Reliability and Performance Analysis of a Complex Manufacturing System with Inspection facility using Copula Methodology

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Abstract

This paper deals with the assessment of various reliability factors of a real-life manufacturing system having inspection facility. This multistate manufacturing system have five workstations those are connected in series configuration as: W_1, W_2, W_3, W_4, W_5. Workstations W_2 and W_4 has the configuration 2-out-of -3: G and 1-out-of-3: F. Due to failure of the any of the workstation, whole manufacturing system can completely fail. Apart from this machine failure can also make system down. To avoid sudden failure in the system pre-emptive maintenance strategy has been adopted. This is a corrective maintenance action before a failure occurs and scheduled during off days. Risk analysis is done because of fault of W_5 workstation in material quality inspection. Probability distributions like exponential time distribution is followed by all failures and general time distribution by all repairs. To study the probabilistic behavior of the system in different possible transition states, Markov process have been used. Supplementary variable technique and copula method of finding joint probability distribution have been used to obtained various reliability features such as steady state behavior of the system, reliability function, availability, Mean time to failure, sensitivity analysis and profit analysis.

Keywords: Reliability analysis, Mean time to failure, Availability, Sensitivity analysis, Risk analysis

1. Introduction

Nowadays, Due to the globalization of the market and business, a lot of problems related to manufacturing industries like delays in product delivery, machine failure, cancellation of demand, etc. are encountered by the industries daily. Therefore, reliability and availability analysis are important for the performance analysis of discrete manufacturing systems. A lot of work has been done to discuss reliability measures of manufacturing systems using different approaches [1, 3, 5, 6 and 7]. Here, a concept of making a methodical approach to analyze a failure-free system for a manufacturing industry is developed for a practical period [9].

The objective of this work is to assess the performance and risk analysis of a manufacturing system under different operating conditions. This multistate manufacturing system contains five workstations that are connected in the series configuration as W_1, W_2, W_3, W_4, *and* W_5. Workstation W_1 consists of the raw material supplied by a merchant or vendor for making finished goods. At workstation W_2 material provided by workstation W_1 is transformed into welded usable form and small and big components are used to make the final product. Later on, these welded components are sent to workstation W_3 for the dye or tint process. Workstation W_4 plays a vital role in this complex manufacturing system as the finished product assembles here only by connecting and arranging equipped components in logical order received from workstation W_3. At last, before

sending the finished product to suppliers in the market, it goes through the inspection process at workstation W_5 for quality inspection. On the workstations W_2 and W_4, three machines are involved in performing the same task connected parallelly. These workstations follow 2-out -of-3:G and 1-out-of-3:F conformations, which means that for the fully operational stage of the system in which it can achieve the required target, it is essential that at least two machines of workstation W_2 and W_4 are in working condition otherwise in the opposite case the system fails [2]. Along with this, Machine failure is also considered which may be major or minor. To get maximum reliability, two groups of repairmen are involved in repairing the system according to their knowledge and skills. Here, a joint probability distribution is obtained using copula methodology when both groups are involved in repairing the system at the same time [4 and 8]. After getting finished goods, product inspection is done by workstation W_5. Here, any fault or ignorance in the inspection of the product can take the system into a risk state that can cause system failure. For example, if a technical fault is there in final assembled product due to wrong assembly or material use which can result in a failure after a certain period of use of the product or in certain climatic conditions, also the product have been not tested for that period or under that climatic conditions. The transition state diagram and state specification of the considered system are shown in figure-1 and table-1 respectively. The figure-1 shows positive transition intensities, and the transition probabilities for time Δ are proportional to the intensities, the remaining transition probabilities for time Δ are equal to o (Δ).

2. Notations

$P_0(t)$	:	Denotes Probability at time t when the system is in initial state S_0
Pi (k, t)	:	Denotes the probability of system getting in breakdown state because of failure of the i^{th} workstation at time t, also elapsed repair time considered in between k and k+Δ, where i= 1, 2, 3, 4, 5, M, QR, and k∈ [0, +∞)
$W_1/W_2/W_3/W_4/W_5$	:	Workstation 1 to Workstation 5
K	:	Elapsed repair time, where k∈ [0, +∞)
ψ_{1W} / ψ_{1A}	:	The Showing Failure rate of the one machine of the Workstation 2/ 4.
ψ_M	:	Machine failure rate
$P_{1W}(t)$	:	Showing the probability of 2-out -of-3: G state of workstation 2 i.e. system is in fully operational mode even after one machine of workstation 2 is failed and rest two are in working condition
$P_{1A}(t)$	:	Showing the probability of 2-out -of-3: G state of workstation 4 i.e. system is in fully operational mode even after one machine of workstation 4 is failed and rest two are in working condition
ψ_i	:	The General failure rate of i^{th} workstation, where i= 1, 2, 3, M, 4, 5.

$\phi_i(k)$: Showing repair rate of i[th] workstation between the time interval (k, k+Δ), where i= 1, 2, 3, 4, 5, M, QR, and k∈ [0, +∞)

γ_Q : Showing risk rate or the factor which indicates the level of risk taken into consideration which can lead the system into the risk stage

Pi, W (k, t) : Shows the probability of the failed state of the system due to failure of the i[th] workstation from the state S_2 when one machine of workstation W_2 is not working. Elapsed repair time for the i[th] subsystem lies between (k, k+Δ), where i=1, 3, 4 and k∈ [0, +∞)

Pi, A (k, t) : Shows the probability of the failed state of the system due to failure of the i[th] workstation from the state S_2 when one machine of workstation 4 is not working. Elapsed repair time for the i[th] subsystem lies between (k, k+Δ), where i= 1, 2, 3 and k∈ [0, +∞).

