RELIABILITY AND AVAILABILITY ANALYSIS OF AN 8-STEP AUTO UNIT MANUFACTURING PROCESS HAVING A FAULT IN MAINTENANCE

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Abstract

Human plays a vital role in the manufacturing process of a product during the planning, design, assembly, production, and maintenance phase. This paper presents a systematic method of determining the reliability and availability of an 8-step auto unit manufacturing system taking into consideration the case of occurring human error during maintenance. The whole process involves eight major units as Combustion engine, power train unit, fuel feed unit, fuel injection unit, drain or exhaust unit, engine cooling unit, brake unit, and body frame. With the failure of any of these units, the whole process can fail. Also, a constant failure rate and a general repair time are taken into the consideration for each operative unit that makes up the process. The integral differential equations were generated based on Markov modeling of the process and solution derived by considering repair time distribution using the Laplace transform. Calculations of different reliability aspects like process availability, mean time to failure steady-state nature, and profit analysis are done using supplementary variable technique and copula methodology.

Keywords: Reliability, Availability, Failure probability, Supplementary variable technique, Markov model, Human error.

1. Introduction

For a very long period, a good amount of work has been done to find the reliability of various manufacturing and industrial systems. Many researchers applied different methods like the Hidden Markov models, state space method, K map approach, probabilistic rational model method, etc. to analyze the reliability and steady-state nature of some realistic manufacturing systems like Aircraft and sea-going ships, bufferless production system, Aircraft commutators, automobile assembly process, fiber plant unit, etc. [1, 4, 5, 12, 13, and 14]. Here the discussion is focused on the reliability and availability analysis of an 8-step auto unit manufacturing process.

The automobile sector has played a significant role in the economic growth and development of any country. Because of the steady growth in the GDP of a country due to the contribution of the auto industry, it is also called an "industry of industries". Although the industry started in Germany and France now it has become one of the global all over the world.

The automobile manufacturing process is a multifaceted process involving various steps starting from designing, building, quality checks, and shipping. The first phase of the process is to design, develop, and product analysis. Once this phase is completed the next step is fulfill the requirements of tools and apparatus for the bulk production of the vehicle. This phase includes everything right from engine assembly, welding and painting to stamping machines. Following this phase, is production planning which decides the quantity needs to manufacture. Before launching the product, it has to undergo different quality and safety checks. The purpose of these checks is to ensure that the product is designed by considering all safety standards and will perform failure-free operation.

In this competitive scenario, to sustain itself in the market and to fulfill customer expectation it is required to increase the product performance, topographies, and quality, as a result, the complexity and mechanization of the product are increased and it has resulted in several issues related to maintenance and repair [8, 9]. When we talk about manufacturing lines, a repairman plays a vital role in this field during the design, installation, production, and maintenance. The probability of occurrence of human error is more in this maintenance phase only. Human error in repair is a concern, that has not gotten the proper attention of the researchers. It can be defined as failure to perform a particular operation that could result in a delay in the production or could damage a machine or equipment. These errors may occur due to various reasons like insufficient facilities and services, less technical skills, design errors or improper planning, etc. These errors may be classified into different categories like Design, operational, installation, quality check, maintenance, etc. Maintenance error is defined as an unintentional failure occurred during the maintenance of the product because of improper repair or proactive measures. The probability of occurrence of maintenance error increases as the product gets older [6, 10].

By considering all the above facts the present study proposes a methodology to assess the reliability and performance of a manufacturing process having a fault in maintenance due to human error. The assumed process involves eight major units as Combustion engine, power train unit, fuel feed unit, fuel injection unit, drain or exhaust unit, engine cooling unit, brake unit, and body frame. The main focus of the study is on failure during maintenance due to human error. The following assumptions have been made for the whole process:

- The combustion engines can fail due to operational errors.
- The power train unit contains: a clutch, transmission gear, differential and final drive
    - It is assumed that the process can fail due to inappropriate fitting of the power train and transmission gear.
    - The process can be in a degraded state because of inappropriate working of differential.
    - Also, the process can completely fail due to final drive failure.
- It is considered that the process can fail due mistake in fuel injection pump timings during an inspection in the fuel feed unit.
- Furthermore, it is also assumed that the process can fail due to maintenance errors and mistakes in quality checks in the fuel injection unit because of misfiring and disturbed pressure levels.
- Improper assembly of the exhaust units can cause process failure and overheating problems in the engine cooling units can take the process into a degraded state.
- The process can fail due to design error in break unit.
- Improper installation of axle and chassis can lead to process failure in the build unit.

