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Sensitivity Analysis of a fibre plant unit due to deliberate failures

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ABSTRACT:
This Paper deals with the sensitive behavior of a Fibre Plant which produces fibre for making clothes. The fibre making plant is a complex system with various subsystems as: Vendor, CS_2 Plant, Acid Plant, Pulp Plant and Processing Plant. The considered system can completely fail due to failure of any of the subsystems. It is also assumed that the system can fail due to workers strike and catastrophic failure. Preventive Maintenance policy has been applied to reduce the failure in the system. Sensitivity analysis of the system has been done using supplementary variable technique due to deliberate failures. Copula has been applied to find the joint probability distribution.

Keywords: Sensitivity analysis, supplementary variable technique, Preventive maintenance, Copula, joint probability distribution.

I. Introduction

A system is a combination of elements forming a planetary whole i.e. there is a functional relationship between its components. The properties and behaviour of each component ultimately affects the properties of the system. Any system has a hierarchy of components that pass through the different stages of operations which can be operational, failure, AND DEGRADED or in repair. Failure doesn't mean that it will always be complete; it can be partial as well. But both these types affect the performance of system and hence the reliability [1, 2]. Majority of the systems in the industries are repairable. The performance of these systems can influence the quality of product, the cost of business, the service to the customers, and thereby the profit of enterprises directly. Modern repairable systems tend to be highly complex due to increase in convolution and automation of systems [4].

As far as the production-operations are concerned, not only reliability but also steady state availability analysis is essential, again on account of increased complexity and cost of present day equipment. Also the markets are getting globalized and more competitive. Penalties for delayed deliveries have been increased. Sometimes the orders are cancelled and defaulting plants are not favoured with orders. To overcome these types of problems, reliability and steady state availability analysis is necessary for performance studies in the area of discrete manufacturing systems. Many researcher discussed reliability and steady state analysis of Manufacturing Plant by using different approaches [4, 5, 9].

The purpose of the present paper is to compute the sensitive behaviour and failure analysis of a Fibre Plant which produces fibre for making clothes. A Viscose Staple Fibre (VSF) Plant consists of five subsystems connected in series, namely Vendor (who supplies raw materials Charcoal and Sulphur), Carbon di sulphide (CS_2) Plant, Acid Plant, Pulp Plant, and Processing Plant. In the Processing Plant ten parallel machines are involved in doing the same job. This subsystem follows 5-out -of-10:d and 6-out-of-10:f configurations which specifies that if 5 machines of the Processing Plant are not working then the system is in reduced efficiency state and not able to fulfil the required target and if more than 5 machines are failed then the system is failed [3]. Also the subsystem CS_2 can fail in two different ways viz, due to the lack of Charcoal (supplied by Vendor) and due to lack of Sulphur (supplied by Vendor) as they both are the raw materials for the process. Preventive maintenance is one of the important aspects of production companies; it is possible by providing rest to all the machines one by one for a particular period of time as per maintenance schedule. This fact has been taken into consideration in the present studies. Supplementary variable technique is used to estimate the sensitivity measures of the considered industrial problem. Copula methodology has also been incorporated to evaluate the joint probability

DISTRIBUTION OF REPAIRS IN CS_2 PLANT. THIS METHOD PROVIDES AN EASY WAY TO ESTIMATE THE VARIATION IN DIFFERENT SYSTEM PERFORMANCE IN TERMS OF RELIABILITY WITH RESPECT TO TIME.

II. SYSTEM DESCRIPTION

In this system there are five plants arranged in series and these five plants have been divided into five subsystems to understand the logical sequence of the processes viz Vendor(who supplies raw materials Sulphur and Charcoal), Carbon di sulphide Plant, Acid Plant, Pulp Plant, Processing Plant. Vendor, supplies the raw materials Charcoal and Sulphur for making CS_2 and Acid (Sulphuric Acid). CS_2 Plant, Acid Plant, Pulp Plant produces Carbon di sulphide, H_2SO_4 and pulp respectively. In the process of making fibre, initially Sulphur and Charcoal (supply by the Vendor) goes to the CS_2 Plant, where Charcoal is heated up to 680^0C in the furnace when it becomes red hot, liquid Sulphur is then mixed with it. Then CS_2 is obtained. To produce H_2SO_4 initially liquid Sulphur is heated into the boilers and then it is converted into the gas. The gas blows to the catalyst, and then H_2SO_4 is obtained [6].

