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PERFORMANCE EVALUATION OF AN INDUSTRIAL CONFIGURED AS SERIES-PARALLEL SYSTEM

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Abstract: This paper deals with the performance evaluation of an industrial configured as series-parallel system. The Markovian approach was adopted to model the system behaviour with the assumption that the failure and repair rates of each system follow exponential distribution. Through the transition diagram, systems of first order differential equations of the developed model were formulated to obtain the steady-state probability. These equations were solved recursively. The availability at steady-state was analyzed and investigated. The effects of failure and repair rates of all the subsystems were presented in the form of availability matrices. From the availability matrices, it has been observed that as Failure/Repair rates increases, the availability tends to decrease/increase. The mathematical model developed in this paper signifies the subsystem which mainly influences system performance. Thus, the developed model is considered an excellent tool for system performance evaluations. The developed model will also assist system engineers and designers, reliability and maintenance managers.

Keywords: performance; availability; series-parallel system; transition diagram; mathematical modeling.

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1. INTRODUCTION

The system reliability has great significance in recent years due to its importance in promoting and sustaining industries and economy. It is technique for improving system performance at the lowest possible maintenance costs. In order to improve system performance, system reliability and availability must be maintained at the highest order. Though failure is inevitable, it can be controlled by proper maintenance, proper training to the operators, and regular inspection. Availability and reliability of the system/equipment may be enhanced using proper design of the system and by maintaining the same during its service life.

In the past, numerous researchers have presented their works in the field of reliability theory by analyzing the performances of systems under different types of mathematical models. See for instance, Singh and Ayagi [1] have discussed the performance of a complex system under preemptive resume repair policy via copula. Ibrahim et al [2] have used Gumbel-Hougaard copula family distribution to present the study of reliability assessment of complex system having two subsystems connected in series configuration. Niwas and Garg [3] studied the availability, reliability and profit of an industrial system based on cost free warranty policy. Singh et al [4] have used copula to study the performance analysis of complex systems connected in series configuration by considering different failure and repair disciplines. Harish Garg [5] recently studied multi objective non-linear programming problem for reliability optimization in intuitionistic algorithm (GSA) and the results have compared with the results computed by practice swarm optimization (PSO) methodology. Ibrahim et al [6] have recently presented the study of profit analysis of a serial-parallel system under partial and complete failures. Monika et al [7] have examined a complex system consisting two subsystems connected in series configuration under k-out-of-n: G policy. Lado et al [8] discussed the performance and cost assessment of the repairable complex system with two subsystems connected in series configuration. Singh et al [9] have studied the performance assessment of two units redundant system under different failure and repair policies using Copula. Monika et al [10] presented a stochastic analysis of a two unit’s complex repairable system with switch and human failure using copula approach.

In this paper, we have constructed availability model consisting of six different subsystems. Our primary focus is to capture the effect of both failure and repair rates on each subsystem so as to determine the most critical unit in the system. The organization of this paper is as follows. Section 2 presents the notations and assumptions. Section 3 contains the description of the system under study while section 4 presents model formulation. The results of our numerical stimulations and discussions are presented in section 5 and finally, the paper is concluded in section 6.

2. NOTATION AND ASSUMPTIONS

2.1 Notations

1. A, B, C, D, E and F represent full working state of subsystem.
2. $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$ represent repair rates of subsystem A, B, C, D, E and F respectively.
3. $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ represent repair rates of subsystem A, B, C, D, E and F respectively.
4. $p_0(t), p_1(t), p_2(t)$: Probability of the system working with full capacity at time t
5. $p_3(t)$ to $p_{18}(t)$ Probability of the system in failed state.
6. d/dt : Derivative with respect to time t.

2.2 Assumptions

1. The system consists of six different subsystems arranged in series.
2. The Failure and repair rates are constant over time, statistically independent of each other and there no simultaneous failures among the subsystems.
3. System fails when one unit fails.
4. The system may be in operating system or in a failed state but not in a reduced capacity.
5. Sufficient repair facilities are provided, i.e. no waiting time to start repairs.
6. A repair system is as good as new, performance wise for a specified duration.

7. Standby units are of the same nature and capacity as the active units.
8. The switchover devices used for standby subsystems are perfect.

3. SYSTEM DESCRIPTION

The system consists of six different subsystems which are:

1. Subsystem A: A single unit arranged in series whose failure causes complete failure of the entire system.
2. Subsystem B: A single unit arranged in series whose failure causes complete failure of the entire system.
3. Subsystem C: A single unit arranged in series. Its failure causes complete failure of the entire system.
4. Subsystem D: A single unit arranged in series. Failure of this subsystem causes complete failure of the system.
5. Subsystem E: A single unit arranged in series whose failure causes complete failure of the entire system.
6. Subsystem F: it consists of four units arranged in parallel. Two remain operative and the other two in cold standby. Failure of three units at a time will cause complete failure of the entire system.