$P_{QR}(q, t)$: Shows the probability at time t when the system is in the risk due to ignorance in inspection at the workstation 5

K_1, K_2 : Profit and service cost per unit time respectively

Also, consider $u_1 = e^r$ and $u_2 = \phi_M(r)$, according to Gumbel- Hougaard copula methodology the joint probability distribution is given by

$$\phi_M = \exp\left[r^{\theta} + [\log \phi_M(r)]^{\theta}\right]^{1/\theta}.$$

2.1. Assumptions

For reliability analysis of this manufacturing system, the following assumptions are taken into consideration.

- All the workstations are fully operational at t=0.
- Failures follow exponential time distribution and are statistically independent while repairs follow arbitrary time distributions.
- Repaired workstations are assumed like in good working conditions.
- Workstations 2 and 4 follow 2-out-of-3: G and 1-out-of-3: F conformation.
- It is also considered that the manufacturing system can fail due to any mechanical failure that may be major or minor or both at the same time. Here joint probability distribution is used to solve these failures using the copula methodology [6]. The whole system can also fail due to machine failures that may be either major or minor or both.

2.2. State specification

Table -1 shows the state specification of the transition diagram-1

Table 1: *State specification table*

States	Description	System State
S0	The system is in the fully operational stage.	G
S1	The system is in the failed state due to the failure of the workstation W_1.	F_R
S2	The system is in a working state when workstation W_2 is in 2-out-of-3: G configuration.	G
S3	Due to the failure of workstation W_3, the whole system is in the failed state.	F_R
S4	The system is in a working state when workstation W_4 is in 2-out-of-3: G configuration.	G
S5	Due to machine failure, the whole system is in a breakdown condition.	F_R
S6	System is working at high risk due to negligence of the workstation W_5.	R_S
S7	The system is in inoperable condition from the risk state i.e. S_6 due to ignorance in the inspection.	F_R
S8	The system is in inoperable condition from the state S_2 as workstation W_1 is unable to work due to some vendor issues.	F_R
S9	The system is in inoperable condition from the state S_2 due to the failure of workstation W_4.	F_R
S10	The system is in the failed state from the state S_2 because workstation W_2 follows 1-out-of-3: F configuration.	F_R
S11	The system is inoperable due to the not functioning of workstation W_3.	F_R
S12	The system is in inoperable condition from the state S4 due to the failure of workstation W_1.	F_R
S13	The system is inoperable from the state S_4 due to the failure of the workstation W_2.	F_R
S14	The system is inoperable from the state S_4 due to the failure of the workstation W_3.	F_R
S15	The system is inoperable from the state S_4 due to the failure of the workstation W_4.	F_R

