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RELIABILITY ANALYSIS OF ACTIVE REDUNDANT SYSTEM USING GEOMETRIC DISTRIBUTION

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Abstract: The present paper is an initiative taken towards study and analysis of industries concerning different maintenance strategies towards their products on behalf of their working and maintenance level. The objective of presenting the concept of the dual nature of repair for units having extra or major failures in addition to regular ones is well explained. The stochastic analysis of reliability characteristics using regenerative techniques for the system consisting of two parallel units following the active-standby redundancy and having different repair time distributions was also studied using geometric distribution. The numerical equations and results are being evaluated for reliability parameters like mean time to system failure, availability of the system in operative form, down period of the system following repair mechanism using regenerative techniques, and geometric distribution. The graphical analysis has also been presented for-profit function with respect to repair and failure rate.

Keywords: *Reliability of systems, stochastic modeling, steady-state probability distribution, redundancy techniques, geometric distribution.*

1. Introduction

Reliability is the probability that a particular system, service or product will seamlessly carry out its operation for a specific period with the maximum success rate. Moreover, with the astounding industrial development and a wide range of machines available globally, one significant factor that holds paramount importance is reliability. Manufacturing involves repair; therefore, critical evaluation of machines and system availability is essential to ensure the working capacity of the machines in all environmental conditions. Over the years, a significant effort has been put into evaluating the performance of industrial models. Researchers have suggested various reliability enhancement techniques such as redundancy, preventative maintenance, and priority to ameliorate system performance.

H. F. Martz et al. [18] have evaluated the reliability of a convoluted system comprising of several binomial series, or parallel subsystems. The components were estimated using a Bayesian approach. Also, E. Acar et al. [1] evaluated the influence of reliability allocation in different failure modes using system reliability-based design optimization (SRBDO) of an automobile for crashworthiness. In different situations of accidents, the relative importance of automotive structural elements was calculated. Y. S. Dai et al. [9] put forth a model for analyzing a grid's performance (service time) and reliability in the context of common cause failures due to communication link sharing. Z. Tian et al. [25] and M. Du. et al. [10] described an optimization approach for multi-state series-parallel systems that improve redundancy at every step. M. Ram et al. [23] analyzed the reliability of a system consisting of one main unit and another standby unit. The standby system would be kept in working mode when the primary unit malfunctions. Considering mechanical systems G. Kumar et al. [14], M. Perman et al. [21] applied the Semi-Markov technique. With M operational functions, W warm standby units, and a single repair server with the restoration plan, W. L. Chen [8] evaluated the reliability of retrial machine system. D. Hua et al. [12,13] presented a significant research problem in terms of analyzing systems with linked unit degradation modes. Considering multi-state systems, different reliability measures were analyzed by Y. Liu et al. [17] and M. Nourelfath et al. [20]. S. H. Lee et al. [15] analyzed the behaviour of vehicle working systems. G. Levitin et al. [16] developed an algorithm for analyzing non-repairable series-parallel multi-state systems. A multi-domain simulation is presented by P. Adler et al. [2] to assess the aluminium electrolytic capacitors reliability. M. Y. Haggag [11] looked at the Mean Time to System Failure, steady-state availability, and cost of a two-dissimilar-unit cold standby system with regular inspection. With the assumption that each unit could operate in one of three states: normal, partial, or complete failure, the proposed system was investigated. To detect and reduce possible failure modes, a detailed design for the reliability model of vehicle systems

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and subsystems was presented by P Popovic et al. [22] along with the failure mode and effects analysis approach.

A. Mihalache et al. [19] analyzed the reliability of a mechatronic system by using the Petri Nets model. P.V. Srihari et al. [24] designed an artificial neural network based on a fault detection system to improve reliability. J. Bhatti et al. [3,4,5,6,7] studied the industrial systems that use a single or multiple repair server to handle a variety of failures and services.