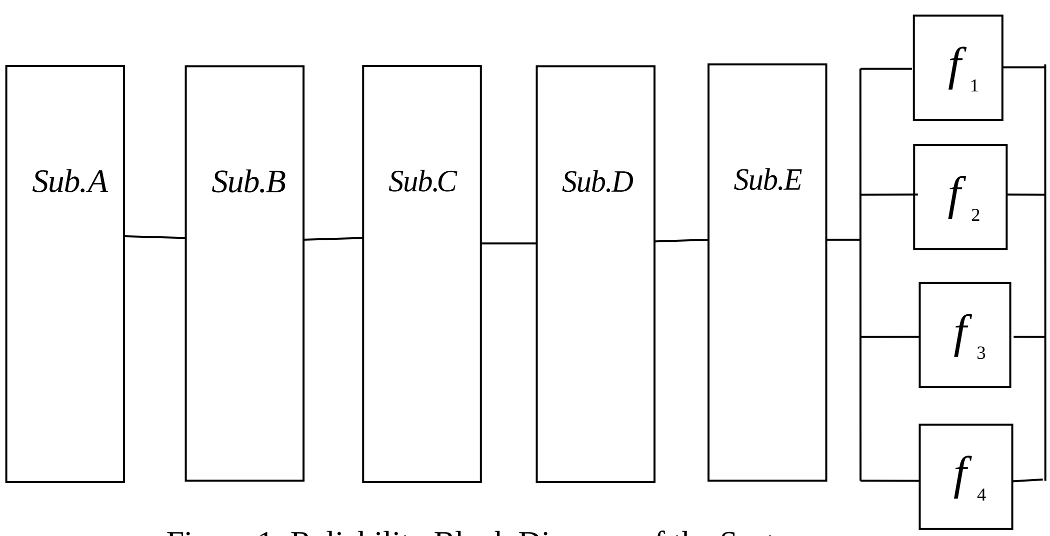

Figure 1: Reliability Block Diagram of the System

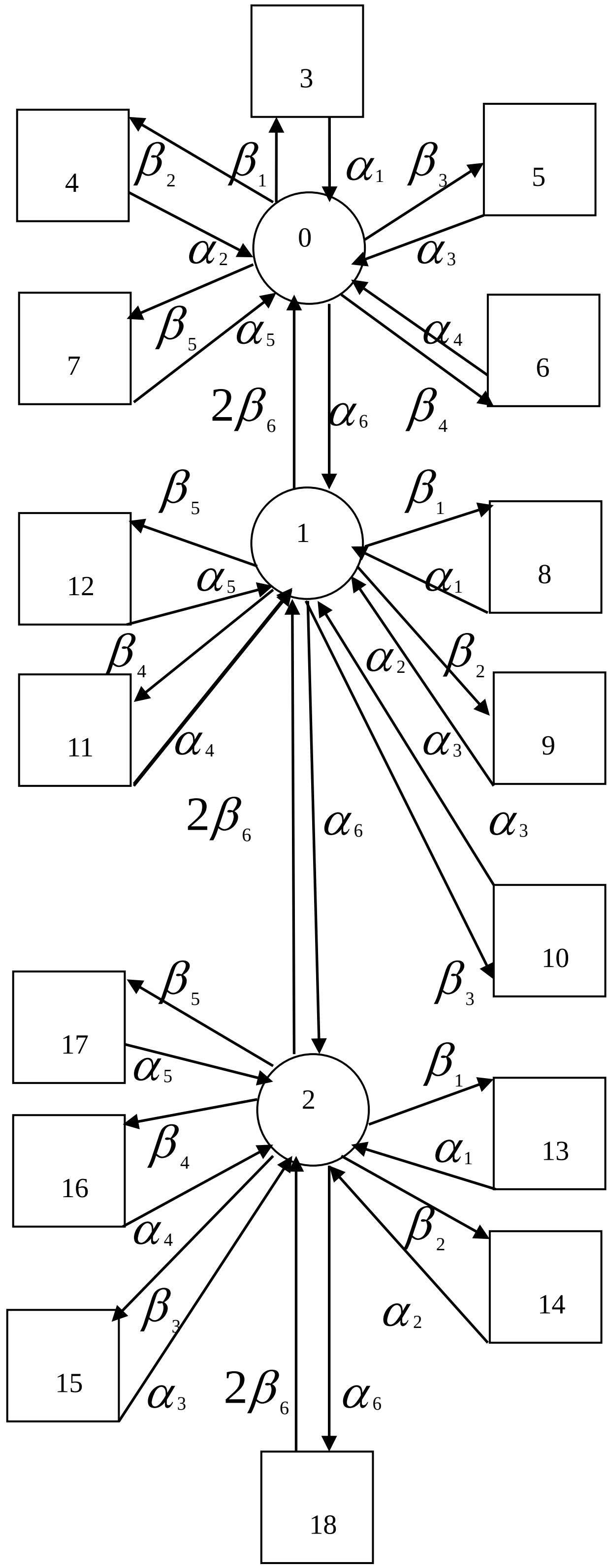

Figure 2: Transition Diagram of the System

4. MODEL FORMULATION

The differential equations associated with the transition diagram were derived on the basis of Markov birth-death process using figure 2. Various probability considerations generate the following sets of differential equations:

$$\left[\left(\frac{d}{dt}\right)+K_0\right]p_0=\alpha_1 p_3+\alpha_2 p_4+\alpha_3 p_5+\alpha_4 p_6+\alpha_5 p_7 \quad (1)$$

$$\left[\left(\frac{d}{dt}\right)+K_1\right]p_1=2\beta_6 p_0+\alpha_6 p_2+\alpha_1 p_8+\alpha_2 p_9+\alpha_3 p_{10}+\alpha_4 p_{11}+\alpha_5 p_{12} \quad (2)$$

$$\left[\left(\frac{d}{dt}\right)+K_1\right]p_2=2\beta_6 p_1+\alpha_1 p_{13}+\alpha_2 p_{14}+\alpha_3 p_{15}+\alpha_4 p_{16}+\alpha_5 p_{17}+\alpha_6 p_{18} \quad (3)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_1\right]p_3=\beta_1 p_0 \quad (4)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_2\right]p_4=\beta_2 p_0 \quad (5)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_3\right]p_5=\beta_3 p_0 \quad (6)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_4\right]p_6=\beta_4 p_0 \quad (7)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_5\right]p_7=\beta_5 p_0 \quad (8)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_1\right]p_8=\beta_1 p_1 \quad (9)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_2\right]p_9=\beta_2 p_1 \quad (10)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_3\right]p_{10}=\beta_3 p_1 \quad (11)$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_4\right]p_{11}=\beta_4 p_1 \tag{12}$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_5\right]p_{12}=\beta_5 p_1 \tag{13}$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_1\right]p_{13}=\beta_1 p_2 \tag{14}$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_2\right]p_{14}=\beta_2 p_2 \tag{15}$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_3\right]p_{15}=\beta_3 p_2 \tag{16}$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_4\right]p_{16}=\beta_4 p_2 \tag{17}$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_5\right]p_{17}=\beta_5 p_2 \tag{18}$$

$$\left[\left(\frac{d}{dt}\right)+\alpha_6\right]p_{18}=2\beta_6 p_2 \tag{19}$$

The initial conditions at time $t=0$ are:

$$p_i(t)=\begin{cases}1 if i=0\\0 if i\neq 0\end{cases} \tag{20}$$

Where $K_0=\beta_1+\beta_2+\beta_3+\beta_4+\beta_5+2\beta_6$

$$K_1=\alpha_6+\beta_1+\beta_2+\beta_3+\beta_4+\beta_5+2\beta_6$$

4.1 Availability equations of the system

To obtain the steady state availability of the system, the derivatives of states probabilities are set equal to zero. Let $p_0(\infty)$ be the probability of full working state when the system is still new and is determine using the condition normalizing:

$$p_0(\infty)+p_1(\infty)+p_2(\infty)+......+p_{18}(\infty)=0 \tag{21}$$

Setting $\frac{d}{dt}=0$ as $t\rightarrow\infty$, equations (1) to (19) together with the initial conditions become:

$$K_0 p_0=\alpha_1 p_3+\alpha_2 p_4+\alpha_3 p_5+\alpha_4 p_6+\alpha_5 p_7 \quad (22)$$

$$K_1 p_1=2\beta_6 p_0+\alpha_6 p_2+\alpha_1 p_8+\alpha_2 p_9+\alpha_3 p_{10}+\alpha_4 p_{11}+\alpha_5 p_{12} \quad (23)$$

$$K_1 p_2=2\beta_6 p_1+\alpha_1 p_{13}+\alpha_2 p_{14}+\alpha_3 p_{15}+\alpha_4 p_{16}+\alpha_5 p_{17}+\alpha_6 p_{18} \quad (24)$$

$$\alpha_1 p_3=\beta_1 p_0 \quad (25)$$

$$\alpha_2 p_4=\beta_2 p_0 \quad (26)$$

$$\alpha_3 p_5=\beta_3 p_0 \quad (27)$$

$$\alpha_4 p_6=\beta_4 p_0 \quad (28)$$

$$\alpha_5 p_7=\beta_5 p_0 \quad (29)$$

$$\alpha_1 p_8=\beta_1 p_1 \quad (30)$$

$$\alpha_2 p_9=\beta_2 p_1 \quad (31)$$

$$\alpha_3 p_{10}=\beta_3 p_1 \quad (32)$$

$$\alpha_4 p_{11}=\beta_4 p_1 \quad (33)$$

$$\alpha_5 p_{12}=\beta_5 p_1 \quad (34)$$

$$\alpha_1 p_{13}=\beta_1 p_2 \quad (35)$$

$$\alpha_2 p_{14}=\beta_2 p_2 \quad (36)$$

$$\alpha_3 p_{15}=\beta_3 p_2 \quad (37)$$

$$\alpha_4 p_{16}=\beta_4 p_2 \quad (38)$$

$$\alpha_5 p_{17}=\beta_5 p_2 \quad (39)$$

$$\alpha_6 p_{18}=2\beta_6 p_2 \quad (40)$$

Solving equations (22) to (40) recursively, the values of steady state probabilities are given by:

$$p_1 = 2\left(\frac{\beta_6}{\alpha_6}\right)p_0 \ , \ p_2 = 4\left(\frac{\beta_6}{\alpha_6}\right)^2 p_0 \ , \ p_3 = \left(\frac{\beta_1}{\alpha_1}\right)p_0 \ , \ p_4 = \left(\frac{\beta_2}{\alpha_2}\right)p_0 \ , \ p_5 = \left(\frac{\beta_3}{\alpha_3}\right)p_0$$

$$p_6 = \left(\frac{\beta_4}{\alpha_4}\right)p_0, p_7 = \left(\frac{\beta_5}{\alpha_5}\right)p_0, p_8 = 2\left(\frac{\beta_1\beta_6}{\alpha_1\alpha_6}\right)p_0, p_9 = 2\left(\frac{\beta_2\beta_6}{\alpha_2\alpha_6}\right)p_0, p_{10} = 2\left(\frac{\beta_3\beta_6}{\alpha_3\alpha_6}\right)p_0,$$

$$p_{11} = 2\left(\frac{\beta_4\beta_6}{\alpha_4\alpha_6}\right)p_0, p_{12} = 2\left(\frac{\beta_5\beta_6}{\alpha_5\alpha_6}\right)p_0, p_{13} = 4\frac{\beta_1}{\alpha_1}\left(\frac{\beta_6}{\alpha_6}\right)^2 p_0, \ p_{14} = 4\frac{\beta_2}{\alpha_2}\left(\frac{\beta_6}{\alpha_6}\right)^2 p_0,$$

$$p_{15} = 4\frac{\beta_3}{\alpha_3}\left(\frac{\beta_6}{\alpha_6}\right)^2 p_0, p_{16} = 4\frac{\beta_4}{\alpha_4}\left(\frac{\beta_6}{\alpha_6}\right)^2 p_0 \ p_{17} = 4\frac{\beta_5}{\alpha_5}\left(\frac{\beta_6}{\alpha_6}\right)^2 p_0,$$

$$p_{18} = 4\left(\frac{\beta_6}{\alpha_6}\right)^3 p_0 \tag{41}$$

Thus, by putting the values of steady-state probabilities given by equation (41) in equation (21), we finally obtain:

$$p_0 = \frac{1}{(1+2X_6+4X_6^2)(1+X_1+X_2+X_3+X_4+X_5)+8X_6^3} \tag{42}$$

Where, $X_1 = \frac{\beta_1}{\alpha_1}, X_2 = \frac{\beta_2}{\alpha_2}, X_3 = \frac{\beta_3}{\alpha_3}, X_4 = \frac{\beta_4}{\alpha_4}, \ X_5 = \frac{\beta_5}{\alpha_5}, \ X_6 = \frac{\beta_6}{\alpha_6}$ (43)

Now, the steady state availability of the system may be obtained as summation of all working state probabilities as:

$$AV = \sum_{i=0}^{2} p_i = p_0 + p_1 + p_2 \tag{44}$$

$$AV = \frac{1+2X_6+4X_6^2}{(1+2X_6+4X_6^2)(1+X_1+X_2+X_3+X_4+X_5)+8X_6^3} \tag{45}$$

Finally, we use equation (45) to obtain the availability of the system.