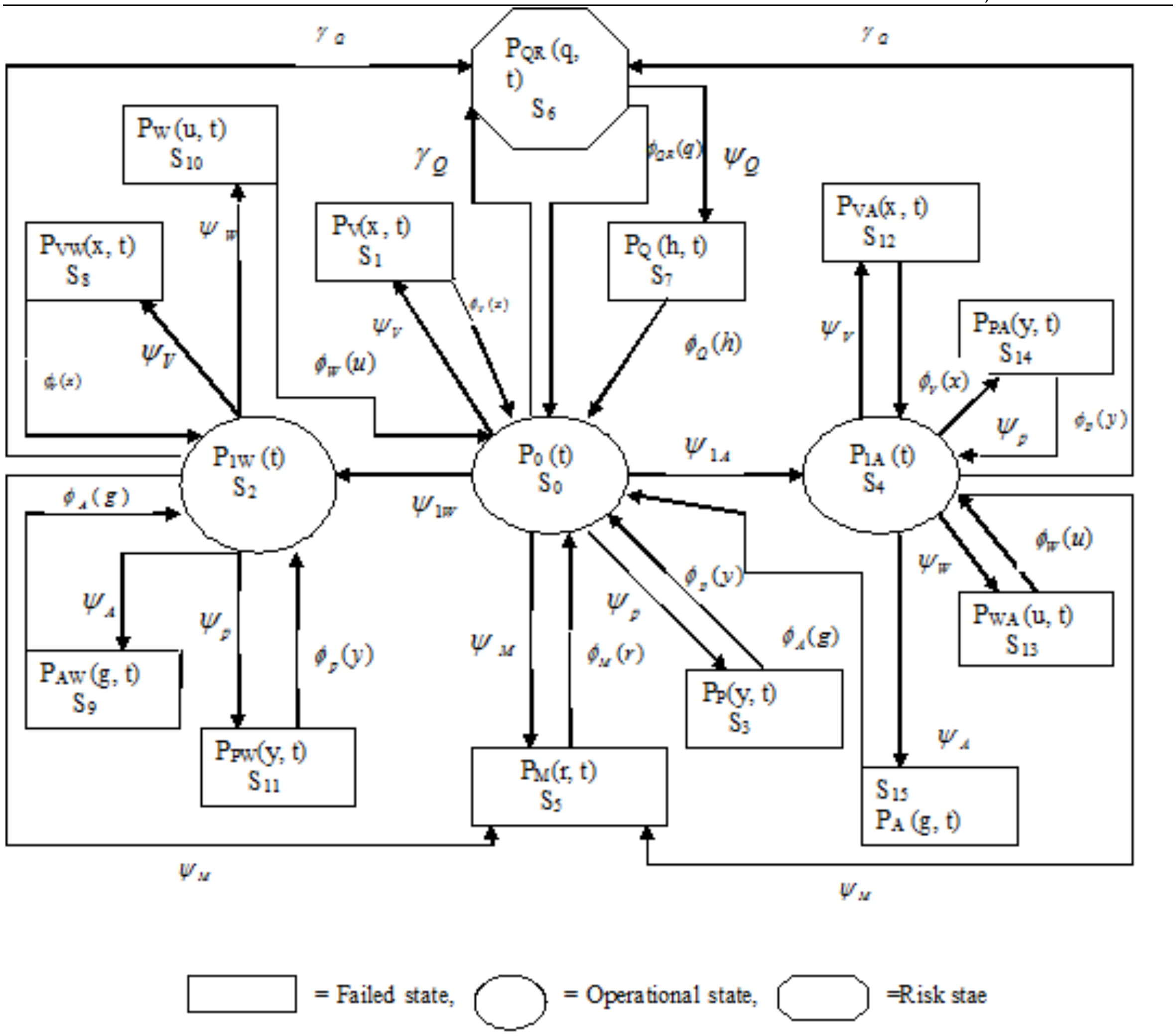

Figure 1: *Transition State diagram*

3. Formulation of the mathematical model

Following integro- differential equations which satisfying the model are obtained after probabilistic considerations and limiting process:

$$\left[\frac{d}{dt}+\psi_{1A}+\psi_{1W}+\psi_{V}+\psi_{M}+\psi_{p}+\gamma_{Q}\right]P_0(t)=\int_0^\infty \phi_V(x)P_V(x,t)dx+\int_0^\infty \phi_p(y)Pp(y,t)dy+$$
$$\int_0^\infty \phi_M(r)P_M(r,t)dg+\int_0^\infty \phi_Q(q)P_Q(q,t)dq+\int_0^\infty \phi_A(g)P_A(g,t)dg+$$
$$\int_0^\infty \phi_W(u)P_W(u,t)du+\int_0^\infty \phi_Q(h)P_Q(h,t)dh \tag{1}$$

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

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

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial r}+\exp\left[r^{\theta}+\{[\log\phi_M(r)]\}^{\theta}\right]^{1/\theta}\right]P_M(r,t)=0 \tag{4}$$

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

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial h}+\phi_Q(h)\right]P_Q(h,t)=0 \tag{6}$$

$$\left[\frac{d}{dt}+\psi_A+\psi_W+\psi_V+\psi_M+\psi_p+\gamma_Q\right]P_{1w}(t)=\int_0^\infty\phi_V(x)P_{VW}(x,t)dx+ \\ +\int_0^\infty\phi_A(g)P_{AW}(g,t)dg+\int_0^\infty\phi_p(y)P_{PW}(y,t)dy+\psi_{1W}P_0(t) \tag{7}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\phi_V(x)\right]P_{VW}(x,t)=0 \tag{8}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial g}+\phi_A(g)\right]P_{AW}(g,t)=0 \tag{9}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial y}+\phi_p(y)\right]P_{PW}(y,t)=0 \tag{10}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial u}+\phi_W(u)\right]P_W(u,t)=0 \tag{11}$$

$$\left[\frac{d}{dt}+\psi_A+\psi_W+\psi_V+\psi_M+\psi_p+\gamma_Q\right]P_{1A}(t)=\int_0^\infty\phi_V(x)P_{VA}(x,t)dx+ \\ \int_0^\infty\phi_p(y)P_{PA}(y,t)dy+\int_0^\infty\phi_W(u)P_{WA}(u,t)du+\psi_{1A}P_0(t) \tag{12}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\phi_V(x)\right]P_{VA}(x,t)=0 \tag{13}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial y}+\phi_p(y)\right]P_{PA}(y,t)=0 \tag{14}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial u}+\phi_W(u)\right]P_{WA}(u,t)=0 \tag{15}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial g}+\phi_A(g)\right]P_A(g,t)=0 \tag{16}$$

3.1 Boundary conditions

$$P_V(0,t)=\psi_V P_0(t) \tag{17}$$

$$P_p(0,t)=\psi_p P_0(t) \tag{18}$$

$$P_M(0,t)=\psi_M P_0(t) \tag{19}$$

$$P_{QR}(0,t) = \gamma_Q\left[P_0(t) + P_A(t) + P_W(t)\right] \quad (20)$$

$$P_Q(0,t) = \psi_Q P_{QR}(t) \quad (21)$$

$$P_{VW}(0,t) = \psi_V P_W(t) \quad (22)$$

$$P_{AW}(0,t) = \psi_A P_W(t) \quad (23)$$

$$P_{PW}(0,t) = \psi_p P_W(t) \quad (24)$$

$$P_W(0,t) = \psi_W P_W(t) \quad (25)$$

$$P_{VA}(0,t) = \psi_V P_A(t) \quad (26)$$

$$P_{pA}(0,t) = \psi_p P_p(t) \quad (27)$$

$$P_{WA}(0,t) = \psi_W P_A(t) \quad (28)$$

$$P_A(0,t) = \psi_A P_A(t) \quad (29)$$

3.2 Initial Condition

$P_0(0) = 1$, otherwise zero. (30)

After solving equations (1) to (16), using initial and boundary conditions by taking Laplace transform, one can obtain following up and down probabilities of the system.