The main heart of Fibre making Plant is Processing Plant, where fibre is produced. The whole Process of making fibre is discussed below. In the Processing Plant initially the Slurry which is a mixer of CS_2 and pulp converted into a Viscose which is looking like as Honey. This Viscose is then passes through H_2So_4 then by the process of spinning regular fibre is obtained. Then washing of this regular fibre is done by after treatment method. Finally cutting and then packing. The transition state diagram describing the system is shown in Figure-1 and states description is given by table-1.

A. RELIABILITY IMPROVEMENT FEATURES USED

1. Use of SS 316L pipeline for CS_2 application.
2. Increase in thickness of CS_2 storage tank to enhance life.
3. Use of Teflon lined ms pipe for dilute acid application.
4. Two acid strength controllers provided for each plant [6].

The following assumption has been taken into the considerations in this study.

- Initially at t=0, all plants are operating well.
- Failures are statistically independent.
- The repair time of the plants are assumed to be arbitrarily distributed.
- Repaired subsystem/ plant(s) works like new.
- All failures follow exponential time distribution.
- Processing Plant has 5-out-of-10: d and 6-out-of-10: f configuration.
- The whole system can also fail due to deliberate failures like; workers strike and catastrophic failures.
- Joint probability distribution has been applied in CS_2 Plant for repair as the plant can fail due the lack of Charcoal as well as Sulphur, the raw materials supplied by the Vendor 8].

III. "Table 1: State specifications"

Table 1 shows the state specifications of the transition diagram.

State	Description	System state
S_0	The state when the system is in fully operational condition.	G
S_1	The state when the system is in failed state due to the failure of Vendor.	F_R
S_2	The state when the system is in failed state due to the failure of CS_2 Plant.	F_R
S_3	The state when the system is in failed state due to the failure of Acid Plant.	F_R
S_4	The state when the system is in failed state due to the failure of Pulp Plant.	F_R
S_5	The state when the system is in failed state due to the workers strike.	F_R

S_6	The state when the system is in failed state due to the catastrophic failure.	F_R
S_7	The state when the system is in reduced efficiency state due to the failure of 5(out of 10) machines of Processing Plant (p_2).	D_R
S_8	The state when the system is in failed state from the degraded state S_7 due to the failure of Vendor.	F_R
S_9	The state when the system is in failed state from the degraded state S_7 due to the failure of CS_2 Plant.	F_R
S_{10}	The state when the system is in failed state from the degraded state S_7 due to the failure of Acid Plant.	F_R
S_{11}	The state when the system is in failed state from the degraded state S_7 due to the failure of Pulp Plant.	F_R
S_{12}	The state when the system is in failed state from the degraded state S_7 due to the failure of other machines of Processing Plant.	F_R

Note: G: Good state; D_R: Degraded State and under repair; F_R= Failed state and under repair.

IV. NOMENCLATURE

Pr	Probability..
$P_0(t)$	Pr{ at time t the system is in state S_0 }
$P_{25}(w,t)$	Pr {the system is in degraded state at time t due to the failure of 5 machines of the processing Plant (p_2) and elapsed repair time lies between *w* and *w+Δ*}.
$P_i(k,t)$	Pr {the system is in failed state due to the failure of the i^{th} subsystem at time t and elapsed repair time lies between *k* and *k+Δ*},where *i*=V, CS_2, Acid, Pulp(p_1), Degraded Processing plant(p_{25}), Processing plant(p_2), Strike and catastrophic failure and *k=x, y, z, u, w, m, q, r*.
$\delta_v / \delta_{cs} / \delta_{Ac}$	Failure rate of Vendor/ CS_2 Plant/ Acid Plant/ Pulp Plant
K	Elapsed repair time, where *k=x,y,z,u,w,m,q,r*.
$\delta_{p_{25}} / \delta_{p_2}$	Failure rate of the 5 machines of the processing Plant/Failure rate of the other (more than 5) machines of the Processing Plant.
$\delta_{s_1} / \delta_{s_2}$	Failure rate due to strike (from the operating state S_0/from the degraded state S_7).
$\delta_{c_1} / \delta_{c_2}$	Failure rate of Catastrophic failure (from the operating state S_0/from the degraded state S_7).
$\phi_i(k)$	General repair rate of i^{th} system in the time interval (*k*, *k+Δ*), where *i*=V, CS_2, Acid, Pulp (p_1), Degraded Processing (p_{25}), Processing plant (p_2), Strike and catastrophic failure and *k=x, y, z, u, w, m, q, r*.

