International Journal of Current Advanced Research
ISSN: O: 2319-6475, ISSN: P: 2319 – 6505, Impact Factor: SJIF: 5.995
Available Online at www.journalijcar.org
Volume 6; Issue 8; August 2017; Page No. 5146-5150
DOI: http://dx.doi.org/10.24327/ijcar.2017.5150.0661

Research Article

DETERMINATION OF OPTIMAL RESERVE INVENTORY BETWEEN MACHINES IN SERIES WITH STOCHASTIC BREAKDOWN DURATIONS HAVING SCBZ PROPERTY

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ARTICLE INFO

Article History:

Received 10th May, 2017
Received in revised form 5th June, 2017 Accepted 16th July, 2017
Published online 28th August, 2017

Key words:

System in Series, Breakdown Duration, SCBZ Property, Optimal Reserve,

ABSTRACT

The determination of optimal inventory theory several variations of inventory problem are discussed. The objective is to derive the optimal re-order level or optimal stock level. In this paper the optimal reserve inventory between two machines in series attempted. The output of machine M_1 is the input for machine M_2^a and M_2^b. Whenever the breakdown of the machine M_1 is at fault i.e not working, then the machine M_2^a and M_2^b may go to an idle stage. The ideal time of M_2^a and M_2^b is very expensive and hence to prevent the ideal time of M_2^a and M_2^b a reserve inventory is maintained in between M_1 and M_2^a, M_2^b. The breakdown durations τ of machine M_1 is a random variable. This random variable is assumed to possess the called Setting the Clock Back to Zero (SCBZ) property for two random variables namely the breakdowns duration and interarrival times between repairs of M_1 the optimal reserve inventory size is obtained. Numerical illustration also substantiated.

INTRODUCTION

In many manufacturing industries the production of products is in series of machines. The optimal reserve between the systems, namely, the system that produces the input and the system that consumes the input obtained from the previous system. If various manufacturing processes operate successively, then in the case of breakdown of one at some stage can affect the entire system. Hence stocking points of inventory are created between adjacent stages so as to achieve a certain degree of independence in operating the stages. In the present model the optimal size of the reserve of raw material to be maintained in between two machines in series is found out. A system in which there are two machine M_1 is in first stage and in the second stage there are two machinesM_2^aandM_2^b is considered. The output of machine M1 is the input for machine M_2^a and M_2^b. Whenever the breakdown of the machine M1 is at fault i.e not working, then the machine M_2^a and M_2^b may go to an idle stage. The ideal time of M_2^a and M_2^b is very expensive and hence to prevent the ideal time of M_2^a and M_2^b a reserve inventory is maintained in between M_1 and M_2^a, M_2^b. The breakdown durations τ of machine M_1 is a random variable. This random variable is assumed to possess the so called Setting the Clock Back to Zero (SCBZ) property for two random variables namely the breakdowns and interarrival times between repairs of M_1 the optimal reserve inventory size is obtained. Numerical illustration also substantiated.

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The determination if the optimal size of reserve inventory between M_1 and M_2 has been discussed by many authors, the have introduced the property called Setting the Clock Back to Zero Property (SCBZ property) RajaRao and Talwalkar (1990). The model is derived for optimal reserve between two machines with repair time having SCBZ (Setting the Clock Back to Zero) property has been discussed by Sachithananatham, *et.al.* (2006). The optimal reserve inventory between two machines under SCBZ property of inter-arrival times between breakdowns has been discussed by Srinivasan, *et.al.* (2007). The expected time to recruitment when threshold distribution has SCBZ property has been discussed by Sathiyamoorthi, and Parthasarathy, (2003). The basic model involving two machines in series and the determination of optimal reserve between two machines has been discussed by Hansman (1962). An extension of model is carried out in this paper.

Notations

S -Level of reserve inventory
X_0 - A continuous random variable which denotes the repair time of M_1 with p.d.f is g(.)

with c.d.f G (.)