5. RESULTS AND DISCUSSION

Using the failure and repair rates values of Aggarwal et al [11], the availability of the system is computed by using equation (45), and the effects of failure and repair rates of each subsystem on the availability of the system are presented in tables and graphs. For model analysis, the following set of parameters values are fixed throughout the simulation for consistency.

Table 1, figure 3a and figure 3b

$$\alpha_2 = 0.1, \alpha_3 = 0.5, \alpha_4 = 0.1, \alpha_5 = 0.4, \alpha_6 = 0.55,$$
$$\beta_2 = 0.005, \beta_3 = 0.0005, \beta_4 = 0.003, \beta_5 = 0.004, \beta_6 = 0.003$$

Table 2, figure 4a and figure 4b

$$\alpha_1 = 0.4, \alpha_3 = 0.5, \alpha_4 = 0.1, \alpha_5 = 0.4, \alpha_6 = 0.55,$$
$$\beta_1 = 0.005, \beta_3 = 0.0005, \beta_4 = 0.003, \beta_5 = 0.004, \beta_6 = 0.003$$

Table 3, figure 5a and figure 5b

$$\alpha_1 = 0.4, \alpha_2 = 0.1, \alpha_4 = 0.1, \alpha_5 = 0.4, \alpha_6 = 0.55,$$
$$\beta_1 = 0.005, \beta_2 = 0.005, \beta_4 = 0.003, \beta_5 = 0.004, \beta_6 = 0.003$$

Table 4, figure 6a and figure 6b

$$\alpha_1 = 0.4, \alpha_2 = 0.1, \alpha_3 = 0.5, \alpha_5 = 0.4, \alpha_6 = 0.55,$$
$$\beta_1 = 0.005, \beta_2 = 0.005, \beta_3 = 0.0005, \beta_5 = 0.004, \beta_6 = 0.003$$

Table 5, figure 7a and figure 7b

$$\alpha_1 = 0.4, \alpha_2 = 0.1, \alpha_3 = 0.5, \alpha_4 = 0.1, \alpha_6 = 0.55,$$
$$\beta_1 = 0.005, \beta_2 = 0.005, \beta_3 = 0.0005, \beta_4 = 0.003, \beta_6 = 0.003$$

Table 6, figure 8a and figure 8b

$$\alpha_1 = 0.4, \alpha_2 = 0.1, \alpha_3 = 0.5, \alpha_4 = 0.1, \alpha_5 = 0.4,$$
$$\beta_1 = 0.005, \beta_2 = 0.005, \beta_3 = 0.0005, \beta_4 = 0.003, \beta_5 = 0.004$$

The impact of α_1 and β_1 of subsystem A on the availability of the system can be observed in table 1, figure 3a and figure 3b. It is evident from table 2 and figure 3a that the availability of the system increases with increase in α_1 while in figure 3b, the availability of the system decreases with increase in β_1. Table 2, figure 4a and figure 4b depict the availability of the system with respect to α_2 and β_2 of subsystem B. It can be seen from table 2 and figure 4a that the availability of the system tends to increase with increase in the value of α_2 but decreases with increase in the value of β_2 as evident from figure 4b. Table 3, figure 5a and 5b show the availability of the system against α_3 and β_3 of subsystem C. It is clear from table 3 and figure 5a that the system availability increases with increase in the value of α_3 while in figure 5b, the availability of the system decreases with increase in the value of β_3. The effect of α_4 and β_4 of subsystem D on the availability of the system can be seen in table 4, figure 6a and figure 6b. From table 4 and figure 6a the availability of the system display increasing pattern with increase in the value of α_4 while in figure 6b, the availability decreases with increase in the value of β_4. Table 5, figure 7a and figure 7b highlight the impact of α_5 and β_5 of subsystem E on the availability of the system. It can be observed from table 5 and figure 6a that the availability of the system tends to increase with increase in the value of α_5 but show a decreasing pattern with increase in the value of β_5 as evident from figure 6b. The effect of α_6 and β_6 of subsystem E is presented in table 6, figure 8a and figure 8b. It is clear from table 6, figure 8a and figure 8b that the availability of the system is constant with increase in the value of α_6 and β_6 respectively. This sensitivity analysis implies that subsystem E is the most critical unit in the system which needs special attention.

Table 1: Effect of failure and repair rates of subsystem A on the availability of the system

β_1 \ α_1	0.35	0.40	0.45	0.50
0.004	0.9071	0.9083	0.9092	0.9099
0.005	0.9047	0.9062	0.9073	0.9083
0.006	0.9024	0.9042	0.9055	0.9066
0.007	0.9001	0.9021	0.9037	0.9050

Table 2: Effect of failure and repair rates of subsystem B on the availability of the system

β_2 \ α_2	0.05	0.10	0.15	0.20
0.004	0.8822	0.9145	0.9258	0.9315
0.005	0.8669	0.9062	0.9201	0.9272
0.006	0.8522	0.8981	0.9145	0.9229
0.007	0.8379	0.8901	0.9090	0.9187