$$\overline{P_0}(s) = \frac{1}{K(s)} \quad (31)$$

$$\overline{P_{1w}}(s) = \frac{B(s)}{K(s)} \quad (32)$$

$$\overline{P_{1A}}(s) = \frac{A(s)}{K(s)} \quad (33)$$

$$\overline{P_v}(s) = \frac{\psi_v}{K(s)} J_v(s) \quad (34)$$

$$\overline{P_P}(s) = \frac{\psi_P}{K(s)} J_P(s) \quad (35)$$

$$\overline{P_M}(s) = \frac{\psi_M}{K(s)} J_M(s) \quad (36)$$

$$\overline{P_{QR}}(s) = \frac{\gamma_Q}{K(s)}\left[1 + B(s) + A(s)\right]J_{QR}(s) \quad (37)$$

$$\overline{P_Q}(s) = \frac{\gamma_Q \psi_Q}{K(s)}\left[1 + A(s) + B(s)\right]J_{QR}(s) J_Q(s) \quad (38)$$

$$\overline{P_{VW}}(s) = \frac{\psi_V\, B(s)}{K(s)} J_V(s) \quad (39)$$

$$\overline{P_{PW}}(s)=\frac{\psi_P\,B(s)}{K(s)}J_P(s) \tag{40}$$

$$\overline{P_{AW}}(s)=\frac{\psi_A\,B(s)}{K(s)}J_A(s) \tag{41}$$

$$\overline{P_{W}}(s)=\frac{\psi_W\,B(s)}{K(s)}J_W(s) \tag{42}$$

$$\overline{P_{VA}}(s)=\frac{\psi_V\,A(s)}{K(s)}J_V(s) \tag{43}$$

$$\overline{P_{PA}}(s)=\frac{\psi_P\,A(s)}{K(s)}J_P(s) \tag{44}$$

$$\overline{P_{WA}}(s)=\frac{\psi_W\,A(s)}{K(s)}J_W(s) \tag{45}$$

$$\overline{P_{A}}(s)=\frac{\psi_A\,A(s)}{K(s)}J_A(s) \tag{46}$$

where,

$$K(s)=s+\psi_V+\psi_M+\psi_P+\psi_{1A}+\psi_{1W}+\gamma_Q-\psi_V\overline{S}_V(s)-\psi_P\overline{S}_P(s)-\psi_M\overline{S}_M(s)-$$
$$\gamma_Q\overline{S}_{QR}(s)-\left[\gamma_Q\overline{S}_{QR}(s)+\psi_A\overline{S}_A(s)\right]\frac{\psi_{1A}}{C_1}-\left[\gamma_Q\overline{S}_{QR}(s)+\psi_W\overline{S}_W(s)\right]\frac{\psi_{1w}}{c_2}-$$
$$\psi_Q\gamma_Q\overline{S}_Q(s)\left[1+\frac{\psi_{1W}}{C_1}+\frac{\psi_{1A}}{C_2}\right]J_{QR}(s) \tag{47}$$

$$J_i(s)=\frac{1-\overline{S_v(s)}}{s},\ \text{for}\ i=V,P,M,QR,Q,A,W \tag{48}$$

$$J_{QR}(s)=\frac{1-\overline{S}_{QR}(s)}{s+\psi_Q} \tag{49}$$

$$A(s)=\frac{\psi_{1A}}{C_1} \tag{50}$$

$$B(s)=\frac{\psi_{1W}}{C_2}$$

(51)

$$C_1=s+\psi_V+\psi_M+\psi_P+\psi_A+\psi_W+\gamma_Q-\psi_V\overline{S}_V(s)-\psi_P\overline{S}_P(s)-\psi_W\overline{S}_W(s) \tag{52}$$

$$C_2=s+\psi_V+\psi_M+\psi_P+\psi_A+\psi_W+\gamma_Q-\psi_V\overline{S}_V(s)-\psi_P\overline{S}_P(s)-\psi_A\overline{S}_A(s) \tag{53}$$

$$\overline{S}_i(j)=\int_0^\infty\phi_i(j)\exp[-s_j-\int_0^i\phi_i(j)dj]dj,\ for\ i=V,P,M,QR,Q,A,W\ \&\ j=x,y,r,q,h,g,u. \tag{54}$$

$$\phi_M=\exp\left[r^\theta+\left[\log\phi_M(r)\right]^\theta\right]^{1/\theta} \tag{55}$$

Also,

$$\overline{P}_{up}(s)+\overline{P}_{down}(s)=\frac{1}{s} \tag{56}$$

To study the steady-state behavior of the system using Abel's lemma we have

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

$$\overline{Pup}(s) = P_0(s) + P_{1W}(s) + P_{1A}(s) \tag{57}$$

$$P_0 = \frac{1}{K^{'}(0)} \tag{58}$$

$$P_{1W} = \frac{B(0)}{K^{'}(0)} \tag{59}$$

$$P_{1A} = \frac{A(0)}{K^{'}(0)} \tag{60}$$

where,

$$K^{'}(0) = \left[\frac{d}{ds}K(s)\right]_{s=0} \tag{61}$$

$T_i = -\bar{S}_i(0)$ =Mean time to repair the i^th failure (62)

$$A(0) = \frac{\psi_{1A}}{\psi_M + \psi_A + \gamma_Q} \tag{63}$$

$$B(0) = \frac{\psi_{1W}}{\psi_M + \psi_A + \gamma_Q} \tag{64}$$

$$\underline{Lim} J_{QR}(s) = \frac{1}{\psi_Q} M_{QR} \quad \text{(As s tends to 0)} \tag{65}$$

$$S_{\phi_i}(j) = \frac{\phi_i}{j + \phi_i} \tag{66}$$

For a non-repairable system, the Laplace transform of the reliability when all repair rates of the system are zero, then from equation (31), we have

$$\bar{R}(s) = \frac{1}{s + \psi_v + \psi_P + \psi_{1A} + \psi_{1W} + \psi_M + \gamma_Q}$$

where R(s) is the Laplace transform of the reliability function.

