CHAPTER VII
CHAPTER VII

STOCHASTIC MODELING AND ANALYSIS OF A SYSTEM HAVING ONE MAIN UNIT AND TWO HELPING UNITS IN STANDBY CONFIGURATION

7.1 INTRODUCTION

This chapter deals with the stochastic modeling and analysis of a system having one main unit and two helping units in standby configuration. In this system, scheduled repair is performed after a random period. Helping units are also repaired on line. Since main unit is a costly unit so its maintenance at a regular interval is very necessary otherwise the system may face a very heavy loss.

Reliability is a very fast growing and very important field in consumer & capital goods industries, in space & defense industries. Reliability provides the theoretical & practical tools to ascertain the probability & capacity of parts, components, products and system to perform their required functions in specified environments for the desired function period without failure. It is very essential for an industry and technology to be competitive in today's highly competitive world market place. Reliability helps them in knowing the reliability of their products and to produce them at the optimum reliable level. Very few work have been reported by taking practical models and real data. Takami et al [1982] have analyzed electrical and electronic components systems. Osaki et al have developed a systematic method for investment decision for a three unit hybrid redundant system. Pandey et al [1996] have analyzed a powerloom plant with cold standby unit. By working towards industries, Singh et al [1997] have studied a two identical parallel mineral crushing systems. They [1996] have also studied a system having one master unit and two slave units. Further Singh et al [1999] have also analyzed a manufacturing plant. However very few work have been done so far related to helping units.
7.2 MODEL

This model deals with the stochastic modeling and analysis of system having one main unit and two helping units in standby configuration. Helping units help the main unit in processing the raw material of the main unit. Besides regular repair, scheduled maintenance is also performed. Failure time distributions are taken to be negative exponential, whereas repair time distributions are taken to be arbitrary. Using regenerative point technique, several system characteristics which are useful to the system managers and designers, are evaluated.

EXAMPLE: Twin Hearth furnace system which plays an important role in the steel melting shop area of an integrated steel plant is an example of it. It is used to convert the raw material into liquid steel. Two helping units in standby configuration are used to poured the specified raw material in the twin hearth furnace. Twin hearth furnace is fixed type device with basic lining and basic roof. Main fuel is mixture of Blast Main unit and Coke Oven gas.

In each main unit there is a provision for:

(i). Injecting liquid fuel through gas ports for improving heat transfer.

(ii). Increasing the oxygen content upto 30%

(iii) Lancing the bath with oxygen through water-cooled lance installed in the roof.

(iv). Injection of compressed air for better fuel combustion.

Main unit has evaporation Cooling System for cooling gas ports, skew backs and charging door frames. Each main unit has five doors on the charging side. Bulkcharge materials and scrap are charged through these doors. Hot metal is poured either through first door or fifth door with the help of a crane and pouring chute.

The main unit side is equipped with 6 helping units of 10 Tonnes capacity and 5 hot metal crane of 125/30 T capacity each.

The charge consists of molten Pig iron, Solid scrap, Iron ore and the Fluxing material, LimeStone. Before charging the main unit, the bottom and the walls are properly inspected and repaired or patched as and when necessary. The normal sequence of charging is to give one layer of Iron Ore at the bottom followed by Limestone and finally by remaining ore. This followed by charging scrap.
7.3 DESCRIPTION OF THE SYSTEM

1. System consists of a main unit with one helping unit in standby configuration.
2. Initially main unit remains in preparation and helping unit helps the main unit in its preparation.
3. Main unit does not fail during preparation.
4. Helping unit may fail either partially or completely.
5. Whenever main unit fails completely, whole system undergoes repair.
6. In case when both the helping units fail either partially or completely, the whole helping unit system undergoes emergent repair.
7. After a random time, with the completion of operation, main unit undergoes preparation.
8. All the failure and repair time distributions are taken exponentially distributed except shut-down repair time and scheduled maintenance time which are taken as arbitrarily distributed.
9. After repair unit works as good as new.

State Transition Diagram and Graphs are shown in Figures 7.1, 7.2, 7.3 and 7.4 respectively.

7.4 NOTATIONS

\( E_1 \) : Set of regenerative states \( \{S_0, S_1, S_2, S_3, S_5, S_6, S_7, S_8, \} \)

\( g_3(t), G_3(t) \) : pdf and cdf time to emergency repair of helping unit

\( g_4(t), G_4(t) \) : pdf and cdf time to system repair.

\( \beta_1, \beta_2, \beta_3 \) : partial / complete / complete from partial failure rates of helping unit.

\( \phi \) : Preparation completion rate of main unit.

\( \alpha \) : failure rate of main unit.

\( r_1, r_2 \) : Constant repair rate of main unit/helping unit.

\( \varphi \) : preparation rate of furnace.

\( n_i \) : unconditional sojourn time in state \( S_i \).

\( p_{ij} \) : Transition from state \( i \) to \( j \).
7.5 SYMBOLS USED FOR THE STATES OF THE SYSTEM

- **T₀ / Tₚ**: Main unit in Operation / under preparation.
- **C₀ / C₅ / Cᵣ / C₀ᵣ**: Helping unit in operation/standby /under repair/under on-line repair.
- **Eᵣ**: Helping unit system under emergency repair.

(d) Up and Regenerative States

- \( S₀ = \{ Tₚ, C₀, C₅ \} \)
- \( S₁ = \{ T₀, C₀, C₅ \} \)
- \( S₂ = \{ Tₚ, C₀ᵣ, C₅ \} \)
- \( S₃ = \{ Tₚ, Cᵣ, C₀ \} \)
- \( S₅ = \{ T₀, C₀ᵣ, C₅ \} \)
- \( S₆ = \{ T₀, Cᵣ, C₀ \} \)
- \( S₇ = \{ Tₚ, Eᵣ \} \)
- \( S₇ = \{ T₀, Eᵣ \} \)

(c) Down State

\( S₄ = \{ Eᵣ \} \)

