf of repair time of Main unit</td>
</tr>
<tr>
<td>g1(t)/G1(t)</td>
<td>pdf/cdf of repair time of Duplicate unit</td>
</tr>
<tr>
<td>qij(t)/Qij(t)</td>
<td>pdf/cdf of passage time from regenerative state i to regenerative state j or to a failed state j without visiting any other regenerative state in (0,t]</td>
</tr>
<tr>
<td>qij.kr(t)/Qij.kr(t)</td>
<td>pdf/cdf 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]</td>
</tr>
<tr>
<td>qij.kr.s(t)/Qij.kr.s(t)</td>
<td>pdf/cdf of direct transition time from regenerative state i to a regenerative state j or to a failed state j visiting state k once and n times states r and s.</td>
</tr>
<tr>
<td>Mi(t)</td>
<td>Probability that the system is up initially in regenerative state Si at time t without visiting to any other regenerative state</td>
</tr>
<tr>
<td>Wj(t)</td>
<td>Probability that the server is busy in state Siupto time t without making any transition to any other regenerative state or returning to the same via one or more non-regenerative states</td>
</tr>
<tr>
<td>mji</td>
<td>The conditional mean sojourn time in regenerative state Si when system is to make transition in to regenerative state Sj. Mathematically, it can be written as</td>
</tr>
<tr>
<td>μj</td>
<td>The mean Sojourn time in state Si this is given by</td>
</tr>
<tr>
<td>S/C/∞/n</td>
<td>Symbol for Laplace Stieltjes convolution/Laplace convolution/Laplace convolution n times</td>
</tr>
<tr>
<td>** / *</td>
<td>Symbol for Laplace Steiltjes Transform (L.S.T.)/ Laplace transform (L.T.)</td>
</tr>
<tr>
<td>′(desh)</td>
<td>Used to represent alternative result</td>
</tr>
</tbody>
</table>
(Model 1)

The following are the possible transition states of the system:

\[ S_0 = (\text{MO, DCs}), S_1 = (\text{MFur, DO}), S_2 = (\text{MWO, DCs}), S_3 = (\text{MFwr, DWO}), \]

\[ S_4 = (\text{MFUR, DFwr}), S_5 = (\text{MCs, DO}), S_6 = (\text{MO, DFur}), S_7 = (\text{MFwr, DFWR}), \]

\[ S_8 = (\text{MFur, DFWR}), S_9 = (\text{MCs, DWO}), S_{10} = (\text{MWO, DFwr}), \]

\[ S_{11} = (\text{MFwr, DFUR}), S_{12} = (\text{MCs, DWO}), S_{13} = (\text{MFWR, DFur}) \]

The states \( S_0, S_1, S_2, S_3, S_5, S_6, S_9 \) and \( S_{10} \) are regenerative while the states \( S_4, S_7, S_8, S_{11}, S_{12} \) and \( S_{13} \) are non-regenerative as shown in figure 1.

![State Transition Diagram](image)

**Fig. 1**

(Model 2)

The following are the possible transition states of the system:

\[ S_0 = (\text{MO, DCs}), S_1 = (\text{MFur, DO}), S_2 = (\text{MO, DCs}), S_3 = (\text{MFwr, DO}), \]

\[ S_4 = (\text{MFUR, DFwr}), S_5 = (\text{MCs, DO}), S_6 = (\text{MFWR, DFwr}), S_7 = (\text{MO, DFur}), \]

\[ S_8 = (\text{MFwr, DFWR}), S_9 = (\text{MFur, DFWR}), S_{10} = (\text{MCs, DWO}), S_{11} = (\text{MFWR, DFur}), \]

\[ S_{12} = (\text{MO, DFwr}) \]

The states \( S_0, S_1, S_2, S_3, S_5, S_7, S_{10} \) and \( S_{12} \) are regenerative while the states \( S_4, S_6, S_8, S_9 \) and \( S_{11} \) are non-regenerative as shown in figure 2.
III. RELIABILITY AND MEAN TIME TO SYSTEM FAILURE (MTSF)