  The whole process can fail due to the failure of any of these units. A joint repair policy is applied to repair the system in the power train when the failure occurs due to failure of the differential and final drive.
- Fuel injection unit when the failure occurs due to misfiring and disturbed pressure level.

Here, the joint probability distribution is applied with the help of the Gumbel-Hougaard Copula methodology [7, 11]. Also, failures follow exponential time distribution while general time distribution is applied for repairs. To help the production industry some parametric investigations for process reliability, availability, mean time to failure, and profit analysis has been made [2, 3]. The state transition figure is shown in figure-1.

2. Notations

Different notations used in the model are given in table 1 and the state specification of the model is described in table 2.

Table 1: *Notations*

$P_0(t)$	:	Indicates the probability that initially the whole system is fully operational, denoted by state S0
$P_i(j,t)$	:	The probability that the process is in the failed state due to failure of the i[th] unit at any time, here, *i=1,2,4,5,6,7,9,10,11* and Elapsed repair time *j= x, y, v, w, m, r, n, v, k*
α_{EO}	:	Combustion engine failure rate due to operational error
α_{TI}/α_{FSS}	:	Failure rates of transmission gear and fuel injection pump in fuel supply
α_D/α_{DS}	:	Differential unit failure rate and final drive failure rate
α_M/α_{LP}	:	The failure rate of misfiring and disturbed pressure level to be low pressure of fuel injection unit
α_{EA}	:	Exhaust unit failure rate
α_{OVH}	:	Failure rate due to overheating
α_{CS}	:	The cooling unit failure rate
α_{BR}	:	Break unit failure rate
α_{BU}	:	Build unit failure rate
$\varphi_k(j)$	:	Shows the repair rate of kth failure in the time interval (j, j+Δ), where, *k = EO, TI, D, DS, FSS, M, LP, EA, OVH, CS, BR, BU,* and *j = x, y, v, w, m, r, n, v, k*
K_1, K_2	:	Profit cost and service cost per unit of time respectively

Consider that, $u_1 = e^m$, $u_2 = \phi_{LP+M}(m)$ and $X_1 = e^w$, $X_2 = \phi_{D+DS}(w)$, then joint probability is given by the expression,

$\phi_{LP+M}(m) = \exp[m^\theta + (\log\phi_{LP+M}(m))^\theta)^{1/\theta}]$, $\phi_{D+DS}(w) = \exp[w^\eta + (\log\phi_{D+DS}(w))^\eta)^{1/\eta}]$

using Gumbel- Hougaard copula methodology.

3. State specification

The state specification of the process is given by the table 2.

Table 2: *Process state specification*

States	Description	System State
S_0	State in which the process is fully operational	G
S_1	State in which the process gets failed due to operational error in combustion engine	FR
S_2	State in which the process is failed due to inappropriate fitting of the power train and transmission gear	FR

S_3	State in which the process is in a degraded state because of inappropriate working of differential	D
S_4	State in which the process is completely failed due to final drive failure	FR
S_5	State in which the process fails due mistakes in fuel injection pump timings during an inspection in the fuel feed unit	FR
S_6	State in which the process fails due to maintenance error and mistake in quality check in fuel injection unit because of misfiring and disturbed pressure level	FR
S_7	State in which process gets fail due to improper assembly of the exhaust unit	FR
S_8	State in which the process gets degraded because of overheating problem in the engine cooling unit	D
S_9	State in which process is failed due to failure of the cooling unit	FR
S_{10}	State in which process gets failed due to design error in break unit	FR
S_{11}	State in which the process gets failed due to improper installation of axle and chassis in the build unit	FR