μ - mean time interval between the successive breakdowns of machine M_1

τ - A random variable which denotes the duration of breakdown / repair time M_1 and it has p.d.f g(.) with c.d.f G(.) and $\tau \sim \exp(\lambda)$.

h - Inventory holding cost per unit time
d_1 - Cost per unit of idle time of machine M_2^a
d_2 - Cost per unit of idle time of machine M_2^b
r_1 -Consumption rate per unit time of machine M_2^a
r_2 - Consumption rate per unit time of machine M_2^b

Assumptions

1. The output at the M_1 which is a semi finished products is the input for M_2^a and M_2^b
2. Machine M_1 undergoes breakdown for a random duration
3. Whenever M_1 undergoes a breakdown, then the supply of the raw material for M_2^a and M_2^b is from the reserve inventory
4. The consumption rate of M_2^a and M_2^b are fixed Constants
5. The breakdown time of M_1 is a random variable

Results I

In this model two machines M_1 and M_2^a and M_2^b in series is considered and the optimal value of reserve inventory between M_1 and M_2^a and M_2^b for the system given above in the introduction is discussed.

if T is a random variable denoting idle time of machines M_2^a and M_2^bduring a repair time of machine M_1 will be noted that

$$T = \begin{cases} o & if \quad \tau < \dfrac{s}{r_1 + r_2} \\ \tau - \dfrac{s}{r_1 + r_2} & if \quad \tau > \dfrac{s}{r_1 + r_2} \end{cases}$$

As there are $\frac{1}{\mu}$ breakdowns per unit time, the expected cost per unit time becomes

$$E(c) = hs + \left(\frac{d_1 + d_2}{\mu}\right) \int_{\frac{S}{r_1+r_2}}^{\infty} \left(\tau - \frac{S}{r_1 + r_2}\right) g(\tau) d\tau \qquad \ldots(1)$$

To obtain optimal reserve inventory S,

To find $\frac{dE(c)}{ds} = 0$, it may be observed that the differentiating (1) both sides w.r.t S by using the Leibnitz rule of differentiation of integral, we get,

$$\frac{dE(c)}{ds} = h - \left(\frac{d_1+d_2}{\mu(r_1+r_2)}\right) \int_{\frac{s}{r_1+r_2}}^{\infty} g(\tau)\ d\tau \qquad \ldots(2)$$

Thus,

$$\frac{dE(c)}{ds} = h - \left(\frac{d_1 + d_2}{\mu(r_1 + r_2)}\right)\left(1 - G\left(\frac{S}{r_1 + r_2}\right)\right) \qquad \ldots(3)$$

To determine the optimal reserve inventory level $\hat{S}$, it is required to solve

$$\frac{dE(c)}{ds} = 0 \qquad \cdots(4)$$

Therefore, the optimal reserve inventory level $\hat{S}$ is given as,

$$G\left(\frac{\hat{S}}{r_1 + r_2}\right) = 1 - \frac{(r_1 + r_2)\ \mu h}{(d_1 + d_2)} \qquad \cdots(5)$$

Results II

In this model it is assumed that the breakdown duration of machine M_1 which is denoted as a random variable τ with p.d.f g(t) is such that satisfies the Setting the Clock Back to Zero (SCBZ) property. For detailed Study of the SCBZ property, one refers to Raja Rao and Talwalker (1990). According to this property the probability distribution of the random variable τ has a parametric change when $\tau \geq X_0$, where X_0 is a truncation point of random variable X. The distribution remains the same except for the fact that the parameter changes from θ_0 to θ_1. it may be stated that $f(X, \theta_0) \rightarrow f(X, \theta_1)$ whenever $X > X_0$.

A condition which ensure the existence of the SCBZ property for any distribution is that

$$\frac{S(X + X_0, \theta_1)}{S(X, \theta_0)} = S(X, \theta_1)$$

In the present model it is assumed that the breakdown duration τ which is a random variable has a p.d.f which satisfies SCBZ property.