This paper consists of two parallel units arranged in active-standby redundancy mode. The proposed model possesses two categories, 'A' and 'B', which are initially in operative mode. The new technique of repairman having dual nature of inspecting the minor cause of failure and having the capability of repairing it is well explained for automobiles falling under the 'A' category. If there is any major fault or accident, the failed unit would be transferred from the first stage of repair/inspection to the second stage of repair, with additional cost and time. Additionally, the concept of inspection of the repairs of a major failure is also reflected in the maintenance policy, which helps increase customer satisfaction and product reliability after repair. However, machines reported for regular or standard services fall under the category 'B' and have only simple and fixed price repair time/cost. Thus, the concept introduced in the paper clearly shows the current repairing mechanism followed in the automobile industry. The whole process has been designed and explained with the help of the transition model, as shown in Figure 1.

Operative States:

$$S_0 = (A_0, B_0), S_1 = (A_{r1}, B_0), S_2 = (A_0, B_{r1}), S_4 = (A_{r2}, B_0)$$

Failed States:

$$S_3 = (A_{r1w}, B_{r1}), S_5 = (A_{r2}, B_{r1})$$

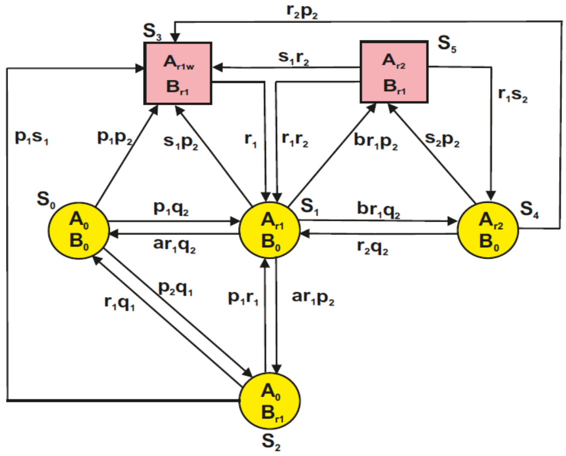

Figure 1. Transition Model

Table 1. Nomenclature

Symbol	Description
A_0, B_o	Units under categories A and B are in operational mode.
Ar_1	Inspection and minor repair of Unit A when it fails.
A_{r2}	Repair Unit A when it needs to be repaired in 1st inspection.
Br_1	Inspection and minor repair of Unit A when it fails.
A_{r1w}	Unit A waiting for its turn to get into the r_1 stage of inspection / repair.
P_1 , P_2	Probability of unit A and B getting into a failed state
r_1	Inspecting and repairing probability of minor failure.
s_1	Failed to repair the failed Units due to major failure.
r_2	Repair rate of a major failure.
s_2	Failed or taking extra time to repair a major failure.
a	Probability of inspecting and repairing the minor failure.
b	Probability to inspect the nature of the major failure

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2. Transition Probabilities and Sojourn Times

2.1 Transition Probabilities

The probabilities of steady-state transition from S_i to S_j is solved by:

$$P_{ij} = \lim_{t \to \infty} Q_{ij} \quad (1)$$

where Q_{ij} is the 'cumulative density function' from regenerative state 'i' to 'j'. The calculated values of transition probability are listed:

$$P_{01}(t) = \frac{p_1 q_2}{1-q_1 q_2} \quad P_{02}(t) = \frac{p_2 q_1}{1-q_1 q_2} \quad P_{03}(t) = \frac{p_1 p_2}{1-q_1 q_2} \quad P_{10}(t) = \frac{a r_1 q_2}{1-s_1 q_2}$$

$$P_{12}(t) = \frac{a r_1 p_2}{1-s_1 q_2} \quad P_{13}(t) = \frac{s_1 p_2}{1-s_1 q_2} \quad P_{14}(t) = \frac{b r_1 q_2}{1-s_1 q_2} \quad P_{15}(t) = \frac{b r_1 p_2}{1-s_1 q_2}$$

