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Profit Evaluation of Three Units Compressor Standby System

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Abstract: The paper presents profit analysis of three units compressor standby system working in Refrigeration system of a milk plant. Initially the system consist of two operating and one standby compressor unit. For the functioning of the system at least two compressor units should be in working state .There can be three types of failure i.e serviceable repairable and replaceable type in any unit. The priority of service or repair or replacement has been given to failed unit on FCFS basis. Various measures of reliability such as MTSF, Availability and Profit Analysis has been calculated by using Semi Markov process and regenerative point techniques. For practical utility of our proposed model previous data of different years from Verka milk plant has been gathered and is used for graphical analysis.

Keywords: Compressor Unit, Regenerative point technique, Refrigeration System, Semi-Markov process.

I. Introduction

Standby systems are commonly used in many industries and therefore, researchers [1 -3] have spent a great deal of efforts in analyzing such systems to get the optimized reliability results which are useful for effective equipment/plant maintenance. For graphical study, they have taken assumed values for failure and repair rates, and not used the observed values. However, some researchers including [4-7] studied some reliability models collecting real data on failure and repair rates of the units used in such systems. A potential application of the reliability concepts has been recently explored in terms of developing a specific probabilistic model for three units compressor standby system where recently failed unit has been be given priority of service ,repair and replacement by Sharma U. and Kaur J. [8].in the present paper same three units compressor standby system has been studied wherein the priority of service, repair or replacement is given to failed unit on FCFS basis. Initially the system consist of two operating and one standby compressor unit. For the functioning of the system at least two compressor units should be in working state various measures of system effectiveness has been calculated by using semi-Markov process and regenerative point techniques. For practical utility of our proposed model previous data of different years from Verka milk plant has been gathered and is used for graphical analysis.

Notations

OI,OII First , Second Compressor are in Operative State

SIII Third Compressor is in Stand by State

(s) Stieltjes Convolution

© Laplace Convolution

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

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

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

FwrII, FwsII , FwrepII Second compressor is waiting for Repair, Service, Replacement respectively

FwrIII, FwsIII , FwrepIII Third 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].

$ø_i(t)$ c.d.f of the first passage time from regenerative state i to a failed state

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]

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]

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 states1to3 with different failure rates.

2) All failure times are assumed to have exponential distribution.

3) After each servicing/ repair/replacement at states the unit works as good as new.

4) Priority given to failed unit for service, repair and replacement.

Transition Probabilities and Mean Sojourn Times

A state transition diagram showing the various states of transition of the system is shown in Table 1. The epochs of entry into states 0, 1, 2, 3, 22, 23, 24, 25, 26 and 27 are regenerative states.

States 4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20 and 21 are down states. The non zero elements p_{ij} are given below

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

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

$$where \lambda = \lambda_{21} + \lambda_{22} + \lambda_{23} + \lambda_{31} + \lambda_{32} + \lambda_{33}$$

$$p_{14}, p_{1,22}^4 = \frac{\lambda_{21}}{\lambda}(1 - g_{11}^*(\lambda)); p_{15}, p_{1,23}^5 = \frac{\lambda_{22}}{\lambda}(1 - g_{11}^*(\lambda))$$

$$p_{16}, p_{1,24}^6 = \frac{\lambda_{23}}{\lambda}(1 - g_{11}^*(\lambda)); p_{17}, p_{1,25}^7 = \frac{\lambda_{31}}{\lambda}(1 - g_{11}^*(\lambda))$$

$$p_{18}, p_{1,26}^8 = \frac{\lambda_{32}}{\lambda}(1 - g_{11}^*(\lambda)); p_{19}, p_{1,27}^9 = \frac{\lambda_{33}}{\lambda}(1 - g_{11}^*(\lambda))$$

$$p_{2,10}, p_{2,22}^{10} = \frac{\lambda_{21}}{\lambda}(1 - g_{12}^*(\lambda)); p_{2,11}, p_{2,23}^{11} = \frac{\lambda_{22}}{\lambda}(1 - g_{12}^*(\lambda))$$

$$p_{2,12}, p_{2,24}^{12} = \frac{\lambda_{23}}{\lambda}(1 - g_{12}^*(\lambda)); p_{2,13}, p_{2,25}^{13} = \frac{\lambda_{31}}{\lambda}(1 - g_{12}^*(\lambda))$$