Note: G= Good state; FR= Failed state under repair; D = Degraded state

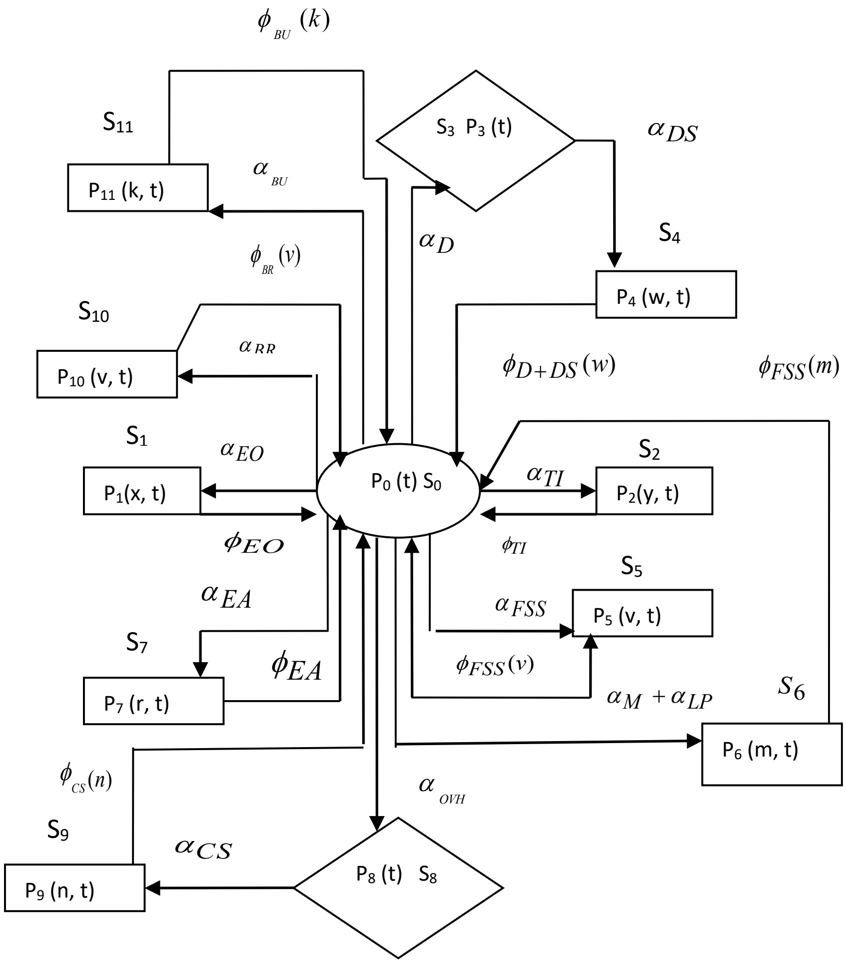

Figure 1: *State transition diagram for 8-step auto manufacturing process*

4. Mathematical formulation of the model

The differential transition state probabilities for different states of the model are given by the following equations

$$\left[\frac{d}{dt}+\alpha_{EO}+\alpha_{TI}+\alpha_{D}+\alpha_{FSS}+(\alpha_{M}+\alpha_{LP})+\alpha_{EA}+\alpha_{OVH}+\alpha_{BR}+\alpha_{BU}\right]P_0(t)=$$
$$\int_0^\infty \phi_{EO}(x)P_1(x,t)dx+\int_0^\infty \phi_{TI}(y)P_2(y,t)dy+\int_0^\infty \phi_{D+DS}(w)P_4(w,t)dw+$$
$$\int_0^\infty \phi_{FSS}(v)P_5(v,t)dv+\int_0^\infty \phi_{M+LP}(m)P_6(m,t)dm+\int_0^\infty \phi_{EA}(r)P_7(r,t)dr+$$
$$\int_0^\infty \phi_{CS}(n)P_9(n,t)dn+\int_0^\infty \phi_{BR}(l)P_{10}(l,t)dl+\int_0^\infty \phi_{BU}(k)P_{11}(k,t)dk \quad (1)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\phi_{EO}(x)\right]P_1(x,t)=0 \quad (2)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial y}+\phi_{TI}(y)\right]P_2(y,t)=0 \quad (3)$$

$$\left[\frac{d}{dt}+\alpha_{DS}\right]P_3(t)=\alpha_{D}P_0(t) \quad (4)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial w}+\phi_{D+DS}(w)\right]P_4(w,t)=0 \quad (5)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial v}+\phi_{FSS}(v)\right]P_5(v,t)=0 \quad (6)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial m}+\phi_{LP+M}(m)\right]P_6(m,t)=0 \quad (7)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial r}+\phi_{EA}(r)\right]P_7(r,t)=0 \quad (8)$$

$$\left[\frac{d}{dt}+\alpha_{CS}\right]P_8(t)=\alpha_{OVH}P_0(t) \quad (9)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial n}+\phi_{CS}(n)\right]P_9(n,t)=0 \quad (10)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial v}+\phi_{BR}(v)\right]P_{10}(v,t)=0 \quad (11)$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial k}+\phi_{BU}(k)\right]P_{11}(k,t)=0 \quad (12)$$