$$P_{20}(t) = \frac{q_1 r_1}{1-s_1 q_1} \quad P_{21}(t) = \frac{p_1 r_1}{1-s_1 q_1} \quad P_{23}(t) = \frac{s_1 p_1}{1-s_1 q_1} \quad P_{31}(t) = \frac{r_1}{1-s_1}$$

$$P_{41}(t) = \frac{r_2 q_2}{1-s_2 q_2} \quad P_{43}(t) = \frac{r_2 p_2}{1-s_2 q_2} \quad P_{45}(t) = \frac{s_2 p_2}{1-s_2 q_2} \quad P_{51}(t) = \frac{r_1 r_2}{1-s_1 s_2}$$

$$P_{53}(t) = \frac{s_1 r_2}{1-s_1 s_2} \quad P_{54}(t) = \frac{r_1 s_2}{1-s_1 s_2}$$

2.2 Mean Sojourn Times

The value of mean sojourn time for state Si is calculated by referring to sojourn time in state Si (i = 0 to 5) with the symbol μ :

$$\mu_0 = \frac{1}{1-q_1 q_2} \quad \mu_1 = \frac{1}{1-s_1 q_2} \quad \mu_2 = \frac{1}{1-s_1 q_1} \quad \mu_3 = \frac{1}{1-s_1} \quad \mu_4 = \frac{1}{1-s_2 q_2} \quad \mu_5 = \frac{1}{1-s_1 s_2}$$

3. Mean Time to System Failure (MTSF)

Mean time to system failure (MTSF) is known to be a maintenance metric that measures the average amount of time a non-repairable unit or system operates before it fails.

The absorbing states depicted in Figure 1 are used to compute the proposed system's MTSF. The reliability analysis R_i at time 't' is obtained is obtained by solving the equation 2-5.

$$\begin{aligned} \Upsilon_0 &= Z_0 + q_{01}©\Upsilon_1 + q_{02}©\Upsilon_2 \\ \Upsilon_1 &= Z_1 + q_{10}©\Upsilon_0 + q_{12}©\Upsilon_2 + q_{14}©\Upsilon_4 \\ \Upsilon_2 &= Z_2 + q_{20} © \Upsilon_0 + q_{21} © \Upsilon_1 \\ \Upsilon_4 &= Z_4 + q_{41}© \Upsilon_1 \end{aligned} \quad (2\text{-}5)$$

Solving the above equations, we obtain

$$\text{MTSF} = \frac{N_1}{D_1}, \quad (6)$$

where,

$$N_1 = \mu_0(1 - P_{12}P_{21} - P_{14}P_{41}) + \mu_1(P_{01} + P_{02}P_{21}) + \mu_2(P_{01}P_{12} + P_{02} - P_{02}P_{14}P_{41}) + \mu_4(P_{01}P_{14} + P_{02}P_{14}P_{21}) \quad (7)$$

$$D_1 = (1 - P_{12}P_{21} - P_{14}P_{41}) - P_{10}(P_{01} + P_{02}P_{21}) - (P_{02} + P_{01}P_{12} - P_{02}P_{14}P_{41}) \quad (8)$$

4. System Availability/Operative Period Analysis

The availability of the considered system is the chance that a repairable system or system part is operational at a given moment and under a specific set of environmental circumstances.

If Γ_i denotes availability period of system at time 't', then taking probabilistic argument, the derived relations will be as:

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$$\Gamma_0 = Z_0 + q_{01}© \Gamma_1 + q_{02}© \Gamma_2 + q_{03}© \Gamma_3$$
$$\Gamma_1 = Z_1 + q_{10}© \Gamma_0 + q_{12}© \Gamma_2 + q_{13}© \Gamma_3 + q_{14}© \Gamma_4 + q_{15}© \Gamma_5$$
$$\Gamma_2 = Z_2 + q_{20}© \Gamma_0 + q_{21}© \Gamma_1 + q_{23}© \Gamma_3$$
$$\Gamma_3 = q_{31}© \Gamma_1$$
$$\Gamma_4 = Z_4 + q_{41}© \Gamma_1 + q_{43}© \Gamma_3 + q_{45}© \Gamma_5$$
$$\Gamma_5 = q_{51}© \Gamma_1 + q_{53}© \Gamma_3 + q_{54}© \Gamma_4 \quad (9\text{-}14)$$

