Cost Benefit Analysis of a Compressor Standby System with Preference of Service, Repair and Replacement is given to Recently Failed Unit

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Abstract — *The paper deals with cost benefit analysis of a compressor standby system working in milk plant with preference of service, repair and replacement is given to recently failed unit. Failure in any compressor unit brings the unit to complete halt and effect the system seriously. It has been observed that unit can fail due to various types of failure which can be categorized as-serviceable type, repairable type and replaceable type. For analysis purpose, data for various rates for failure, service, repair and replacement have been collected from milk plant. Various reliability indices of the system effectiveness are estimated numerically and graphically by using semi Markov process and regenerative point techniques.*

Keywords — *Compressor unit, Regenerative point technique, Refrigeration system, Semi-Markov process.*

I. Introduction

Study of standby systems is very popular in the field of reliability. A good number of researchers [1]-[9] have analyzed such systems for various reliability measures. None of the researcher has studied compressor unit standby system working in milk plant .Our present study is a sincere effort to fill this gap in the literature of reliability.
Keeping the above in view, In the present study Cost Benefit analysis of compressor standby system has been carried out. The system comprises three compressor units and where initially two are in operative state and one is in standby state, At least two units should be in operative state for functioning of this system. It has been observed that the unit can fail due to various types of failures which can be categorized as- serviceable type, repairable type and replaceable type .

In the present system preference is given to recent failed unit for service, repair and replacement . For profit analysis of the unit real failure as well as repair time data from a milk plant have been collected and various measures of system effectiveness i.e. mean time to unit failure, availability, busy periods and profit analysis has been computed numerically as well as graphically by using semi-Markov process and regenerative point technique.

Notations

OI, OII, OIII First, Second and Third Compressor are in Operative State

SII, SIII Second and Third Compressors are in Standby state

λ_{i1}, λ_{i2}, λ_{i3} Failure rate when failure is of serviceable , repairable and replacable for first second and third compressor respectively (i= 1,2,3and i symbol used for compressor unit)

α_{i1}, α_{i2}, α_{13} Repair rates when failure is of serviceable , repairable and replaceable type for first, second and third compressor respectively (i=1,2,3)

FsI , FsII ,FsIII Failure category of serviceable type for first, Second and third compressor

FrI,FrII,FrIII Failure category of repairable type for first ,second and third compressor

FrepI ,FrepII ,FrepIII Failure category of replaceable type for First , Second and third compressor

FwrI,FwsI,FwrepI First compressor is waiting for Repair, Service, Replacement respectively

$G_{i1}(t)$, $g_{i1}(t)$ c.d.f and p.d.f of time for service when failure is of serviceable type for first, second and third compressor respectively

$G_{i2}(t)$, $g_{i2}(t)$ c.d.f and p.d.f of time for repair when failure is of repairable type for first, second and third compressor respectively

$G_{i3}(t)$, $g_{i3}(t)$ c.d.f and p.d.f of time for replacement when failure is of replaceable type for first , second and third compressor respectively

Q_{ij}, q_{ij} c.d.f and p.d.f of first passage time from a regenerative state i to j or to a failed state j in (0, t].

q_{ij}^k p.d.f of first passage from regenerative state i to regenerative state j or to failed state j visting k once in (0,t]

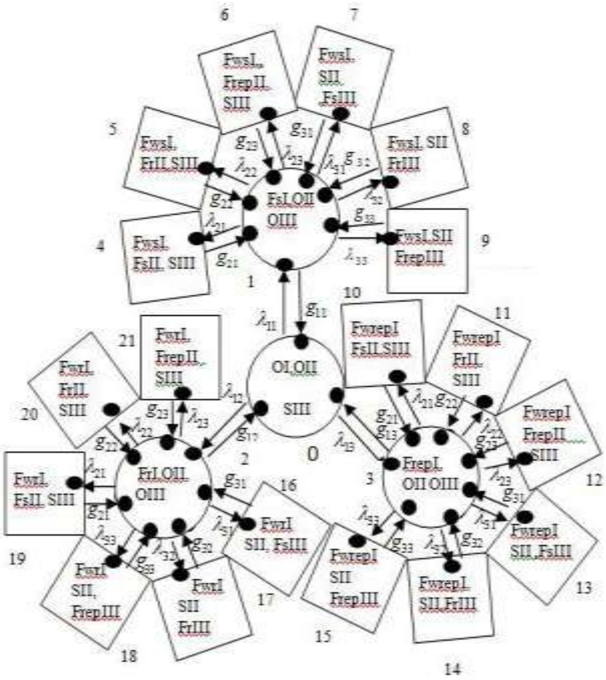
p_{ij}, p_{ij}^k probability of transition from regenerative state i to regenerative state j without visiting any other state in (0,t],visiting state k once in (0,t]

