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A Model for Optimal Reserve Inventory Between two Machines with Reference to Truncation Point of the Repair Time

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Abstract

In Inventory control theory, many suitable models for real life systems are constructed with the objective of determining the optimal inventory level. In a system where the machines are in series for producing the finished products. The reserve of semi-finished products between two machines becomes unavoidable to minimize the idle time of machines in series. In this model the repair time of machines is assumed to be a random variable and it follows exponential distribution which satisfies the so called Setting the Clock Back to Zero (SCBZ) property. Also, the truncation point of the repair time distribution is itself a random variable and it follows mixed exponential distribution. Under this assumption an optimal reserve inventory is obtained.

Key words: Reserve Inventory, SCBZ property, Repair time, Truncation point and Optimal reserve.

1. Introduction

Describing the behaviour of the inventory system in terms of the mathematical model carries out a determination of optimal inventory under different real life circumstances. When working systems are considered, avoiding the breakdown of the system if quiet possible by keeping reserve inventory between the machines are in series. A system in which there are two machines M_1 and M_2 are in series. The output of the machine M_1 is the input of the machine M_2. The breakdown of M_1 causes the idle time of M_2, since there is no input to M_2 from M_1. The idle time of M_2 is very costly and hence to avoid it, a reserve inventory is maintained in between M_1 and M_2. The repair time of M_1 is considered as a random variable and after the repair time of M_1 is exceeded, it supplies to the reserve inventory. If the reserve inventory is surplus in quantity, there is an inventory holding cost. If the reserve inventory slacks in its quantity, then it assumes the high idle time cost. Hence, in order to balance these costs, an optimal reserve inventory must be maintained between these two machines. Therefore, the problem is to determine the optimal reserve between M_1 and M_2. The very basic model has been discussed by Hanssmann. F[1]. The extension over this model is discussed by Ramachandran and Sathyamoorthi[2].

This type of models has been discussed by many authors under the assumptions that the repair time is a random variable. Sachithanantham. S *et al.*[3] discussed this model with the assumption that the probability function of the repair time undergoes a parametric change after the truncation point. The very basic concept of parametric change known as SCBZ property was discussed by Raja Rao. B and Talwalker. S.[4]. The model for optimal reserve inventory between two machines under the assumption that the repair time of machine M_1 satisfies the SCBZ property with the truncation point being a random variable is derived bySachithananantham. S. *et al.*[5]. And the same model with a modification of the probability function of truncation point is discussed by Ramathilagam. S. *et al.*[6]. The improvement over this model is being discussed in this paper, in which the truncation point is a random variable, which follows the mixed exponential distribution with parameters θ_1 *and* θ_2.

2. Notations

h	: Inventory holding cost/ unit/ unit time.
d	: Idle time cost due to M_2 / unit time.
μ	: Mean time interval between successive breakdown of machine M_1, assuming exponential distribution of inter-arrival times.
t	: Continuous random variable denoting the repair time of M_1 with pdf g(.) and c.d.f G(.)
r	: Constant consumption rate of M_2 per unit of time.
S	: Reserve inventory between M_1 and M_2
T	: Random variable denoting the idle time of M_2
θ	: Parameter of exponential distribution before the truncation point.
θ^*	: Parameter of exponential distribution after the truncation point.
β	: Probability value involved in the mixed exponential distribution.
θ_1 & θ_2	: Parameters of mixed exponential distribution.

3. Model I:

If T is a random variable denoting idle time of M_2, it can be seen that

$$T = \begin{cases} 0 & if \ \frac{s}{r} > t \\ t - \frac{s}{r} & if \ \frac{s}{r} \le t \end{cases} \qquad (1)$$

The expected total cost of inventory holding and idle time of M_2 per unit of time is given by

$$E(c) = hs + \frac{d}{\mu}\int_{\frac{s}{r}}^{\infty}\left(t - \frac{s}{r}\right) g(t)\, dt \qquad (2)$$

The optimal reserve $\hat{S}$ can be obtained by solving the equation $\frac{dE(c)}{ds} = 0$.

The expression for optimal reserve inventory is given by

$$G\left(\frac{\hat{S}}{r}\right) = 1 - \frac{r\mu h}{d}$$

This result is discussed in Hanssmann. F.[1]. It may be observed that the above expression for optimal value of S has a constraint that $\frac{h\mu r}{d} < 1$, otherwise the solution is not a feasible one. Hence, a slight modification in the expression for the expected total cost can be incorporated as below.