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

Model I:
$$
\begin{align*}
\phi_0(t) &= Q_{01}(t)\phi_1(t) + Q_{02}(t)\phi_2(t) \\
\phi_1(t) &= Q_{13}(t)\phi_3(t) + Q_{15}(t)\phi_5(t) + Q_{14}(t) \\
\phi_2(t) &= Q_{20}(t)\phi_0(t); \phi_3(t) = Q_{31}(t)\phi_1(t) \\
\phi_5(t) &= Q_{56}(t)\phi_6(t) + Q_{59}(t)\phi_9(t) \\
\phi_6(t) &= Q_{60}(t)\phi_0(t) + Q_{610}(t)\phi_{10}(t) + Q_{611}(t) \\
\phi_9(t) &= Q_{95}(t)\phi_5(t); \phi_{10}(t) = Q_{10,6}(t)\phi_6(t)
\end{align*}
$$

Model II:
$$
\begin{align*}
\phi_0(t) &= Q_{01}(t)\phi_1(t) + Q_{02}(t)\phi_2(t) \\
\phi_1(t) &= Q_{13}(t)\phi_3(t) + Q_{15}(t)\phi_5(t) + Q_{14}(t) \\
\phi_2(t) &= Q_{20}(t)\phi_0(t) + Q_{23}(t)\phi_3(t); \phi_3(t) = Q_{31}(t)\phi_1(t) + Q_{36}(t) \\
\phi_5(t) &= Q_{57}(t)\phi_7(t) + Q_{5,10}(t)\phi_{10}(t) \\
\phi_7(t) &= Q_{70}(t)\phi_0(t) + Q_{7,12}(t)\phi_{12}(t) + Q_{7,11}(t)
\end{align*}
$$
\[ \psi(t) = Q_{12.7}(t) \psi(t) + Q_{10.12}(t) \psi(t); \psi(t) = Q_{12.7}(t) \psi(t) + Q_{12.8}(t) \]

Taking L.S.T. of above relations and solving for \( \psi_0^* (s) \), we get

\[ R^*(s) = \frac{1 - \phi^*_0 (s)}{s} \]

The reliability of the system can be obtained by taking inverse Laplace transform

The mean time to system failure (MTSF) is given by \((\text{Model I} \& \text{Model I})\)

\[ MTSF = \lim_{s \to 0} \frac{1 - \phi^*_0 (s)}{s} = \frac{N_1}{D_1} \]

IV. STEADY STATE AVAILABILITY

Let \( A_t(t) \) be the probability that the system is in up-state at instant ‘t’ given that the system entered regenerative state \( S \) at \( t=0 \). The recursive relations for \( A_t(t) \) are given as:

\text{(Model I)}

\[ A_0(t) = M_0(t) + q_{01}(t) \psi_0(t) + q_{02}(t) \psi_0(t) \]

\[ A_1(t) = M_1(t) + q_{13}(t) A_0(t) + q_{15}(t) \psi_0(t) + q_{16.4}(t) + q_{16.4,17.8}(t) \psi_0(t) \psi_0(t) + A_0(t) \]

\[ A_2(t) = q_{20}(t) A_0(t); A_1(t) = q_{20}(t) A_1(t) \]

\[ A_3(t) = \psi_0(t) A_0(t) + \psi_0(t) A_1(t) + \psi_0(t) A_2(t) \]

\[ A_4(t) = \psi_0(t) A_3(t); A_4(t) = q_{01}(t) A_4(t) \]

\[ A_5(t) = q_{02}(t) A_4(t); A_5(t) = q_{02}(t) A_5(t) \]

\[ A_6(t) = q_{01}(t) A_6(t); A_6(t) = q_{02}(t) A_6(t) \]

\[ A_7(t) = q_{01}(t) A_7(t); A_7(t) = q_{02}(t) A_7(t) \]

where \( M(t) \) is the probability that the system is up initially in state \( S \). \( E \) is up at time \( t \) without visiting to any other regenerative state, we have

\[ M_0(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

\[ M_1(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

\[ M_2(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

\[ M_3(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

\[ M_4(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

\[ M_5(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

\[ M_6(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

\[ M_7(t) = \frac{e^{-(\beta + \lambda)t}}{G(t)} \]