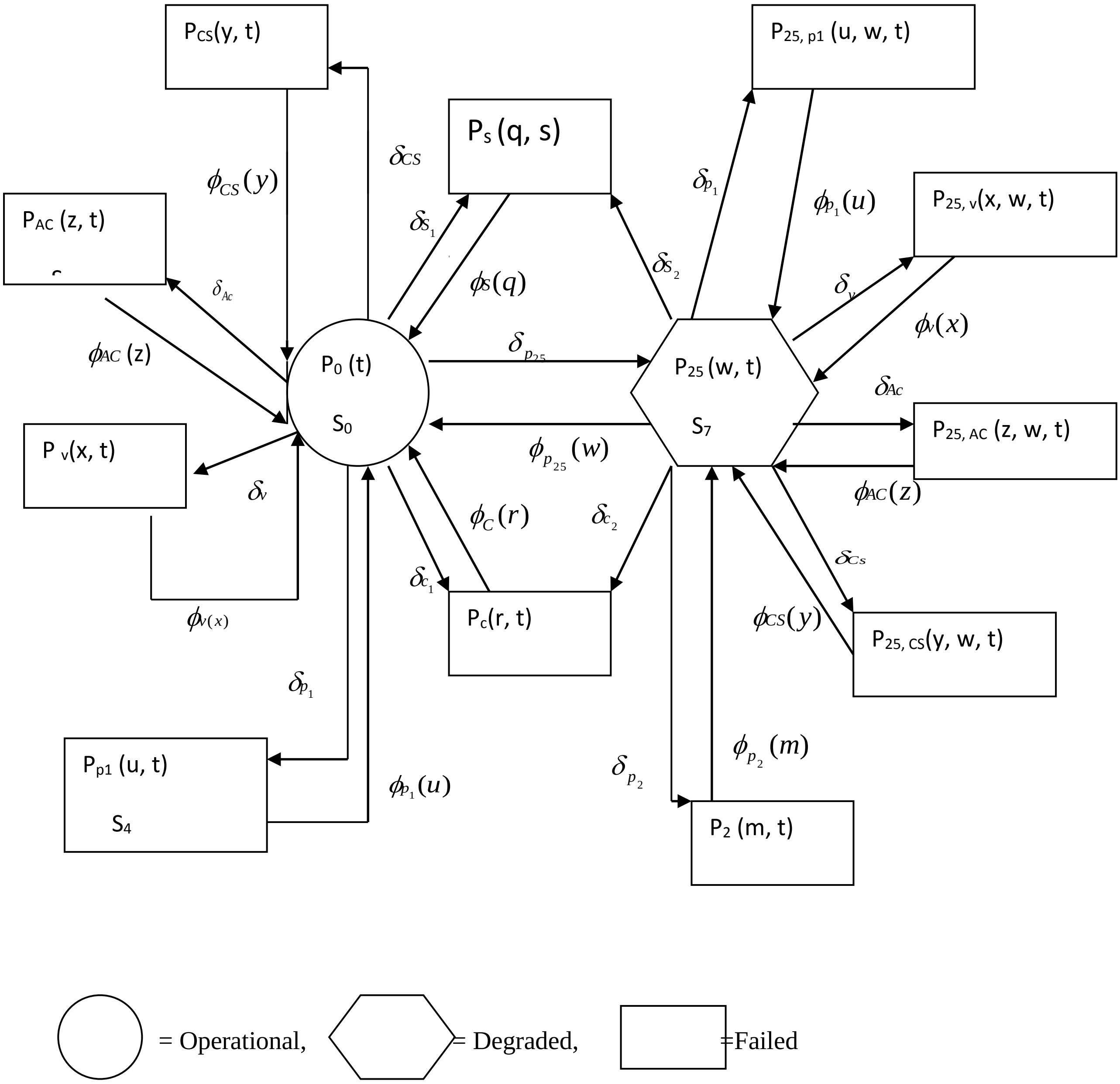
$\phi_{p_{25}} / \phi_{p_2}$ General repair rate of 5 machines of Processing Plant (p2)/other (more than 5) machines of Processing Plant.