1. Model II:

In this model it is assumed that the repair time distribution satisfies the SCBZ property is basically discussed by Raja Rao and Talwalker(1991). Under this assumption

$$g(t) = \begin{cases} g(t,\theta), & t \le X_0 \\ g(t,\theta^*), & t > X_0 \end{cases}$$

where X_0 is a random variable denoting the truncation point of repair time and it is distributed as exponential with parameter λ.

$$g(t,\theta) = \begin{cases} \theta e^{-\theta t} & , if \ t \le X_0 \\ \theta^* e^{-\theta^* t}\, e^{X_0(\theta^* - \theta)} & , if \ t > X_0 \end{cases} \qquad (3)$$

Thus

$$E(c) = hs + \frac{d}{\mu}\int_{s/r}^{\infty}\left[\int_{s/r}^{x_0}(t - s/r)g(t,\theta)dt + \int_{x_0}^{\infty}(t - s/r)\, g(t,\theta^*)dt\right] f(x_0)\, dx_0$$

$$+ \frac{d}{\mu}\int_0^{s/r}\left[\int_{s/r}^{\infty}(t - s/r)\, g(t,\theta^*)dt\right] f(x_0)dx_0$$

Under this model the optimal reserve inventory obtained by solving the equation $\frac{dE(c)}{ds} = 0$

$$(\theta - \theta^*)e^{-(\lambda+\theta)(s/r)} + \lambda e^{-\theta^*(s/r)} = \frac{h\mu r\left(\lambda+\theta-\theta^*\right)}{d}$$

This model discussed by Sachithanandam *et. al.*,[5]

1. Results

In this model, it is assumed that the repair time of machine M_1 is a random variable and undergoes a parametric change. That is the pdf of the repair time is exponential and it undergoes a parametric change.

$$g(t,\theta) = \begin{cases} \theta e^{-\theta t}, if\ t \le X_0 \\ \theta^* e^{-\theta^* t} e^{X_0(\theta^*-\theta)},\ if\ t > X_0 \end{cases} \quad (4)$$

where X_0 is a random variable denoting that truncation point and it is distributed as mixed exponential with parameter θ_1 and θ_2. Hence the pdf of repair time can be rewritten as

$$f(t) = g(t,\theta)\ P(t \le X_0) + g(t,\theta^*)\ P(t > X_0)$$

Here $P(t \le X_0) = P(X_0 \ge t) = \int_t^\infty f(x_0)\, dx_0$

$$= \int_t^\infty \beta\theta_1\ e^{-\theta_1 y} + (1-\beta)\theta_2 e^{-\theta_2 y} dy$$

$$= \beta\theta_1 \left(\frac{e^{-\theta_1 y}}{-\theta_1}\right)_t^\infty + (1-\beta)\theta_2 \left(\frac{e^{-\theta_2 y}}{-\theta_2}\right)_t^\infty$$

$$= \beta\left(e^{-\theta_1 t} - 0\right) + (1-\beta)\left(e^{-\theta_2 t} - 0\right)$$

$$\therefore P(t \le X_0) = \beta e^{-\theta_1 t} + (1-\beta)\left(e^{-\theta_2 t}\right)$$

$$\therefore f(t) = g(t,\theta)\left(\beta e^{-\theta_1 t} + (1-\beta)\left(e^{-\theta_2 t}\right)\right)$$

$$+\int_0^t g(t,\theta^*)\ \beta\theta_1 e^{-\theta_1 x_0} + (1-\beta)\theta_2 e^{-\theta_2 x_0} dx \quad (5)$$