The random variable τ follows $g(\tau, \theta_0)$ if $\tau < X_0$, and it follows $g(\tau, \theta_1)$ if $\tau \geq X_0$ where X_0 is the truncation point and G(.) is the c.d.f of τ.

Now the expected total cost can be represented as

$$E(c) = hs + \frac{(d_1 + d_2)}{\mu}\left[\int_{\frac{S}{(r_1+r_2)}}^{x_0} g(\tau, \theta_0)\ d\tau + \int_{x_0}^{\infty} g(\tau, \theta_1) d\tau\right] \cdots(6)$$

Special Case

Consider the following p.d.f.

$$g(t) = \begin{cases} \theta_0 e^{-x\theta_0} & if \quad \tau \leq x_0 \\ e^{x_0(\theta_1 - \theta_0)}\ \theta_1 e^{-x\theta_1} & if \quad \tau > x_0 \end{cases}$$

It can be shown that $g(\tau)$ satisfies the SCBZ property.

Result I

When $\frac{S}{r_1+r_2}$ lies before X_0, (i.e.,) $\frac{S}{r_1+r_2} \leq X_0$, where S is the initial reserve inventory level Kept and it is an assumed value.

$$E(c) = hs + \frac{(d_1 + d_2)}{\mu}\left[\int_{\frac{S}{(r_1+r_2)}}^{x_0} \left(\tau - \frac{S}{r_1 + r_2}\right) g(\tau) d\tau + \int_{x_0}^{\infty} \left(\tau - \frac{S}{r_1 + r_2}\right) g(\tau) d\tau\right] \cdots(7)$$

To find $\frac{dE(c)}{ds} = o$,

$$h + \left[\frac{d}{ds}\left\{\int_{\frac{S}{(r_1+r_2)}}^{x_0} \left(\tau - \frac{S}{r_1 + r_2}\right) g(\tau) d\tau + \int_{x_0}^{\infty} \left(\tau - \frac{S}{r_1 + r_2}\right) g(\tau) d\tau\right\}\right]$$

Let we have

$$I_1 = \frac{d}{ds} \int_{\frac{S}{(r_1+r_2)}}^{x_0} \left(\tau - \frac{S}{r_1 + r_2}\right) g(\tau) d\tau \qquad \cdots(8)$$

And

$$I_2 = \frac{d}{ds} \int_{x_0}^{\infty} \left(\tau - \frac{S}{r_1 + r_2}\right) g(\tau) d\tau \qquad \cdots(9)$$

Using above equation the Leibnitz rule of differentiation of integral, we get,

$$I_1 = 0 - \frac{1}{r_1+r_2} + \left(\frac{S}{r_1+r_2}, \quad s\right) + \int_{\frac{S}{(r_1+r_2)}}^{x_0} \left(\frac{-1}{r_1+r_2}\right) g(\tau)d\tau$$

$$= -\frac{1}{r_1+r_2} \int_{\frac{s}{r_1+r_2}}^{x_0} g(t)dt$$

$$= -\frac{1}{r_1+r_2}\left[G(x_0,\theta_0) - G(\frac{s}{r_1+r_2})\right] \quad \cdots (10)$$

therefore, we have

$$I_2 = \int_{x_0}^{\infty} \left(\frac{-1}{r_1+r_2}\right) g(t)dt$$

$$= -\frac{1}{r_1+r_2}\int_{x_0}^{\infty} g(t)dt$$

$$= \frac{-1}{r_1+r_2}\bar{G}(x_0,\theta_1) \quad \cdots (11)$$

where

$$\bar{G}(x_0,\theta_1) = p(\tau \geq x_0)$$

$$\frac{d\,E(c)}{ds} = h + \frac{d_1+d_2}{\mu}\frac{d}{ds}\left[\int_{s/r_1+r_2}^{x_0}\left(\tau - {}^{s}/_{r_1+r_2}\right)g(t)dt + \int_{x_0}^{\infty}\left(\tau - {}^{s}/_{r_1+r_2}\right)g(t)dt\right]$$