$P_{25,i}(k,w,t)$ Pr (at time t system is failed due to the failure of the i^{th} subsystem while 5 machines of the Processing Plant are already failed). Elapsed repair time for i^{th} subsystem lies between (k, $k+\Delta$) and for Processing Plant it lies between(w ,$w+\Delta$),where i= V, CS_2, Acid, Pulp(p_1) and k= x, y, z, u.

K_1, K_2 Revenue per unit time and service cost per unit time respectively.

$$\overline{S}_i(j): \int_0^\infty \phi_i(j)\exp[-sj - \int_0^i \phi_i(j)dj]dj, \text{ for } i = V, CS_2, AC, p_1, S, C \;\&\; j = x, y, z, u, w, m, q, r.$$

Let $u_1 = e^y$ and $u_2 = \phi_{CS}(y)$ then the expression for joint probability according to Gumbel-Hougaard family of copula is given as $\phi_{cs} = \exp\left[y^\theta + [\log\phi_{cs}(y)]^\theta\right]^{1/\theta}$



"Figure 1. State-transition diagram"

V. FORMULATION OF MATHEMATICAL MODEL

Probabilistic considerations and limiting procedure yield the following integro-differential equations satisfying the model:

$$\left[\frac{d}{dt}+\delta_v+\delta_{cs}+\delta_{Ac}+\delta_{p_1}+\delta_{c_1}+\delta_{s_1}+\delta_{P_{25}}\right]P_0(t)=\int_0^\infty P_v(x,t)\phi_v(x)dx+\int_0^\infty P_{cs}(y,t)\exp\left[y^\theta+(\log\phi_{cs}(y))^\theta\right]^{1/\theta}dy+$$
$$\int_0^\infty P_{Ac}(z,t)\phi_{Ac}(z)dz+\int_0^\infty P_{p_1}(u,t)\phi_{p_1}(u)du+\int_0^\infty P_c(r,t)\phi_c(r)dr+\int_0^\infty P_s(q,t)\phi_s(q)dq+\int_0^\infty P_{25}(w,t)\phi_{P_{25}}(w)dw. \tag{1}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\phi_v(x)\right]P_v(x,t)=0 \tag{2}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial y}+\phi_{CS}(y)\right]P_{CS}(y,t)=0 \tag{3}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial z}+\phi_{Ac}(z)\right]P_{Ac}(z,t)=0 \tag{4}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial u}+\phi_{p_1}(u)\right]P_{p_1}(u,t)=0 \tag{5}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial w}+\delta_v+\delta_{cs}+\delta_{Ac}+\delta_{p_1}+\delta_{p_2}+\delta_{s_2}+\delta_{c_2}+\phi_{p_{25}}(w)\right]P_{25}(w,t)=\int_0^\infty P_{25,v}(x,w,t)\phi_v(x)dx+$$
$$\int_0^\infty P_{25,cs}(y,w,t)\phi_{cs}(y)dy+\int_0^\infty P_{25,Ac}(z,w,t)\phi_{Ac}(z)dz+\int_0^\infty P_{25,p_1}(u,w,t)\phi_{p_1}(u)du \tag{6}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\phi_v(x)\right]P_{25,v}(x,w,t)=0. \tag{7}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial y}+\phi_{cs}(y)\right]P_{25,cs}(y,w,t)=0 \tag{8}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial z}+\phi_{Ac}(z)\right]P_{25,Ac}(z,w,t)=0. \tag{9}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial u}+\phi_{p_1}(u)\right]P_{25,p_1}(u,w,t)=0 \tag{10}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial m}+\phi_{p_2}(m)\right]P_2(m,t)=0 \tag{11}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial q}+\phi_s(q)\right]P_s(q,t)=0. \tag{12}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial r}+\phi_c(r)\right]P_c(r,t)=0 \qquad (13)$$