It may be observed that the random variable 'T' defined in equation (1) also undergoes a parametric change and the average idle time of M_2 is

$$E(T) = \int_{s/r}^\infty (t - {}^{S}/_{r}) f(t) dt$$

$$= \int_{s/r}^\infty (t - {}^{S}/_{r}) \left\{ g(t,\theta)[\left(\beta e^{-\theta_1 t}\right) + (1-\beta)\left(e^{-\theta_2 t}\right)] + \int_0^t g(t,\theta^*)[\beta\theta_1 e^{-\theta_1 x_0} + (1-\beta)\theta_2 e^{-\theta_2 x_0}] dx_0 \right\} dt$$

$$E(T) = \int_{s/r}^\infty (t - {}^{S}/_{r})\, g(t,\theta)[\left(\beta e^{-\theta_1 t}\right) + \left(e^{-\theta_2 t}\right)] dt + \int_{s/r}^\infty (t - {}^{S}/_{r})[\int_0^t g(t,\theta^*)[\beta\theta_1 e^{-\theta_1 x_0} + (1-\beta)\theta_2 e^{-\theta_2 x_0}] dx_0] dt$$

Thus the expected total cost is

$$E(c) = hs + \frac{d}{\mu}\int_{s/_r}^\infty \left[\int_{s/_r}^{x_0} (t - {}^{S}/_{r}) g(t,\theta) dt + \int_{x_0}^\infty (t - {}^{S}/_{r})\, g(t,\theta^*) dt\right] f(x_0)\, dx_0$$

$$+ \frac{d}{\mu}\int_0^{S/_r} \left[\int_{s/_r}^\infty (t - {}^{S}/_{r})\, g(t,\theta^*) dt\right] f(x_0) dx_0$$

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

$$\Rightarrow h + \frac{d}{\mu}\int_{s/_r}^\infty \left[\frac{d}{ds}\left\{\int_{s/_r}^{x_0} (t - {}^{S}/_{r}) g(t,\theta) dt + \int_{x_0}^\infty (t - {}^{S}/_{r})\, g(t,\theta^*) dt\right\}\right]\left[\beta\theta_1 e^{-\theta_1 x_0} + (1-\beta)\theta_2 e^{-\theta_2 x_0}\right] dx_0 +$$

$$\frac{d}{\mu}\int_0^{S/_r} \frac{d}{ds}\left(\int_{s/_r}^\infty (t - {}^{S}/_{r}) g(t,\theta^*) dt\right)\left(\beta\theta_1 e^{-\theta_1 x_0} + (1-\beta)\theta_2 e^{-\theta_2 x_0}\right) dx_0 = 0 \quad (6)$$

$$h + \frac{d}{\mu}\int_{s/_r}^\infty \frac{d}{ds}(I_1 + I_2)\left(\beta\theta_1 e^{-\theta_1 x_0} + (1-\beta)\theta_2 e^{-\theta_2 x_0}\right) dx_0 + \frac{d}{\mu}\int_0^{S/_r} \frac{d}{ds} I_3\left(\beta\theta_1 e^{-\theta_1 x_0} + (1-\beta)\theta_2 e^{-\theta_2 x_0}\right) dx_0 = 0$$

Consider

$$\frac{d}{ds}(I_1 + I_2) = \frac{d}{ds}\int_{s/_r}^{x_0} (t - {}^{S}/_{r})\theta e^{-\theta t} dt + \frac{d}{ds}\int_{x_0}^\infty (t - {}^{S}/_{r})\theta^* e^{-\theta^* t} e^{x_0(\theta^*-\theta)} dt$$

$$= \int_{s_r}^{x_0} \left(-\frac{1}{r}\right)\theta e^{-\theta t} dt + \int_{x_0}^\infty \left(-\frac{1}{r}\right)\theta^*\, e^{-\theta^* t} e^{x_0(\theta^*-\theta)} dt$$

$$=-\frac{\theta}{r}\left[\frac{e^{-\theta t}}{-\theta}\right]_{S/r}^{x_0}-\frac{\theta^*}{r}e^{x_0(\theta^*-\theta)}\left[\frac{e^{-\theta^* t}}{-\theta^*}\right]_{x_0}^{\infty}$$

$$=\frac{1}{r}\left[e^{-x_0\theta}-e^{-\theta(S/r)}\right]+\frac{e^{x_0(\theta^*-\theta)}}{r}\left[0-e^{-\theta^* x_0}\right]$$

$$=\frac{1}{r}\left[e^{-x_0\theta}-e^{-\theta(S/r)}\right]-\frac{e^{-x_0\theta}}{r}$$

$$\frac{d}{ds}(I_1+I_2)=-\frac{1}{r}e^{-\theta(S/r)} \tag{7}$$

And $\frac{dI_3}{ds}=\frac{d}{ds}\int_{S/r}^{\infty}(t-S/r)\,\theta^* e^{-\theta^* t}e^{x_0(\theta^*-\theta)}dt$