$$\frac{d\,E(c)}{ds} = 0$$

$$h - \frac{d_1+d_2}{\mu\,(r_1+r_2)}\left[G(x_0,\theta_0) - G\left(\frac{s}{r_1+r_2}\right) + \bar{G}(x_0,\theta_1)\right] = 0$$

$$G(x_0,\theta_0) - G\left(\frac{s}{r_1+r_2}\right) + \bar{G}(x_0,\theta_1) = \frac{h\,\mu(r_1+r_2)}{d_1+d_2} \cdots (12)$$

$$G(x_0,\theta_0) - G\left(\frac{s}{r_1+r_2},\theta_0\right) = \int_{\frac{s}{r_1+r_2}}^{x_0} g(\tau)d\tau \quad = \int_{\frac{s}{r_1+r_2}}^{x_0} (\theta_0 e^{-x\theta_0})\,d\tau$$

$$= \theta_0 \int_{\frac{s}{r_1+r_2}}^{x_0} \left(e^{-x\theta_0}\right)d\tau$$

$$= \theta_0\left[\frac{e^{-x\theta_0}}{-\theta_0}\right]_{\frac{s}{r_1+r_2}}^{x_0}$$

$$= -e^{-x\theta_0}\quad e^{-\frac{s}{r_1+r_2}\theta_0} \quad \cdots (13)$$

Now we consider,

$$\bar{G}(x_0,\theta_1) = \int_{x_0}^{\infty}\left(e^{x_0(\theta_1-\theta_0)}\ \theta_1 e^{-x\theta_1}\right)d\tau$$

$$= e^{x_0(\theta_1-\theta_0)}\int_{x_0}^{\infty}\left(\theta_1 e^{-x\theta_1}\right)d\tau$$

$$= e^{x_0(\theta_1-\theta_0)}\left[\theta_1\frac{e^{-x\theta_1}}{-\theta_1}\right]_{x_0}^{\infty}$$

$$= e^{x_0(\theta_1-\theta_0)}\ e^{-x_0\theta_1}$$

$$= e^{x_0\theta_1}\ e^{-x_0\theta_0}\ e^{-x_0\theta_1}$$

$$= e^{x_0(\theta_1-\theta_0-\theta_1)}$$

$$= e^{-x_0\theta_0} \quad \ldots (14)$$

Substitute (13) and (14) in equation (12).

$$G(x_0,\theta_0) - G\left(\frac{s}{r_1+r_2},\theta_0\right) + \bar{G}(x_0,\theta_1) = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$-e^{-x\theta_0}\quad e^{-\frac{s}{r_1+r_2}\theta_0} + e^{-x_0\theta_0} = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$e^{-\frac{s}{r_1+r_2}\theta_0} = \frac{h\mu(r_1+r_2)}{d_1+d_2} \quad \ldots (15)$$

The above equation (15) by taking log on both sides becomes,

$$-\theta_0\frac{s}{r_1+r_2}log_e = log\left[\frac{h\mu(r_1+r_2)}{d_1+d_2}\right]$$

Therefore, the optimal reserve inventory level $\hat{S}$ is given as,

$$\hat{S} = \frac{log\left[\frac{h\mu(r_1+r_2)}{d_1+d_2}\right](r_1+r_2)}{-\theta_0 log_e} \quad \cdots (16)$$

Result (ii)

When $\frac{s}{r_1+r_2}$ falls after X_0 i.e $\frac{s}{r_1+r_2} > x_0$

$$E(c) = hs + \frac{d_1+d_2}{\mu}\left[\int_{\frac{s}{r_1+r_2}}^{\infty}\left(\tau - \frac{s}{r_1+r_2}\right)g(\tau)\,d\tau\right]$$