Possible transitions between states are shown in Fig. 7.1

7.6 TRANSITION PROBABILITIES AND SOJOURN TIMES

Simple probabilistic considerations yields the following expressions for non-zero transition probabilities \( p_{ij} \):

\[
p_{0₁} = \int_0^\infty \phi e^{-X₁t} \, dt
\]

\[
p_{0₂} = \int_0^\infty \beta₁ e^{-X₂t} \, dt \quad ; \quad p_{0₃} = \int_0^\infty \beta₂ e^{-X₃t} \, dt \quad ; \quad p_{1₄} = \int_0^\infty \alpha e^{-X₂t} \, dt
\]

\[
p_{1₀} = \int_0^\infty \phi e^{-X₂t} \, dt \quad ; \quad p_{1₅} = \int_0^\infty \beta₁ e^{-X₃t} \, dt \quad ; \quad p_{1₆} = \int_0^\infty \beta₂ e^{-X₄t} \, dt
\]

\[
p_{2₀} = \int_0^\infty \eta e^{-X₃t} \, dt
\]

\[
p_{2₃} = \int_0^\infty \beta₃ e^{-X₃t} \, dt \quad ; \quad p_{2₅} = \int_0^\infty \phi e^{-X₃t} \, dt \quad ; \quad p_{3₀} = \int_0^\infty \beta₂ e^{-X₄t} \, dt
\]
\[ p_{36} = \int_0^\infty e^{-X_{4t}} dt \quad ; \quad p_{37} = \int_0^\infty (\beta_1 + \beta_2 + \phi) e^{-X_{4t}} dt \quad ; \quad p_{40} = \int_0^\infty e^{-X_{4t}} dt \]

\[ p_{31} = \int_0^\infty r_1 e^{-X_{5t}} dt \quad ; \quad p_{52} = \int_0^\infty \phi e^{-X_{5t}} dt \quad ; \quad p_{54} = \int_0^\infty e^{-X_{5t}} dt \]

\[ p_{56} = \int_0^\infty \beta_3 e^{-X_{5t}} dt \quad ; \quad p_{56} = \int_0^\infty r_2 e^{-X_{6t}} dt \quad ; \quad p_{63} = \int_0^\infty \phi e^{-X_{6t}} dt \]

\[ p_{64} = \int_0^\infty \alpha e^{-X_{6t}} dt \quad ; \quad p_{68} = \int_0^\infty (\beta_1 + \beta_2 + \phi) e^{-X_{6t}} dt \quad ; \quad p_{70} = \int_0^\infty r_3 e^{-X_{7t}} dt \]

\[ p_{78} = \int_0^\infty \phi e^{-X_{7t}} dt \quad ; \quad p_{81} = \int_0^\infty r_3 e^{-X_{8t}} dt \quad ; \quad p_{84} = \int_0^\infty \alpha e^{-X_{8t}} dt \]

\[ p_{87} = \int_0^\infty \phi e^{-X_{8t}} dt \]

where:

\[ X_1 = \phi + \beta_1 + \beta_2 \quad ; \quad X_2 = \beta_1 + \beta_2 + \alpha + \phi \quad ; \quad X_3 = \phi + r_1 + \beta_3 \]

\[ X_4 = \phi + \beta_1 + \beta_2 + r_2 \quad ; \quad X_5 = r_1 + \beta_3 + \phi + \alpha \quad ; \quad X_6 = \beta_1 + \beta_2 + \alpha + r_2 \]

\[ X_7 = \phi + r_3 \quad ; \quad X_8 = \alpha + \phi + r_3 \]

Mean sojourn time \( \mu_i \) in \( S_i \) is defined as the time that the system continues in state \( S_i \) before transiting to any other state.

\[ \mu_0 = \int_0^\infty e^{-X_{1t}} dt \quad ; \quad \mu_1 = \int_0^\infty e^{-X_{2t}} dt \quad ; \quad \mu_2 = \int_0^\infty e^{-X_{3t}} dt \]

\[ \mu_3 = \int_0^\infty e^{-X_{4t}} dt \quad ; \quad \mu_4 = 1 \quad ; \quad \mu_5 = \int_0^\infty e^{-X_{5t}} dt \]

\[ \mu_6 = \int_0^\infty e^{-X_{6t}} dt \quad ; \quad \mu_7 = \int_0^\infty e^{-X_{7t}} dt \quad ; \quad \mu_8 = \int_0^\infty e^{-X_{8t}} dt \]

[28-36]

It can be seen that
\[ m_{01} + m_{02} + m_{03} + m_{04} = \mu_0 \]
\[ m_0 + m_{1,3,6} + m_{1,5,5} + m_{1,5,6} + m_{1,7,8} + m_{1,7,5} \]
\[ m_{1,5,6} + m_{1,5,7} + m_{1,5,8} = n_1 \]
\[ m_{41} + m_{42} + m_{45} = \mu_4 \quad m_{50} = \mu_5 \]

### 7.7 Mean Time to System Failure

Time to system failure can be regarded as first passage time to the failed state. To obtain it, we regard the down states as absorbing states. Using arguments as for the regenerative process we obtain the following recursive relations for \( \pi_j(t) \).

\[
\begin{align*}
\pi_0(t) &= \sum_{j=1,2,3} Q_{0j}(t) \pi_j(t) \\
\pi_1(t) &= \sum_{j=0,5,6} Q_{1j}(t) \pi_j(t) + Q_{14}(t) \\
\pi_2(t) &= \sum_{j=0,3,5} Q_{2j}(t) \pi_j(t) + Q_{54}(t) \\
\pi_3(t) &= \sum_{j=0,6,7} Q_{3j}(t) \pi_j(t) + Q_{64}(t) \\
\pi_4(t) &= \sum_{j=0,8} Q_{4j}(t) \pi_j(t) + Q_{84}(t) \\
\pi_5(t) &= \sum_{j=1,2,4,6} Q_{5j}(t) \pi_j(t) + Q_{54}(t) \\
\pi_6(t) &= \sum_{j=1,3,8} Q_{6j}(t) \pi_j(t) + Q_{64}(t) \\
\pi_7(t) &= \sum_{j=0,8} Q_{7j}(t) \pi_j(t) + Q_{84}(t) \\
\pi_8(t) &= \sum_{j=1,4,8} Q_{8j}(t) \pi_j(t) + Q_{84}(t)
\end{align*}
\]

Taking Laplace-Stieltjes transforms of equations [1-8], the solution for \( \overline{\pi}_0(s) \), we have:

\[
\text{MTSF} = E(T) = \left. \frac{d}{ds} \overline{\pi}_0(s) \right|_{s=0} = \frac{D'(0) - N'(0)}{D_1(0)}
\]

\[
\text{MTSF} = E(T) = \frac{\mu_0 a_0 + \mu_1 a_1 + \mu_2 a_2 + \mu_3 a_3 + \mu_4 a_4 + \mu_5 a_5 + \mu_6 a_6}{D_1(0)}
\]