Taking L.T. of above relations and solving for \( A_0^*(s) \), the steady state availability is given by

\[ A_0^*(s) = \lim_{s \to 0} s A_0^*(s) = \frac{N_2}{D_2} \]

V. BUSY PERIOD ANALYSIS

Let \( B_t(t) \) be the probability that the server is busy in repairing the unit at an instant ‘t’ given that the system entered regenerative state \( S \) at \( t=0 \). The recursive relations for \( B_t(t) \) are as follows:

\text{(Model I)}

\[ B_0(t) = q_{01}(t) B_0(t) + q_{02}(t) B_0(t) \]

\[ B_1(t) = W_0(t) + q_{13}(t) B_0(t) + q_{15}(t) B_0(t) + q_{16.4}(t) + q_{16.4,17.8}(t) \psi_0(t) \psi_0(t) + B_0(t) \]

\[ B_2(t) = q_{20}(t) B_0(t); B_2(t) = q_{20}(t) B_0(t) \]

\[ B_3(t) = q_{01}(t) B_0(t) + q_{02}(t) B_0(t) + q_{01}(t) B_0(t) + q_{02}(t) B_0(t) \]

\[ B_4(t) = q_{01}(t) B_0(t); B_4(t) = q_{02}(t) B_0(t) \]

\[ B_5(t) = q_{01}(t) B_0(t); B_5(t) = q_{02}(t) B_0(t) \]

\[ B_6(t) = q_{01}(t) B_0(t); B_6(t) = q_{02}(t) B_0(t) \]

\[ B_7(t) = q_{01}(t) B_0(t); B_7(t) = q_{02}(t) B_0(t) \]
where $W_t(t)$ be the probability that the server is busy in state $S_i$ due to failure up to time without making any transition to any other regenerative state or returning to the same via one or more non regenerative states so,

$$W_t(t) = e^{-(\beta + \lambda)t} G(t) + (\lambda e^{-(\beta + \lambda)t} \otimes 1) G(t) \cdot W_0(t) = e^{-(\beta + \lambda)t} G(t) + (\lambda e^{-(\beta + \lambda)t} \otimes 1) G(t)$$

\subsection*{(MODEL II)}

\begin{align*}
B_0(t) &= B_0(t) \otimes B_0(t) + q_{02}(t) \otimes B_2(t) \\
B_1(t) &= B_1(t) + q_{13}(t) \otimes B_0(t) + q_{16}(t) \otimes B_6(t) + (q_{17.4}(t) + q_{17.4.8}(t)) \otimes B_{17}(t) \\
B_2(t) &= B_2(t) + q_{20}(t) \otimes B_0(t) + q_{23}(t) \otimes B_3(t) \\
B_3(t) &= B_3(t) + q_{32}(t) \otimes B_2(t) + (q_{37.6}(t) + q_{37.6.9}(t)) \otimes B_{37}(t) \\
B_4(t) &= B_4(t) + q_{45.10}(t) \otimes B_{10}(t) \\
B_5(t) &= B_5(t) + q_{51.11}(t) \otimes B_{11}(t) + (q_{57.11.6.9}(t) + q_{57.11.6.9.8}(t)) \otimes B_{57}(t) + q_{57.12}(t) \otimes B_{12}(t) \\
B_6(t) &= B_6(t) + q_{63}(t) \otimes B_3(t) + q_{10.12}(t) \otimes B_{12}(t) + (q_{12.7}(t) + q_{12.7.9}(t)) \otimes B_{12}(t)
\end{align*}