Now taking,

$$\frac{d\,E(c)}{ds} = 0$$

$$h + \frac{d_1+d_2}{\mu}\left[\frac{d}{ds}\int_{s/r_1+r_2}^{x_0}\left(\tau - {}^{s}/_{r_1+r_2}\right)g(\tau)d\tau\right] = 0$$

$$\frac{d\,E(c)}{ds} = 0$$

$$h - \frac{d_1+d_2}{\mu(r_1+r_2)}\int_{s/r_1+r_2}^{x_0}\left(\tau - {}^{s}/_{r_1+r_2}\right)g(\tau)d\tau = 0$$

$$\int_{s/r_1+r_2}^{x_0} g(t)dt = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$1 - G\left(\frac{s}{r_1+r_2}\right) = \frac{h\mu(r_1+r_2)}{d_1+d_2} \quad \cdots (17)$$

$$\int_{\frac{s}{r_1+r_2}}^{\infty} g(t)dt = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$\int_{\frac{s}{r_1+r_2}}^{\infty}[e^{x_0(\theta_1-\theta_0)}\ \theta_1 e^{-x\theta_1}]dt = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$e^{x_0(\theta_1-\theta_0)}\int_{\frac{s}{r_1+r_2}}^{\infty}[\theta_1 e^{-x\theta_1}]dt = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$e^{x_0(\theta_1-\theta_0)}\left[\theta_1\frac{e^{-x\theta_1}}{-\theta_1}\right]_{\frac{s}{r_1+r_2}}^{\infty} = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$e^{x_0(\theta_1-\theta_0)}\; e^{-\frac{s}{r_1+r_2}\theta_1} = \frac{h\mu(r_1+r_2)}{d_1+d_2}$$

$$e^{-\frac{s}{r_1+r_2}\theta_1} = \frac{h\mu(r_1+r_2)}{d_1+d_2}\, e^{x_0(\theta_1-\theta_0)} \quad \dots (18)$$

The above equation (18) by taking log on both sides becomes,

$$-\theta_1\frac{s}{r_1+r_2}\log e = log\left[\frac{h\mu(r_1+r_2)}{d_1+d_2}\right] + x_0(\theta_1-\theta_0)$$

Therefore, the optimal reserve inventory level $\hat{S}$

$$\hat{S} = \frac{\left[log\left[\frac{h\mu(r_1+r_2)}{d_1+d_2}\right] + x_0(\theta_1-\theta_0)\right](r_1+r_2)}{-\theta_1\log e} \quad \cdots (19)$$

The optimal valve of $\hat{S}$ can be obtained by using (16) and (19).

$$\hat{S} = \begin{cases} \dfrac{log\left[\frac{h\mu(r_1+r_2)}{d_1+d_2}\right](r_1+r_2)}{-\theta_0 log_e} & if \quad \dfrac{s}{r_1+r_2} \le x_0 \\ \dfrac{\left[log\left[\frac{h\mu(r_1+r_2)}{d_1+d_2}\right] + x_0(\theta_1-\theta_0)\right](r_1+r_2)}{-\theta_1\log e} & if \quad \dfrac{s}{r_1+r_2} > x_0 \end{cases}$$

Numerical Illustration

The variation in the values of $\hat{S}$ consequent to the changes in parameter h, $\mu, \theta_0, \theta_1, x_0,$ the demand rate r_1, r_2, and ideal time cost d_1, d_2, have been taking numerical illustration. The table and corresponding graphs are given as.

If the value of inventory holding cost h increases the optimal inventory size namely $\hat{S}$ decreases therefore a smaller reserve inventory will increase the profit, in both the cases namely $(s/(r_1+r_2)) \le x_0$ and $(s/(r_1+r_2)) > x_0$. This is observed in Table 1 and Fig 1.

