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# Profit Analysis of a Single Unit Redundant System Having Perfect Switch

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**Abstract**
In this paper Profit Analysis of a Single Unit Redundant System Having Perfect Switch using Regenerative Point Graphical Technique (RPGT) is discussed. Problem is formulated and solved using RPGT. Repair and Failure are statistically independent. Expressions for system parameters i.e. availability, number of server visits and busy period of the server are evaluated to study the profit and behavior of the system for steady state. System behavior is discussed with the help of graphs and tables.

**Keywords:** Availability, Base-State, RPGT, System Parameters.

## 1. Introduction

Considering the importance of individual units in system Kumar, J. & Malik, S. C. [1] have discussed the concept of preventive maintenance for a single unit system. Liu, R. [2], Malik, S. C. [3], Nakagawa, T. and Osaki, S. [4] have discussed reliability analysis of a one unit system with un-repairable spare units and its applications. Goel, P. & Singh J. [5], Gupta, P., Singh, J. & Singh, I.P. [6], Kumar, S. & Goel, P. [7], Gupta, V. K. [8], Chaudhary, Goel & Kumar [9] Sharma & Goel [10], Ritikesh & Goel [11] and Goyal & Goel [12] have discussed behavior with perfect and imperfect switch-over of systems using various techniques.

In this paper Profit Analysis of a Single Unit Redundant System Having Perfect Switch using Regenerative Point Graphical Technique (RPGT) is discussed. Problem is formulated and solved using RPGT. Repair and Failure are statistically independent. Expressions for system parameters i.e. availability, number of server visits and busy period of the server are evaluated to study the profit and behavior of the system for steady state. System behavior is discussed with the help of graphs and tables.

The single-unit systems are frequently used in many sphere of life due to their inherent reliability and common man's affordability, the single unit cold stand-by system is discussed, which remains in working conditions if any of unit either main unit or stand-by unit is in good state. For example Gear system in Automobile industry, Two-stroke Jet engine, Electrical invertors used in industries and houses. Sometimes, it may be difficult to detect manually that which of the working units has failed and it involves risks that the failed unit is not switched out and the stand-by unit is not switched in successfully or the repaired unit is not put back in the system. It is also possible that the failed unit is not detected or the failed unit is not switched out and the stand-by unit is not switched in time. To deal with such a situation a switch over device is necessary which overcomes such problems and can detect and disconnect the failed unit with a high degree of precision. A switch over device to switch out the failed unit and to switch in the stand-by unit is necessary. Switch-over system is perfect, so that on the failure of an operating unit, the stand-by unit is switched in with a high degree of precision by mean of a switch over device. The switch may take action by electric relays, hydraulic valves, electric control circuits or some other devices. Switch-over is instantaneous, as soon as the main unit fails, the standby unit is switch in. The system is down when both units are failed and nothing can fail further when the system is in failed state. If the main unit fails, the system is in degraded state and the main unit is immediately put under repair. Repairs are perfect i.e. the repair facility never does any damage to the units and a repaired unit works like a new-one. Upon failure, if the repairman is busy and if standby unit also fails, it joints the end of the queue of failed unit. The distributions of the failure times and repair times are exponential and general respectively and also different for operating and standby unit. They are also assumed to be independent of each other. The system is discussed for steady state conditions.

## 2 Assumptions and Notations

The following assumptions and notations/symbols are used:

1) The system consists of two non-identical units. Initially, one unit is operative and other unit is kept as cold standby. i.e. the standby unit does not fail during its standby state.
2) The distributions of the failure times and repair times are exponential and general respectively and also different for operating and standby unit. They are also assumed to be independent of each other.
3) Repairs are perfect i.e. the repair facility never does any damage to the units.
4) A repaired unit works like a new-one.
5) The system is down when both units are failed.
6) Nothing can fail further when the system is in failed state. If the main unit fails, the system is in degraded state and the main unit is immediately put under repair.
7) The system is discussed for steady state conditions.
8) As soon as the main unit fails, the standby unit is switch in.
9) If standby unit is on line, and main unit is repaired in the meantime, then, the main unit is switched in as on line.

10) Upon failure, if the repairman is busy and if standby unit also fails, it joints the end of the queue of failed unit.
11) Switch-over system is perfect.
12) Switch-over is instantaneous. The repair of a failed unit starts at once.

pr/pf : Probability/transition probability factor.