© Laplace convolution

(s) Stieltjes convolution

Model Description and Assumptions

1) The unit is initially operative at state 0 and its transition depends upon the type of failure category to any of the three states 1 to 3 with different failure rates.
2) When two units are failed then the third unit automatically go to the standby state.
3) All failure times are assumed to have exponential distribution .
4) After each servicing/ repair/replacement at states the unit works as good as new.



(Fig 1)

II. Transition Probabilities and Mean Sojourn Times

A state transition diagram showing the various states of transition of the system is shown in Fig.1.The epochs of entry into states0,1,2,3,4,5,6,7,8,9,10,11,1213,14,15,16,17,18,19 ,20 and 21 are regenerative state.

States4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21 are down states and 0,1,2,3 are upstates. The non zero elements p_{ij} are given below:

$$p_{01} = \frac{\lambda_{11}}{\lambda *}, p_{02} = \frac{\lambda_{12}}{\lambda *}, p_{03} = \frac{\lambda_{13}}{\lambda *},$$

$$p_{10} = g_{11}^*(\lambda), p_{20} = g_{12}^*(\lambda), p_{30} = g_{13}^*(\lambda)$$

$$Where \lambda^* = \lambda_{11} + \lambda_{12} + \lambda_{13}, \lambda = \lambda_{21} + \lambda_{22} + \lambda_{23} + \lambda_{31} + \lambda_{32} + \lambda_{33}$$

$$p_{2,16}, p_{22}^{16} = \frac{\lambda_{31}}{\lambda}(1 - g_{12}^*(\lambda)), p_{2,17}, p_{22}^{17} = \frac{\lambda_{32}}{\lambda}(1 - g_{12}^*(\lambda))$$

$$p_{2,18}, p_{22}^{18} = \frac{\lambda_{33}}{\lambda}(1 - g_{12}^*(\lambda)) p_{2,19}, p_{22}^{19} = \frac{\lambda_{21}}{\lambda}(1 - g_{12}^*(\lambda))$$

$$p_{2,20}, p_{22}^{20} = \frac{\lambda_{22}}{\lambda}(1 - g_{12}^*(\lambda)), p_{2,21}, p_{22}^{21} = \frac{\lambda_{23}}{\lambda}(1 - g_{12}^*(\lambda))$$

$$p_{14}, p_{11}^4 = \frac{\lambda_{21}}{\lambda}(1 - g_{11}^*(\lambda)), p_{15}, p_{11}^5 = \frac{\lambda_{22}}{\lambda}(1 - g_{11}^*(\lambda))$$

$$p_{16}, p_{11}^6 = \frac{\lambda_{23}}{\lambda}(1 - g_{11}^*(\lambda)), p_{17}, p_{11}^7 = \frac{\lambda_{31}}{\lambda}(1 - g_{11}^*(\lambda))$$

$$p_{18}, p_{11}^8 = \frac{\lambda_{32}}{\lambda}(1 - g_{11}^*(\lambda)), p_{19}, p_{11}^9 = \frac{\lambda_{33}}{\lambda}(1 - g_{11}^*(\lambda))$$

$$p_{3,10}, p_{33}^{10} = \frac{\lambda_{21}}{\lambda}(1 - g_{13}^*(\lambda)), p_{3,11}, p_{33}^{11} = \frac{\lambda_{22}}{\lambda}(1 - g_{13}^*(\lambda))$$

$$p_{3,12}, p_{33}^{12} = \frac{\lambda_{23}}{\lambda}(1 - g_{13}^*(\lambda)), p_{3,13}, p_{33}^{13} = \frac{\lambda_{31}}{\lambda}(1 - g_{13}^*(\lambda))$$

$$p_{3,14}, p_{33}^{14} = \frac{\lambda_{32}}{\lambda}(1 - g_{13}^*(\lambda)), p_{3,15}, p_{33}^{15} = \frac{\lambda_{33}}{\lambda}(1 - g_{13}^*(\lambda))$$