Where

$$W_t(t) = e^{-(\beta + \lambda)t} G(t) + (\lambda e^{-(\beta + \lambda)t} \otimes 1) G(t) \cdot W_0(t) = e^{-(\beta + \lambda)t} G(t) + (\lambda e^{-(\beta + \lambda)t} \otimes 1) G(t)$$

Taking L.T. of above relations and solving for $B_s(t)$, we obtain

The time for which server is busy due to repair is given by

$$B_0(s) = \lim_{s \to 0} sB_0(s) = \frac{N_1}{D_2}$$

\section*{VI. EXPECTED NUMBER OF VISITS BY THE SERVER}

Let $N_i(t)$ be the expected number of visits by the server in $(0, t]$ given that the system entered the regenerative state $S_i$ at $t=0$. The recursive relations for $N_i(t)$ are given as

\subsection*{(MODEL I)}

\begin{align*}
N_0(t) &= Q_{01}(t) S(1 + N_1(t)) + Q_{02}(t) S N_2(t) \\
N_1(t) &= Q_{10}(t) S N_1(t) + Q_{12}(t) S N_2(t) + Q_{16.4}(t) S N_6(t) + Q_{16.4.7.8}(t) S N_{16}(t) + (1 + N_6(t)) \\
N_2(t) &= Q_{20}(t) S N_0(t) + N_3(t) = Q_{31}(t) S^2(1 + N_1(t)) \\
N_3(t) &= Q_{36}(t) S (1 + N_5(t)) + Q_{50}(t) S N_5(t) \\
N_4(t) &= Q_{56}(t) S N_0(t) + Q_{61.12}(t) S N_1(t) + Q_{61.11.12.13}(t) S (1 + N_1(t)) + Q_{6.10}(t) S N_{10}(t) \\
N_5(t) &= Q_{65}(t) S N_3(t) + N_{10}(t) = Q_{60.12}(t) S (1 + N_5(t))
\end{align*}

\subsection*{(MODEL II)}

\begin{align*}
N_0(t) &= Q_{01}(t) S(1 + N_1(t)) + Q_{02}(t) S N_2(t) \\
N_1(t) &= Q_{12}(t) S N_0(t) + Q_{15}(t) S N_1(t) + Q_{23}(t) S N_3(t) + Q_{17.4}(t) S N_{17}(t) \\
N_2(t) &= Q_{36}(t) S N_0(t) + Q_{32}(t) S N_3(t) + Q_{31}(t) S (1 + N_1(t)) + (Q_{37.6}(t) + Q_{37.6.9}(t)) S (1 + N_7(t)) \\
N_3(t) &= Q_{37}(t) S (1 + N_5(t)) + Q_{35.10}(t) S N_{10}(t) \\
N_4(t) &= Q_{50}(t) S N_0(t) + Q_{71.11}(t) S N_1(t) + (Q_{77.11.6.9}(t) + Q_{77.11.6.9.8}(t)) S (1 + N_1(t)) + Q_{7.12}(t) S N_{12}(t) \\
N_5(t) &= Q_{10.5}(t) S N_5(t) + Q_{4.10.12}(t) S N_{12}(t) + N_{12}(t) = (Q_{12.7}(t) + Q_{12.7.9}(t)) S (1 + N_7(t))
\end{align*}

\section*{VII. PROFIT ANALYSIS}

The profit incurred to the system model in steady state can be obtained as

$$P = K_0 A_0 - K_1 B_0 - K_2 N_0$$

Where

- $K_0$: Revenue per unit up-time of the system
- $K_1$: Cost per unit for which server is busy
- $K_2$: Cost per unit visit by the server

$A_0$, $B_0$, $N_0$ are already defined

$$\text{MTSF (T)} = \frac{N_1}{D_1}, \quad \text{Steady state availability (A)} = \frac{N_2}{D_2}$$
Busy period of the server \((B_0) = \frac{N_1}{D_2}\), Expected number of visits by the server \((N_0) = \frac{N_1}{D_2}\)

VIII. PARTICULAR CASES (MODEL I)

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

\[ p_{ij} = Q_{ij}(\infty) = \int_0^\infty q_{ij}(t)\,dt \]