$\overline{cycle}$ : a circuit formed through un-failed states.

k-cycle : a circuit (may be formed through regenerative or non-regenerative/failed states) whose terminals are at the regenerative state k.

k-$\overline{cycle}$ :a circuit (may be formed through only un-failed regenerative / non- regenerative states) whose terminals are at the regenerative state k.

$\left(i \xrightarrow{s_r} j\right)$ : $r$-th directed simple path from $i$-state to j-state; r takes positive integral values for different paths from $i$-state to j-state.

$\left(\xi \xrightarrow{sff} i\right)$ : a directed simple failure free path from $\xi$-state to i-state.

$V_{k,k}$ :$pf$ of the state k reachable from the terminal state k of the k-cycle.

$V_{\overline{k,k}}$ : $pf$ of the state k reachable from the terminal state k of the k-$\overline{cycle}$.

$B_i(t)$ : probability that the server is busy doing a particular job at epoch t, given that the system entered regenerative state i at t=0.

$V_i(t)$ : the expected number of visits of the server for a given job in (0,t], given that the system entered regenerative state i at t=0.

$\mu_i^1$ : the total un-conditional time spent before transiting to any other regenerative states, given that the system entered regenerative state 'i' at t=0.

$\eta_i$ : expected waiting time spent while doing a given job, given that the system entered regenerative state 'i' at t=0; $\eta_i = W_i^*(0)$.

$f_j$ : Fuzziness measure of the j-state.

$\lambda/\lambda_1$ : Constant failure rate of the main operative unit/the redundant unit.

$g(t)/G(t)$ : Probability density function/cumulative distribution function of the repair-time of the operative unit.

$h(t)/H(t)$ : Probability density function/cumulative distribution function of the repair-time of the redundant unit.

A/a : main unit in the operative state/ failed state.

(B)/B/b : redundant unit in the stand-by state/ operative state/ failed state.

The system can be in any of the following states with respect to the above symbols.

$S_0$ = A(B) $S_1$ = aB

$S_2$ = ab $S_3$ = Ab

States $S_0, S_1, S_2,$ $and$ $S_3$ are regenerative states. The possible transitions between states along with transition time c.d.f. are shown in Fig. 1

**3. Transition Diagram of the System**

Following the above assumptions and notations, the transition diagram of the system is shown in Fig. 1.

**Table 1.**

| State | Symbol | Model |
|---|---|---|
| Regenerative state/point | • | 0-3 |
| Up-state: | ○ | 0,3 |
| Failed state: | ▭ | 2 |
| Degenerated/Reduced state | ⬭ | 1 |

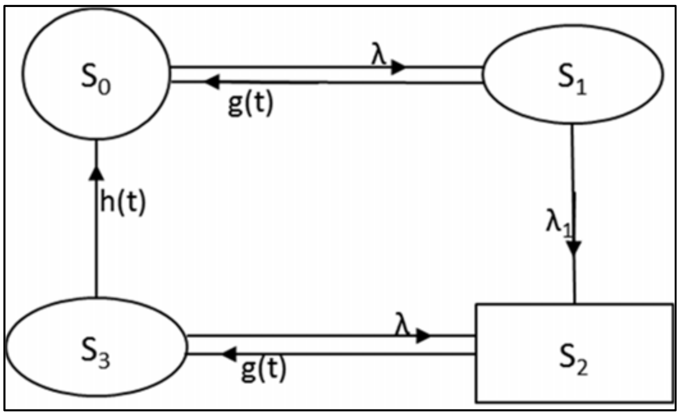


**Fig 1.**

## 4. Evaluation of Parameters of the System

The key parameters (under steady state conditions) of the system are evaluated by determining a 'base-state' and applying RPGT. The system parameters are obtained by using base-state.

### 4.1 Determination of base-state

From the transition diagram (Fig. 1), all the paths (P0) from one regenerative state to the other reachable states are determined and shown in Table-2. The Primary, Secondary, Tertiary circuits at all vertices are shown in Table-3.The number of primary circuits(CL1)at the vertices '0-3' are two each and number of secondary circuits(CL2) are one each without having any of tertiary circuits(CL3). Therefore, any of state can be chosen as base-state. We may choose state '0' as base-state.