Where

\[
a_0 = 1 - p_{15}(p_{51} + p_{56}p_{61})(1 - p_{78}p_{87}) - p_{16}p_{61}(1 - p_{78}p_{87})(1 - p_{25}p_{52}) - p_{36}p_{63}(1 - p_{78}p_{87})(1 - p_{15}p_{51}) - p_{25}p_{52}(1 - p_{78}p_{87})(1 - p_{36}p_{63}) - p_{15}p_{23}p_{36}p_{61}p_{52}(1 - p_{78}p_{87}) - (p_{37}p_{63}p_{78}p_{81} + p_{68}p_{81})(p_{15}p_{56} + p_{16}) - p_{15}p_{37}p_{52}p_{78}p_{81}(p_{23} - p_{16}p_{25}p_{63}) + p_{52}p_{68}p_{81}(p_{16}p_{25} - p_{15}p_{23}p_{36})
\]
\[ a_1 = p_{01}(1 - p_{36}P_{63})(1 - p_{78}P_{87})(1 - p_{25}P_{52}) + p_{02}p_{23}P_{36}P_{61}(1 - p_{78}P_{87}) \\
+ p_{03}P_{36}P_{61}(1 - p_{25}P_{52})(1 - p_{78}P_{87}) + p_{02}p_{25}(p_{51} + p_{56}P_{61})(1 - p_{78}P_{87}) \\
- p_{02}p_{25}P_{36}P_{51}P_{63}(1 - p_{78}P_{87}) + p_{02}p_{68}P_{81}(p_{25}P_{56} + p_{23}P_{36}) \\
+ p_{03}P_{36}P_{68}P_{81}(1 - p_{25}P_{52}) + p_{02}p_{25}P_{78}P_{81}(p_{02}p_{23} + p_{03}) \\
+ p_{02}P_{25}P_{37}P_{56}P_{63}p_{78}P_{81} = p_{03}p_{25}P_{37}P_{52}P_{78}P_{81} \]

\[ a_2 = (1 - p_{78}P_{87})p_{02}(1 - p_{36}P_{63}) - p_{02}p_{16}P_{61} + p_{01}p_{15}P_{52} \\
- p_{02}p_{15}(p_{51} + p_{56}P_{61}) + p_{02}p_{15}P_{36}P_{51}P_{63} \\
+ p_{03}P_{15}P_{36}P_{52}P_{61} - p_{01}p_{15}P_{36}P_{51}P_{63} \\
- p_{02}P_{81}(p_{16} + p_{15}p_{56})(p_{37}P_{63}p_{78} - p_{68}) \\
+ p_{03}P_{15}P_{52}P_{81}(p_{36}P_{68} + p_{37}P_{78}) \]

\[ a_3 = (1 - p_{78}P_{87})p_{02}p_{23} + p_{03}(1 - p_{16}P_{61})(1 - p_{25}P_{52}) - p_{01}p_{15}p_{23}P_{52} \\
- p_{02}p_{15}P_{23}P_{51} - p_{03}p_{15}P_{51} + p_{01}p_{15}P_{63}p_{56} + p_{01}p_{16}P_{63}(1 - p_{25}P_{52}) \\
+ p_{02}p_{25}P_{56}P_{63} + p_{02}p_{16}p_{25}p_{51}P_{63} + p_{02}p_{23}P_{61}(p_{16} + p_{15}p_{56}) \\
- p_{03}p_{61}P_{15}p_{56} - p_{02}p_{23}P_{68}P_{81}(p_{16} + p_{15}p_{56}) \\
- p_{03}P_{15}P_{56}P_{68}P_{81} = p_{03}p_{16}P_{68}P_{81}(1 - p_{25}P_{52}) \]

\[ a_5 = (1 - p_{25}P_{52})(1 - p_{78}P_{87})(p_{01}p_{15} + p_{02}p_{25})(1 - p_{78}P_{87})p_{03}p_{15}P_{61} \\
+ p_{02}p_{15}p_{23}P_{36}P_{61} - p_{02}p_{16}P_{25}p_{56} + p_{03}p_{15}P_{81}(p_{36}P_{68} + p_{37}P_{78}) \\
+ p_{02}P_{15}p_{23}P_{81}(p_{36}P_{68} + p_{37}P_{78}) - p_{02}p_{81}P_{16}P_{25}(p_{68} + p_{37}P_{63}p_{78}) \]

\[ a_6 = (1 - p_{78}P_{87})p_{01}p_{13}p_{56} + p_{01}p_{16}(1 - p_{25}P_{52}) + p_{02}p_{25}(p_{56} + p_{16}p_{51}) \\
+ p_{02}P_{23}P_{36} + p_{03}p_{36}(1 - p_{25}P_{52}) + p_{01}p_{15}P_{23}p_{36}p_{52} - p_{02}p_{15}p_{23}P_{36}P_{51} \\
- p_{03}p_{15}P_{36}P_{51} + p_{02}p_{15}p_{23}P_{37}P_{56}p_{78}P_{81} + p_{02}p_{16}p_{23}p_{37}P_{78}P_{81} \\
+ p_{03}p_{15}P_{37}P_{56}p_{78}P_{81} + p_{03}p_{16}P_{37}P_{78}P_{81}(1 - p_{25}P_{52}) \]
\[a_7 = p_{01}p_{15}p_{56}p_{68} + p_{01}p_{16}p_{68}(1-p_{25}p_{52}) + p_{02}p_{25}(p_{56} + p_{16}p_{51})
\]
\[
= p_{01}p_{15}p_{56}p_{68} + p_{02}p_{25}(p_{56} + p_{16}p_{51}) + p_{03}p_{36}(p_{56} + p_{16}p_{51}) + p_{02}p_{25}(p_{56} + p_{16}p_{51})
\]
\[
= p_{01}p_{15}p_{56}p_{68} + p_{02}p_{25}(p_{56} + p_{16}p_{51}) + p_{03}p_{36}(p_{56} + p_{16}p_{51}) + p_{02}p_{25}(p_{56} + p_{16}p_{51}) + p_{03}p_{36}(p_{56} + p_{16}p_{51})
\]

\[a_8 = p_{01}p_{15}p_{56}p_{68} + p_{01}p_{16}p_{68}(1-p_{25}p_{52}) + p_{02}p_{25}(p_{56} + p_{16}p_{51})
\]
\[+ p_{02}p_{23}p_{36}p_{68}p_{87}(1-p_{15}p_{51}) + p_{02}p_{23}p_{36}p_{68}p_{87}(1-p_{15}p_{51})
\]
\[+ p_{02}p_{23}p_{36}p_{68}p_{87}(1-p_{15}p_{51}) + p_{02}p_{23}p_{36}p_{68}p_{87}(1-p_{15}p_{51})
\]
\[+ p_{02}p_{23}p_{36}p_{68}p_{87}(1-p_{15}p_{51}) + p_{02}p_{23}p_{36}p_{68}p_{87}(1-p_{15}p_{51})
\]