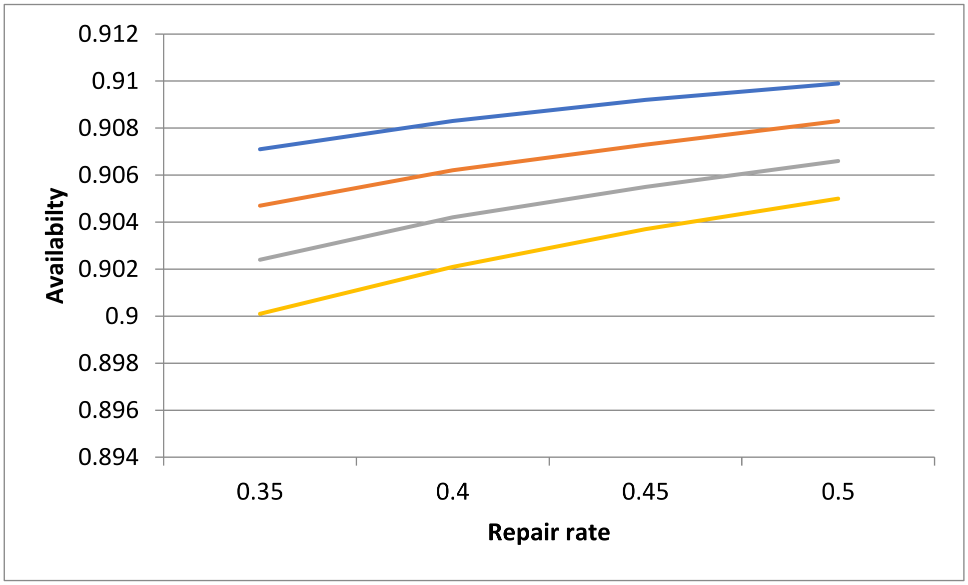

Figure 3a: Effect of repair rate α_1 on Availability

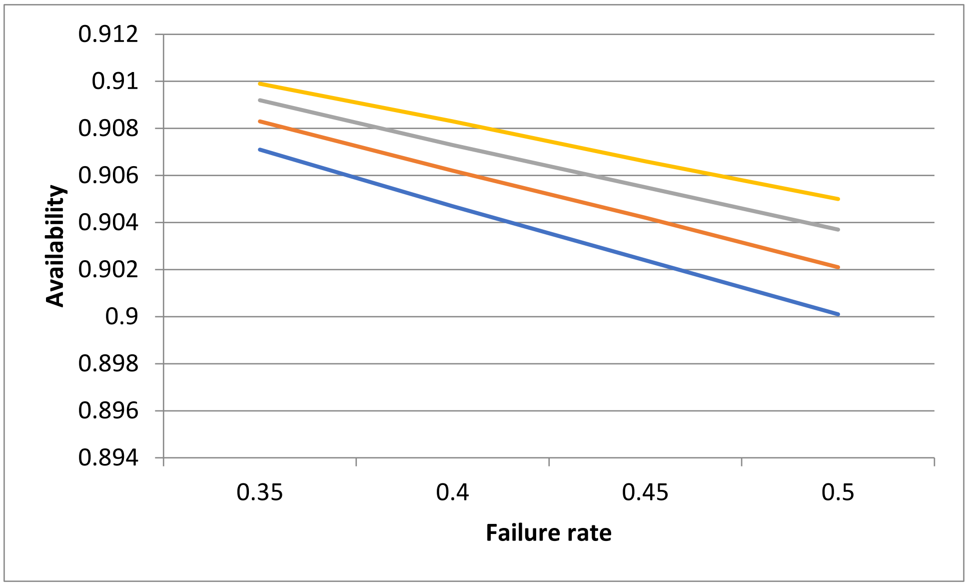

Figure 3b: Effect of failure rate β_1 on Availability

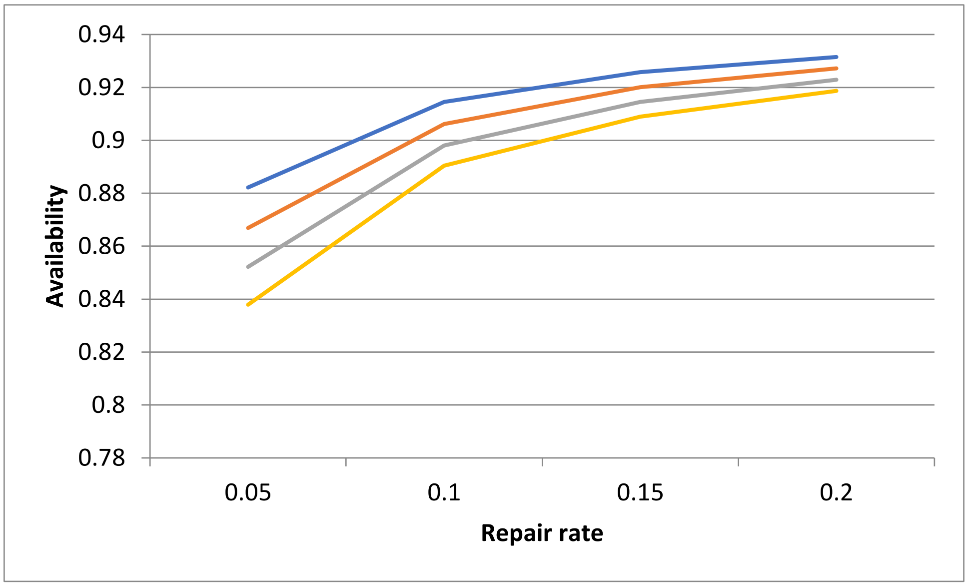

Figure 4a: Effect of repair rate α_2 on Availability

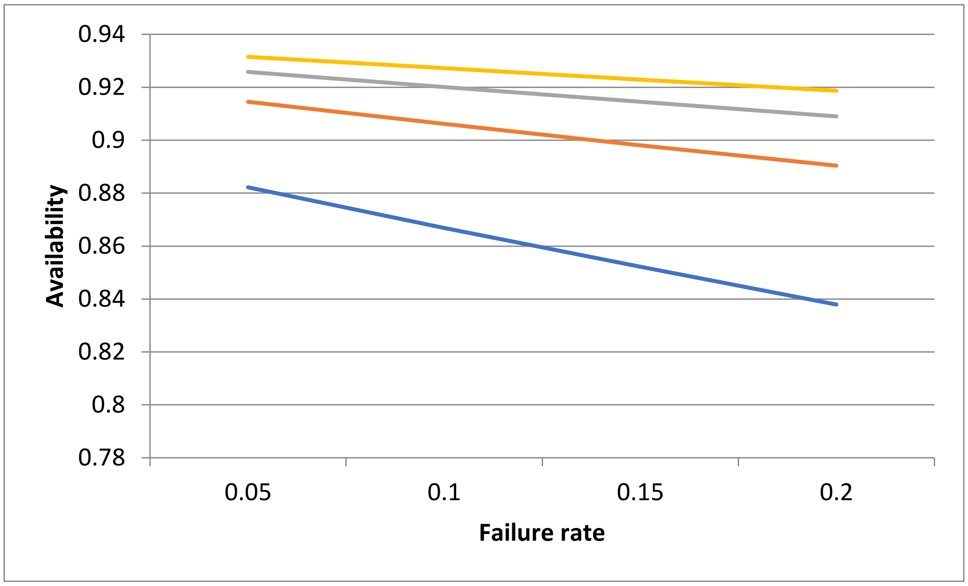

Figure 4b: Effect of failure rate β_2 on Availability

Table 3: Effect of failure and repair rates of subsystem C on the availability of the system