$$p_{2,14}, p_{2,26}^{14} = \frac{\lambda_{32}}{\lambda}(1 - g_{12}^*(\lambda)); p_{2,15}, p_{2,27}^{15} = \frac{\lambda_{33}}{\lambda}(1 - g_{12}^*(\lambda))$$

$$p_{3,16}, p_{3,22}^{16} = \frac{\lambda_{21}}{\lambda}(1 - g_{13}^*(\lambda)); p_{3,17}, p_{3,23}^{17} = \frac{\lambda_{21}}{\lambda}(1 - g_{13}^*(\lambda))$$

$$p_{3,18}, p_{3,24}^{18} = \frac{\lambda_{21}}{\lambda}(1 - g_{13}^*(\lambda)); p_{3,19}, p_{3,25}^{19} = \frac{\lambda_{31}}{\lambda}(1 - g_{13}^*(\lambda))$$

$$p_{3,20}, p_{3,26}^{20} = \frac{\lambda_{31}}{\lambda}(1 - g_{13}^*(\lambda)); p_{3,21}, p_{3,27}^{21} = \frac{\lambda_{31}}{\lambda}(1 - g_{13}^*(\lambda))$$

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

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

$$p_{10} + p_{1,22}^4 + p_{1,23}^5 + p_{1,24}^6 + p_{1,25}^7 + p_{1,26}^8 + p_{1,27}^9 = 1$$

$$p_{20} + p_{2,10} + p_{2,11} + p_{2,12} + p_{2,13} + p_{2,14} + p_{2,15} = 1$$

$$p_{20} + p_{2,22}^{10} + p_{2,23}^{11} + p_{2,24}^{12} + p_{2,25}^{13} + p_{2,26}^{14} + p_{2,27}^{15} = 1$$

$$p_{30} + p_{3,16} + p_{3,17} + p_{3,18} + p_{3,19} + p_{3,20} + p_{3,21} = 1$$

$$p_{30} + p_{3,22}^{16} + p_{3,23}^{17} + p_{3,24}^{18} + p_{3,25}^{19} + p_{3,26}^{20} + p_{3,27}^{21} = 1$$

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:

$$\mu_0 = \frac{1}{\lambda^*}, \mu_1 = \frac{1}{\lambda}, \mu_2 = \frac{1}{\lambda}, \mu_3 = \frac{1}{\lambda}$$

$$\mu_{22} = \int_0^\infty \overline{G}_{21}(t)dt = K_1, \mu_{23} = \int_0^\infty \overline{G}_{22}(t)dt = K_2$$

$$\mu_{24} = \int_0^\infty \overline{G}_{23}(t)dt = K_3, \mu_{25} = \int_0^\infty \overline{G}_{21}(t)dt = K_4$$

$$\mu_{26} = \int_0^\infty \overline{G}_{22}(t)dt = K_5, \mu_{27} = \int_0^\infty \overline{G}_{23}(t)dt = K_6$$

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State No.	Status	State No.	Status
0	O_I ,O_{II} ,S_{III}	14	F_{urI}, O_{II} , F_{wrIII}
1	F_{sI} ,O_{II} ,O_{III}	15	F_{urI}, O_{II} , $F_{wrepIII}$
2	F_{rI} , O_{II} ,O_{III}	16	F_{urepI} , F_{wsII} ,O_{III}
3	F_{repI} ,O_{II} ,O_{III}	17	F_{urepI} , F_{wrII}, O_{III}
4	F_{usI} , F_{wsII} ,O_{III}	18	F_{urepI} ,F_{wrepII} ,O_{III}
5	F_{usI} , F_{wrII} ,O_{III}	19	F_{urepI} ,O_{II} , F_{wsIII}
6	F_{usI}, F_{wrepII} ,O_{III}	20	F_{urepI} ,O_{II} , F_{wrIII}
7	F_{usI} , O_{II} , F_{wsIII}	21	F_{urepI},O_{II}, $F_{wrepIII}$
8	F_{usI} , O_{II} , F_{wrIII}	22	O_I , F_{usII} , O_{III}
9	F_{usI},O_{II} , $F_{wrepIII}$	23	O_I , F_{urII} , O_{III}
10	F_{urI}, F_{wsII} , O_{III}	24	O_I , F_{urepII} ,O_{III}
11	F_{urI}, F_{wrII} , O_{III}	25	O_I , O_{II}, F_{usIII}
12	F_{urI},F_{wrepII} , O_{III}	26	O_I ,O_{II}, F_{urIII}
13	F_{urI}, O_{II} , F_{wsIII}	27	O_I ,O_{II}, $F_{urepIII}$