The resulted value of availability U_0 is calculated from the above equations as:

$$U_0 = -\frac{N_2}{D_2}, \quad (15)$$

where,

$$D_2 = [(1 - P_{12}P_{23}P_{31} - P_{12}P_{21})(1 - P_{45}P_{54}) + P_{31}\{-P_{13}(1 - P_{45}P_{54}) - P_{14}(P_{43} + P_{45}P_{53}) - P_{15}(P_{43}P_{54} + P_{53})\} - P_{14}(P_{41} + P_{45}P_{51}) - P_{15}(P_{41}P_{54} + P_{51})] + P_{10}[(P_{02}P_{21} + P_{02}P_{23}P_{31} + P_{01} + P_{03}P_{31})(1 - P_{45}P_{54})] - P_{20}[P_{02}P_{31}\{-P_{13}(1 - P_{45}P_{54}) - P_{14}(P_{43} + P_{45}P_{53}) - P_{15}(P_{43}P_{54} + P_{53})\} + (P_{01}P_{12} + P_{03}P_{12}P_{31})(1 - P_{45}P_{54}) + P_{02}\{(1 - P_{45}P_{54}) - P_{14}(P_{41} + P_{45}P_{51}) - P_{15}(P_{41}P_{54} + P_{51})\}] + P_{30}[(1 - P_{45}P_{54})(P_{03}P_{12}P_{21} - P_{01}P_{12}P_{23}) - (P_{01} + P_{02}P_{21})\big(P_{13}(1 - P_{45}P_{54}) + P_{14}(P_{43} + P_{45}P_{53}) + P_{15}(P_{43}P_{54} + P_{53})\big) - (P_{03} + P_{02}P_{23})(1 - P_{45}P_{54}) - P_{14}(P_{41} + P_{45}P_{51}) - P_{15}(P_{41}P_{54} + P_{51})] - P_{40}[(P_{14} + P_{15}P_{54})(P_{02}P_{23}P_{31} + P_{03}P_{31} + P_{01} + P_{02}P_{21})] + \mu_5[(P_{14}P_{45} + P_{15})(P_{02}P_{23}P_{31} + P_{03}P_{31} + P_{01} + P_{02}P_{21})] \quad (16)$$

$$N_2 = \mu_0[(1 - P_{12}P_{23}P_{31} - P_{12}P_{21})(1 - P_{45}P_{54}) + P_{31}\{-P_{13}(1 - P_{45}P_{54}) - P_{14}(P_{43} + P_{45}P_{53}) - P_{15}(P_{43}P_{54} + P_{53})\} - P_{14}(P_{41} + P_{45}P_{51}) - P_{15}(P_{41}P_{54} + P_{51})] + \mu_1[(P_{02}P_{21} + P_{02}P_{23}P_{31} + P_{01} + P_{03}P_{31})(1 - P_{45}P_{54})] + \mu_2[P_{02}P_{31}\{-P_{13}(1 - P_{45}P_{54}) - P_{14}(P_{43} + P_{45}P_{53}) - P_{15}(P_{43}P_{54} + P_{53})\} + (P_{03}P_{12}P_{31} + P_{01}P_{12})(1 - P_{45}P_{54}) + P_{02}\{(1 - P_{45}P_{54}) - P_{14}(P_{41} + P_{45}P_{51}) - P_{15}(P_{41}P_{54} + P_{51})\}] + \mu_4[(P_{14} + P_{15}P_{54})(P_{02}P_{23}P_{31} + P_{03}P_{31} + P_{01} + P_{02}P_{21})] \quad (17)$$