Table 1 Optimal value of the Reserve Inventory when holding cost is fixed

h	5	10	15	20	25	30	35	40	45	50
$\hat{S} = (s/(r_1+r_2)) \le x_0$	23.15	16.22	12.17	9.29	7.06	5.24	3.69	2.36	1.18	0.132
$\hat{S} = (s/(r_1+r_2)) > x_0$	95.18	84.78	78.70	74.38	71.03	68.30	65.99	63.98	62.22	60.64

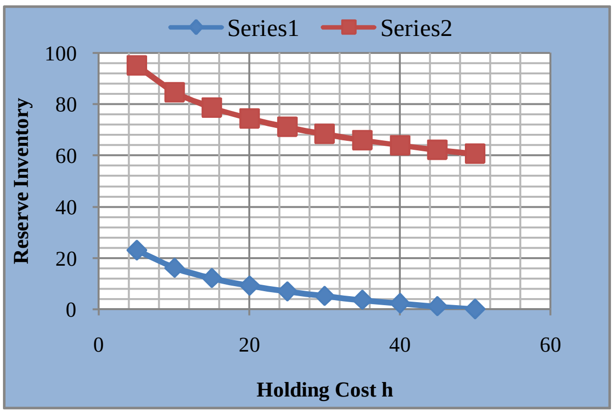

Fig 1 Optimal value of $\hat{S}$ when holding cost is fixed

If the value of d_1 which denotes the shortage cost due to inadequate supply to machine M_2^a increases then as increasing the reserve inventory $\hat{S}$ is suggested in both the cases namely $(s/(r_1+r_2)) \le x_0$ and $(s/(r_1+r_2)) > x_0$ and this is a indicated in Table 2 and Fig 2.

Table 2 Optimal value of the Reserve Inventory when shortage cost for M_2^a is fixed

d_1	180	190	200	210	220	230	240	250	260	270
$\hat{S} = (s/(r_1+r_2)) \le x$	23.15	23.418	23.671	23.918	24.159	24.394	24.62	24.84	25.06	25.28
$\hat{S} = (s/(r_1+r_2)) > x$	95.18	95.570	95.950	96.321	96.682	97.035	97.38	97.71	98.04	98.36

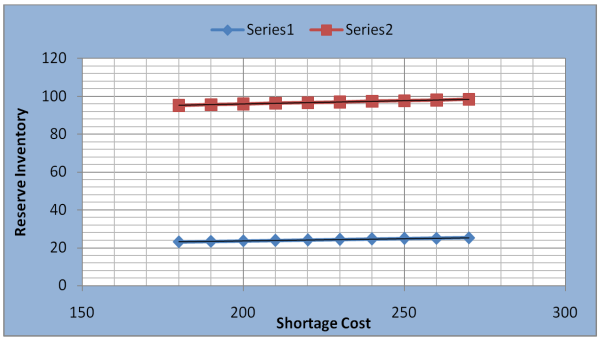

Fig 2 Optimal value of $\hat{S}$ when shortage cost for M_2^a is fixed

If the value of d_2 which the shortage cost arising due to machine M_2^b increase then an increase in the values of $\hat{S}$ is also observed and therefore if the shortage cost of machine 2 increases a higher level of reserve inventory is suggested in both the cases namely $(s/(r_1+r_2)) \le x_0$ and $(s/(r_1+r_2)) > x_0$. It is observed in Table 3 and Fig 3.

Table 3 Optimal value of the Reserve Inventory when shortage cost for M_2^b is fixed

d_2	200	210	220	230	240	250	260	270	280	290
$\hat{S} = (s/(r_1+r_2)) \le x_0$	23.15	23.418	23.671	23.918	24.159	24.394	24.62	24.84	25.06	25.28
$\hat{S} = (s/(r_1+r_2)) > x_0$	95.18	95.570	95.950	96.321	96.682	97.035	97.38	97.71	98.04	98.36