$$=\theta^* e^{x_0(\theta^*-\theta)}\int_{S/r}^{\infty}\left(-\frac{1}{r}\right)e^{-\theta^* t}\,dt$$

$$=\frac{-\theta^* e^{x_0(\theta^*-\theta)}}{r}\left[\frac{e^{-\theta^* t}}{-\theta^*}\right]_{S/r}^{\infty}$$

$$=\frac{e^{x_0(\theta^*-\theta)}}{r}\left(0-e^{-\theta^*(S/r)}\right)$$

$$\therefore\frac{dI_3}{ds}=\frac{-e^{-\theta^*(S/r)}}{r}e^{x_0(\theta^*-\theta)} \tag{8}$$

$$\frac{dE(c)}{ds}=0.$$

$=> h+$

$$\frac{d}{\mu}\int_{S/r}^{\infty}\left(\frac{-e^{-\theta(S/r)}}{r}\right)\left(\beta\theta_1 e^{-\theta_1 x_0}+(1-\beta)\theta_2 e^{-\theta_2 x_0}\right)dx_0+\frac{d}{\mu}\int_0^{S/r}\left(\frac{-e^{-\theta^*(S/r)}}{r}e^{x_0(\theta^*-\theta)}\right)\left(\beta\theta_1 e^{-\theta_1 x_0}+(1-\beta)\theta_2 e^{-\theta_2 x_0}\right)dx_0=0 \tag{9}$$

$$h+\frac{d}{\mu}I_4+\frac{d}{\mu}I_5=0 \tag{10}$$

Consider

$$I_4=\frac{d}{\mu r}\int_{S/r}^{\infty}\left(-e^{-\theta(S/r)}\right)\left(\beta\theta_1 e^{-\theta_1 x_0}+(1-\beta)\theta_2 e^{-\theta_2 x_0}\right)dx_0$$

$$=\frac{-d}{\mu r}\left\{\beta\theta_1 e^{-\theta(S/r)}\left[\frac{e^{-\theta_1 x_0}}{-\theta_1}\right]_{S/r}^{\infty}+(1-\beta)\theta_2 e^{-\theta S/r}\left[\frac{e^{-\theta_2 x_0}}{-\theta_2}\right]_{S/r}^{\infty}\right\}$$

$$=\frac{-d}{\mu r}\left\{\beta e^{-\theta(S/r)}e^{-\theta_1(S/r)}+(1-\beta)e^{-\theta(S/r)}e^{-\theta_2(S/r)}\right\}$$

$$=\frac{-d}{\mu r}\left\{\beta e^{-S/r(\theta+\theta_1)}+(1-\beta)e^{-S/r(\theta+\theta_2)}\right\}$$

$$I_5=\frac{-d}{\mu r}\left[\int_0^{S/r}\beta\theta_1 e^{-\theta^* S/r}e^{-x_0(\theta_1+\theta-\theta^*)}dx_0+\int_0^{S/r}e^{-\theta^*(S/r)}e^{-x_0(\theta_2+\theta-\theta^*)}\theta_2(1-\beta)dx_0\right]$$

$$=\frac{-d}{\mu r}\left[\beta\theta_1 e^{-\theta^* S/r}\frac{e^{-x_0(\theta_1+\theta-\theta^*)}}{-(\theta_1+\theta-\theta^*)}\bigg|_0^{S/r}+(1-\beta)\theta_2 e^{-\theta^*(S/r)}\frac{e^{-x_0(\theta_2+\theta-\theta^*)}}{-(\theta_2+\theta-\theta^*)}\bigg|_0^{S/r}\right]$$

$$=\frac{-d}{\mu r}\left[\beta\theta_1 e^{-\theta^*(S/r)}\left(\frac{e^{-S/r(\theta_1+\theta-\theta^*)}-1}{-(\theta_1+\theta-\theta^*)}\right)+(1-\beta)\theta_2\,e^{-\theta^*(S/r)}\left(\frac{e^{-S/r(\theta_2+\theta-\theta^*)}-1}{\theta_2+\theta-\theta^*}\right)\right]$$