A. Boundary Conditions

$$P_v(0,t)=\delta_v P_0(t) \qquad (14)$$

$$P_{cs}(0,t)=\delta_{cs} P_0(t) \qquad (15)$$

$$P_{Ac}(0,t)=\delta_{Ac} P_0(t) \qquad (16)$$

$$P_{p_1}(0,t)=\delta_{p_1} P_0(t) \qquad (17)$$

$$P_s(0,t)=\delta_{s_1} P_0(t)+\delta_{s_2} P_{25}(w,t) \qquad (18)$$

$$P_c(0,t)=\delta_{c_1} P_0(t)+\delta_{c_2} P_{25}(w,t) \qquad (19)$$

$$P_{25}(0,t)=\delta_{p_{25}} P_0(t)+\int_0^\infty P_2(m,t)\phi_{p_2}(m)dm \qquad (20)$$

$$P_{25,v}(0,w,t)=\delta_v P_{25}(w,t). \qquad (21)$$

$$P_{25,cs}(0,w,t)=\delta_{cs} P_{25}(w,t) \qquad (22)$$

$$P_{25,Ac}(0,w,t)=\delta_{Ac} P_{25}(w,t) \qquad (23)$$

$$P_{25,p_1}(0,w,t)=\delta_{p_1} P_{25}(w,t) \qquad (24)$$

$$P_2(0,t)=\delta_{p_2} P_{25}(t) \qquad (25)$$

B. Initial Condition

$P_0(0)=1$, otherwise zero. (26)

VI. SOLUTION OF THE MODEL

Solving equations (1) through (13) by taking Laplace transform and using initial and boundary conditions, one may obtain following transition state probabilities of the system.

$$\overline{P_0}(s)=\frac{1}{K(s)} \qquad (27)$$

$$\overline{P_{25}}(s)=\frac{I(s)}{K(s)} \qquad (28)$$

$$\overline{P_v}(s)=\frac{\delta_v}{K(s)}J_v(s) \qquad (29)$$

$$\overline{P_{cs}}(s)=\frac{\delta_{cs}}{K(s)}J_{cs}(s) \qquad (30)$$

$$\overline{P_{Ac}}(s)=\frac{\delta_{Ac}}{K(s)}J_{Ac}(s) \qquad (31)$$

$$\overline{P_{p_1}}(s) = \frac{\delta_{p_1}}{K(s)} J_{p_1}(s) \tag{32}$$

$$P_{25,v}(s) = \frac{\delta_v}{K(s)} J_v(s)\left[\delta_{p_{25}} + \delta_{p_2} \overline{S}_{p_2}(s) I(s)\right] J_{p_{25}}(A) \tag{33}$$

$$P_{25,cs}(s) = \frac{\delta_{cs}}{K(s)} J_{cs}(s)\left[\delta_{p_{25}} + \delta_{p_2} \overline{S}_{p_2}(s) I(s)\right] J_{p_{25}}(A) \tag{34}$$

$$P_{25,Ac} = \frac{\delta_{Ac}}{K(s)} J_{Ac}(s)\left[\delta_{p_{25}} + \delta_{p_2} \overline{S}_{p_2}(s) I(s)\right] J_{p_{25}}(A) \tag{35}$$

$$P_{25,p_1}(s) = \frac{\delta_{p_1}}{K(s)} J_{p_1}(s)\left[\delta_{p_{25}} + \delta_{p_2} S_{p_2}(s) I(s)\right] J_{p_{25}}(A) \tag{36}$$