(by taking all the distribution exponentially)

(Suppose \(g(t) = ae^{-\alpha t}\), \(g_1(t) = \alpha_1 e^{-\alpha_1 t}\))

\[
\begin{align*}
p_{01} &= \frac{\lambda}{\beta + \lambda}, \quad p_{02} = \frac{\beta}{\beta + \lambda}, \quad p_{13} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{14} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{15} = \frac{\alpha}{\alpha + \beta + \lambda}, \quad p_{20} = \frac{\beta}{\beta + \lambda}, \quad p_{31} = 1, \quad p_{16} = \frac{\alpha}{\alpha + \beta + \lambda}, \\
p_{46} &= \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{56} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{59} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{60} = \frac{\alpha}{\alpha + \beta + \lambda}, \quad p_{6,11} = \frac{\beta}{\alpha + \beta + \lambda}, \\
p_{8,12} &= \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{11,12} = \frac{\beta}{\alpha + \beta + \lambda}, \quad p_{13,12} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{16,4} = \frac{\lambda}{\alpha + \beta + \lambda}, \\
\mu_0 &= \frac{1}{\beta + \lambda}, \quad \mu_1 = \frac{1}{\beta + \lambda}, \quad \mu_2 = \frac{1}{\beta + \lambda}, \quad \mu_3 = \frac{1}{\beta + \lambda}, \quad \mu_5 = \frac{1}{\beta + \lambda}, \quad \mu_6 = \frac{1}{\beta + \lambda}, \\
\mu_{11} &= \frac{1}{\beta + \lambda}, \quad \mu_{12} = \frac{1}{\beta + \lambda}, \quad \mu_{13} = \frac{1}{\beta + \lambda}, \quad \mu_{16} = \frac{1}{\beta + \lambda}, \\
\mu_{16,4,7,8} &= \frac{\alpha_1}{\alpha + \beta + \lambda}, \quad \lambda_1 = \frac{\lambda}{\alpha + \beta + \lambda}, \quad \lambda_2 = \frac{\lambda}{\alpha + \beta + \lambda}, \quad \lambda_3 = \frac{\lambda}{\alpha + \beta + \lambda}, \quad \lambda_4 = \frac{\lambda}{\alpha + \beta + \lambda}, \quad \lambda_5 = \frac{\lambda}{\alpha + \beta + \lambda}, \quad \lambda_6 = \frac{\lambda}{\alpha + \beta + \lambda}, \\
W_{1}^{*}(0) &= \frac{(\alpha + \lambda)}{(\alpha + \beta + \lambda)}, \quad W_{6}^{*}(0) = \frac{(\alpha + \lambda)}{(\alpha + \beta + \lambda)}, \\
J_I &= \frac{\alpha_1 \lambda_1 \lambda_2 \lambda_3 \lambda_4 \lambda_5 \lambda_6}{(\alpha + \beta + \lambda)}.
\end{align*}
\]

where

\[
\begin{align*}
N_1 &= (\beta + \beta_1)(\lambda_1(\alpha_1 + \lambda_1)(\alpha_1 + \lambda_1 + \lambda_1) + \alpha \lambda(\alpha_1 + \lambda_1)), \\
D_1 &= \lambda_1 \beta_1(\alpha_1 + \lambda_1(\alpha_1 + \lambda_1)), \\
N_2 &= \alpha \lambda(\lambda_1(\alpha_1 + \lambda_1)), \\
D_2 &= \alpha \lambda(\lambda_1(\alpha_1 + \lambda_1)), \\
N_3 &= \alpha \lambda(\lambda_1(\alpha_1 + \lambda_1)), \\
D_3 &= \alpha \lambda(\lambda_1(\alpha_1 + \lambda_1)), \\
N_4 &= \alpha \lambda(\lambda_1(\alpha_1 + \lambda_1)), \\
D_4 &= \alpha \lambda(\lambda_1(\alpha_1 + \lambda_1)).
\end{align*}
\]