β_3 \ α_3	0.45	0.50	0.55	0.60
0.0005	0.9061	0.9062	0.9063	0.9063
0.0010	0.9052	0.9054	0.9055	0.9057
0.0015	0.9043	0.9046	0.9048	0.9050
0.0020	0.9034	0.9037	0.9040	0.9043

Table 4: Effect of failure and repair rates of subsystem D on the availability of the system

β_4 \ α_4	0.05	0.10	0.15	0.20
0.001	0.9145	0.9229	0.9258	0.9272
0.002	0.8981	0.9145	0.9201	0.9229
0.003	0.8822	0.9062	0.9145	0.9187
0.004	0.8669	0.8981	0.9090	0.9145

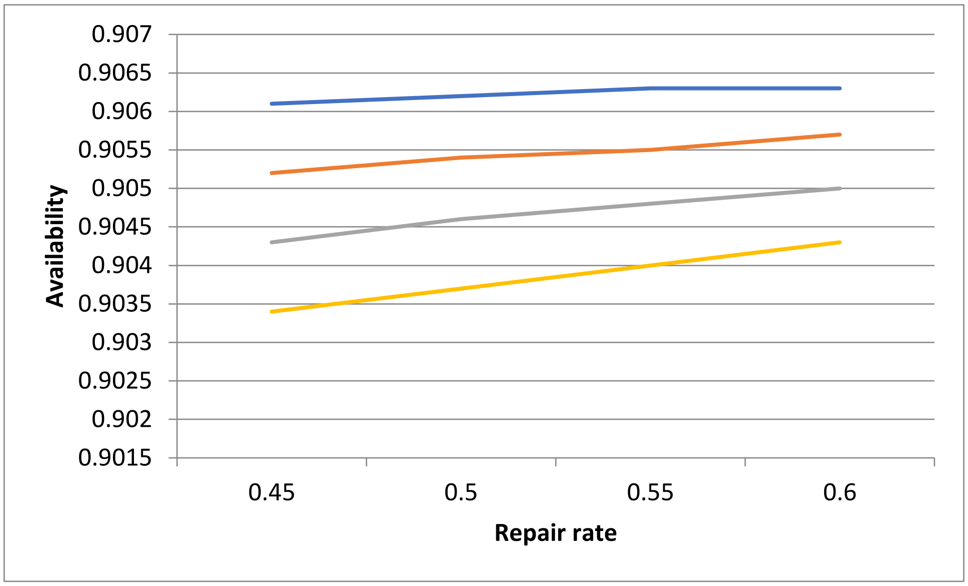

Figure 5a: Effect of repair rate α_3 on Availability

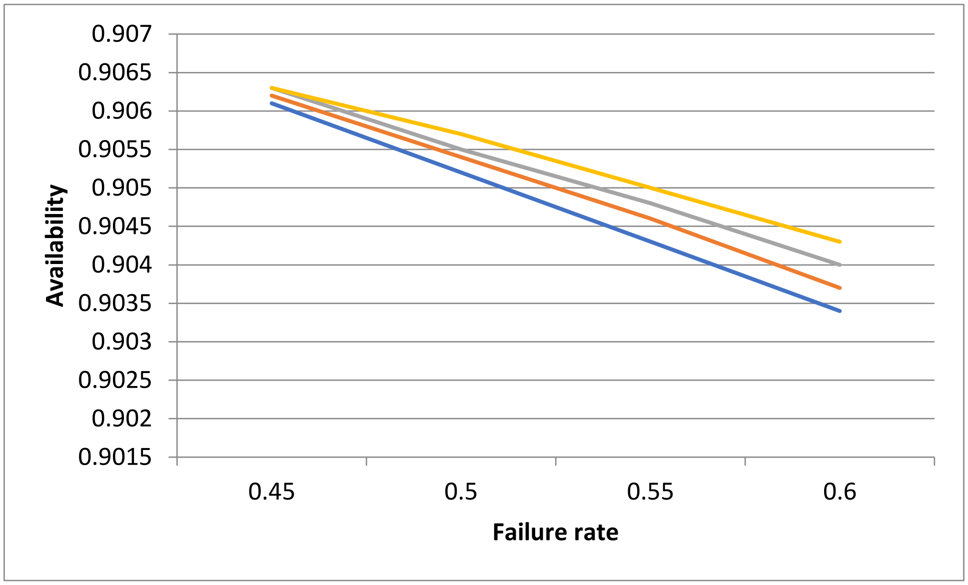

Figure 5b: Effect of failure rate β_3 on Availability

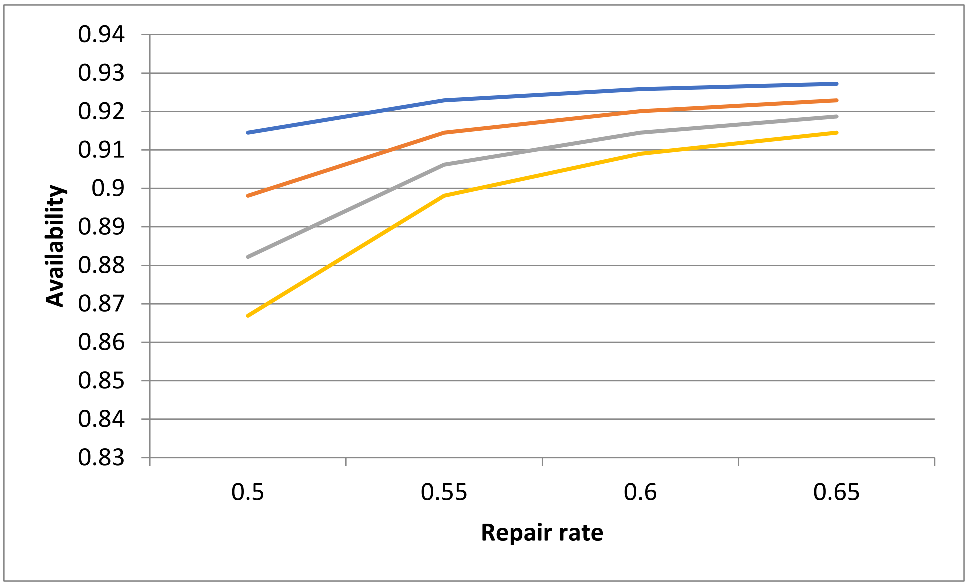