The reliability of the transit system is obtained as:

$$R(t) = \exp[-(\psi_V + \psi_M + \psi_P + \psi_{1A} + \psi_{1W} + \gamma_Q)*t] \tag{67}$$

The mean time to failure of the system is given by,

$$\text{MTTF} = Lim\overline{R}(s) = \int_0^{\infty} R(t)dt$$

$$MTTF = \frac{1}{\psi_V + \psi_M + \psi_P + \psi_{1A} + \psi_{1W} + \gamma_Q} \tag{68}$$

Availability of the system is given by,

$$\overline{Pup(s)} = P_0(s) + P_{1W}(s) + P_{1A}(s)$$

$$\overline{P}up(s) = \frac{1}{K(s)}\left[1 + B(s) + A(s)\right]$$

$$\overline{P}up(s) = \frac{1 + \frac{.016}{s + .055}}{s + .054}$$

Taking inverse Laplace transforms, we have

$$Pup(t) = -16.e^{(-.0550000000t)} + 17.e^{(-.0540000000t)} \tag{69}$$

Sensitivity analysis is performed for monitoring changes in reliability and MTTF of the system with respect to workstations W1, W3, and risk factor γ_Q.

we obtain

$$\frac{\partial R(t)}{\partial \psi_V} = -te^{(-(\psi_v + \psi_P + \psi_{1A} + \psi_{1W} + \psi_M + \gamma_Q)*t)} \tag{70}$$

Also, we can get $\frac{\partial R(t)}{\partial \psi_P}$ and $\frac{\partial R(t)}{\partial \gamma_Q}$.

$$\frac{\partial}{\partial \psi_V} MTTF = -\frac{1}{(\psi_v + \psi_P + \psi_{1A} + \psi_{1W} + \psi_M + \gamma_Q)^2} \tag{71}$$

Also, $\partial MTTF / \partial \psi_P$ and $\partial MTTF / \partial \gamma_Q$.

The profit function of the considered manufacturing system is given by

$$G(t) = K_1 \cdot \int_0^t P_{up}(t)dt - K_2 t$$

where, K1 and K2 are revenue and repair costs per unit time, respectively.
Also

$$G(t) = K_1 \int_0^t e^{(-(\psi_v + \psi_P + \psi_{1A} + \psi_{1W} + \psi_M + \gamma_Q)t)} + \left[\frac{\psi_{1A} + \psi_{1W}}{\psi_{1A} + \psi_{1W} - \psi_W - \psi_A}\right] e^{(-(\psi_v + \psi_P + \psi_{1A} + \psi_{1W} + \psi_M + \gamma_Q)t)} - \left[\frac{\psi_{1A} + \psi_{1W}}{\psi_{1A} + \psi_{1W} - \psi_W - \psi_A}\right] e^{(-(\psi_v + \psi_P + \psi_A + \psi_W + \psi_M + \gamma_Q)t)} dt - K_2 t \tag{72}$$

4. Results and discussion

To check more concrete behavior of the system, Numerical computation of reliability, availability, and profit function is done concerning time by keeping other parameter fixed and also MTTF of the system for different failure rates.

Figure 2 shows the movement of reliability with respect to time. It reveals that due to ignorance of the workstation W_5 in inspection, the reliability decreases with the passage of time. Figure 3 shows a rapid decrease in MTTF with an increment in Workstation W_1, W_3, and machine failure rate. It is also observed that in some instances MTTF is almost the same with respect to these three failure rates. Also, as the risk rate increases, the MTTF of the system decreases smoothly shown in figure 4. Figure 5 gives an idea about the availability of the system that decreases constantly as time increases.

Sensitivity analysis of system reliability is done for different workstations failure rates as shown in figures 6, 7, 8, and 9. Here we observe that the system has almost same sensitivity for W_1 workstation failure and risk rate, although machine failure and workstation W_2 come next in magnitude.

Finally, Figure 10 shows that the cost of the system increases in general with time.