$$=\frac{-d}{\mu r}\left[-\beta\theta_1\frac{e^{-S/r(\theta+\theta_1)}}{\theta_1+\theta-\theta^*}+\frac{\beta\theta_1 e^{-\theta^*(S/r)}}{(\theta_1+\theta-\theta^*)}-(1-\beta)\theta_2\frac{e^{-S/r(\theta+\theta_2)}}{(\theta_2+\theta-\theta^*)}+(1-\beta)\theta_2\frac{e^{-\theta^*(S/r)}}{(\theta_2+\theta-\theta^*)}\right]$$

$$\therefore\frac{dE(c)}{ds}=0 => h-\frac{d}{\mu r}\left[\beta\,e^{-S/r(\theta+\theta_1)}+(1-\beta)e^{-S/r(\theta+\theta_2)}\right]-\frac{d}{\mu r}\left[-\beta\theta_1\frac{e^{-S/r(\theta+\theta_1)}}{(\theta_1+\theta-\theta^*)}+\frac{\beta\theta_1\,e^{-\theta^*(S/r)}}{(\theta_1+\theta-\theta^*)}-(1-\beta)\theta_2\frac{e^{-S/r(\theta+\theta_2)}}{(\theta_2+\theta-\theta^*)}+(1-\beta)\theta_2\frac{e^{-\theta^*(S/r)}}{(\theta_2+\theta-\theta^*)}\right]=0$$

$$h-\frac{d}{\mu r}\beta e^{-S/r(\theta+\theta_1)}-\frac{d}{\mu r}(1-\beta)e^{-S/r(\theta+\theta_2)}+\frac{d}{\mu r}\beta\theta_1\frac{e^{-S/r(\theta+\theta_1)}}{(\theta_1+\theta-\theta^*)}-\frac{d}{\mu r}\beta\theta_1\frac{e^{-\theta^*(S/r)}}{(\theta_1+\theta-\theta^*)}+\frac{d}{\mu r}(1-\beta)\theta_2\frac{e^{-S/r(\theta+\theta_2)}}{(\theta_2+\theta-\theta^*)}-\frac{d}{\mu r}(1-\beta)\theta_2\frac{e^{-S/r(\theta^*)}}{(\theta_2+\theta-\theta^*)}=0$$

$$h - \frac{d}{\mu r}\,\beta\, e^{-S/r(\theta+\theta_1)}\left(1 - \frac{\theta_1}{(\theta_1+\theta-\theta^*)}\right) - \frac{d}{\mu r}(1-\beta)e^{-S/r(\theta+\theta_2)}\left(1 - \frac{\theta_2}{(\theta_2+\theta-\theta^*)}\right)$$
$$- \frac{d}{\mu r}\left(e^{-\theta^*(S/r)}\left(\frac{\beta\theta_1}{(\theta_1+\theta-\theta^*)} + \frac{(1-\beta)\theta_2}{(\theta_2+\theta-\theta^*)}\right)\right) = 0$$

$$h - \frac{d}{\mu r}\left[\beta e^{-S/r\ (\theta+\theta_1)}\left(1 - \frac{\theta_1}{(\theta_1+\theta-\theta^*)}\right) + (1-\beta)e^{-S/r(\theta+\theta_2)}\left(1 - \frac{\theta_2}{(\theta_2+\theta-\theta^*)}\right)\right]$$
$$+ e^{-\theta^*(S/r)}\left(\frac{\beta\theta_1}{(\theta_1+\theta-\theta^*)} + \frac{(1-\beta)\theta_2}{(\theta_2+\theta-\theta^*)}\right) = 0$$

$$\frac{h\mu r}{d} = \left[\beta e^{-S/r(\theta+\theta_1)}\left(\frac{\theta-\theta^*}{(\theta_1+\theta-\theta^*)}\right) + (1-\beta)e^{-S/r(\theta+\theta_2)}\left(\frac{\theta-\theta^*}{(\theta_2+\theta-\theta^*)}\right) + e^{-\theta^*(S/r)}\left(\frac{\beta\theta_1}{(\theta_1+\theta-\theta^*)} + \frac{(1-\beta)\theta_2}{(\theta_2+\theta-\theta^*)}\right)\right] \quad (11)$$

Using the appropriate values of h, d, r, Using the appropriate values of h, d, r,μ, $\beta, \theta_1, \theta_2 \& \theta^*$, the optimal value of S can be obtained.