$$p_{01} + p_{02} + p_{03} = 1$$

$$p_{10} + p_{14} + p_{15} + p_{16} + p_{17} + p_{18} + p_{19} = 1$$

$$p_{10} + p_{11}^4 + p_{11}^5 + p_{11}^6 + p_{11}^7 + p_{11}^8 + p_{11}^9 = 1$$

$$p_{20} + p_{2,16} + p_{2,17} + p_{2,18} + p_{2,19} + p_{2,20} + p_{2,21} = 1$$

$$p_{20} + p_{22}^{16} + p_{22}^{17} + p_{22}^{18} + p_{22}^{19} + p_{22}^{20} + p_{22}^{21} = 1$$

$$p_{30} + p_{3,10} + p_{3,11} + p_{3,12} + p_{3,13} + p_{3,14} + p_{3,15} = 1$$

$$p_{30} + p_{33}^{10} + p_{33}^{11} + p_{33}^{12} + p_{33}^{13} + p_{33}^{14} + p_{33}^{15} = 1$$

The mean sojourn time (μ_i) in the regenerative state 'i' is defined as time of stay in that state before transition to any other state:

$$\mu_0 = \frac{1}{\lambda *}, \mu_1 \mu_2, \mu_3 = \frac{1}{\lambda} \mu_4, \mu_{10}, \mu_{16} = \int_0^\infty \overline{G}_{21}(t)dt$$

$$\mu_5, \mu_{11}, \mu_{17} = \int_0^\infty \overline{G}_{22}(t)dt, \mu_6, \mu_{12}, \mu_{18} = \int_0^\infty \overline{G}_{23}(t)dt$$

$$\mu_7, \mu_{13}, \mu_{19}, = \int_0^\infty \overline{G}_{31}(t)dt, \mu_8, \mu_{14}, \mu_{20} = \int_0^\infty \overline{G}_{32}(t)dt$$

$$\mu_9, \mu_{15}, \mu_{21} = \int_0^\infty \overline{G}_{33}(t)dt$$

The unconditional mean time taken by the system to transit for any regenerative state 'j' when it (time) is counted from the epoch of entrance into state 'i' is mathematically state as:

$$mij = \int_0^\infty t dQ_{ij}(t) = -q_{ij}'^*(0)$$

$$m_{01} + m_{02} + m_{03} = \frac{1}{\lambda *} = \mu_0$$

$$m_{10} + m_{11}^4 + m_{11}^5 + m_{11}^7 + m_{11}^8 + m_{11}^9 = \mu_1(1 - g_{11}^*(\lambda))$$

$$m_{20} + m_{22}^{16} + m_{22}^{17} + m_{22}^{18} + m_{22}^{19} + m_{22}^{20} + m_{22}^{21} = \mu_2(1 - g_{12}^*(\lambda))$$

$$m_{20} + m_{2,16} + m_{2,17} + m_{2,18} + m_{2,19} + m_{2,20} + m_{2,21} = \mu_2(1 - g_{12}^*(\lambda))$$

$$m_{30} + m_{3,10} + m_{3,11} + m_{3,12} + m_{3,13} + m_{3,14} + m_{3,15} = \mu_3(1 - g_{13}^*(\lambda))$$

$$m_{30} + m_{33}^{10} + m_{33}^{11} + m_{33}^{12} + m_{33}^{13} + m_{33}^{14} + m_{33}^{15} = \mu_3(1 - g_{13}^*(\lambda))$$

III. Mean Time to System Failure

To determine the mean time to system failure (MTSF) of the system, we regard the failed states of the system absorbing. By probabilistic arguments ,we obtain the following recursive relation for $\phi_i(t)$

$$\phi_0(t)=Q_{01}(t)(s)\phi_1(t)+Q_{02}(t)(s)\phi_2(t)+Q_{03}(t)(s)\phi_3(t)$$
$$\phi_1(t)=Q_{14}(t)+Q_{15}(t)+Q_{16}(t)+Q_{17}(t)+Q_{18}(t)+Q_{19}(t)+Q_{10}(s)\phi_0(t)$$
$$\phi_2(t)=Q_{2,16}(t)+Q_{2,17}(t)+Q_{2,18}(t)+Q_{2,19}(t)+Q_{2,20}(t)+Q_{2,21}(t)+Q_{20}(s)\phi_0(t)$$
$$\phi_3(t)=Q_{3,10}(t)+Q_{3,11}(t)+Q_{3,12}(t)+Q_{3,13}(t)+Q_{3,14}(t)+Q_{3,15}(t)+Q_{30}(s)\phi_0(t)$$