Figure 6a: Effect of repair rate α_4 on Availability

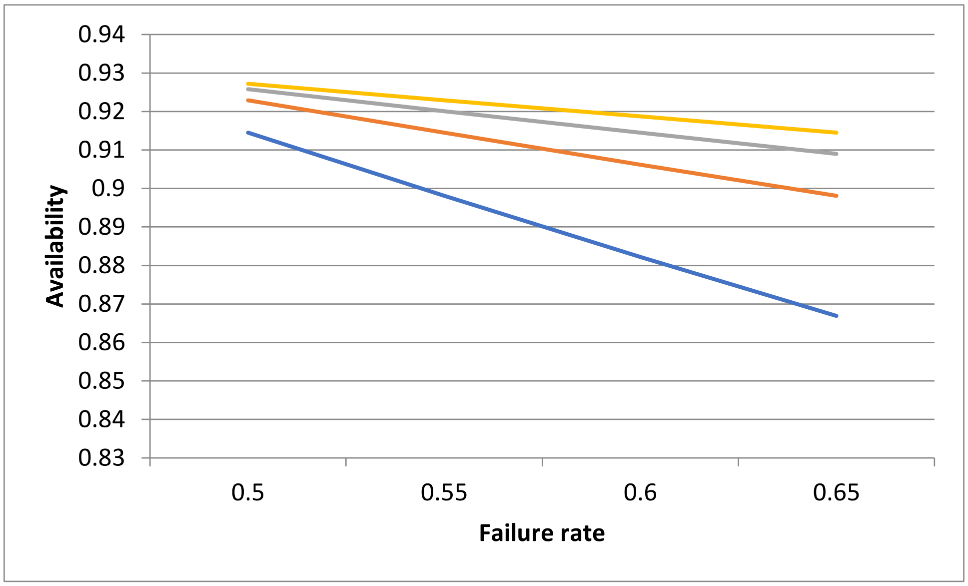

Figure 6b: Effect of failure rate β_4 on Availability

Table 5: Effect of failure and repair rates of subsystem E on the availability of the system

β_5 \ α_5	0.35	0.40	0.45	0.50
0.003	0.9074	0.9083	0.9090	0.9095
0.004	0.9050	0.9062	0.9071	0.9079
0.005	0.9027	0.9042	0.9053	0.9062
0.006	0.9004	0.9021	0.9035	0.9046

Table 6: Effect of failure and repair rates of subsystem F on the availability of the system

β_6 \ α_6	0.50	0.55	0.60	0.65
0.002	0.9062	0.9062	0.9062	0.9062
0.003	0.9062	0.9062	0.9062	0.9062
0.004	0.9062	0.9062	0.9062	0.9062
0.005	0.9062	0.9062	0.9062	0.9062