### 7.8 AVAILABILITY ANALYSIS

\[M_0(t) = e^{-X_1t}
\]
\[M_1(t) = e^{-X_2t}
\]
\[M_2(t) = e^{-X_3t}
\]
\[M_3(t) = e^{-X_4t}
\]
\[M_4(t) = e^{-X_5t}
\]
\[M_5(t) = e^{-X_6t}
\]
\[M_7(t) = e^{-X_7t}
\]
\[M_8(t) = e^{-X_8t}
\]
Recursive relations giving the point wise availability $A_i(t)$ are:

$$A_0(t) = M_0(t) + \sum_{j=1,2,3} q_{0j} A_j(t) \quad ; \quad A_1(t) = M_1(t) + \sum_{j=0,4,5,6} q_{1j} A_j(t)$$

$$A_2(t) = M_2(t) + \sum_{j=0,3,5} q_{2j} A_j(t) \quad ; \quad A_3(t) = M_3(t) + \sum_{j=0,6,7} q_{3j} A_j(t)$$

$$A_4(t) = q_{40}(t) A_0(t) \quad ; \quad A_5(t) = M_5(t) + \sum_{j=1,2,4,6} q_{5j} A_j(t)$$

$$A_6(t) = M_6 + \sum_{j=1,3,4,8} q_{6j} A_j(t) \quad ; \quad A_7(t) = M_7 + \sum_{j=0,8} q_{7j} A_j(t)$$

$$A_8(t) = M_8(t) + \sum_{j=1,4,7} q_{8j} A_j(t)$$

$$A_9(t) = M_9(t) + B_{90}(t) A_0(t) + B_{96} A_6(t) + B_{97} A_7(t)$$

Where:

$$B_{90} = q^* + q^* \quad ; \quad B_{96} = q^* + q^* \quad ; \quad B_{97} = q^*$$

Taking laplace transforms of \([9-17]\), and after solving for $A_i^*(s)$, using equation \([1-27]\) of section 3, the steady state availability of the system when the system starts from $S_i \in \mathcal{E}$ is obtained as follows:

$$A_0(\infty) = \lim_{s\to0} s^2 A_0^*(s) = N_2(0)/D_2(0)$$

Where:

$$N_2(0) = \mu_0 a_0 + \mu_1 a_1 + \mu_2 a_2 + \mu_3 a_3 + \mu_4 a_4 + \mu_5 a_5 + \mu_7 a_7 + \mu_8 a_8 + M_0^*(0)a_9$$
Using above [19-20] in [18] we get the expression for \( A_0(\infty) \).

7.9 BUSY PERIOD ANALYSIS

(a). EXPECTED BUSY PERIOD ANALYSIS OF THE REPAIRMAN IN SIMPLE REPAIR (ELECTRICAL, MECHANICAL, ON-LINE) IN \((0,t]\)

By probabilistic arguments we have

\[
W_1(t) = \overline{G}_5(t)e^{-(\lambda+\beta)t}; \quad W_2(t) = \overline{G}_1(t)e^{-(\lambda+\beta)t}; \quad W_7(t) = \overline{G}_6(t)e^{-(\lambda+\beta)t}; \quad W_8(t) = \overline{G}_5(t)e^{-\lambda t}
\]
We define $B_i^j(t)$, the probability that repairman is busy at epoch $t$ starting from state $S_i E$. By probabilistic arguments, we have

$$B_0^1(t) = \sum_{j=1,2,3,4} q_{0j}(t) B_j^1(t); \quad B_1^1(t) = W_1(t) + \sum_{j=5,6} q_{1j}(t) B_j^1(t)$$

$$B_2^2(t) = W_2(t) + \sum_{j=0,6,7,8} q_{2j}(t) B_j^2(t); \quad B_3^3(t) = q_{35}(t) B_5^3(t) + \sum_{j=0,6} q_{3j} B_j^3(t)$$

$$B_4^4(t) = q_{45}(t) B_5^4(t); \quad B_5^5(t) = \sum_{j=0,6} q_{5j} B_j^5(t)$$

$$B_6^6(t) = q_{65}(t) B_5^6(t); \quad B_7^7(t) = W_7(t) + \sum_{j=5,6} q_{7j} B_j^7(t)$$

$$B_8^8(t) = W_8(t) + \sum_{j=6,9} q_{8j} B_j^8(t)$$

$$B_9^9(t) = W_9(t) + q_{90}(t) B_0^9(t) + q_{96} B_6^9(t) + q_{97} B_7^9(t) + q_{98} B_8^9(t)$$

Taking laplace transforms of \{6-15\}, and using relation [1-27] of section 3 we get

$$N_3(0) = \mu_1 p_0 c_0 + \mu_2 p_0 c_0 + \mu_7 [p_0 p_2 c_0 + p_0 p_2 c_0 + p_2 p_8 c_0 + p_0 p_2 p_8 c_0] + \mu_8 p_0 p_2 c_0 + W_9^*(0) - p_8 p_8 p_2 c_0$$

Therefore, in the long run, the fraction of time for which the system is under repair is given by:

$$B_0^1(\infty) = \lim_{t \to \infty} B_0^1(t) = \lim_{s \to 0} sB_0^1(s) = \frac{N_3(0)}{D_2(0)}$$
Similarly,

(b) **EXPECTED BUSY PERIOD ANALYSIS OF THE REPAIRMAN IN COLD REPAIR IN** \((0,t]\) is given by

\[
B_3^0(\infty) = \lim_{t \to \infty} B_3^0(t) = \lim_{s \to 0} sB_3^0(s) = \frac{N_4(0)}{D_2(0)}
\]  

(c). **EXPECTED BUSY PERIOD ANALYSIS OF THE REPAIRMAN IN EMERGENCY REPAIR IN** \((0,t]\) is given by

\[
B_3^3(\infty) = \lim_{t \to \infty} B_3^3(t) = \lim_{s \to 0} sB_3^3(s) = \frac{N_5(0)}{D_2(0)}
\]  