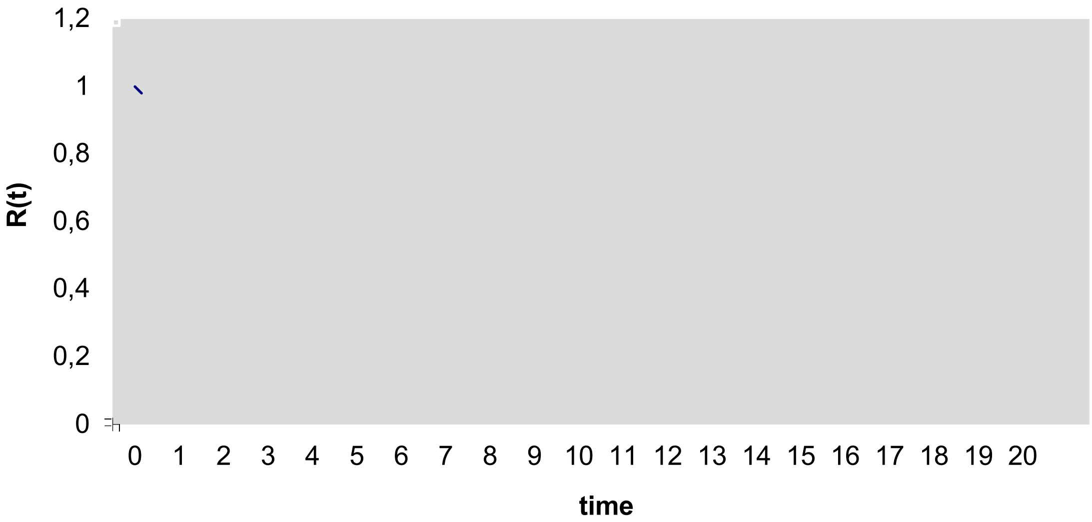

Figure 2: *Reliability Vs Time*

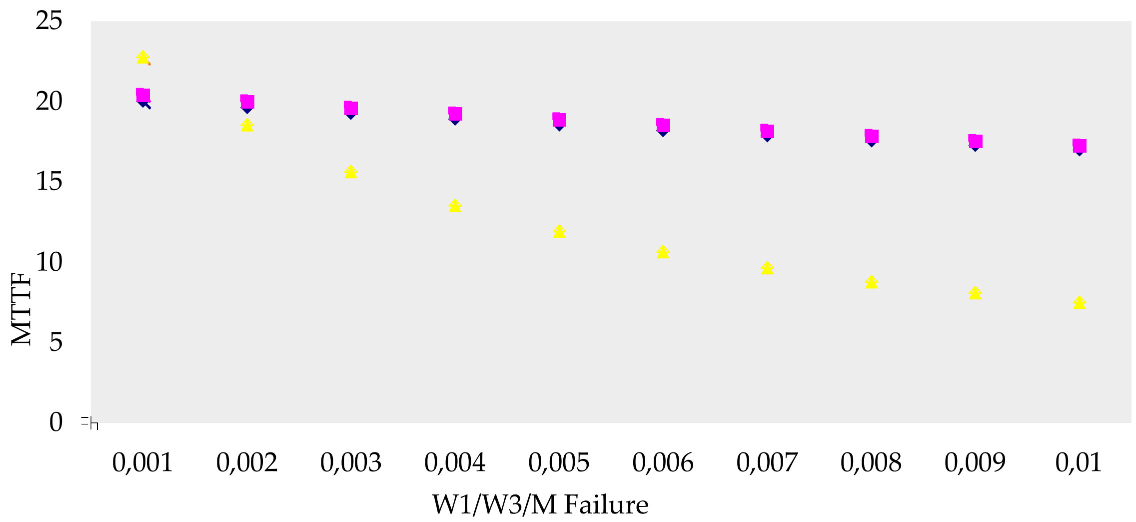

Figure 3: *MTTF Vs workstation W_1, workstation W_3 and Machine failure*

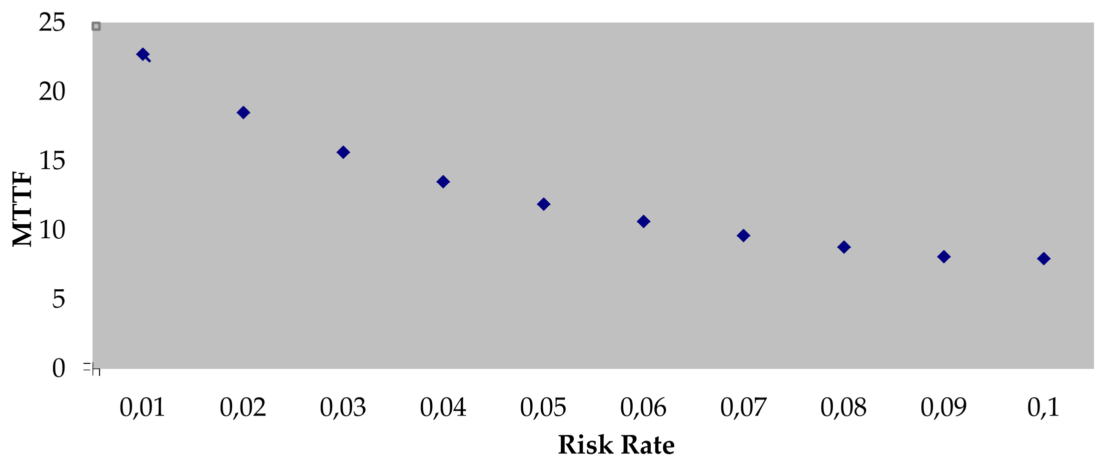

Figure 4: *MTTF Vs Risk Rate*

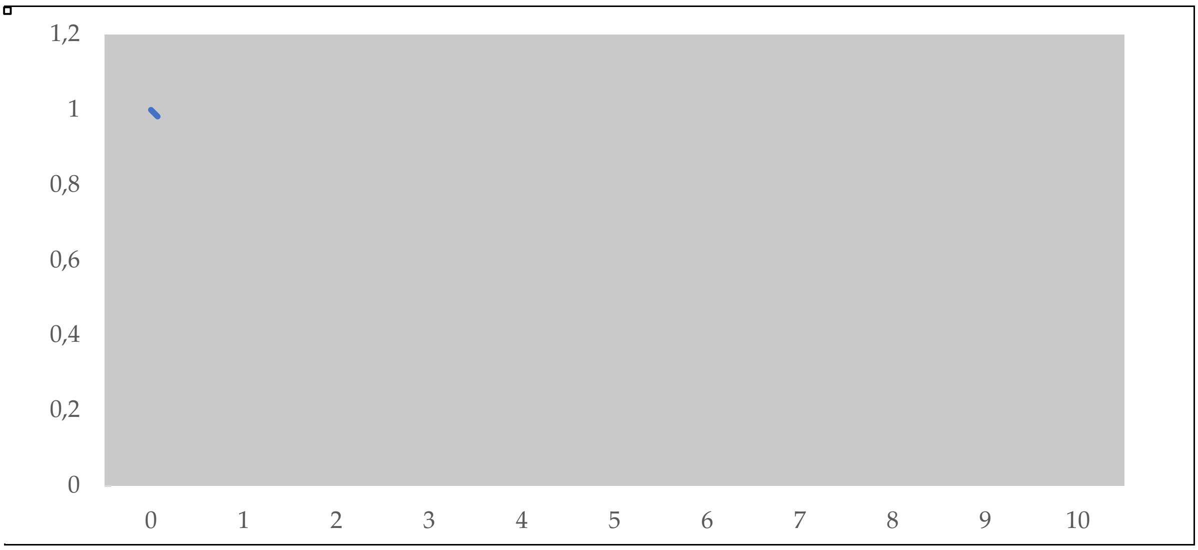

Figure 5: *Availability Vs Time*

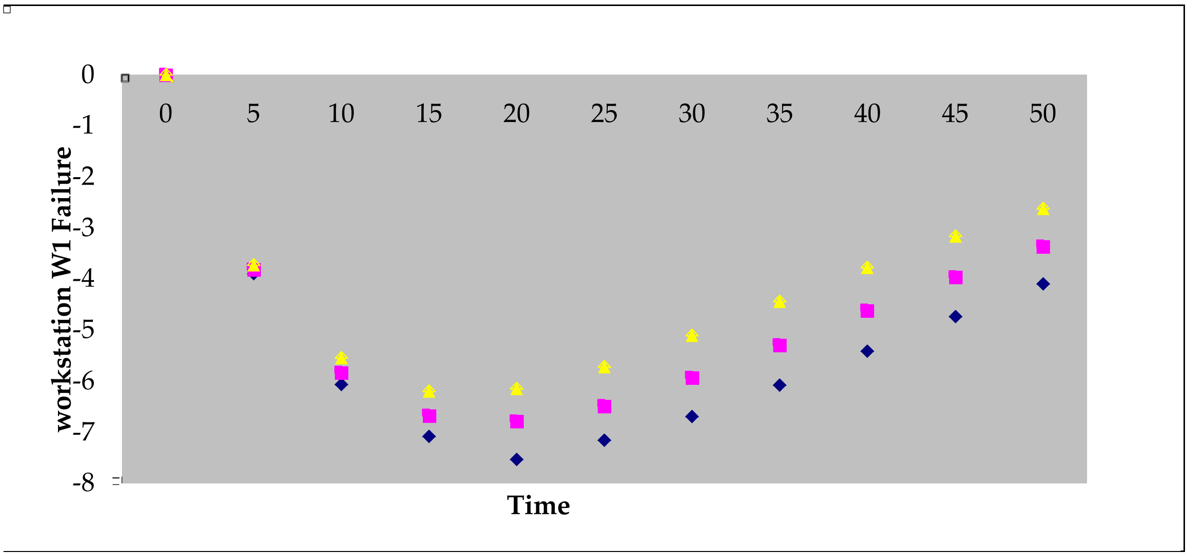