**Table 2:** Paths from State 'i' to the Reachable State 'j':P0

| i | j = 0 | j = 1 | j = 2 | j = 3 |
|---|---|---|---|---|
| 0 | {0,1,0}<br>{0,1,2,3,0} | {0,1} | {0,1,2} | {0,1,2,3} |
| 1 | {1,0}<br>{1,2,3,0} | {1,0,1}<br>{1,2,3,0,1} | {1,2} | {1,2,3} |
| 2 | {2,3,0} | {2,3,0,1} | {2,3,2}<br>{2,3,0,1,2} | {2,3} |
| 3 | {3,0} | {3,0,1} | {3,2}<br>{3,0,1,2} | {3,2,3}<br>{3,0,1,2,3} |

**Table 3:** Primary, Secondary, Tertiary circuits at a Vertex

| Vertex i | Primary (CL1) | Secondary (CL2) | Tertiary (CL3) |
|---|---|---|---|
| 0 | {0,1,0}<br>{0,1,2,3,0} | {2,3,2} | Nil |
| 1 | {1,0,1}<br>{1,2,3,0,1} | {2,3,2} | Nil |
| 2 | {2,3,2}<br>{2,3,0,1,2} | {0,1,0} | Nil |
| 3 | {3,2,3}<br>{3,0,1,2,3} | {0,1,0} | Nil |

**Table 4:** Primary, Secondary, Tertiary Circuits w.r.t. the Simple Paths (Base-State '0')

| Vertex j | $\left(0 \overset{S_r}{\rightarrow} j\right)$: (P0) | (P1) | (P2) | (P3) |
|---|---|---|---|---|
| 1 | $\left(0 \overset{S_1}{\rightarrow} 1\right)$:{0,1} | Nil | Nil | Nil |
| 2 | $\left(0 \overset{S_1}{\rightarrow} 2\right)$:{0,1,2} | {2,3,2} | Nil | Nil |
| 3 | $\left(0 \overset{S_1}{\rightarrow} 3\right)$:{0,1,2,3} | {2,3,2} | Nil | Nil |

### 4.2 Transition Probabilities and the Mean Sojourn Times Transition Probabilities

**Table 5.**

| $q_{i,j}(t)$ | $p_{i,j} = q^*_{i,j}(0)$ |
|---|---|
| $q_{0,1}(t) = \lambda e^{-\lambda t}$ | $p_{0,1} = 1$ |
| $q_{1,0}(t) = g(t)e^{-\lambda_1 t}$<br>$q_{1,2}(t) = \lambda_1 e^{-\lambda_1 t}\bar{G}(t)$ | $p_{1,0} = g^*(\lambda_1)$<br>$p_{1,2} = 1 - g^*(\lambda_1)$ |
| $q_{2,3}(t) = g(t)$ | $p_{2,3} = g^*(0)$ |
| $q_{3,0}(t) = h(t)e^{-\lambda t}$<br>$q_{3,2}(t) = \lambda e^{-\lambda t}\bar{H}(t)$ | $p_{3,0} = h^*(\lambda)$<br>$p_{3,2} = 1 - h^*(\lambda)$ |

It can be easily verified that;
$p_{0,1} = 1$; $p_{1,0} + p_{1,2} = 1$; $p_{2,3} = g^*(0) = 1$; $p_{3,0} + p_{3,2} = 1$

**Mean Sojourn Times:**

$R_i(t)$ : reliability of the system at time t, given that the system in regenerative state i.
$\mu_i$ : mean sojourn time spent in state i, before visiting any other states;

$$\mu_i = \int_0^\infty R_i(t)dt = R_i^*(0).$$

**Table 6.**

| $R_i(t)$ | $\mu_i = R_i^*(0)$. |
|---|---|
| $R_0(t) = e^{-\lambda t}$ | $\mu_0 = 1/\lambda$ |
| $R_1(t) = e^{-\lambda_1 t}\bar{G}(t)$ | $\mu_1 = \frac{1-g^*(\lambda_1)}{\lambda_1}$ |
| $R_2(t) = \bar{G}(t)$ | $\mu_2 = -g^{*\prime}(0)$ |
| $R_3(t) = e^{-\lambda t}\bar{H}(t)$ | $\mu_3 = \frac{1-h^*(\lambda)}{\lambda}$ |

### 4.3 Evaluation of Parameters

The mean time to system failure and all the key parameters of the system (under steady state conditions) are evaluated, by applying *Regenerative Point Graphical Technique* ***(RPGT)*** and using '0' as the base-state of the system as under:
The transition probability factors of all the reachable states from the base state '0' are:

$V_{0,0} = \left[(0,1,0) + \frac{(0,1,2,3,0)}{\{1-(2,3,2)\}}\right] = 1,\quad V_{0,1} = (0,1) = p_{0,1} = 1$

$V_{0,2} = \frac{(0,1,2,)}{1-L_2} = \frac{p_{0,1}p_{1,2}}{1-p_{3,2}} = \frac{p_{1,2}}{1-p_{3,2}}$ ;where $L_2 = (2,3,2) = p_{2,3}p_{3,2} = p_{3,2}$

$V_{0,3} = \frac{(0,1,2,3)}{1-L_2} = \frac{p_{0,1}p_{1,2}p_{2,3}}{1-p_{3,2}} = \frac{p_{1,2}}{1-p_{3,2}}$ ;where $L_2 = (2,3,2) = p_{2,3}p_{3,2} = p_{3,2}$

**(a). Availability of the system:** From Fig. 1, the regenerative states, at which the system is available are: j = 0,1,3 and the regenerative states are i = 0 to 3. Using (1.8.13) for '$\xi$' = '0',

$$A_0 = \left[\sum_{j,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} j)\} f_j.\mu_j}{\prod_{k_1\neq\xi}\{1-V_{k_1,k_1}\}}\right\}\right] \div \left[\sum_{i,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} i)\}.\mu_i^1}{\prod_{k_2\neq\xi}\{1-V_{k_2,k_2}\}}\right\}\right] = \left[\sum_j V_{\xi,j}\,.\,f_j.\,\mu_j\right] \div \left[\sum_i V_{\xi,i}\,.\,\mu_i^1\right]$$

$$= \left[V_{0,0}\,.\,f_0.\,\mu_0 + V_{0,1}\,.\,f_1.\,\mu_1 + V_{0,3}\,.\,f_3.\,\mu_3\right] \div \left[V_{0,0}\mu_0^1 + V_{0,1}\mu_1^1 + V_{0,2}\mu_2^1 + V_{0,3}\mu_3^1\right]$$

$$= [f_0\mu_0 + f_1\,\mu_1 + \frac{p_{1,2}}{1-p_{3,2}} f_3\mu_3] \div \left[\mu_0^1 + \mu_1^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_2^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_3^1\right]$$

$$= N_0 \div D_0$$

Where,

$N_0 = [f_0\mu_0 + f_1\,\mu_1 + \frac{p_{1,2}}{1-p_{3,2}} f_3\mu_3]$ $\quad D_0 = \left[\mu_0^1 + \mu_1^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_2^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_3^1\right]$

$A_0 = N_1 \div D_1$ $\quad N_1 = [(1-p_{3,2})(\mu_0 + \mu_1) + p_{1,2}\mu_3];(f_j = 1\ \forall\ j)$

$D_1 = [(1-p_{3,2})(\mu_0^1 + \mu_1^1) + p_{1,2}(\mu_2^1 + \mu_3^1)];(\mu_j^1 = \mu_j\ \forall\ j)$

**(b). Busy period of the Server:** From Fig. 1, the regenerative states where Server is busy while doing repairs are: j = 1,2,3; the regenerative states are: i = 0 to 3.Using (1.8.14) for '$\xi$' = '0', the Server remains busy is

$$B_0 = \left[\sum_{j,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} j)\}.\eta_j}{\prod_{k_1\neq\xi}\{1-V_{k_1,k_1}\}}\right\}\right] \div \left[\sum_{i,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} i)\}.\mu_i^1}{\prod_{k_2\neq\xi}\{1-V_{k_2,k_2}\}}\right\}\right]$$

$B_0 = \left[\sum_j V_{\xi,j}\,.\,\eta_j\right] \div \left[\sum_i V_{\xi,i}\,.\,\mu_i^1\right]$

$= \left[V_{0,1}\,.\,\eta_1 + V_{0,2}\,.\,\eta_2 + V_{0,3}.\,\eta_3\right] \div \left[V_{0,0}\mu_0^1 + V_{0,1}\mu_1^1 + V_{0,2}\mu_2^1 + V_{0,3}\mu_3^1\right]$

$= [\,\eta_1 + \frac{p_{1,2}}{1-p_{3,2}}\eta_2 + \frac{p_{1,2}}{1-p_{3,2}}\eta_3] \div \left[\mu_0^1 + \mu_1^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_2^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_3^1\right]$