(d). **EXPECTED BUSY PERIOD ANALYSIS OF THE REPAIRMAN IN CAPITAL REPAIR IN** \((0,t]\) is given by

\[
B_3^0(\infty) = \lim_{t \to \infty} B_3^0(t) = \lim_{s \to 0} sB_3^0(s) = \frac{N_6(0)}{D_2(0)}
\]  

Where:

\[
N_4(0) = \mu_3p_{03}c_0 \quad ; \quad N_5(0) = \mu_4p_{04}c_0
\]

\[
N_5(0) = \mu_6[p_{04}p_{46} + p_{01}p_{16} + p_{02}p_{26} + p_{02}p_{28}p_{86} + p_{02}p_{28}p_{89}p_{96} + p_{02}p_{27}p_{76} + p_{02}p_{28}p_{76}p_{77}p_{79} + p_{03}P_{36} + p_{04}p_{56}p_{45} + p_{01}p_{56}p_{15} + p_{03}p_{56}p_{35} + p_{02}p_{27}p_{56}p_{56}p_{75} + p_{01}p_{56}p_{15} + p_{03}p_{56}p_{35} + p_{02}p_{27}p_{56}p_{75} + P_{02}p_{28}p_{56}p_{75}p_{79}p_{97} + \mu_7[p_{02}p_{27}c_0 + p_{02}p_{28}p_{89}c_0] + p_{02}p_{27}c_0 + p_{02}p_{28}p_{89}c_0
\]
7.10 PARTICULAR CASES

When all the repair time distributions including shut-down and capital repair time distributions along with preparation time distribution are n-phase Erlang distributed i.e.

\[ g_i(t) = nr_i(nr_i)^{n-1} e^{-nr_i t} / (n-1)! \quad , i = 1, 2 \]

\[ a_i(t) = na_i(na_i)^{n-1} e^{-na_i t} / (n-1)! \quad , i = 1, 2 \]

\[ h_i(t) = nb_i(nb_i)^{n-1} e^{-nb_i t} / (n-1)! \quad , i = 1, 2 \]

and other time distributions are negative exponential.

Then steady state equations become:

\[
\text{MTSF} = K_0 / K_1 \quad ; \quad \text{A}_0 = K_{01} / K_2 \quad ; \quad \text{B}_0 = K_{02} / K_2
\]

\[
\text{B}_0^2 = K_{02} / K_2 \quad ; \quad \text{B}_0^3 = K_{02}^3 / K_2 \quad ; \quad \text{B}_0^4 = K_{02}^4 / K_2
\]

Where:

\[
K_0 = a_0 (1 - p_2 \lambda a_6 a_{12} a_{17}) + \lambda a_6 a_4 (1 - p_2 \lambda a_6 a_{12} a_{17})
+ \beta a_6 a_4 (1 - p_2 \lambda a_6 a_{12} a_{17}) a_8 (1 - p_2)
+ \lambda a_6 a_{12} a_{17} + a_2 a_10 (1 - p_2 \lambda a_6 a_{12} a_{17}) +
+ a_{20} a_{15} + \lambda p_2 \lambda a_6 a_{11} a_{16} + \beta p_2 \lambda a_6 a_{11} a_{13} + \beta p_2 \lambda
+ a_6 a_{12} a_{19} a_0
\]

\[
K_1 = 1 - p_2 \lambda a_6 a_{12} a_{17} - \beta a_6 a_5 + a_{23} - \lambda a_6 a_{13} a_{14} - a_1 a_7 a_{14}
+ a_2 a_9 a_{14} - \beta a_0 \lambda p_1 a_6 a_{11} (\lambda + \beta) - \beta p_2 \lambda a_0 a_{12} a_{18}
\]

\[
K_2 = a_0 a_{14} + \lambda a_4 a_0 a_{14} + a_6 a_0 \beta + a_8 a_{14} + a_2 a_10 a_{14} + a_{21} a_{15}
+ p_1 \lambda a_6 a_{11} a_{16} + a_{21} a_{16} + \beta p_2 \lambda a_6 a_{11} a_{13}
+ \beta p_2 \lambda a_6 a_{12} a_{19} a_0
\]

\[
K_{02}^1 = \lambda a_4 a_{14} + a_6 a_0 \beta + p_1 \lambda a_6 a_{16} a_{11}
+ \beta p_2 \lambda a_6 a_{10} a_{13} + \beta p_2 \lambda a_6 a_{12} a_{19} a_0
\]
\[ k_{02}^2 = a_1 a_{14} \quad ; \quad k_{02}^3 = a_2 a_{16} \quad ; \quad k_{02}^3 = a_2 a_{10} a_{14} \quad ; \quad k_0 = k_{01} \]

\[ a_0 = \sum_{j=0}^{n-1} \sum_{j=0}^{n-1} (na)^j (nb)^j (2j + 1) / (j!)^2 (\lambda + \beta + na + nb)^{j+1} \]

\[ a_1 = \sum_{j=0}^{n-1} (na)^j (nb)^j (n + j - 1)! / (j!) (n - 1)! (\lambda + \beta + na + nb)^{n+j} \]

\[ a_2 = \sum_{j=0}^{n-1} (nb)^j (na)^j (n + j - 1)! / (j!) (n - 1)! (\lambda + \beta + na + nb)^{n+j} \]

\[ a_3 = (nr_3)^n / (\lambda + \beta + nr_3)^n \quad ; \quad a_4 = \sum_{j=0}^{n-1} (nr_3)^j / (\lambda + \beta + nr_3)^{j+1} \]

\[ a_5 = (nr_1)^n / (\lambda + \beta + nr_1)^n \]

\[ a_6 = \sum_{j=0}^{n-1} (nr_1)^j / (\lambda + \beta + nr_1)^{j+1} \quad ; \quad a_7 = (nr_2)^n / (\lambda + \beta + nr_2)^n \]

\[ a_8 = \sum_{j=0}^{n-1} (nr_2)^j / (\lambda + \beta + nr_2)^{j+1} \quad ; \quad a_9 = (nr_4)^n / (\lambda + \beta + nr_4)^n \]

\[ a_{10} = \sum_{j=0}^{n-1} (nr_4)^j / (\lambda + \beta + nr_4)^{j+1} \quad ; \quad a_{11} = \sum_{j=0}^{n-1} (nr_6)^j / (\lambda + \beta + nr_6)^{j+1} \]