Figure 6: *Sensitivity of system reliability with respect to workstation W_1 failure.*

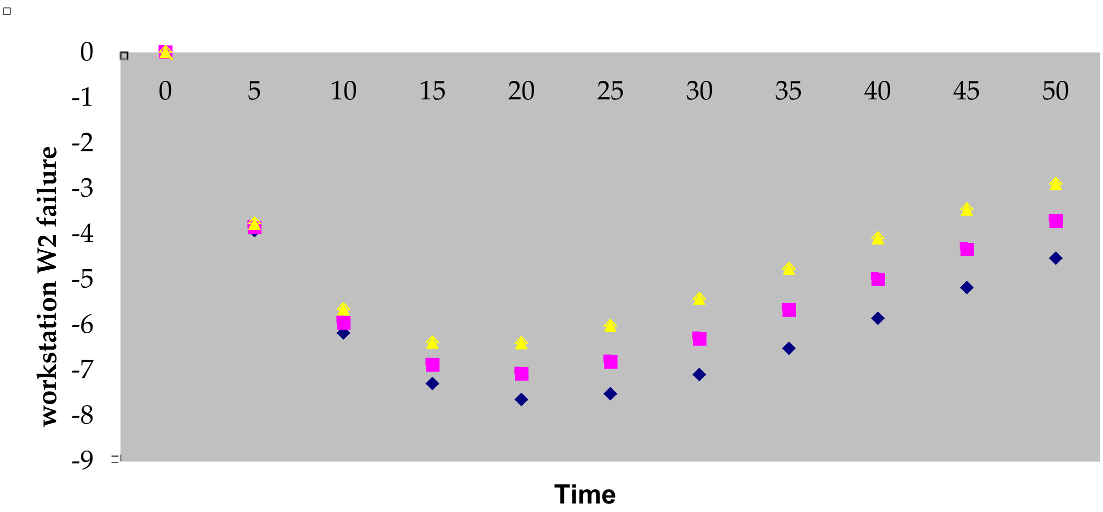

Figure 7: *Sensitivity of system reliability with respect to workstation W_2 failure.*

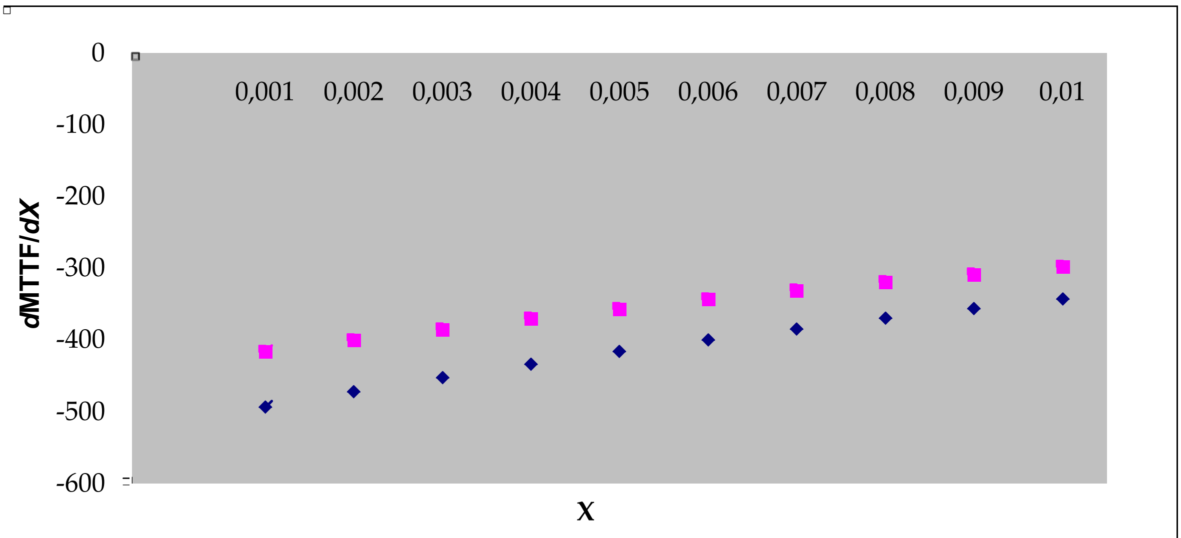

Figure 8: *Sensitivity for MTTF with respect to $X1=\psi_V$, $X2=\psi_P$. $(X=X1=X2)(\psi_V=\psi_P=.001, .002 \ldots .01)$*