TABLE 1 POSSIBLE STATES WITH STATUS

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:

$$mij = \int_0^\infty t d\mathrm{Q}_{ij}(t) = -q_{ij}{}'^*(0)$$

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

$$m_{10} + m_{14} + m_{15} + m_{16} + m_{17} + m_{18} + m_{19} = \mu_1(1 - g_{11}^*(\lambda))$$

$$m_{10} + m_{1,22}^4 + m_{1,23}^5 + m_{1,24}^6 + m_{1,25}^7 + m_{1,26}^8 + m_{1,27}^9 = \mu_1(1 - g_{11}^*(\lambda))$$

$$m_{20} + m_{2,10} + m_{2,11} + m_{2,12} + m_{2,13} + m_{2,14} + m_{2,15} = \mu_2(1 - g_{12}^*(\lambda))$$

$$m_{20} + m_{2,22}^{10} + m_{2,23}^{11} + m_{2,24}^{12} + m_{2,25}^{13} + m_{2,26}^{14} + m_{2,27}^{15} = \mu_2(1 - g_{12}^*(\lambda))$$

$$m_{30} + m_{3,16} + m_{3,17} + m_{3,18} + m_{3,19} + m_{3,20} + m_{3,21} = \mu_3(1 - g_{13}^*(\lambda))$$

$$m_{30} + m_{3,22}^{16} + m_{3,23}^{17} + m_{3,24}^{18} + m_{3,25}^{19} + m_{3,26}^{20} + m_{3,27}^{21} = \mu_3(1 - g_{13}^*(\lambda))$$

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 as absorbing states and the mean time to system failure (MTSF) when the system starts from state S_0 is

$$\mathrm{MTSF} = \mathrm{T}_0 = \lim_{s \to O} \frac{1 - \varnothing_0{}^{**}(s)}{s}$$

using L' Hospital's Rule and putting the value of $ø_0^{**}(s)$, we have

$$T_0 = N / D$$

where

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

$$D = 1 - p_{01} p_{10} - p_{02} p_{20} - p_{03} p_{30}$$

Availability Analysis

Using the arguments of the theory of regenerative processes, In steady state availability of the system is

$$A_0 = \lim_{s \to 0}(s A_0^*(s)) = \mathrm{N}_1 / D_1$$

where

$$N_1 = \mu_0 + M_1 p_{01} + M_2 p_{02} + M_3 p_{03} + M_{22} p_{1,22}^4 p_{01} + M_{23} p_{01} p_{1,23}^5$$
$$+ M_{24} p_{01} p_{1,24}^6 + M_{25} p_{1,25}^7 p_{01} + M_{26} p_{01} p_{1,26}^8 + M_{27} p_{01} p_{1,27}^9$$
$$+ M_{22} p_{2,22}^{10} p_{02} + M_{23} p_{02} p_{2,23}^{11} + M_{24} p_{02} p_{2,24}^{12} + M_{25} p_{2,25}^{13} p_{02}$$
$$+ M_{26} p_{02} p_{2,26}^{14} + M_{27} p_{02} p_{2,27}^{15} + M_{22} p_{3,22}^{16} p_{03} + M_{23} p_{03} p_{3,23}^{17}$$
$$+ M_{24} p_{03} p_{3,24}^{18} + M_{25} p_{3,25}^{19} p_{03} + M_{26} p_{03} p_{3,26}^{20} + M_{27} p_{03} p_{3,27}^{21}$$