\[ a_{12} = (nr_3)^n / (\lambda + nr_3)^n \quad ; \quad a_{13} = \sum_{i=0}^{n-1} (nr_3)^i / (\lambda + nr_3)^{i+1} \quad ; \quad (1 - p_{28} p_{89} p_{92}) = a_{14} \]
\[ a_{15} = (-p_{01}p_{15} - p_{03}p_{35} - p_{04}p_{45} + p_{02}p_{27}p_{75}) + p_{15}p_{28}p_{89} \]
\[ = (p_{01}p_{16} + p_{02}p_{26} + p_{03}p_{36} + p_{04}p_{46}) + p_{01}p_{16} + p_{15}p_{28}p_{89} \]
\[ a_{16} = (p_{01}p_{16} + p_{02}p_{26} + p_{03}p_{36} + p_{04}p_{46}) + p_{01}p_{16} + p_{15}p_{28}p_{89} \]

\[ a_{17} = \sum_{j=0}^{n-1} \frac{(nh)^{j}(n+j)(\lambda + nh + nr_{1})}{j!} \]
\[ a_{18} = \sum_{j=0}^{n-1} \frac{(nh)^{j}(nr_{1})^{n}(n+j)}{(n-1)!} \]
\[ a_{19} = \sum_{j=0}^{n-1} \frac{(nh)^{j}(nr_{1})^{n}(2j+1)}{(j!)^2} \]
\[ a_{20} = \sum_{j=0}^{n-1} \frac{(nh)/(\lambda + \beta + nh)}{j!} \]

\[ a_{22} = (nr_{6})^{n}/(\lambda + \beta + nr_{6})^{n} \]

\[ a_{23} = (nh)^{n}/(\lambda + \beta + nh)^{n} \]

\[ p_{02} = \beta a_0 \]
\[ p_{03} = a_1 \]
\[ p_{04} = a_2 \]
\[ p_{15} = a_3 \]

\[ p_{16} = (\lambda + \beta)a_4 \]
\[ p_{28} = p_2 \lambda a_6 \]
\[ p_{46} = (\lambda + \beta)a_{10} \]
\[ p_{76} = (\lambda + \beta)a_{11} \]
\[ p_{92} = a_{17} \]
\[ p_{20} = a_5 \]
\[ p_{26} = \beta a_6 \]
\[ p_{35} = a_7 \]
\[ p_{36} = (\lambda + \beta)a_8 \]
\[ p_{45} = a_9 \]
\[ p_{50} = a_{23} \]
\[ p_{56} = (\lambda + \beta)a_{20} \]
\[ p_{75} = a_{22} \]
\[ p_{86} = \lambda a_{13} \]
\[ p_{95} = a_{18} \]
\[ p_{96} = \lambda a_{19} \]
When we put \( n = 1 \) in above equations then repair time follows exponential distribution and we have

\[
K_1 = 1 - (p_2 \lambda_5 h / X_3 X_8 X_9) - \beta r / X_1 X_3 + h / X_6 [-\lambda r / X_1 X_2 \\
(1 - p_2 \lambda_5 h / X_3 X_8 X_9) - ar_2 / X_4 \\
X_1[-(p_2 \lambda_5 h / X_3 X_8 X_9)] - br_4 / X_1 X_1 \\
[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] - \beta p_1 r / X_1 X_3 X_1 - \\
\beta p_2 \lambda_5 r / X_1 X_3 X_8 X_9
\]

\[
K_0 = 1 / X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] + \lambda / X_2 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] \\
+ \beta / X_1 X_3 + a / X_4 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] + b / X_3 X_1[1 \\
-(p_2 \lambda_5 h / X_3 X_8 X_9)] + 1 / X_6 [-(\alpha r / X_2 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] \\
- br_4 / X_3 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] \\
-(\beta p_1 r / X_1 X_3 X_1) + \beta p_2 \lambda / X_1 X_3 X_8 X_9 + \\
\beta p_2 \lambda / X_3 X_3 X_8 + \beta p_2 \lambda r / X_1 X_3 X_8 X_9
\]

\[
K_{02}^{-1} = \lambda / X_2 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] + \beta / X_1 X_3 + \beta p_2 \lambda / X_3 X_1 X_8 \\
+ \beta p_2 \lambda / X_1 X_3 X_8 X_9 + 1 / r_3 \{\alpha (\lambda + \beta) / X_2 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] + \alpha (\lambda + \beta) / X_4 X_1[ \\
-(p_2 \lambda_5 h / X_3 X_8 X_9)] + b (\lambda + \beta) / X_3 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] + \lambda r_3 (\lambda + \beta) / X_2 X_6 X_1[ \\
-(p_2 \lambda_5 h / X_3 X_8 X_9)] \\
+ ar_2 (\lambda + \beta) / X_4 X_1[1 - (p_2 \lambda_5 h / X_3 X_8 X_9)] + br_4 (\lambda + \beta) / X_3 X_6 X_1[ \\
-(p_2 \lambda_5 h / X_3 X_8 X_9)] + \beta^2 / X_1 X_3 + \beta^2 / X_1 X_3 X_8 + \beta^2 r_3 (\lambda + \beta) / X_1 X_3 X_8 X_9 \\
- \beta p_1 (\lambda + \beta) / X_3 X_1 X_7 \beta p_2 \lambda (\lambda + \beta) / X_1 X_3 X_6 X_9
\]

\[
K_{02}^1 = a / X_4 X_1[1 - (p_2 \lambda_3 h / X_3 X_8 X_9) \quad ; \quad K_0^3 = \beta p_1 (\lambda + \beta) / X_3 X_1 X_7 \\
K_{02}^4 = b / X_3 X_1[1 - (p_2 \lambda_3 h / X_3 X_8 X_9)]
\]
Similarly, When we put n=2 then repair time follows 2-phase Erlang distribution and we have

\[ K_1 = 1 - a_{33}a_{42}a_{45} - a_{25}a_{36} + a_{38}(-a_{24}a_{28}(1 - a_{33}a_{42}a_{45}) - a_{26}a_{34}(1 - a_{33}a_{42}a_{45}) + a_{36}a_{37} \]

\[ K_0 = a_{48}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{49}(1 - a_{33}a_{42}a_{45}) + a_{50}a_{25} + a_{51}(1 - a_{33}a_{42}a_{45}) + a_{52}a_{27}(1 - a_{33}a_{42}a_{45}) + a_{53}(-a_{24}a_{28}(1 - a_{33}a_{42}a_{45}) - a_{26}a_{34}(1 - a_{33}a_{42}a_{45}) - a_{27}a_{36}(1 - a_{33}a_{42}a_{45}) - a_{28}a_{37}(1 - a_{33}a_{42}a_{45})) \]