6. Special Case:

Let $\beta = 1$,, then

$$\frac{h\mu r}{d} = \left[e^{-S/r(\theta+\theta_1)}\left(\frac{\theta-\theta^*}{(\theta_1+\theta-\theta^*)}\right) + e^{-\theta^*(S/r)}\left(\frac{\theta_1}{(\theta_1+\theta-\theta^*)}\right)\right]$$

$$\frac{h\mu r(\theta_1+\theta-\theta^*)}{d} = \left[e^{-S/r(\theta+\theta_1)}(\theta-\theta^*) + \theta_1 e^{-\theta^*(S/r)}\right] \quad (12)$$

This equation obtained by Sachithanandham *et. al.*,[5], in which it is assumed that the truncation point follows exponential and it could be seen that the model (11) is reduced to the above equation when $\beta = 1$.

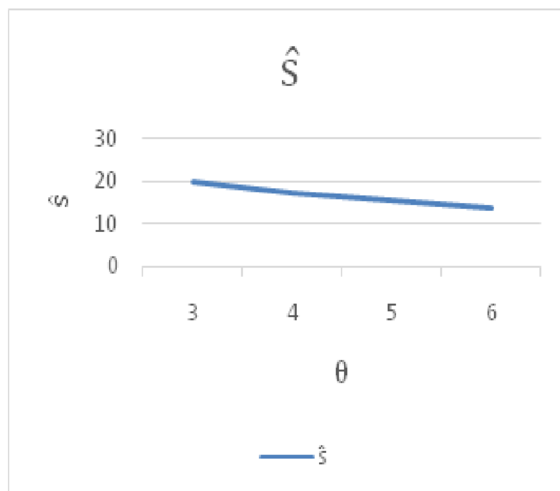
7. Numerical Illustrations :

The variations in the values of optimal reserve inventory "$\hat{S}$ " , consequent on the changes in the parameters θ, θ*, r, d, h, and μ have been studied by taking numerical illustrations. The tables and the corresponding graphs are given.

Case (i)

For h=5, μ=2, r=30, d=3000, β=0.5, θ*=4, θ_1=2,θ_2=3, the optimal value of S is obtained and the variations in $\hat{S}$ for the changes in the value of θ.

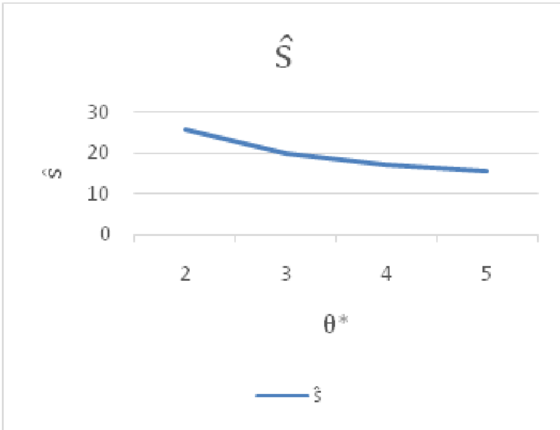
θ	3	4	5	6
$\hat{S}$	19.940	17.270	15.223	13.583



Case (ii)

For h=5, μ=2, r=30, d=3000, β=0.5, θ=4, θ_1=2, θ_2=3, the optimal value of S is obtained and the variations in $\hat{S}$ for the changes in the value of β*.

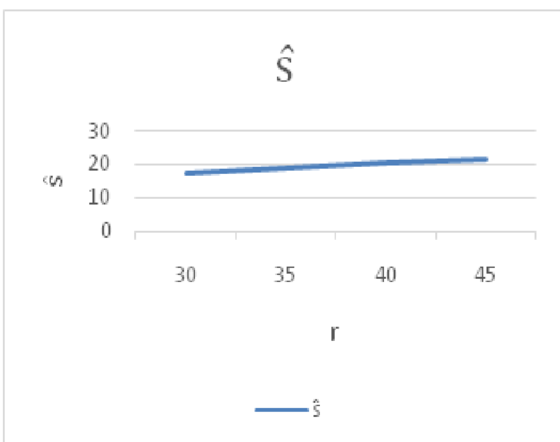
θ*	2	3	4	5
$\hat{S}$	25.859	20.009	17.270	15.686



Case (iii)

For h=5, μ=2, d=3000, β=0.5, θ=4, θ*=4, θ_1=2,θ_2=3, the optimal value of S is obtained and the variations in $\hat{S}$ for the changes in the value of r.