Taking Laplace –Stieltjes Transforms(L.S.T) of above relations and solving for(ϕ_0^{**} (s)).Now the mean time to system failure(MTSF) when system starts from the state 0.

$$\text{MTSF}=T_0=\lim_{S\to 0}\frac{1-\phi_0{}^{**}(s)}{s}=N/D$$
$$N=m_{01}p_{10}+m_{10}p_{01}+m_{02}p_{20}+m_{20}p_{02}+m_{03}p_{30}+m_{30}p_{03}$$
$$+m_{01}+m_{02}+m_{03}-m_{01}p_{10}-m_{02}p_{20}-m_{03}p_{30}-m_{30}p_{03}$$
$$-m_{20}p_{02}-m_{10}p_{01}+p_{03}\mu_3(1-g_{13}^*(\lambda))+p_{02}\mu_2(1-g_{12}^*(\lambda))$$
$$+p_{01}\mu_1(1-g_{11}^*(\lambda)),D=1-p_{01}p_{10}-p_{02}p_{20}-p_{03}p_{30}$$

IV. Availability Analysis

Let $A_i(t)$ be the probability that the system is in up state at instant t given that the system entered regenerative state i at t=0. The availability $A_i(t)$ is to satisfy the following recursive relations:

$$A_0(t)=M_0(t)+q_{01}©A_1(t)+q_{02}©A_2(t)+q_{03}©A_3(t)$$
$$A_1(t)=M_1(t)+q_{10}©A_0(t)+q_{11}{}^{(4)}©A_1(t)+q_{11}{}^{(5)}©A_1(t)$$
$$+q_{11}{}^{(6)}©A_1(t)+q_{11}{}^{(7)}©A_1(t)+q_{11}{}^{(8)}©A_1(t)+q_{11}{}^{(9)}©A_1(t)$$
$$A_2(t)=M_2(t)+q_{20}©A_0(t)+q_{22}{}^{(16)}©A_1(t)+q_{22}{}^{(17)}©A_1(t)$$
$$+q_{22}{}^{(18)}©A_1(t)+q_{22}{}^{(19)}©A_1(t)+q_{22}{}^{(20)}©A_1(t)+q_{22}{}^{(21)}©A_1(t)$$
$$A_3(t)=M_3(t)+q_{30}©A_0(t)+q_{33}{}^{(10)}©A_1(t)+q_{33}{}^{(11)}©A_1(t)$$
$$+q_{33}{}^{(12)}©A_1(t)+q_{33}{}^{(13)}©A_1(t)+q_{33}{}^{(14)}©A_1(t)+q_{33}{}^{(15)}©A_1(t)$$
$$A_4=q_{41}©A_1(t),A_5=q_{51}©A_1(t),A_6=q_{61}©A_1(t)$$
$$A_7=q_{71}©A_1(t),A_8=q_{81}©A_1(t),A_9=q_{91}©A_1(t)$$
$$A_{10}=q_{10,3}©A_3(t),A_{11}=q_{11,3}©A_3(t),A_{12}=q_{12,3}©A_3(t)$$
$$A_{13}=q_{13,3}©A_3(t),A_{14}=q_{14,3}©A_3(t),A_{15}=q_{15,3}©A_3(t)$$
$$A_{16}=q_{16,2}©A_2(t),A_{17}=q_{17,2}©A_2(t),A_{18}=q_{18,2}©A_2(t)$$
$$A_{19}=q_{19,2}©A_2(t),A_{20}=q_{20,2}©A_2(t),A_{21}=q_{21,2}©A_2(t)$$

where

$$M_0(t)=e^{-(\lambda_{11}+\lambda_{12}+\lambda_{13})t}$$
$$M_1(t)=e^{-(\lambda_{21}+\lambda_{22}+\lambda_{23}+\lambda_{31}+\lambda_{32}+\lambda_{33})t}\,\bar{G}_{11}(t)$$
$$M_2(t)=e^{-(\lambda_{21}+\lambda_{22}+\lambda_{23}+\lambda_{31}+\lambda_{32}+\lambda_{33})t}\,\bar{G}_{12}(t)$$
$$M_3(t)=e^{-(\lambda_{21}+\lambda_{22}+\lambda_{23}+\lambda_{31}+\lambda_{32}+\lambda_{33})t}\,\bar{G}_{13}(t)$$