$$D_1 = -\mu_0 + p_{01}\mu_1(1 - g_{11}{}^*(\lambda)) + p_{02}(\mu_2(1 - g_{12}{}^*(\lambda))$$
$$+ (p_{03}\mu_3(1 - g_{13}{}^*(\lambda)) + p_{01}(p_{1,22}^4 m_{22,0} + p_{1,23}^5 m_{23,0} + p_{1,24}^6 m_{24,0}$$
$$+ p_{1,25}^7 m_{25,0} + p_{1,26}^8 m_{26,0} + p_{1,27}^9 m_{27,0}) + p_{02}(p_{1,22}^{10} m_{22,0} + p_{2,23}^{11} m_{23,0}$$
$$+ p_{2,24}^{12} m_{24,0} + p_{2,25}^{13} m_{25,0} + p_{2,26}^{14} m_{26,0} + p_{2,27}^{15} m_{27,0}) + p_{03}(p_{3,22}^{16} m_{22,0}$$
$$+ p_{3,23}^{17} m_{23,0} + p_{3,24}^{18} m_{24,0} + p_{3,25}^{19} m_{25,0} + p_{3,26}^{20} m_{26,0} + p_{3,27}^{21} m_{27,0})$$

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

Busy Period Analysis for Service Time Only

$$B_0 = N_2 / D_1$$

where

$$N_2 = p_{01}\mu_1 + p_{01} p_{1,22}^4 K_1 + p_{02} p_{2,22}^{10} K_1 + p_{03} p_{3,22}^{16} K_1$$
$$+ p_{01} p_{1,25}^7 K_4 + p_{02} p_{2,25}^{13} K_4 + p_{03} p_{3,25}^{19} K_4$$

Busy Period Analysis for Repair Time Only

$$B_1 = N_3 / D_1$$

where

$$N_3 = p_{02}\mu_2 + p_{01} p_{1,23}^5 K_2 + p_{02} p_{2,23}^{11} K_2 + p_{03} p_{3,23}^{17} K_2$$
$$+ p_{01} p_{1,26}^8 K_5 + p_{02} p_{2,26}^{14} K_4 + p_{03} p_{3,27}^{20} K_4$$

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Busy Period Analysis for Replacement Time Only

$B_2 = N_4 / D_1$
where
$$N_4 = p_{03}\mu_3 + p_{01}p^6_{1,24}K_3 + p_{02}p^{12}_{2,24}K_3 + p_{03}p^{18}_{3,24}K_2 + p_{01}p^9_{1,27}K_6 + p_{02}p^{15}_{2,27}K_6 + p_{03}p^{21}_{3,27}K_6$$

Expected Number of Service

$S_E = N_5 / D_1$
where
$$N_5 = p_{01} + p_{01}(p_{1,0} + p^4_{1,22} + p^5_{1,23} + p^6_{1,24} + p^7_{1,25} + p^8_{1,26} + p^9_{1,27}) + p_{01}p^4_{1,22}p_{22,0} + p_{02}p^{10}_{2,22}p_{22,0} + p_{01}p^7_{1,25}p_{25,0} + p_{02}p^{13}_{2,25}p_{25,0} + p_{03}p_{22,0}p^{16}_{3,22} + p_{03}p_{25,0}p^{19}_{3,25}$$

Expected Number of Repairs

$R_E = N_6 / D_1$
where
$$N_6 = p_{02} + p_{02}(p_{2,0} + p^{10}_{2,22} + p^{11}_{2,23} + p^{12}_{2,24} + p^{13}_{2,25} + p^{14}_{2,26} + p^{15}_{2,27}) + p_{02}p^{11}_{2,23}p_{23,0} + p_{01}p^8_{1,26}p_{26,0} + p_{02}p^{14}_{2,26}p_{26,0} + p_{03}p^{17}_{3,23}p_{23,0} + p_{03}p_{26,0}p^{20}_{3,26} + p_{03}p_{25,0}p^{19}_{3,25}$$

Expected Number of Replacements

$R = N_7 / D_1$
where
$$N_7 = p_{03} + p_{03}(p_{3,0} + p^{16}_{3,22} + p^{17}_{3,23} + p^{18}_{3,24} + p^{19}_{3,25} + p^{20}_{3,26} + p^{21}_{3,27}) + p_{01}p^6_{1,24}p_{24,0} + p_{02}p^{12}_{2,24}p_{24,0} + p_{01}p^9_{1,27}p_{27,0} + p_{02}p^{15}_{2,27}p_{27,0} + p_{03}p_{24,0}p^{18}_{3,24} + p_{03}p_{27,0}p^{21}_{3,27}$$