\[ K_2 = a_{48}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{49}(1 - a_{33}a_{42}a_{45}) + a_{50}a_{25} + a_{51}(1 - a_{33}a_{42}a_{45}) + a_{52}a_{27}(1 - a_{33}a_{42}a_{45}) + a_{53}(-a_{24}a_{28}(1 - a_{33}a_{42}a_{45}) - a_{26}a_{34}(1 - a_{33}a_{42}a_{45}) - a_{27}a_{36}(1 - a_{33}a_{42}a_{45}) - a_{28}a_{37}(1 - a_{33}a_{42}a_{45}) - a_{29}a_{38}(1 - a_{33}a_{42}a_{45})) \]

\[ K_0^2 = a_{51}(1 - a_{33}a_{42}a_{45}) \]

\[ K_2^2 = a_{52}a_{27}(1 - a_{33}a_{42}a_{45}) \]

\[ K_0^3 = a_{55}a_{25}a_{32} \]

\[ K_0^4 = a_{52}a_{27}(1 - a_{33}a_{42}a_{45}) \]
Similarly, when we put \( n = 2 \) then repair time follows 2-phase Erlang distribution and we have

\[
K_1 = 1 - a_{33}a_{42}a_{45} - a_{25}a_{30} + a_{35}( - a_{24}a_{28}(1 - a_{33}a_{42}a_{45}) - a_{26}a_{34}(1 - a_{33}a_{42}a_{45}) + a_{36}a_{27} - a_{38}a_{42}a_{45} - a_{25}a_{32}a_{41} - a_{25}a_{33}a_{42}a_{46})
\]

\[
K_0 = a_{48}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{49}(1 - a_{33}a_{42}a_{45}) + a_{50}a_{25} + a_{51}(1 - a_{33}a_{42}a_{45}) + a_{52}a_{27}(1 - a_{33}a_{42}a_{45}) + a_{53}a_{25}a_{41} - a_{24}a_{28}(1 - a_{33}a_{42}a_{45}) - a_{26}a_{34}(1 - a_{33}a_{42}a_{45}) - a_{27}a_{36}(1 - a_{33}a_{42}a_{45}) - a_{24}a_{29}(1 - a_{33}a_{42}a_{45}) + a_{26}a_{35}(1 - a_{33}a_{42}a_{45}) + a_{27}a_{37}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{28}a_{39}(1 - a_{33}a_{42}a_{45}) + a_{26}a_{34}a_{39}(1 - a_{33}a_{42}a_{45}) + a_{27}a_{37}a_{39}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{31} + a_{25}a_{33}a_{43} + a_{25}a_{31} - a_{24}a_{32}a_{40} + a_{39}a_{25}a_{33}a_{45}a_{46}a_{39})
\]

\[
K_2 = a_{48}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{49}(1 - a_{33}a_{42}a_{45}) + a_{50}a_{25} + a_{51}(1 - a_{33}a_{42}a_{45}) + a_{52}a_{27}(1 - a_{33}a_{42}a_{45}) + a_{53}a_{25}a_{41} - a_{24}a_{28}(1 - a_{33}a_{42}a_{45}) - a_{26}a_{34}(1 - a_{33}a_{42}a_{45}) - a_{27}a_{36}(1 - a_{33}a_{42}a_{45}) - a_{24}a_{29}(1 - a_{33}a_{42}a_{45}) + a_{26}a_{35}(1 - a_{33}a_{42}a_{45}) + a_{27}a_{37}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{28}a_{39}(1 - a_{33}a_{42}a_{45}) + a_{26}a_{34}a_{39}(1 - a_{33}a_{42}a_{45}) + a_{27}a_{37}a_{39}(1 - a_{33}a_{42}a_{45}) + a_{24}a_{31} + a_{25}a_{33}a_{43} + a_{25}a_{31} - a_{24}a_{32}a_{40} + a_{39}a_{25}a_{33}a_{45}a_{46}a_{39})
\]

\[
K_3 = a_{35}a_{25}a_{32} + a_{56}a_{25}a_{33} + a_{39}a_{25}a_{33}a_{42}
\]

\[
K_4 = a_{52}a_{27}(1 - a_{33}a_{42}a_{45})
\]
Where:

\[ a_{24} = \lambda / (\lambda + \beta + 2a + 2b) + +2\lambda(a + b) / (\lambda + \beta + 2a + 2b)^2 + 8\lambda ab / (\lambda + \beta + 2a + 2b)^3 \]

\[ a_{25} = \beta / (\lambda + \beta + 2a + 2b) + 2\beta(a + b) / (\lambda + \beta + 2a + 2b)^2 + 8\beta ab / (\lambda + \beta + 2a + 2b)^3 \]

\[ a_{26} = (2a)^2 / (\lambda + \beta + 2a + 2b)^2 + 16a^2 b / (\lambda + \beta + 2a + 2b)^3 \]

\[ a_{27} = (2b)^2 / (\lambda + \beta + 2a + 2b)^2 + 16ab^2 / (\lambda + \beta + 2a + 2b)^3 \]

\[ a_{28} = (2r_5)^2 / (\lambda + \beta + 2r_5)^2; a_{29} = (\lambda + \beta) / (\lambda + \beta + 2r_5) + 2r_5(\lambda + \beta) / (\lambda + \beta + 2r_5) \]

\[ a_{30} = (2r_1)^2 / (\lambda + \beta + 2r_1)^2; a_{31} = \beta / (\lambda + \beta + 2r_1) + \beta 2r_1(\lambda + \beta) / (\lambda + \beta + 2r_1)^2 \]

\[ a_{32} = p_1\lambda / (\lambda + \beta + 2r_1) + 2r_1p_1\lambda / (\lambda + \beta + 2r_1)^2; a_{33} = p_2\lambda / (\lambda + \beta + 2r_1) + 2r_1p_2\lambda / (\lambda + \beta + 2r_1)^2 \]

\[ a_{34} = (2r_2)^2 / (\lambda + \beta + 2r_2)^2 ; a_{35} = (\lambda + \beta) / (\lambda + \beta + 2r_2) + 2r_2(\lambda + \beta) / (\lambda + \beta + 2r_2)^2 \]

\[ a_{36} = (2r_4)^2 / (\lambda + \beta + 2r_4) ; a_{37} = (\lambda + \beta) / (\lambda + \beta + 2r_4) + 2r_4(\lambda + \beta) / (\lambda + \beta + 2r_4)^2 \]