$$\overline{P}_2(s) = \delta_{p_2} \frac{I(s)}{K(s)} J_{p_2}(s) \tag{37}$$

$$\overline{P}_S(s) = \left[\delta_{S_1} + \delta_{S_2} I(s)\right] \frac{J_S(s)}{K(s)} \tag{38}$$

$$\overline{P}_C(s) = \left[\delta_{C_1} + \delta_{C_2} I(s)\right] \frac{J_C(s)}{K(s)} \tag{39}$$

where,

$$\begin{aligned} K(s) = {} & s + \delta_v + \delta_{cs} + \delta_{Ac} + \delta_{p_1} + \delta_{C_1} + \delta_{S_1} + \delta_{p_{25}} - \delta_v \overline{S}_v(s) - \delta_{cs} \overline{S}_{cs}(s) - \delta_{Ac} \overline{S}_{Ac}(s) - \\ & \delta_{p_1} \overline{S}_{p_1}(s) - \left[\delta_{C_1} + \delta_{C_2} I(s)\right] \overline{S}_C(s) - \left[\delta_{S_1} + \delta_{S_2} I(s)\right] \overline{S}_s(s) - \left[\delta_{p_{25}} + \delta_{p_2} \overline{S}_{p_2}(s) I(s)\right] \overline{S}_{p_{25}}(A) \end{aligned} \tag{40}$$

$$I(s) = \frac{\delta_{p_{25}} J_{p_{25}}(A)}{1 - \delta_{p_2} \overline{S}_{p_2}(s) J_{p_{25}}(A)} \tag{41}$$

$$A = s + \delta_v + \delta_{cs} + \delta_{Ac} + \delta_{p_1} + \delta_{C_2} + \delta_{S_2} - \delta_v \overline{S}_v(s) - \delta_{cs} \overline{S}_{cs}(s) - \delta_{Ac} \overline{S}_{Ac}(s) - \delta_{p_1} \overline{S}_{p_1}(s) \tag{42}$$

$$J_{p_{25}}(A) = \frac{1 - \overline{S}_{p_{25}}(A)}{A} \tag{43}$$

$$J_i(s) = \frac{1 - \overline{S_v(s)}}{s}, \text{for } i = v, cs, Ac, p_1, S, C \tag{44}$$

$$\overline{S}_i(j) = \int_0^\infty \phi_i(j) \exp[-s_j - \int_0^i \phi_i(j) dj] dj, \ \ for \ \ i = v, cs, Ac, p_1, S, C \ \& \ j = x, y, z, u, w, m, q, r \tag{45}$$

$$\phi_{cs} = \exp\left[y^\theta + \left[\log \phi_{cs}(y)\right]^\theta\right]^{1/\theta}$$

A. Verification

$$\overline{P}_{up}(s) + \overline{P}_{down}(s) = \frac{1}{s} \tag{46}$$

VII. STEADY STATE BEHAVIOR OF THE SYSTEM

Using Abel's lemma in Laplace transforms, viz;

$$\lim_{s \to 0} s\overline{f}(s) = \lim_{t \to \infty} f(t) = f(\text{say}) \tag{47}$$

provided the limit on the right hand side exists, the time independent operational probabilities are obtained as follows.

VIII. RELIABILITY OF THE SYSTEM

If the system is non repairable then the probabilities will be independent of *x* and repair rates are zero then the reliability function is obtained as mentioned below.