5. Repairman (r_1) and Inspection Period in The System

As per the system reliability concern, it is always essential to have the best repair mechanism for its products for customer satisfaction and to increase profit. However, as we know, any mechanical and working system has many reasons for failure. So, it becomes more critical to get the failed unit to be inspected to know the nature of the failure and proceed using the correct repair mechanism to avoid wasting time and giving exact information to the customer about the time and cost of repair. Hence the repair mechanism has been distributed into two stages: a) inspection of failure or repairing of minor failure or regular service by the repairman (r_1) and b) repair of major failure denoted by repairman (r_2).

If Ψ_i denotes the repairman (r_1)period of the system at time 't,' then the resulting relations will be designed as:

$$\Psi_0 = q_{01}© \Psi_1 + q_{02}© \Psi_2 + q_{03}© \Psi_3$$
$$\Psi_1 = Z_1 + q_{10}© \Psi_0 + q_{12}© \Psi_2 + q_{13}© \Psi_3 + q_{14}© \Psi_4 + q_{15}© \Psi_5$$
$$\Psi_2 = Z_2 + q_{20}© \Psi_0 + q_{21}© \Psi_1 + q_{23}© \Psi_3$$
$$\Psi_3 = Z_3 + q_{31}© \Psi_1$$
$$\Psi_4 = q_{41}© \Psi_1 + q_{43}© \Psi_3 + q_{45}© \Psi_5$$
$$\Psi_5 = Z_5 + q_{51}© \Psi_1 + q_{53}© \Psi_3 + q_{54}© \Psi_4 \quad (18\text{-}23)$$

The resulted value of availability V_0 is calculated from the above equations as:

$$V_0 = -\frac{N_3}{D_2} \quad (24)$$

$$N_3 = \mu_1[(P_{02}P_{21} + P_{02}P_{23}P_{31} + P_{01} + P_{03}P_{31})(1 - P_{45}P_{54})] + \mu_2[P_{02}P_{31}\{-P_{13}(1 - P_{45}P_{54}) - P_{14}(P_{43} + P_{45}P_{53}) - P_{15}(P_{43}P_{54} + P_{53})\} + (P_{01}P_{12} + P_{03}P_{12}P_{31})(1 - P_{45}P_{54}) + P_{02}\{(1 - P_{45}P_{54}) - P_{14}(P_{41} + P_{45}P_{51}) - P_{15}(P_{41}P_{54} + P_{51})\}] - \mu_3[(1 - P_{45}P_{54})(P_{03}P_{12}P_{21} - P_{01}P_{12}P_{23}) - (P_{01} + P_{02}P_{21})(P_{13}(1 - P_{45}P_{54}) + P_{14}(P_{43} + P_{45}P_{53}) + P_{15}(P_{43}P_{54} + P_{53})) - (P_{03} + P_{02}P_{23})(1 - P_{45}P_{54}) - P_{14}(P_{41} + P_{45}P_{51}) - P_{15}(P_{41}P_{54} + P_{51})] + \mu_5[(P_{14}P_{45} + P_{15})(P_{02}P_{23}P_{31} + P_{03}P_{31} + P_{01} + P_{02}P_{21})] \quad (25)$$

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6. Repairman (r_2) Period of the System

If Φ_i denotes the repairman (r_2)period of the system at time 't,' then the resulting relations will be designed as:

$$\Phi_0 = q_{01} © \Phi_1 + q_{02} © \Phi_2 + q_{03} © \Phi_3$$
$$\Phi_1 = q_{10} © \Phi_0 + q_{12} © \Phi_2 + q_{13} © \Phi_3 + q_{14} © \Phi_4 + q_{15} © \Phi_5$$
$$\Phi_2 = q_{20} © \Phi_0 + q_{21} © \Phi_1 + q_{23} © \Phi_3$$
$$\Phi_3 = q_{31} © \Phi_1$$
$$\Phi_4 = Z_4 + q_{41} © \Phi_1 + q_{43} © \Phi_3 + q_{45} © \Phi_5$$
$$\Phi_5 = Z_5 + q_{51} © \Phi_1 + q_{53} © \Phi_3 + q_{54} © \Phi_4$$