$= N_{00} \div D_0$

Where, $N_{00} = [\,\eta_1 + \frac{p_{1,2}}{1-p_{3,2}}\eta_2 + \frac{p_{1,2}}{1-p_{3,2}}\eta_3]$

$B_0 = N_{01} \div D_1$

$N_{01} = [(1-p_{3,2})\,\eta_1 + p_{1,2}(\eta_2 + \eta_3)];(\eta_j = \mu_j\ \forall\ j)$

$D_1 = [(1-p_{3,2})(\mu_0^1 + \mu_1^1) + p_{1,2}(\mu_2^1 + \mu_3^1)];(\mu_j^1 = \mu_j\ \forall\ j)$

**(c). Expected number of Server's visits:** From Fig. 1, the regenerative states where the Server visits (afresh) for repairs of the system are: j = 1; the regenerative states are: i = 0 to 3. Using (1.8.15) for '$\xi$' = '0',

$V_0 = \left[\sum_{j,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} j)\}}{\prod_{k_1 \neq \xi}\{1-V_{k_1,k_1}\}}\right\}\right] \div \left[\sum_{i,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} i)\}.\mu_i^1}{\prod_{k_2 \neq \xi}\{1-V_{k_2,k_2}\}}\right\}\right]$

$V_0 = [\sum_j V_{\xi,j}] \div [\sum_i V_{\xi,i} \cdot \mu_i^1]$

$= V_{0,1} \div [V_{0,0}\mu_0^1 + V_{0,1}\mu_1^1 + V_{0,2}\mu_2^1 + V_{0,3}\mu_3^1] = 1 \div D_0$

Where, $D_0 = \left[\mu_0^1 + \mu_1^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_2^1 + \frac{p_{1,2}}{1-p_{3,2}}\mu_3^1\right]$;( $\mu_j^1 = \mu_j \ \forall$ j)]

**5. Particular Case**

Let us take; $g(t) = \omega e^{-\omega t}$, $h(t) = \omega_1 e^{-\omega_1 t}$

We have

$p_{0,1} = 1$, $p_{1,0} = \frac{\omega}{\omega+\lambda_1}$, $p_{1,2} = \frac{\lambda_1}{\omega+\lambda_1}$, $p_{2,3} = 1$, $p_{3,0} = \frac{\omega_1}{\omega_1+\lambda}$, $p_{3,2} = \frac{\lambda}{\omega_1+\lambda}$

$\mu_0 = \frac{1}{\lambda}$, $\mu_1 = \frac{1}{\omega+\lambda_1}$, $\mu_2 = \frac{1}{\omega}$, $\mu_3 = \frac{1}{\omega_1+\lambda}$

**6. Special Cases**

For Warm Stand-by : $0 < \lambda_1 < \lambda$

For Hot Stand-by : $\lambda_1 = \lambda$

The corresponding results from the Section 2.6 are obtained.

**7. Profit Function of the System**

The Profit analysis of the system can be done by using the profit function:

$P_0 = C_1.A_0 - C_2.B_0 - C_3.V_0$

Where, $C_1$ = Revenue per unit of time the system is available.

$C_2$ = Cost per unit time the server remains busy for the repairs.

$C_3$ = Cost per visit of the server.

$P_0 = C_1[ww_1(w+\lambda+\lambda_1)+w\lambda\lambda_1/ww_1(w+\lambda+\lambda_1)+\lambda\lambda_1(w+w_1+\lambda)]-C_2[ww_1\lambda+\lambda\lambda_1(w+\lambda+\lambda_1)/ww_1(w+\lambda+\lambda_1)+\lambda\lambda_1(w+w_1+\lambda)]-C_3[ww_1\lambda+(w+\lambda_1)/ww_1(w+\lambda+\lambda_1)+\lambda\lambda_1(w+w_1+\lambda)]$

Particularly $w = w_1$, $\lambda = \lambda_1$, $C_1 = 10$, $C_2 = C_3 = 1$, we get

$P_0 = w^3(10-\lambda)+w^2(19\lambda-\lambda^2)+w(8\lambda^2)+\lambda^3/(w^3+2\lambda w^2+2\lambda^2 w+\lambda^3)$