Boundary Conditions:

$$P_i(0,t)=\alpha_k P_0(t) \quad (13)$$

$$P_4(0,t)=\alpha_{DS}P_3(t) \quad (14)$$

$$P_9(0,t)=\alpha_{CS}P_8(t) \quad (15)$$

Where, *i=1,2,5,6,7,10,11 and k=EO, TI, D, FSS, M, LP, EA, OVH, BR, BU*

Initial Condition:

$$P_0(0)=1 \text{, otherwise zero.} \tag{16}$$

For finding the solution of the mathematical model, Taking Laplace transforms of equation (1) to (12), subject to the initial condition (16), and then solving them, we get the following transition state probabilities of the model:

$$\overline{P_0}(s)=\frac{1}{B(s)} \tag{17}$$

$$\overline{P_i}(s)=\frac{\alpha_k \times D_{\varphi_k}(s)}{B(s)} \tag{18}$$

where i=1, 2, 5, 6, 7, 10, 11 and k= EO, TI, FSS, LP+M, EA, BR, BU

$$\overline{P_3}(s)=\frac{\alpha_D}{[s+\alpha_{DS}]}\times\frac{1}{B(s)} \tag{19}$$

$$\overline{P_4}(s)=\frac{\alpha_D\alpha_{DS}}{[s+\alpha_{DS}]}\times\frac{D\phi_{D+DS}(s)}{B(s)} \tag{20}$$

$$\overline{P_8}(s)=\frac{\alpha_{OVH}}{[s+\alpha_{CS}]}\times\frac{1}{B(s)} \tag{21}$$

$$\overline{P_9}(s)=\frac{\alpha_{CS}\times\alpha_{OVH}\times D_{\phi_{CS}}(s)}{(s+\alpha_{CS})\times B(s)} \tag{22}$$

where,

$$\begin{aligned} B(s)={}& s+\alpha_{EO}+\alpha_{TI}+\alpha_D+\alpha_{FSS}+(\alpha_M+\alpha_{LP})+\alpha_{EA}+\alpha_{OVH}+\alpha_{BR}+\alpha_{BU} \\ & -\alpha_{EO}\times\overline{S}_{\phi_{EO}}(s)-\alpha_{TI}\times\overline{S}_{\phi_{TI}}(s)-\frac{\alpha_D\alpha_{DS}}{[s+\alpha_{DS}]}\times\overline{S}_{\phi_{D+DS}}(s)-\alpha_{FSS}\times\overline{S}_{\phi_{FSS}}(s) \\ & -\alpha_{LP+M}\times\overline{S}_{\phi_{LP+M}}(s)-\alpha_{EA}\times\overline{S}_{\phi_{EA}}(s)-\frac{\alpha_{CS}\alpha_{OVH}}{(s+\alpha_{CS})}\times\overline{S}_{\phi_{CS}}(s)-\alpha_{BR}\times\overline{S}_{\phi_{BR}}(s) \\ & -\alpha_{BU}\times\overline{S}_{\phi_{BU}}(s) \end{aligned} \tag{23}$$

$$\phi_{LP+M}(m)=\exp[m^\theta+(\log\phi_{LP+M}(m))^\theta)^{1/\theta}] \tag{24}$$

$$\phi_{D+DS}(w)=\exp[w^\eta+(\log\phi_{LP+M}(w))^\eta)^{1/\eta}] \tag{25}$$

Also, up-state and down-state probabilities of the system are given by:

$$\begin{aligned} \overline{P}up(s)&=\overline{P}_0(s)+\overline{P}_3(s)+\overline{P}_8(s) \\ &=\frac{1}{B(s)}\times\left[1+\frac{\alpha_D}{[s+\alpha_{DS}]}+\frac{\alpha_{OVH}}{[s+\alpha_{CS}]}\right] \end{aligned} \tag{26}$$

$$\overline{P}_{down}(s)=\overline{P}_1(s)+\overline{P}_2(s)+\overline{P}_4(s)+\overline{P}_5(s)+\overline{P}_6(s)+\overline{P}_7(s)+\overline{P}_9(s)+\overline{P}_{10}(s)+\overline{P}_{11}(s)$$