Insteady state availability of the system is given as

$$A_0=\lim_{s\to 0}(sA_0^*(s))=N_1/D_1$$

where

$$N_1=\mu_0p_{10}p_{20}p_{30}+p_{01}\mu_1(1-g_{11}{}^*)p_{20}p_{30}+p_{02}\mu_2(1-g_{12}{}^*)p_{10}p_{30}$$
$$+p_{03}\mu_3(1-g_{13}{}^*)p_{10}p_{20}$$
$$D_1=(\mu_1(1-g_{11}{}^*)-m_{10})p_{20}p_{30}+(\mu_2(1-g_{12}{}^*)-m_{20})p_{10}p_{30}$$
$$+(\mu_3(1-g_{13}{}^*)-m_{30})p_{10}p_{20}++m_{01}p_{01}p_{20}p_{30}+p_{10}m_{01}p_{20}p_{30}$$
$$-(\mu_2(1-g_{12}{}^*)-m_{20})p_{10}p_{30}p_{01}-(\mu_3(1-g_{13}{}^*)-m_{30})p_{10}p_{20}p_{01}$$
$$+p_{10}m_{02}p_{20}p_{30}+p_{02}m_{20}p_{10}p_{30}-(\mu_1(1-g_{11}{}^*)-m_{10})p_{20}p_{30}p_{02}$$
$$-(\mu_3(1-g_{13}{}^*)-m_{30})p_{10}p_{20}p_{02}+p_{10}m_{02}p_{20}p_{30}+p_{02}m_{20}p_{10}p_{30}$$
$$-(\mu_1(1-g_{11}{}^*)-m_{10})p_{03}p_{30}p_{20}-(\mu_2(1-g_{12}{}^*)-m_{20})p_{10}p_{30}p_{03}$$

Proceeding in the similar fashion as above following measures in steady state have also been obtained

A. Busy period analysis for Service time only

In steady state ,the total fraction of the time for which the system is under service is given by

$$B_0=\lim_{s\to 0}(sB_0^*(s))=N_2/D_1$$

where

$$N_2=p_{01}p_{20}p_{30}K_1$$

B. Busy period analysis for Repair time only

In steady state ,the total fraction of the time for which the system is under repair is given by

$$B_1=\lim_{s\to 0}(sB_1^*(s))=N_3/D_1$$

where

$$N_3=p_{02}p_{10}p_{30}K_2$$

C. Busy period analysis for Replacement time only

In steady state , the total fraction of the time for which the system is under replacement is given by

$$B_2=\lim_{s\to 0}(sB_2^*(s))=N_4/D_1$$

where

$$N_4=p_{03}p_{10}p_{20}K_3$$

D. Expected number of Services

In steady state ,the number of services per unit time is given by

$$S_E=\lim_{t\to\infty}[S_0(t)]=N_5/D_1$$

where

$$N_5=p_{01}p_{20}p_{30}+p_{02}p_{10}p_{30}(p_{22}^{16}+p_{22}^{19})$$
$$+p_{03}p_{10}p_{20}(p_{33}^{10}+p_{33}^{13})$$

E. Expected number of Repairs

In steady state, the number of repairs per unit time is given by

$$R_E = \lim_{t \to \infty}[R_0(t)] = N_6 / D_1$$

where

$$N_6 = p_{01}(p_{1,1}^5 + p_{1,1}^8)p_{20}p_{30} + p_{02}p_{10}p_{30} + p_{03}p_{10}p_{20}(p_{33}^{10} + p_{33}^{13})$$

F. *Expected number of Replacements*

In steady state ,the number of replacements per unit time is given by

$$R_{REP} = \lim_{t \to \infty}[R_0(t)] = N_7 / D_1$$

where

$$N_7 = p_{01}(p_{1,1}^6 + p_{1,1}^9)p_{20}p_{30} + p_{02}p_{10}p_{30}(p_{22}^{18} + p_{22}^{21}) + p_{03}p_{10}p_{20}$$

PARTICULAR CASES

For graphical representation ,let us suppose that

$$g_{11}(t) = \alpha_{11}e^{-\alpha_{11}t}, g_{12}(t) = \alpha_{12}e^{-\alpha_{12}t}, g_{13}(t) = \alpha_{13}e^{-\alpha_{13}t}$$

using the above particular case, the following values are estimated as

$$\alpha_{11} = 0.006896, \alpha_{12} = 0.000586, \alpha_{13} = 0.04166,$$
$$\alpha_{21} = 0.0000983, \alpha_{22} = 0.0001347, \alpha_{23} = 0.0001587$$
$$\lambda_{11}, \lambda_{12}, \lambda_{13} = 0.00003868, \lambda_{21}, \lambda_{22}, \lambda_{23} = 0.0007352$$
$$\lambda_{31}, \lambda_{32}, \lambda_{33} = 0.0000456071$$

V . CONCLUSION

Mean time to unit/compressor MTSF =14081.82649 hrs.