**Table 7.**

| | w = 0.80 | w = 0.85 | w = 0.90 | w = 0.95 | w = 1.00 |
|---|---|---|---|---|---|
| λ = 0.005 | 9.9884 | 9.9888 | 9.9892 | 9.9895 | 9.9898 |
| λ = 0.006 | 9.9880 | 9.9865 | 9.9869 | 9.9873 | 9.9877 |
| λ = 0.007 | 9.9836 | 9.9842 | 9.9847 | 9.9851 | 9.9856 |
| λ = 0.008 | 9.9811 | 9.9818 | 9.9824 | 9.9829 | 9.9834 |
| λ = 0.009 | 9.9786 | 9.9794 | 9.9801 | 9.9807 | 9.9813 |
| λ = 0.01 | 9.9761 | 9.9770 | 9.9778 | 9.9785 | 9.9791 |

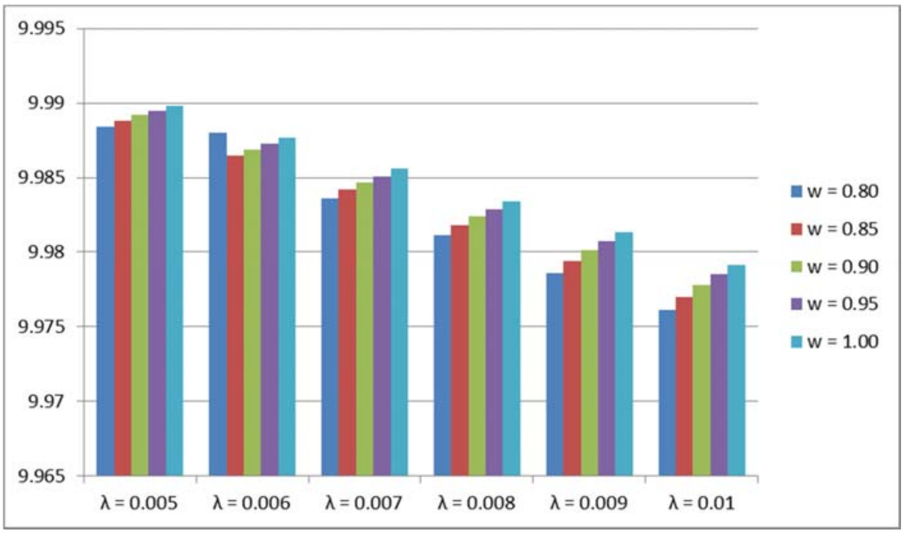


**Fig 2.**

## 8. Analytical Discussion

The following results, graphs, and conclusions are obtained for:

$\lambda_1$= 0.01; $\mu_1$= 0.80

### 8.1 Availability ($A_0$) vs. the Repair Rate ($\omega$):

The Availability of the system is calculated for different values of the failure rate ($\lambda$) by taking $\lambda$ = 0.005, 0.006, 0.007, 0.008, 0.009 and 0.01 and for different values of the repair rate ($\omega$) by taking $\omega$ = 0.80, 0.85, 0.90, 0.95 and 1.0. The data so obtained are shown in Table 8.

**Table 8.**

| $\lambda$ | $A_0$ ($\omega$=0.80) | $A_0$ ($\omega$=0.85) | $A_0$ ($\omega$=0.90) | $A_0$ ($\omega$=0.95) | $A_0$ ($\omega$=1.0) |
|---|---|---|---|---|---|
| 0.005 | 0.99992284 | 0.99993158 | 0.99993891 | 0.99994512 | 0.99995044 |
| 0.006 | 0.99990742 | 0.99991789 | 0.99992668 | 0.99993414 | 0.99994051 |
| 0.007 | 0.99989204 | 0.99990420 | 0.99991446 | 0.99992314 | 0.99993058 |
| 0.008 | 0.99987656 | 0.99989051 | 0.99990222 | 0.99991215 | 0.99992064 |
| 0.009 | 0.99986113 | 0.99987682 | 0.99988998 | 0.99990115 | 0.99991070 |
| 0.01 | 0.99984570 | 0.99986312 | 0.99987775 | 0.99989015 | 0.99990076 |

Table 8 shows the behavior of the Availability ($A_0$) vs. the Repair Rate ($\omega$) of the Unit of the System for different values of the Failure Rate ($\lambda$). It is concluded that Availability increases with increase in the values of the Repair Rate ($\omega$).

## 9. Conclusion

From the table and graph for profit function we see that for a unit cost there is a profit of almost five time the cost, it increases with the increase of repair rates and decreases with the increase in failure rates, which should be so practically.

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