$$=\frac{1}{B(s)}\times[$$

$$\alpha_{EO}\times D_{\phi_{EO}}(s)+\alpha_{TI}\times D_{\phi_{TI}}(s)+\frac{\alpha_D\alpha_{DS}}{[s+\alpha_{DS}]}D_{\phi_{D+DS}}(s)+\alpha_{FSS}\times D_{\phi_{FSS}}(s)$$

$$+\alpha_{LP+M}\times D_{\phi_{LP+M}}(s)+\alpha_{EA}\times D_{\phi_{EA}}(s)+\frac{\alpha_{CS}\times\alpha_{OVH}D_{\phi_{CRSG}}(s)}{(s+\alpha_{CS})}+$$
$$\alpha_{BR}\times D_{\phi_{BR}}(s)+\alpha_{BU}\times D_{\phi_{BU}}(s) \quad (27)$$

4.1. Steady-state behavior of the system

By using Abel's lemma,

$$\lim_{s\to 0}\{s\overline{F}(s)\}=\lim_{t\to\infty}F(t)$$

We get following up and down time independent operational probabilities:

$$\overline{P}up=\frac{1}{B(0)}\times\left[1+\frac{\alpha_D}{\alpha_{DS}}+\frac{\alpha_{OVH}}{\alpha_{CS}}\right] \quad (28)$$

$$\overline{P}down=\frac{1}{B(0)}\times[\ \alpha_{EO}\times\overline{M}_{\phi_{EO}}+\alpha_{TI}\times\overline{M}_{\phi_{TI}}(s)+\frac{\alpha_D}{\alpha_{DS}}+\frac{\alpha_D\times\alpha_{DS}}{[\alpha_{DS}]}\times M_{\phi_{D+DS}}$$
$$+\alpha_{FSS}\times M_{\phi_{FSS}}+\alpha_{LP+M}\times M_{\phi_{LP+M}}+\alpha_{EA}\times M_{\phi_{EA}}+\frac{\alpha_{OVH}}{\alpha_{CS}}$$
$$+\frac{\alpha_{CS}\alpha_{OVH}}{\alpha_{CS}}M_{\phi_{CS}}+\alpha_{BR}\times M_{\phi_{BR}}+\alpha_{BU}\times M_{\phi_{BU}}\ ] \quad (29)$$

where,

$$B(0)=\lim_{s\to 0}B(s) \quad (30)$$

$$\overline{M}_i=\lim_{s\to 0}\left\{\frac{1-\overline{S}_i(s)}{s}\right\},\ i=\phi_{EO},\phi_{TI},\phi_{D+DS},\phi_{FSS},\phi_{LP+M},\phi_{EA},\phi_{CS},\phi_{BR},\phi_{BU} \quad (31)$$

$$S_{\phi_i}(s)=\frac{\phi_i}{s+\phi_i},\ i=\phi_{EO},\phi_{TI},\phi_{D+DS},\phi_{FSS},\phi_{LP+M},\phi_{EA},\phi_{CS},\phi_{BR},\phi_{BU} \quad (32)$$

4.2. Special case

when repair rates follow exponential time distribution then,

Let, $\overline{S}_{\phi_i}(s)=\dfrac{\phi_i}{s+\phi_i},\forall i$, $\overline{S}_{\phi_{LP+M}}(s)=\dfrac{\exp\left[m^\theta+\left[\log\phi_{LP+M}(m)\right]^\theta\right]^{1/\theta}}{s+\exp\left[m^\theta+\left[\log\phi_{LP+M}(m)\right]^\theta\right]^{1/\theta}}$ and

$\overline{S}_{\phi_{D+DS}}(s)=\dfrac{\exp\left[w^\theta+\left[\log\phi_{D+DS}(w)\right]^\eta\right]^{1/\eta}}{s+\exp\left[w^\theta+\left[\log\phi_{D+DS}(w)\right]^\eta\right]^{1/\eta}}$ in equations (17) to (22) we get,

$$\overline{P}up(s)=\frac{1}{B_1(s)}\times\left[1+\frac{\alpha_D}{[s+\alpha_{DS}]}+\frac{\alpha_{OVH}}{[s+\alpha_{CS}]}\right]$$