IX. PARTICULAR CASES (MODEL II)

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

\[ p_{ij} = Q_{ij}(\infty) = \int_0^\infty q_{ij}(t)\,dt \]

(Suppose \(g(t) = ae^{-\alpha t}\), \(g_1(t) = \alpha_1 e^{-\alpha_1 t}\))

\[
\begin{align*}
p_{01} &= \frac{\lambda}{\beta + \lambda}, \quad p_{02} = \frac{\beta}{\beta + \lambda}, \quad p_{13} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{14} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{15} = \frac{\alpha}{\alpha + \beta + \lambda}, \quad p_{20} = \frac{\beta}{\beta + \lambda}, \\
p_{23} &= \frac{\beta}{\beta_1 + \lambda}, \quad p_{31} = \frac{\beta}{\beta_1 + \lambda}, \quad p_{36} = \frac{\lambda}{\beta_1 + \lambda}, \quad p_{47} = \frac{\alpha}{\alpha + \beta + \lambda}, \quad p_{48} = \frac{\beta}{\alpha + \beta + \lambda}, \quad p_{57} = \frac{\lambda}{\beta_1 + \lambda}, \quad p_{5,10} = \frac{\beta}{\beta + \lambda}, \quad p_{60} = 1, \\
p_{70} &= \frac{\alpha}{\alpha + \beta + \lambda}, \quad p_{7,11} = \frac{\lambda}{\alpha + \beta + \lambda}, \quad p_{7,12} = \frac{\beta}{\alpha + \beta + \lambda}, \quad p_{80} = 1, \quad p_{97} = \frac{\alpha}{\alpha + \beta + \lambda}.
\end{align*}
\]
\[
\begin{align*}
\mathbf{p}_{18} &= \frac{\beta}{\alpha + \beta}, \quad \mathbf{P}_{10.5} = \frac{\beta_1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{10.12} = \frac{\lambda_1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{11.1} = \frac{\alpha_1}{\alpha_1 + \beta}, \quad \mathbf{P}_{11.6} = \frac{\beta_1}{\alpha_1 + \beta}, \quad \mathbf{P}_{12.7} = \frac{\lambda}{\beta_1 + \lambda}, \quad \mathbf{P}_{12.8} = \frac{\lambda}{\beta_1 + \lambda}, \quad \mathbf{P}_{17.4} = \frac{\lambda}{\alpha + \beta + \lambda_1} \\
\alpha &= \frac{\beta}{\alpha + \beta}, \quad \mathbf{P}_{17.4 (8.9)} = \frac{\lambda_1}{\alpha + \beta + \lambda_1}, \quad \mathbf{P}_{37.6(9.8)} = \frac{\alpha}{\alpha + \beta}, \quad \mathbf{P}_{37.7(9.8)} = \frac{\lambda}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{p_{17.1}} = \frac{\lambda}{\alpha + \beta + \lambda_1} \\
\mu_1 &= \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{14.3} = \frac{1}{\alpha + \beta + \lambda_1}, \quad \mathbf{P}_{15.2} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{16.1} = \frac{1}{\alpha + \beta + \lambda_1}, \quad \mathbf{P}_{17.5} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{18.6} = \frac{1}{\beta_1 + \lambda_1} \\
\mu_1 &= \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{18.5} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{19.1} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{20.11} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{21.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{22.12} = \frac{1}{\beta_1 + \lambda_1} \\
\mu_1 &= \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{23.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{24.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{25.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{26.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{27.12} = \frac{1}{\beta_1 + \lambda_1} \\
N_1 &= \lambda_1 (\beta_1 + \lambda_1), \quad \mathbf{P}_{28.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{29.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{30.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{31.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{32.12} = \frac{1}{\beta_1 + \lambda_1} \\
\mathbf{D}_1 &= \lambda_1 A_1, \quad \mathbf{B}_1 = \lambda_1 A_1, \quad \mathbf{C}_1 = \alpha_1 A_1, \quad \mathbf{D}_1 = \lambda_1 A_1, \quad \mathbf{B}_1 = \lambda_1 A_1, \quad \mathbf{C}_1 = \alpha_1 A_1, \quad \mathbf{D}_1 = \lambda_1 A_1, \quad \mathbf{B}_1 = \lambda_1 A_1, \quad \mathbf{C}_1 = \alpha_1 A_1, \quad \mathbf{D}_1 = \lambda_1 A_1, \quad \mathbf{B}_1 = \lambda_1 A_1, \quad \mathbf{C}_1 = \alpha_1 A_1 \\
N_2 &= \alpha_1 (\beta_1 + \lambda_1), \quad \mathbf{P}_{33.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{34.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{35.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{36.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{37.12} = \frac{1}{\beta_1 + \lambda_1} \\
N_3 &= \lambda_1 (\beta_1 + \lambda_1), \quad \mathbf{P}_{38.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{39.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{40.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{41.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{42.12} = \frac{1}{\beta_1 + \lambda_1} \\
N_4 &= \alpha_1 (\beta_1 + \lambda_1), \quad \mathbf{P}_{43.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{44.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{45.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{46.12} = \frac{1}{\beta_1 + \lambda_1}, \quad \mathbf{P}_{47.12} = \frac{1}{\beta_1 + \lambda_1} \\
A &= \alpha_1 + \beta_1 + \lambda_1 + \beta_1 \lambda, \quad B = (\beta_1 + \lambda_1 + \beta_1 \lambda + \beta_1 \lambda), \quad C = \alpha_1 + \beta_1 + \lambda_1, \quad D = \alpha_1 + \beta_1 + \lambda_1, \quad E = (\alpha_1 + \beta_1 + \lambda_1 + \beta_1 \lambda)
\end{align*}
\]
### TABLES OF MODEL I