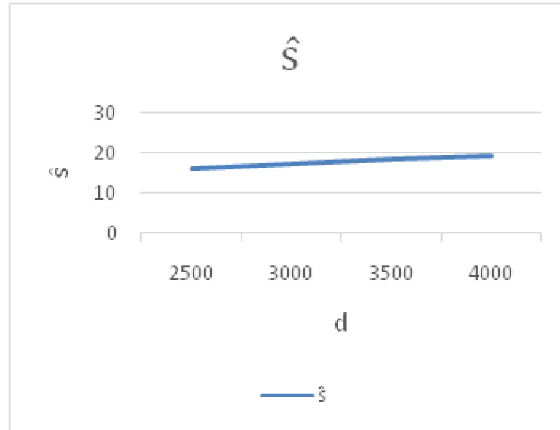
r	30	35	40	45
$\hat{S}$	17.270	18.799	20.149	21.343



Case (iv)

For h=5, μ=2, r=30, β=0.5, θ=4, θ*=4, θ_1=2,θ_2=3, the optimal value of S is obtained and the variations in $\hat{S}$ for the changes in the value of d.

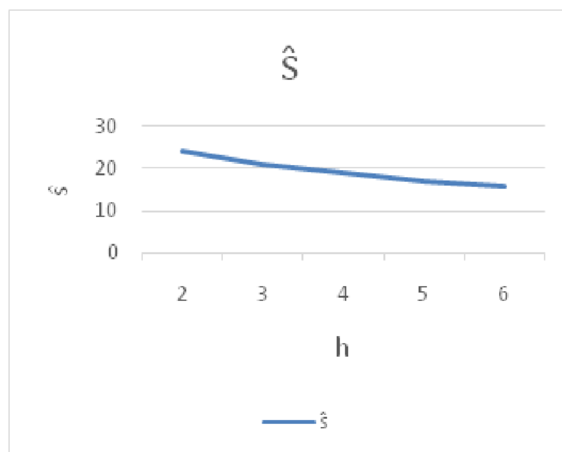
d	2500	3000	3500	4000
$\hat{S}$	15.902	17.270	18.426	19.427



Case (v)

For μ=2, r=30, d=3000, β=0.5,θ=4, θ*=4, θ_1=2, θ_2=3, the optimal value of S is obtained and the variations in $\hat{S}$ for the changes in the value of h.

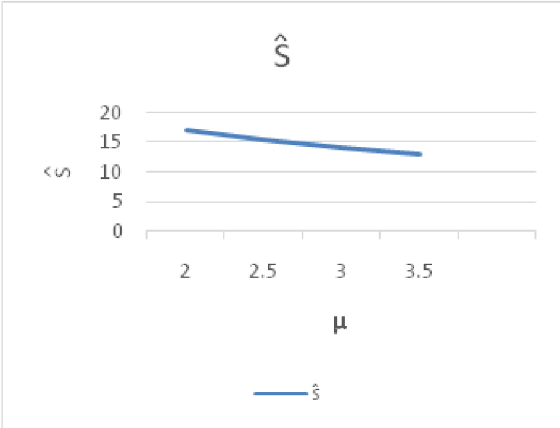
h	2	3	4	5	6
$\hat{S}$	24.142	21.101	18.943	17.27	15.902



Case (vi)

For h=5, r=30, d=3000, β=0.5, θ=4, θ*=4, θ_1=2, θ_2=3, the optimal value of S is obtained and the variations in $\hat{S}$ for the changes in the value of μ.

μ	2	2.5	3	3.5
$\hat{S}$	17.270	15.596	14.229	13.073



From the tables and graphs it is observed that,
As θ, the parameter of the repair time increases, the optimal reserve inventory $\hat{S}$ decreases.
As θ*, the repair time increases, the optimal reserve inventory decreases.
As r, the consumption rate of M_2 increases, the optimal reserve inventory $\hat{S}$ increases.
As h, the parameter of the holding cost increases, the optimal reserve inventory $\hat{S}$ decreases. It is understood that, the model suggests small size inventory, when the inventory holding cost increases.

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