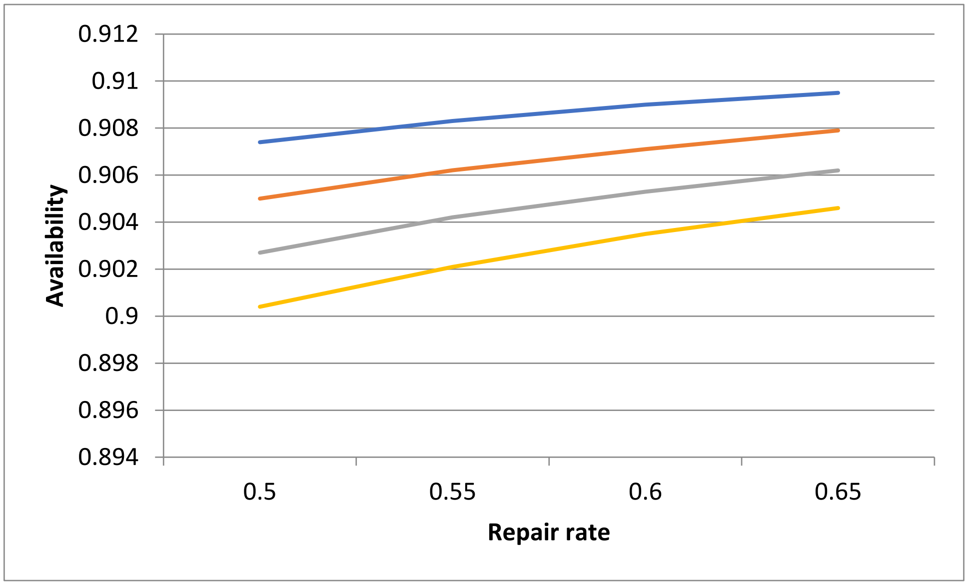

Figure 7a: Effect of repair rate α_5 on Availability

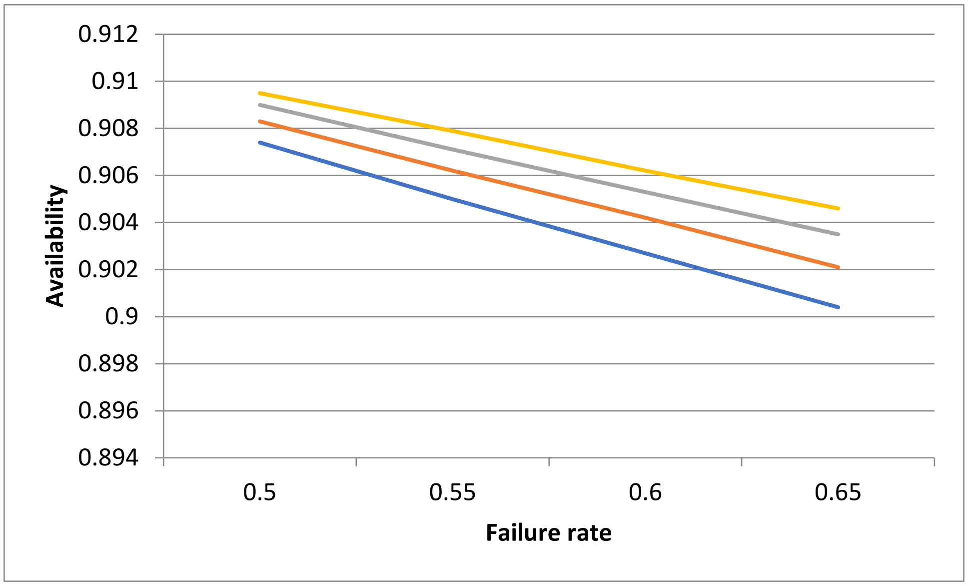

Figure 7b: Effect of failure rate β_5 on Availability

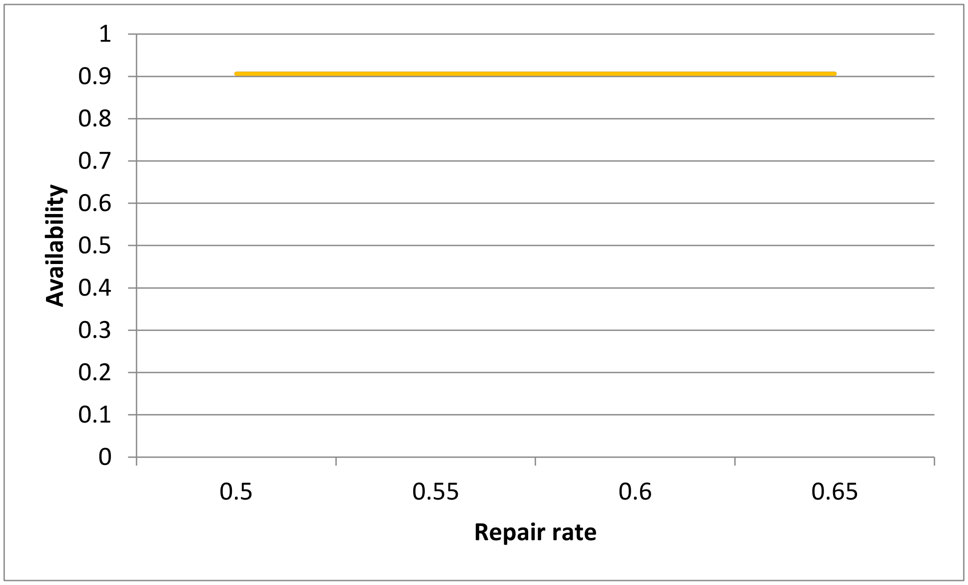

Figure 8a: Effect of repair rate α_6 on Availability

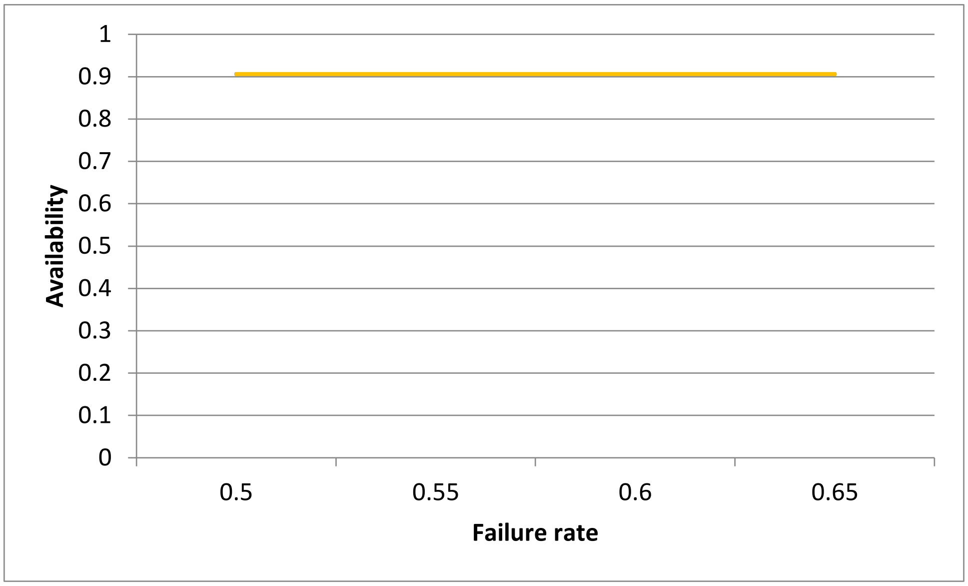

Figure 8b: Effect of failure rate β_6 on Availability

6. CONCLUSION

In this paper, we have constructed a series-parallel system consisting of six different subsystems to study the availability of the system. We have developed explicit expression for steady-state availability for the system. We also perform a parametric investigation of system parameters on system availability and captured their effects. From the analysis, it is evident that availability of the system can be improved significantly by the proper maintenance planning of subsystem F. The other subsystems also affect the availability of the system, but these are lesser effective than subsystem F. The effects of failure and repair rates of all the subsystems are presented in the form of availability matrices (tables). From the availability matrices, it is clear that as failure\repair rates increases, the system availability decrease\increase and it is also evident that subsystem F is the most critical unit in the system whose failure is disastrous to the entire system. The findings of this paper are found to be beneficial to system engineers to evaluate the system performance and carry out modifications (if needed).

The results derived in this paper would be applied in practical fields by making suitable modification and extensions. Further studies for such subject would be expected.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests.

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