Availability of the unit/compressor (A_0) =0.999999999

Busy period analysis for service time (B_0) = 0.0164300805

Busy period analysis for repair time(B_1) = 0.0612879499

Busy period for replacement time (B_2) = 0.0129537798

Expected number of services (S_E) = 0.000436

Expected number of repair (R_E) = 0.000206

Expected number of replacements (R_{REP}) = 0.000570

Expected number of visits (V_0) = 0.000086183

VI . PROFIT ANALYSIS

The expected total profit incurred to the system in steady state is given by

$P = C_0A_0 - C_1B_0 - C_2B_1 - C_3B_2 - C_4V_0 - C_5S_E - C_6R_E C_7R_{REP}$,

Where

C_0= Revenue per unit up time

C_1=Cost per unit time for which repairman is busy for service

C_2= Cost per unit time for which repairman is busy for repair C_3= Cost per unit time for which repairman is busy for replacement

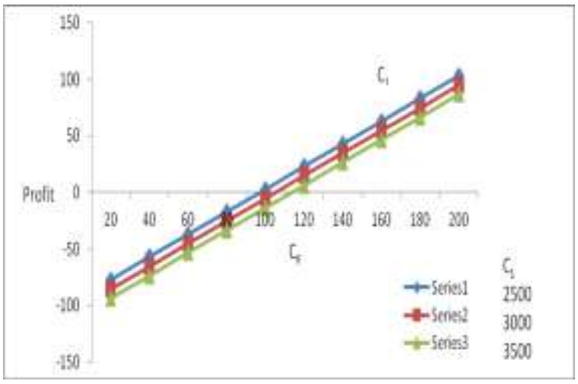
C_4=Cost per visit of Repairman

C_5=Cost per visit of service

C_6=Cost per visit of Repair

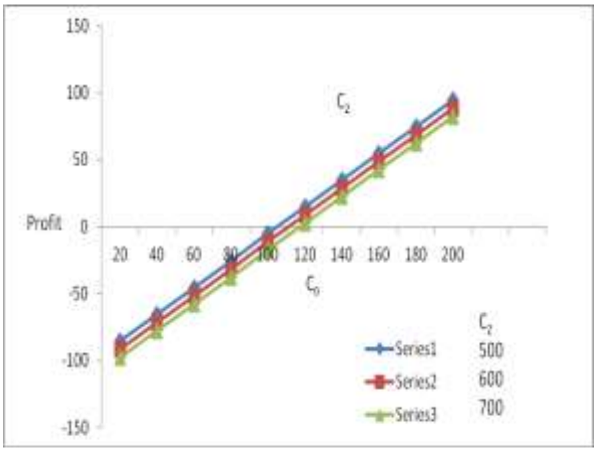
C_7= Cost per visit of Replacement

Graph between Profit vs Revenue (C_0) per unit for different values of cost per unit time for which repairman is busy for service (C_1)(fig2)



It can be interpreted from graph that profit increases with increase in values of revenue per unit up time (C_0).It can also be noticed that if C_1=2500 , then P>or=or<0 according as C_0 >or =or<97 So for C_1=2500 , revenue per unit up time should be fixed greater than 97.Similarly for C_1=3000 and 3500 , the revenue per unit up time should be greater than 105.2 and 113.43respectively.

Graph between Profit vs Revenue per unit time(C_0) for different values of cost per unit for which repairman is busy for repair(C_2)(fig3)



It can be interpreted from graph that profit increases with increase in values of revenue per unit up time (C_0).It can also be noticed that if C_2=500 , then P>or=or<0 according as C_0 >or =or<105.2. So for C_2=500 , revenue per unit up time should be fixed greater than 105.2.Similarly for C_2=600 and 700 , the revenue per unit up time should be greater than 111.4 and 117.5 respectively.

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