$$\overline{P}down(s)=\frac{1}{B_1(s)}\times[\frac{\alpha_{EO}}{[s+\phi_{EO}]}+\frac{\alpha_{TI}}{[s+\phi_{TI}]}+\frac{\alpha_D}{[s+\phi_{DS}]}+\frac{\alpha_D\alpha_{DS}}{[s+\phi_{DS}]}\frac{1}{[s+\phi_{D+DS}]}+$$
$$\frac{\alpha_{FSS}}{[s+\phi_{FSS}]}+\frac{\alpha_{LP+M}}{[s+\phi_{LP+M}]}+\frac{\alpha_{EA}}{[s+\phi_{EA}]}+\frac{\alpha_{OVH}}{[s+\alpha_{CS}]}+\frac{\alpha_{CS}\alpha_{OVH}}{[s+\phi_{CS}][s+\alpha_{CS}]}$$
$$+\frac{\alpha_{BR}}{[s+\phi_{BR}]}+\frac{\alpha_{BU}}{[s+\phi_{BU}]}]$$

where,

$$B_1(s) = s + \alpha_{EO} + \alpha_{TI} + \alpha_D + \alpha_{FSS} + (\alpha_M + \alpha_{LP}) + \alpha_{EA} + \alpha_{OVH} + \alpha_{BR} + \alpha_{BU} - \frac{\alpha_{EO} \times \phi_{EO}}{[s+\phi_{EO}]}$$

$$- \frac{\alpha_{TI} \times \phi_{TI}}{[s+\phi_{TI}]} - \frac{\alpha_D \times \alpha_{DS}}{[s+\alpha_{DS}]} \frac{\phi_{D+DS}}{[s+\phi_{D+DS}]} - \frac{\alpha_{FSS} \times \phi_{FSS}}{[s+\phi_{FSS}]} - \frac{\alpha_{LP+M} \times \phi_{LP+M}}{[s+\phi_{LP+M}]} - \frac{\alpha_{EA} \times \phi_{EA}}{[s+\phi_{EA}]}$$

$$- \frac{\alpha_{CS} \times \alpha_{OVH} \times \phi_{CS}}{[s+\phi_{CS}][s+\alpha_{CS}]} - \frac{\alpha_{BR} \times \phi_{BR}}{[s+\phi_{BR}]} - \frac{\alpha_{BU} \times \phi_{BU}}{[s+\phi_{BU}]} \quad (33)$$

5. Numerical Computation

Considering different values of failure rates like α_{EO} = 0.006, α_{TI} = 0.009, α_D = 0.008, α_{DS} = 0.01, α_{FSS} = 0.07, α_M = 0.008, α_{LP}=0.006, α_{EA}=0.002, α_{OVH} =0.005, α_{CS}=0.003, α_{BR}=0.009, α_{BU} =0.004, Φi = 1 for i= EO, TI, D, DS, FSS, M, LP, EA, OVH, CS, BR, BU, θ = η = 1, and x= y= w= v= m= r= n= v=k = 1. Consider that all repair follows exponential time distribution then by substituting these values in equation (26) and taking inverse Laplace transformation, we have

$$P_{up}(t) = -0.002992831292\, e^{(-0.003000000000\, t)} + 0.09089745085\, e^{(-1.10098171\, t)} - 0.1045972416\; 10^{(-7)}\, e^{(-.99699905879t)} - 0.04625367733 e^{(-0.2043987365\, t)} - 0.009328505569 e^{(-0.00471367337\, t)} + 0.9676775738 \quad (34)$$

By, putting *t=0,1, 2…,10* in equation (34) we obtain the variation of availability for time shown in figure 2. Similarly, by considering different numerical values for failure rates we get the graphs of reliability and mean time to failure given in figures 3, 4 and 5.

5.1. Cost Analysis

If it is considered that the service facility is always available, then the expected profit function in the interval (0, t] is given by

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

where, K1 and K2 are the revenue and service cost per unit of time respectively, then

E P (t) = K_1 [0.2602109240 e(-0.5000000000 t) + 0.003420894509 e(-0.9100000000 t) +0.3707166241 e(-1.577110005 t) +0.2282704474 e(-0.8601482323 t) cos(0.007394121216 t) +0.2901464146 e(-0.8601482323 t) sin(0.007394121216 t) -0.05867072106 e(-0.7862665523 t) –0.2283382234 e(-0.7285677930 t)-0.003350319082 e(-0.6042513821 t)-9.234941008 e(-0.1268411365 t) +8.996326343]-K_2t (35)

Keeping K_1 = 1 and varying K_2 at 0.1, 0.2, 0.3, 0.4, 0.5 in equation (35), one can obtain Figure 6.

6. Results & Conclusion

For the more concrete behavior analysis of the process, a numerical calculation of availability, reliability, mean time to failure for various failure rates and cost function have been made. The following conclusions may be drawn based on the study conducted in the present paper.