The Laplace transform of the reliability when all repair rates of the system are zero, then from equation (27), we have

$$\overline{P_0}(s) = \frac{1}{K(s)}$$

When all repair rates of the system are zero.

$$\overline{\mathrm{R}}(\mathrm{s}) = \frac{1}{s + \delta_v + \delta_{cs} + \delta_{Ac} + \delta_{p_1} + \delta_{C_1} + \delta_{S_1} + \delta_{p_{25}}}$$

where, R(s) is the Laplace transform of the reliability function.
The reliability of the transit system is obtained as:

$$R(t) = e^{\{-(\delta_v + \delta_{CS} + \delta_{AC} + \delta_{p_1} + \delta_{C_1} + \delta_{S_1} + \delta_{p25})t\}} \quad (48)$$

IX. SENSITIVITY ANALYSIS FOR R (t)

First we perform sensitivity analysis for changes in the R (t) resulting from changes in system parameters δ_V and δ_{S_1} . Differentiating equation (78) with respect to ψ_V , we obtain

$$\frac{\partial R(t)}{\partial \delta_V} = -te^{(-(\delta_V + \delta_{CS} + \delta_{Ac} + \delta_{C_1} + \delta_{S_1} + \delta_{p_{25}} + \delta_{p_1})t} \quad (49)$$

Using the same procedure we can get $\frac{\partial R(t)}{\partial \delta_{S_1}}$

X. NUMERICAL COMPUTATION

For a more concrete study of the system's behavior, we calculate the values of reliability, availability and cost function of the system with respect to time and keeping the other parameter fixed and MTTF of the system for different failure rates.

A. RELIABILITY ANALYSIS

Consider $\delta_v = .005, \delta_{CS} = .007, \delta_{Ac} = .006, \delta_{C_1} = .03, \delta_{p_1} = .007, \delta_{S_1} = .02, \delta_{p_{25}} = .004$ in equation (78) and by putting different values of t such as 0, 1, 2, 3, 4…., one can obtain the output as shown in Figure-2.

B. SENSITIVITY ANALYSIS

B.1 for Vendor failure rate

Putting, $\delta_{CS} = .007, \delta_{Ac} = .006, \delta_{C_1} = .03, \delta_{p_1} = .007, \delta_{S_1} = .02, \delta_{p_{25}} = .004$ and δ_v =.001, .005 and .01 in equation (82) one can obtain the figure-7 which shows the sensitivity of the system reliability with respect to Vendor failure rate.

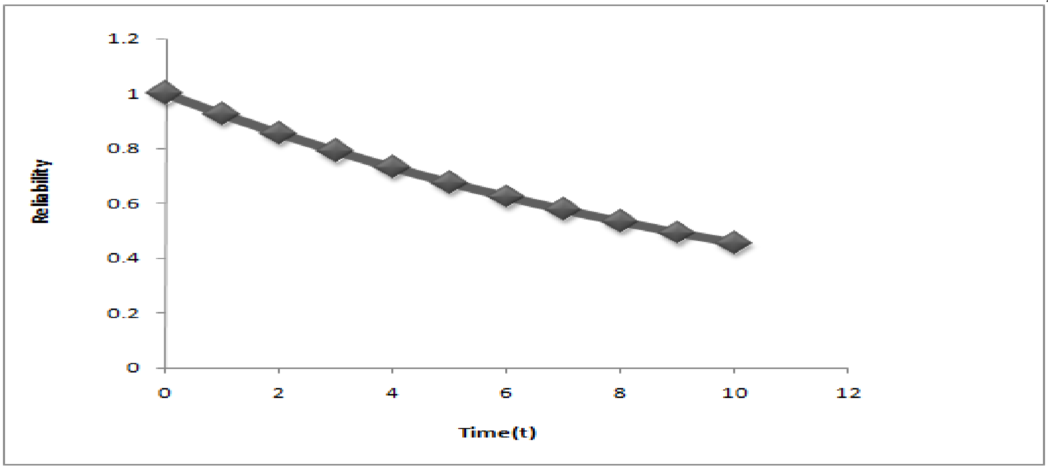
B.2 for Strike rate

Putting, $\delta_v = .005, \delta_{CS} = .007, \delta_{Ac} = .006, \delta_{C_1} = .03, \delta_{p_1} = .007, \delta_{p_{25}} = .004$ and δ_{S_1} =.01, .05 and .1 in equation (82) one can obtain the figure-8 which shows the sensitivity of the system reliability with respect to Strike rate.