(26-31)

The resulted value of availability W_0 is calculated from the above equations as:

$$W_0 = -\frac{N_4}{D_2} \quad (32)$$

$$N_4 = \mu_4[(P_{14} + P_{15}P_{54})(P_{02}P_{23}P_{31} + P_{03}P_{31} + P_{01} + P_{02}P_{21})] + \mu_5[(P_{14}P_{45} + P_{15})(P_{02}P_{23}P_{31} + P_{03}P_{31} + P_{01} + P_{02}P_{21})] \quad (33)$$

7. Conclusion

The required steady-state profit is calculated as:

$$P = E_1U_0 - E_2V_0 - E_3W_0 \quad (34)$$

where,

E_1: System per unit up time revenue.
E_2 and E_3: System per unit down time expenditure.

As per analysis, the profit function (P) behaviour has been studied by the fixing specific parameters $E_1, E_2, E_3 p_2.$, and 'a' as:

$$E_1 = 10000, E_2 = 500, E_3 = 2000, p_2 = 0.6 \text{ and } a = 0.7$$

Table 2, 3 and Figure 2, 3 depict the behaviour of reliability parameters, including profit function that decrease and increase as the failure rate p_1 and repair rate r_1 increase from 0.1 to 0.8. Hence, with the help of numerical and graphical analysis, it has been proved that the profit function decreases/increases with increasing/decreasing failure rate. In other words, the research paper's objective to benefit the industries by developing new techniques using prescribed repairing techniques for different failures is verified.

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Table 2. Reliability parameter values corresponding to Repair Rate r_1.

Repair Rate	MTSF	U_0	V_0	W_0	PROFIT (P)
$r_1 = 0.1$	10.4878	0.211063	0.98271	0.00615	1606.977
	5.459438	0.176317	0.988435	0.006454	1256.044
	3.813798	0.164058	0.990541	0.006566	1132.178
	3.011392	0.157832	0.991669	0.006627	1069.232
	2.544592	0.154086	0.99239	0.006665	1031.338
	2.244375	0.151598	0.992902	0.006693	1006.148
	2.038438	0.149834	0.99329	0.006714	988.2712
	1.89073	0.148524	0.993598	0.00673	974.9816
$r_1 = 0.3$	11.02186	0.414257	0.930175	0.017014	3643.452
	5.775144	0.339174	0.954097	0.019551	2875.585
	4.043345	0.308992	0.963807	0.02058	2566.853
	3.189426	0.292734	0.969106	0.021139	2400.507
	2.68604	0.282589	0.972464	0.021493	2296.668
	2.357445	0.275666	0.974796	0.021738	2225.784
	2.128361	0.270649	0.97652	0.021919	2174.389
	1.961171	0.266851	0.977852	0.022058	2135.47
$r_1 = 0.5$	11.67403	0.55911	0.86331	0.026572	5106.3
	6.138472	0.468568	0.906238	0.03337	4165.824
	4.30075	0.427053	0.925924	0.036474	3734.615
	3.387312	0.403199	0.937236	0.038248	3486.878
	2.843453	0.387696	0.94459	0.039393	3325.88
	2.484277	0.376799	0.94976	0.040192	3212.728
	2.230545	0.368712	0.953598	0.040779	3128.764
	2.042643	0.362466	0.956563	0.041228	3063.917