\[ a_{38} = (2h)^2 / (\lambda + \beta + 2h)^2 ; a_{39} = (\lambda + \beta) / (\lambda + \beta + 2h) + 2h(\lambda + \beta) / (\lambda + \beta + 2h)^2 \]

\[ a_{40} = (\lambda + \beta) / (\lambda + \beta + 2r_6) + 2r_6(\lambda + \beta) / (\lambda + \beta + 2r_6)^2; \]

\[ a_{41} = (2r_6)^2 / (\lambda + \beta + 2r_6)^2; a_{42} = (2r_5)^2 / (\lambda + 2r_5)^2 \]

\[ a_{43} = \lambda / (\lambda + 2r_5) + 2r_5\lambda / (\lambda + 2r_5)^2; \]

\[ a_{45} = 2h^2 / (\lambda + h + 2r_1)^2 + 4h^2 / (\lambda + h + 2r_1)^3; \]

\[ a_{46} = 2r_1^2 / (\lambda + h + 2r_1)^2 + 4r_1^2 h / (\lambda + h + 2r_1)^3 \]
\[ a_{47} = \lambda (\lambda + 2h + 2r_1) + 2(r_1 + h)\lambda (\lambda + 2h + 2r_1)^2 + 8r_1\lambda h (\lambda + 2h + 2r_1)^3 \]
\[ a_{48} = \lambda (\lambda + \beta + 2a + 2h) + 2(a + h)\lambda (\lambda + \beta + 2a + 2h)^2 + 8ah (\lambda + \beta + 2a + 2h)^3 \]
\[ a_{49} = \lambda (\lambda + \beta + 2r_5) + 2r_5 (\lambda + \beta) (\lambda + \beta + 2r_5)^2 ; \]
\[ a_{50} = \lambda (\lambda + \beta + 2r_1) + 2r_1 (\lambda + \beta + 2r_1)^2 ; \]
\[ a_{51} = \lambda (\lambda + \beta + 2r_2) + 2r_2 (\lambda + \beta + 2r_2)^2 ; \]
\[ a_{52} = \lambda (\lambda + \beta + 2r_4) + 2r_4 (\lambda + \beta + 2r_4)^2 ; \]
\[ a_{53} = \lambda (\lambda + \beta + 2r_4) + 2r_4 (\lambda + \beta + 2r_4)^2 ; \]
\[ a_{54} = \lambda (\lambda + h + 2r_6) + 2r_6 (\lambda + h + 2r_6)^2 ; \]
\[ a_{57} = \lambda (\lambda + h + 2r_1) + 2(r_1 + h) (\lambda + h + 2r_1)^2 + 8r_1 h (\lambda + h + 2r_1)^3 \]

### 7.11 PROFIT ANALYSIS

The cost benefit analysis of the system can be carried out by considering the expected busy period of the repairman in repair in \((0, t]\). Therefore,

\[ G(t) = \text{expected revenue earned by the system in } (0, t] - \text{expected repair cost of the repair facility in } (0, t] \]

\[ = C_1 \mu_{up}(t) - C_2 \mu_b(t) - C_3 \mu_b^2(t) - C_4 \mu_b^3(t) - C_5 \mu_b^4(t) \]

Here

\[ \mu_{up}(t) = \int_0^t \mu_0(t) \, dt \quad ; \quad \mu_1(t) = \int_0^t \mu_1(t) \, dt \quad ; \quad \mu_2(t) = \int_0^t \mu_2(t) \, dt \]

\[ \mu_3(t) = \int_0^t \mu_3(t) \, dt \quad ; \quad \mu_4(t) = \int_0^t \mu_4(t) \, dt \]

The expected profit per unit of time in steady state is

\[ G = \lim_{t \to \infty} G(t) = \lim_{s \to 0} s^2 G^*(s) = C_1 \mu_{up}(t) - C_2 \mu_b(t) - C_3 \mu_b^2(t) - C_4 \mu_b^3(t) - C_5 \mu_b^4(t) \]
where \( C_1 \) is the revenue per unit up time and \( C_2, C_3, C_4, C_5 \) are the simple repair cost, cold repair cost, emergency repair cost and capital repair cost respectively.

7.12 GRAPHICAL REPRESENTATION

Fig. 7.2 shows the behaviour of the mean-time-to-system-failure of the Twin Hearth Main unit system with respect to \( \alpha \) for varying values of \( \beta_2 \), while in particular repair time distributions of all the equipments are taken as exponentially distributed. From the graph it can be observed that MTSF of the machine increases as failure rate \( \lambda \) decreases. In case of availability also, with the increase or decrease in failure rate, availability of the system decreases or decreases correspondingly. Same case arises in case of expected cost or profit. Figures for all characteristics are shown in figure 7.3 & figure 7.4 respectively.
STATE TRANSITION DIAGRAM OF TWIN HEART SURGICAL

- **Up State**
- **Down State**
- **Regeneration Point**
EFFECT OF $|\mu|$ ON MTSF FOR VARYING VALUES OF $|\beta_2|$

- $\beta_2 = 0.001$
- $\beta_2 = 0.002$
- $\beta_2 = 0.04$

- $\phi = 0.1$, $\psi = 0.02$, $\beta_1 = 0.001$, $\beta_3 = 0.003$
- $r_1 = 0.04$, $r_2 = 0.02$, $r_3 = 2$, $r_4 = 4$

FAILURE RATE OF MAIN UNIT

Figure 4.2
EFFECT OF $[\mu]$ ON AVAILABILITY FOR VARYING VALUES OF $[\mu]$

Failure Rate of MAIN UNIT

$\phi = .01, \psi = .02, \beta_1 = .001, \beta_3 = .003$

$r_1 = .04, r_2 = .02, r_3 = .2, r_4 = .4$
EFFECT OF \( \beta_2 \) ON EXPECTED COST FOR VARYING VALUES OF \( \beta_2 \)

\[ \phi = 0.01, \psi = 0.02, \beta_1 = 0.01, \beta_3 = 0.003 \]
\[ r_1 = 0.04, r_2 = 0.02, r_3 = 2, r_4 = 4 \]
\[ C_1 = 800, C_2 = 100, C_3 = 100 \]
\[ C_4 = 150, C_5 = 200 \]

\( \beta_2 = 0.001 \)
\( \beta_2 = 0.002 \)
\( \beta_2 = 0.04 \)

\( \text{FAILURE RATE OF MAIN UNIT} \)