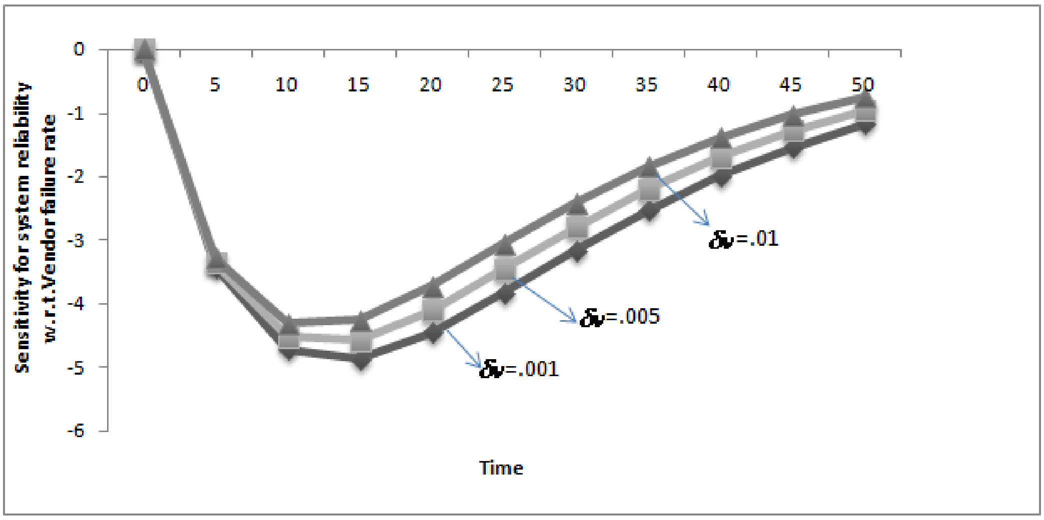
XI. RESULTS AND DISCUSSION

Figure-2 shows the trends of reliability of the system with respect to time when all the failure rates and all the repair rates have some fixed values. From the graph we conclude that the reliability of the system decreases with passage of time when all failures follows exponential time distribution.

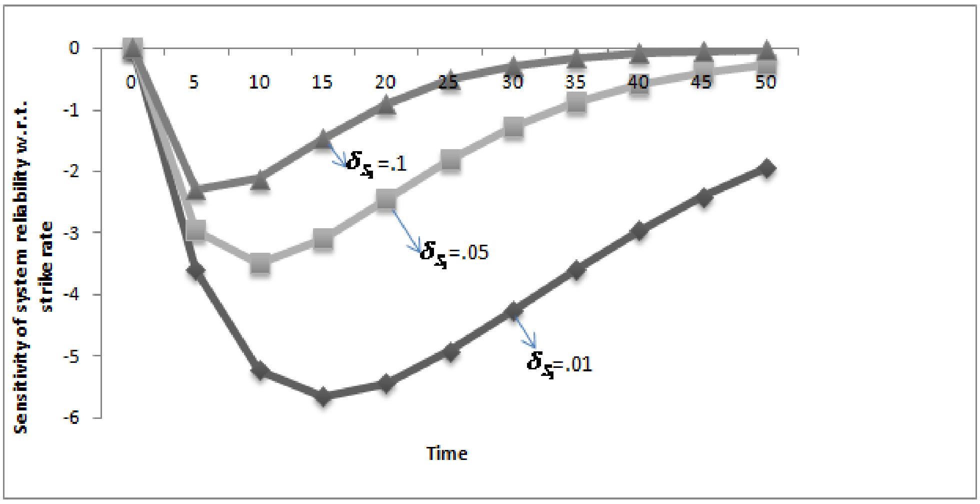
The sensitivities of the system reliability R (t) with respect to system parameters δ_V and δ_{S_1} are shown in figures-7 and 8. It can easily be observed that the biggest impact almost happened at the same time for all the system parameters. Moreover, we find that δ_{S_1} are most prominent parameters and almost have the equal sensitive effect on the system reliability. δ_V is the second in magnitude.



"Figure 2: Reliability vs time"



"Figure 3: Sensitivity of system reliability w. r. t. vendor failure"



"Figure 4. Sensitivity of system reliability w. r. t. Strike rate"

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