Expected Number of Visits by Repairman

$V_0 = N_8 / D_1$
where
$$N_8(s) = p_{01} + p_{02} + p_{03}$$

Particular Cases

For graphical representation, let us suppose that
$$g_{11}(t) = \alpha_{11}e^{-\alpha_{11}t}, g_{12}(t) = \alpha_{12}e^{-\alpha_{12}t}, g_{13}(t) = \alpha_{13}e^{-\alpha_{13}t}$$
$$g_{21}(t) = \alpha_{21}e^{-\alpha_{21}t}, g_{22}(t) = \alpha_{22}e^{-\alpha_{22}t}, g_{23}(t) = \alpha_{23}e^{-\alpha_{23}t}$$
$$g_{11}(t) = \alpha_{31}e^{-\alpha_{31}t}, g_{12}(t) = \alpha_{32}e^{-\alpha_{32}t}, g_{13}(t) = \alpha_{33}e^{-\alpha_{33}t}$$

using the above particular case, the following values are estimated as
$$\alpha_{11} = 0.006896, \alpha_{12} = 0.000586, \alpha_{13} = 0.04166,$$
$$\alpha_{21} = 0.0000983, \alpha_{22} = 0.0001347, \alpha_{23} = 0.00015873$$
$$\alpha_{31} = 0.000345209, \alpha_{32} = 0.0010162602, \alpha_{33} = 0.0006648936$$
$$\lambda_{11} = 0.00003868, \lambda_{12} = 0.00003879, \lambda_{13} = 0.00003865$$
$$\lambda_{21} = 0.0007359, \lambda_{22} = 0.0007367, \lambda_{23} = 0.0007352$$
$$\lambda_{31} = 0.0000456079, \lambda_{32} = 0.0000456089, \lambda_{33} = 0.0000456071$$
$$C_1 = 3000, C_2 = 500, C_3 = 550, C_4 = 800, C_5 = 27700,$$
$$C_6 = 7600, C_7 = 7975, N = 8887.14331, N_2 = 2637.208740$$
$$N_3 = 2234.277588, N_4 = 1553.829590, N_5 = 1.062829$$
$$N_6 = 1.062856, N_7 = 1.062870, N_8 = 1.0000000$$

Conclusion

The measures of system effectiveness are obtained as:

Mean time to unit/compressor MTSF =14081.8271 hrs.
Availability =.9999999
Busy period for service=.179557
Busy period for repair=0.152123
Busy period for replacement=.105794
Expected number of visits=0.000068
Expected number of services=0.000074
Expected number of repairs=0.000075
Expected number of replacements=0.000072

Profit Analysis

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

P $=C_0A_0-C_1B_0-C_2B_1-C_3B_2-C_4V_0-C_5S_E-C_6R_E-C_7R$,
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

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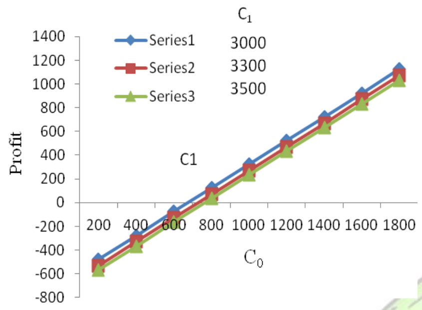
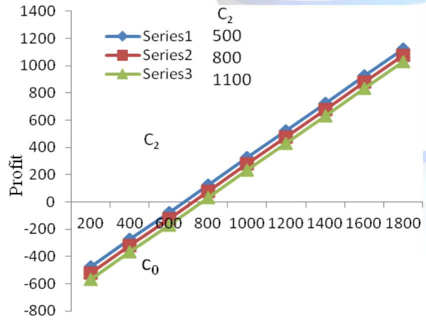
Graph between Profit vs Revenue per unit time (C_0) for different values of cost per unit for which repairman is busy for service (C_1)(fig 2)



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=3000 , then P>or=or<0 according as C_0 >or =or<676.2. So for C_1=3000, revenue per unit up time should be fixed greater than 676.2.Similarly for C_1=3300 and 3500, the revenue per unit up time should be greater than 730 and 765.9 respectively.

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 or =or<676.2. So for C_2=500, revenue per unit up time should be fixed greater than 676.2.Similarly for C_2=800 and 1100, the revenue per unit up time should be greater than 721.8 and 767.4 respectively.

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