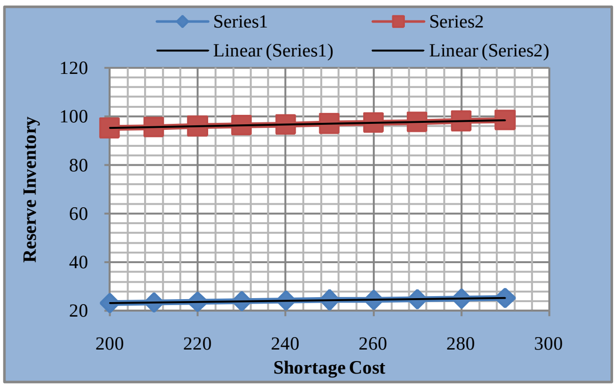

Fig 3 Optimal value of $\hat{S}$ when shortage cost for M_2^b is fixed

If the values of μ which is the average inter arrival time between the successive failure of machine M_1 increases then a smaller reserve inventory $\hat{S}$ is suggested in both the cases namely $(s/(r_1+r_2)) \le x_0$ and $(s/(r_1+r_2)) > x_0$. This is obsevrved in Table 4 and Fig 4.

Table 4 Optimal value of the Reserve Inventory when Successive breakdown of the machine is fixed

μ	**0.5**	**0.7**	**0.9**	**1.1**	**1.3**	**1.5**	**1.7**	**1.9**	**2.1**	**2.3**
$\hat{S} = (s/(r_1 + r_2)) \leq x_0$	23.15	19.79	17.28	15.27	13.60	12.17	10.92	9.80	8.80	7.89
$\hat{S} = (s/(r_1 + r_2)) >$.	95.18	90.13	86.36	83.35	80.85	78.702	76.82	75.15	73.65	72.29

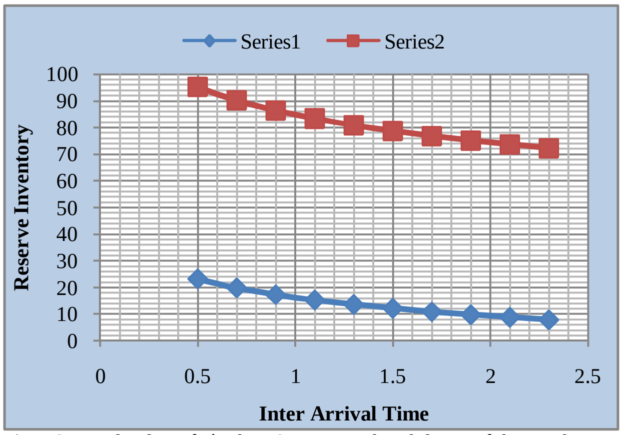

Fig 4 Optimal value of $\hat{s}$ when Successive breakdown of the machine is fixed

CONCLUSIONS

The following conclusions are drawn on the basis of the numerical illustration that has been worked out for this model.

1. As the value of inventory holding cost h increases the optimal inventory size namely $\hat{S}$ decreases therefore a smaller reserve inventory will increase in both the cases namely $(s/(r_1 + r_2)) \leq x_0$ and $(s/(r_1 + r_2)) > x_0$.
2. If the value of d_1 which denotes the shortage cost due to inadequate supply to machine M_2^a has an increase then an increase in the reserve inventory $\hat{S}$ is suggested in both the cases namely $(s/(r_1 + r_2)) \leq x_0$ and $(s/(r_1 + r_2)) > x_0$.
3. If the value of d_2 which the shortage cost arising due to machine M_2^b increases an increase the value of $\hat{S}$ is also observed in both the cases namely $(s/(r_1 + r_2)) \leq x_0$ and $(s/(r_1 + r_2)) > x_0$.
4. If the value of μ which is the average inter arrival time between the successive failure is of machine M_1 increases a smaller reserve inventory $\hat{S}$ is suggested in both the cases namely $(s/(r_1 + r_2)) \leq x_0$ and $(s/(r_1 + r_2)) > x_0$.

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How to cite this article:

Govindhan M and Elangovan R (2017) 'Determination of Optimal Reserve Inventory Between Machines in Series with Stochastic Breakdown Durations Having Scbz Property', *International Journal of Current Advanced Research*, 06(08), pp. 5146-5150. DOI: http://dx.doi.org/10.24327/ijcar.2017.5150.0661

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