#### Table 1.1: MTSF vs. Normal Weather Rate ($\beta_i$)

<table>
<thead>
<tr>
<th>Normal Weather Rate ($\beta_i$)</th>
<th>$\alpha=2, \alpha_i=2.5, \beta=0.01, \lambda=0.5, \lambda_i=0.6$</th>
<th>$\alpha=1.5$</th>
<th>$\alpha_i=2$</th>
<th>$\beta=0.05$</th>
<th>$\lambda=0.3$</th>
<th>$\lambda_i=0.4$</th>
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#### Table 1.2: Availability vs. Normal Weather Rate ($\beta_i$)

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#### Table 1.3: Profit vs. Normal weather rate ($\beta_i$)

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X. CONCLUSION

To make the study more concrete, the numerical results giving particular values to the various parameters and cost are obtained to depict the behavior of Mean Time to System Failure (MTSF), availability and profit functions as shown respectively in table 1.1,1.2 and 1.3. It is revealed that MTSF decreases with the increase in normal weather rate ($\beta_1$) and failure rates ($\lambda, \lambda_1$) of the units. And, it increases with increase of abnormal weather rate ($\beta$) and repair rates ($\alpha, \alpha_1$) of the units. The results show that availability and profit of the system model keep on increasing as normal weather rate ($\beta_1$) and repair rates ($\alpha, \alpha_1$) increase while their values decline with the increase of abnormal weather rate ($\beta$) and failure rates ($\lambda, \lambda_1$) of the units.

### TABLES OF MODEL II

#### Table 2.1: MTSF vs. Normal Weather Rate ($\beta_1$)

<table>
<thead>
<tr>
<th>Normal Weather Rate ($\beta_1$)</th>
<th>$\alpha=2, \alpha_1=2.5, \beta=0.01, \lambda=0.5, \lambda_1=0.6$</th>
<th>$\alpha_1=1.5$</th>
<th>$\alpha=2$</th>
<th>$\beta=0.05$</th>
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#### Table 2.2: Availability vs. Normal Weather Rate ($\beta_1$)