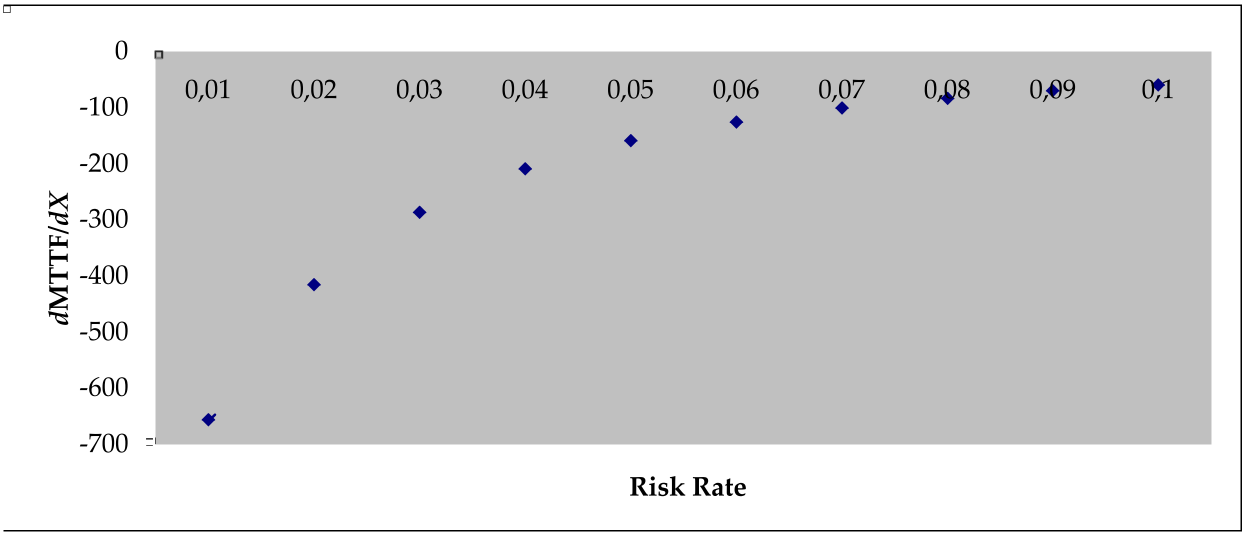

Figure 9: *Sensitivity for MTTF with respect to X=* γ_Q *(* γ_Q *=.01,. 02,…,.1)*

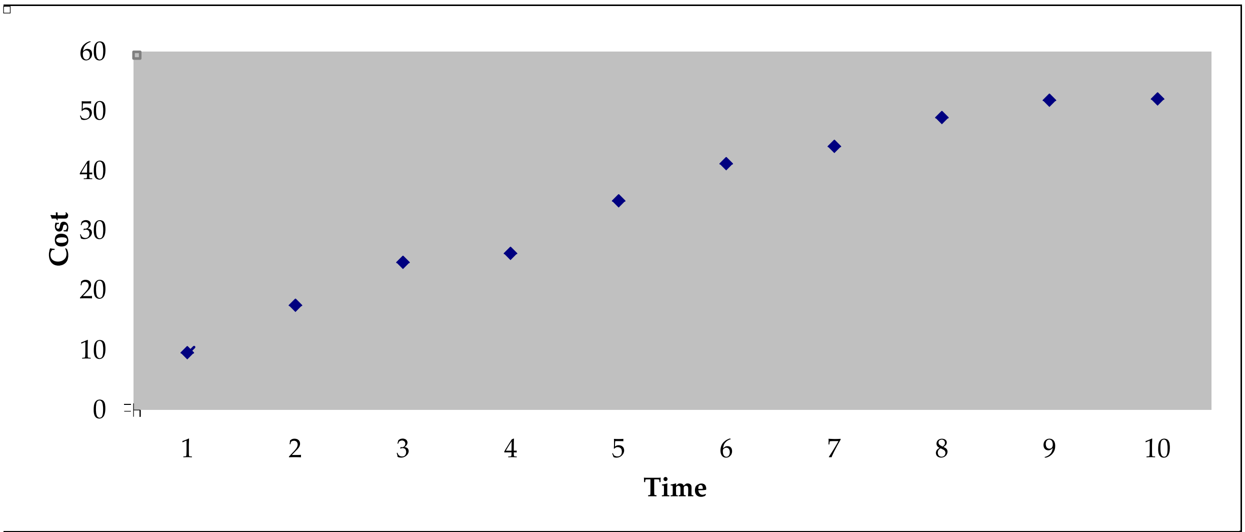

Figure 10: *Cost Vs Time*

5. Conclusion

In this work, the operational behavior of a k-out of-n configuration system is discussed including risk factor using mathematical modelling technique. Also, a comparative analysis of reliability, availability, MTTF, risk, sensitivity, and profit function are done with time for different workstations. The proposed technique has an advantage of analyzing reliability of a complex manufacturing system in a more flexible way.

The study may help a manufacturing industry in:

a. Handling resources and suppliers
b. Planning of production strategies and maintenance policies
c. Decision making.

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