Figure 2 shows a rapid decrease in the availability of the system for time initially because of an error in maintenance but later on, it becomes stable. Although, the reliability of the process shown in figure 3 has a constant decline and stabilizes at 0.4. Figures 4 and 5 show the variations in the meantime to failure (MTTF) for different failure rates. As the failure rates increase, the MTTF decreases and also it is observed that it is highest for fuel supply unit failure shown in figure 4 and 5. Now, cost analysis reveals that an increase in service cost results in decreased profit as shown in figure 6.

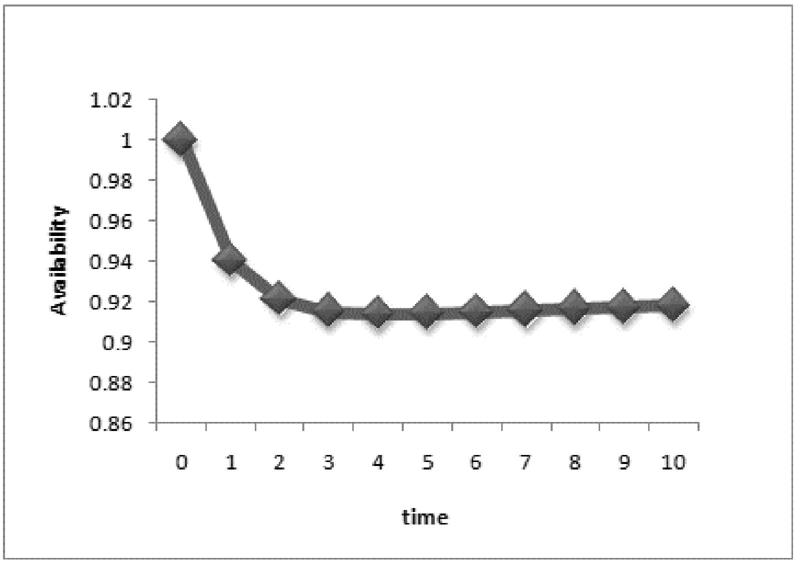

Figure 2: *Time vs. Availability*

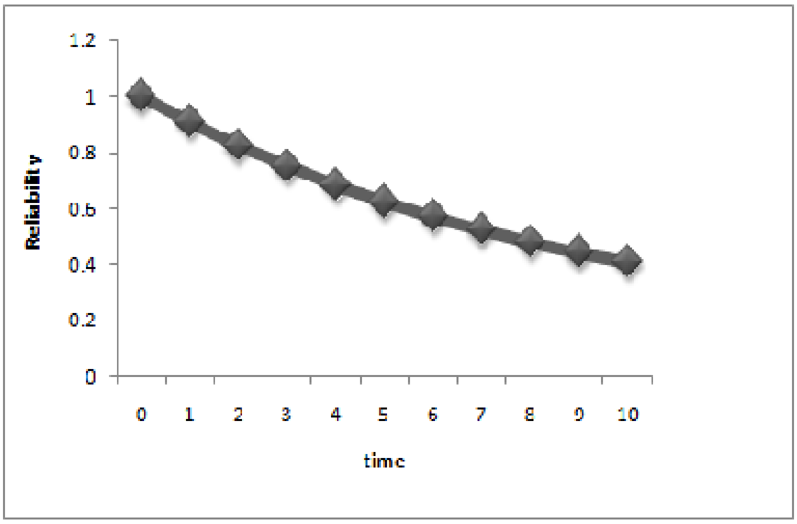

Figure 3: *Time vs. Reliability*

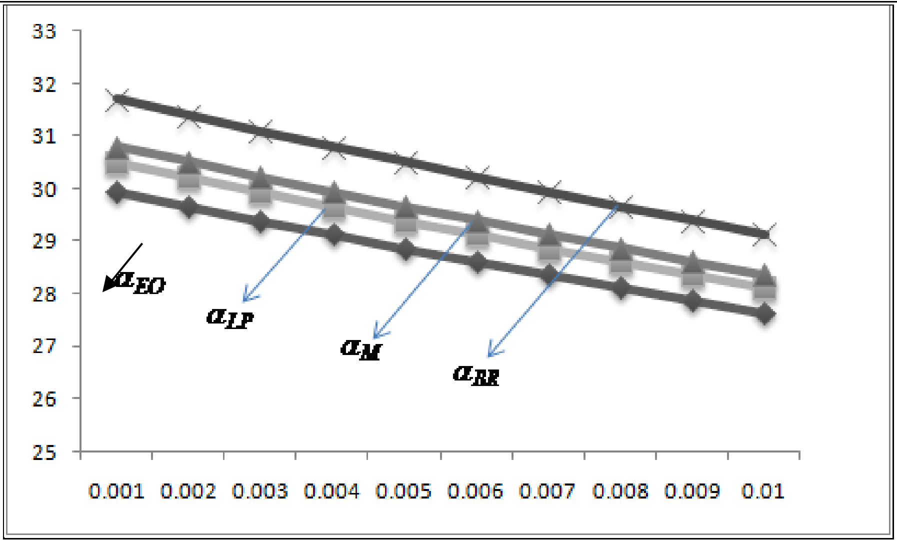

Figure 4: *MTTF vs.* α_{EO}, α_{LP}, α_{M}, α_{BR}

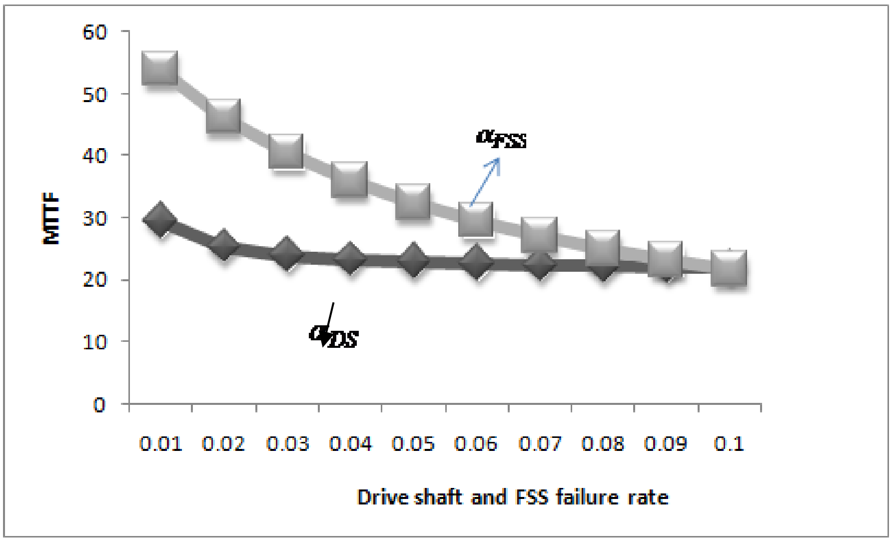

Figure 5: *MTTF vs.* α_{DS}, α_{FSS}

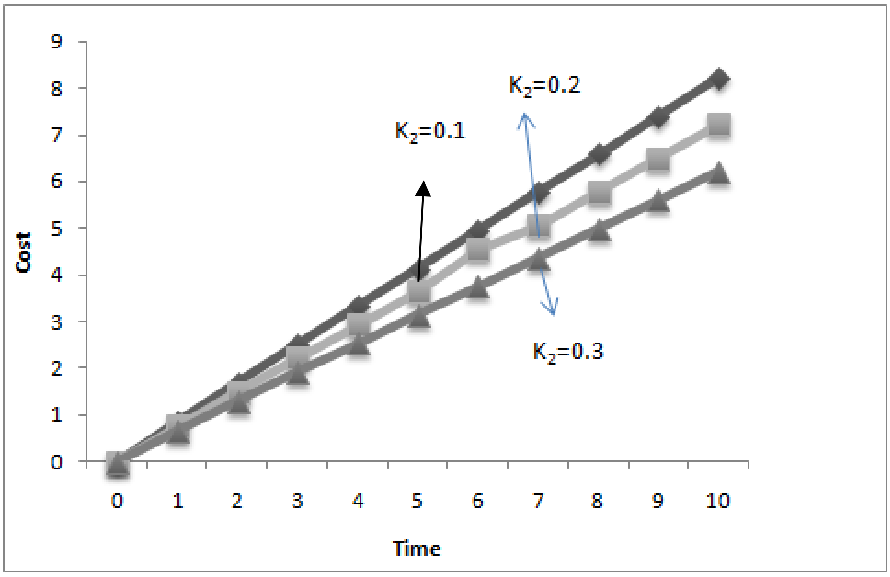

Figure 6: *Time vs. cost*

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