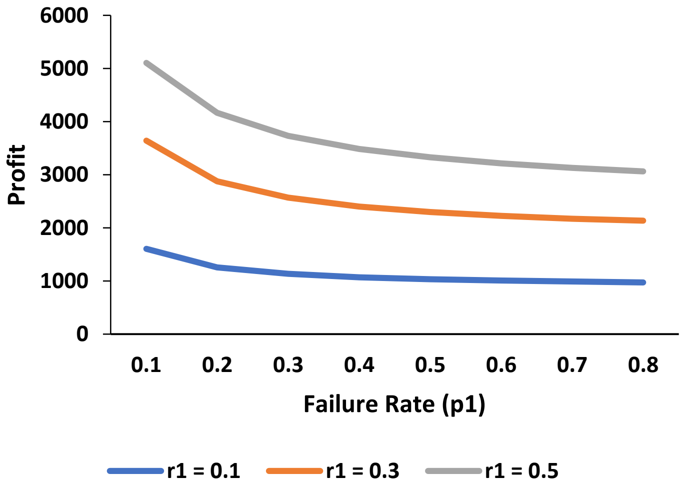

Figure 2. Profit vs Failure Rate p_1

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Table 3. Reliability parameters values corresponding to Failure Rate p_1.

Failure Rate	MTSF	U_0	V_0	W_0	PROFIT (P)
$p_1 = 0.2$	5.459438	0.176317	0.988435	0.006454	1256.044
	5.775144	0.339174	0.954097	0.019551	2875.585
	6.138472	0.468568	0.906238	0.03337	4165.824
	6.54955	0.565673	0.85402	0.045619	5138.48
	7.011458	0.637528	0.802755	0.05581	5862.277
	7.529574	0.691005	0.754844	0.064114	6404.404
	8.111476	0.731387	0.711086	0.070861	6816.603
	8.767186	0.762429	0.671518	0.076375	7135.777
$p_1 = 0.4$	3.011392	0.157832	0.991669	0.006627	1069.232
	3.189426	0.292734	0.969106	0.021139	2400.507
	3.387312	0.403199	0.937236	0.038248	3486.878
	3.608108	0.491995	0.900495	0.05528	4359.146
	3.855721	0.563027	0.862002	0.071062	5057.143
	4.135117	0.620001	0.823702	0.085191	5617.777
	4.45265	0.66601	0.786704	0.097635	6071.477
	4.816551	0.703492	0.751581	0.108517	6442.096
$p_1 = 0.6$	2.244375	0.151598	0.992902	0.006693	1006.148
	2.357445	0.275666	0.974796	0.021738	2225.784
	2.484277	0.376799	0.94976	0.040192	3212.728
	2.627628	0.45945	0.920785	0.059412	4015.281
	2.791014	0.527395	0.889918	0.078058	4672.876
	2.979003	0.583671	0.858504	0.09551	5216.442
	3.197645	0.63066	0.827398	0.111527	5669.848
	3.45514	0.670215	0.797124	0.126073	6051.439

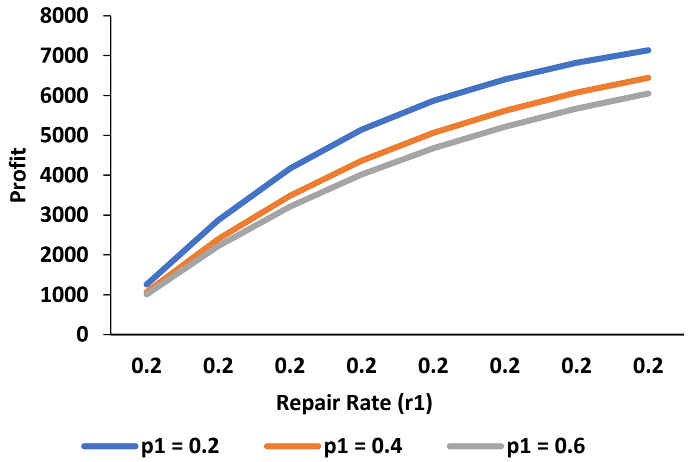

Figure 3. Profit vs Failure Rate r_1

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