<table>
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<tr>
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<th>$\alpha=2, \alpha_1=2.5, \beta=0.01, \lambda=0.5, \lambda_1=0.6$</th>
<th>$\alpha_1=1.5$</th>
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<th>$\lambda_1=0.4$</th>
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XI. CONCLUSION

The graphs for MTSF, availability and profit function of the system are drawn for fixed values of the various parameters and costs as shown respectively in table 2.1, 2.2 and 2.3. These tables indicate that there is substantial positive change in these measures with increase of normal weather rate ($\beta_1$) and repair rates ($\alpha$ and $\alpha_1$) of the units. While these values decline with increase of abnormal weather rate ($\beta$) and failure rates ($\lambda$ and $\lambda_1$) of the units. However, the effect of repair rate of the main unit is more.

Table A: MTSF Difference of Model 1 and Model 2

<table>
<thead>
<tr>
<th>Normal Weather Rate ($\beta_1$)</th>
<th>$\alpha=2, \alpha_1=2.5, \beta=0.01, \lambda=0.5, \lambda_1=0.6$</th>
<th>$\alpha=1.5$</th>
<th>$\alpha_1=2$</th>
<th>$\beta=0.05$</th>
<th>$\lambda=0.3$</th>
<th>$\lambda_1=0.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.215272046</td>
<td>0.17606</td>
<td>0.19515</td>
<td>1.038217</td>
<td>0.3558</td>
<td>0.336366</td>
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<tr>
<td>1.2</td>
<td>0.196624495</td>
<td>0.161004</td>
<td>0.17835</td>
<td>0.951152</td>
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<td>0.306038</td>
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<tr>
<td>1.3</td>
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<td>0.16404</td>
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<td>1.4</td>
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<td>0.137132</td>
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<td>0.812203</td>
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<td>1.5</td>
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<td>0.127531</td>
<td>0.141014</td>
<td>0.756001</td>
<td>0.253055</td>
<td>0.239288</td>
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<td>0.131633</td>
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<td>0.194281</td>
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<tr>
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<td>0.093863</td>
<td>0.10351</td>
<td>0.557558</td>
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<td>0.173328</td>
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</table>
Table B: Profit Difference between Model 2 and Model 1

<table>
<thead>
<tr>
<th>Normal Weather Rate($\beta_1$)</th>
<th>$K_0=5000, K_1=350, K_2=300$</th>
<th>$\alpha=2, \alpha_1=2.5, \beta=0.01, \lambda=0.5, \lambda_1=0.6$</th>
<th>$\alpha=1.5$</th>
<th>$\alpha_1=2$</th>
<th>$\beta=0.05$</th>
<th>$\lambda=0.3$</th>
<th>$\lambda_1=0.4$</th>
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<td>-39.1152</td>
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XII. COMPARATIVE STUDY

i. Comparison of MTSF (Between Model 1 and Model 2)

The MTSF of the system Model 1 is more than that of system Model 2. The MTSF difference (Model 1 - Model 2) of these Models go on decreasing with increase of normal weather rate ($\beta_1$) and repair rates ($\alpha$ and $\alpha_1$) of the units while it increases with increase of abnormal weather rate ($\beta$) and failure rates of the units as shown in Table A. Thus, a system of non-identical units would be more reliable to use in either of the following ways:

- If it is not allowed to operate in abnormal weather
- If it is allowed to operate in abnormal weather, then by increasing repair rates of the failed units

ii. Comparison of Profit (Between Model 2 and Model 1)

The profit difference of the system Models is shown in Table B. The profit difference (Model 2 - Model 1) goes on increasing with increase of normal weather rate ($\beta_1$), repair rates ($\alpha$ and $\alpha_1$) and failure rates ($\lambda$ and $\lambda_1$) of the units. But, it declines rapidly with the increase of abnormal weather rate ($\beta$). Thus, the study reveals that a system of non-identical units working in different weather conditions can be made more profitable by allowing its operation in abnormal weather with high repair rates of the failed units.

REFERENCE


