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An EPQ Model for Two-Parameter Weibully Deteriorated Items with Exponential Demand Rate and Completely Backlogged Shortages

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ABSTRACT

In formulating inventory models, two factors of the problem have been of growing interest to the researchers, one being the variation in the demand rate and the other being the deterioration of items. In the present paper, an EPQ model with demand following exponential pattern and two-parameter Weibull deterioration rate is considered. The time-varying inventory holding cost is a linear function of time. Shortages are allowed and they are completely backlogged. Numerical example is used to illustrate the developed model. Sensitivity analysis and graphical analysis of the optimal solution of various parameters are carried out.

Keywords:- Exponential demand rate, Two-parameter Weibull deterioration rate, Completely backlogged shortages, Time-varying inventory holding cost.

I. INTRODUCTION

One of the assumptions of traditional inventory models was that the items preserve their original characteristics throughout when they are kept in the inventory. This assumption is true for most of the items, but not for all. Most of the physical goods like vegetables, grains, pharmaceuticals, fashion goods, radioactive substances etc. deteriorate over time. They either get decayed, damaged, vaporized or affected by some or other factors and do not remain in a perfect condition to satisfy the demand.

While formulating inventory models, two factors of the problem have been of growing interest to the researchers, one being the variation in the demand rate and the other being the deterioration of items. Demand is the major factor in the inventory management. Hence, decisions of inventory problems are to be made by considering both present and future demands. As demand plays a key role in deteriorating inventory models, researchers have concentrated in the study of variations in demand. Demand may be constant, time-varying, stock-dependent, price-dependent etc. The constant demand is valid only when the phase of the product life cycle is matured and also for finite periods of time.

Parmar and Gothi [11] developed a deterministic inventory model for deteriorating items where time to deterioration has Exponential distribution and time-dependent quadratic demand. Gothi and Parmar [7] extended the above deterministic inventory model by taking two parameter Weibull distribution to represent the time to deterioration, where shortages are allowed and partially backlogged. Jani, Jaiswal and Shah [8] developed (S, q_p) system inventory model for deteriorating items. Bhojak and Gothi [3] developed an EOQ model with time-dependent demand and Weibully distributed deterioration. Parmar, Aggarwal and Gothi [10] developed an Order level inventory model for deteriorating items under varying demand condition.

Venkateswarlu and Mohan [14] developed an EOQ model with 2 parameters Weibull deterioration, time-dependent quadratic demand and salvage value. Further, Mohan and Venkateswarlu [9] proposed an inventory model for time dependent quadratic demand with salvage considering deterioration rate is time-dependent. Amutha and Chandrashekharan [1] developed an EOQ model for deteriorating items and quadratic demand and time-dependent holding cost.

Gothi and Chatterji [6] developed an EPQ model for imperfect quality items under constant demand rate and varying holding cost. Parmar and Gothi [12] developed an EPQ model of deteriorating items using three parameter Weibull distribution with constant production rate and time-varying holding cost. Further, Parmar and Gothi [13] have developed an

EPQ model for deteriorating items under three parameter Weibull distribution and time dependent IHC with shortages. Chatterji and Gothi [4] developed an EOQ model for deteriorating items under two and three parameter Weibull distribution and constant inventory holding cost with partially backlogged shortages. Recently, Chatterji and Gothi [5] have developed an EOQ model for deteriorating items under two and three parameter Weibull distribution and constant IHC with partially backlogged shortages.

Verma and Verma [15] developed an inventory model with exponentially decreasing demand and linearly increasing deterioration. Yang and Wee [16] developed an integrated multi-lot-size production inventory model for deteriorating items with constant production and demand rates. Avikar, Tuli and Sharma [2] developed an Optimal inventory management for exponentially increasing demand with finite rate of production and deterioration. They assumed shortages are allowed and backlogged.

II. NOTATIONS

The following notations are used to develop the model:

1. Q(t) : Instantaneous rate of the inventory level at any time t $(0 \le t \le t_4)$.
2. p : Production rate per unit time.
3. R(t) : Demand rate varying over time.
4. θ(t) : Deterioration rate.
5. a : Initial rate of demand.
6. A : Ordering cost per order during the cycle period.
7. C_d : Deterioration cost per unit per unit time.
8. C_h : Inventory holding cost per unit per unit time.
9. C_s : Shortage cost per unit per unit time.
10. p_c : Production cost per unit per unit time.
11. S_1 : Maximum inventory level at time $t = t_1$.
12. S_2 : Maximum inventory level during the shortage period at $t = t_3$.
13. t_2 : Time at which shortages start, $0 \le t_2 \le t_4$.
14. t_4 : Length of the replenishment cycle.
15. TC : The average total cost for the time period [0, t_4].

III. ASSUMPTIONS

The following assumptions are considered to develop the model:

1. A single item is considered over the prescribed period of time.
2. Replenishment rate is infinite and lead time is zero.
3. The demand rate of the product is of exponential pattern.
4. Once a unit of the product is produced, it is available to meet the demand.
5. No repair or replenishment of the deteriorated items takes place during a given cycle.
6. Holding cost is a linear function of time and it is $C_h = h + rt$ $(h, r > 0)$.
7. $\theta(t) = \alpha\beta t^{\beta-1}$ is the two parameter Weibull deterioration rate in the time interval $[0, t_1]$ and $[t_1, t_2]$ where α is scale parameter $(0 < \alpha << 1)$ and β is shape parameter $(\beta > 0)$.
8. Shortages are allowed and they are fully backlogged.
9. Total inventory cost is a real and continuous function which is convex to the origin.

IV. MATHEMATICAL MODEL AND ANALYSIS

In the mathematical model initially inventory is zero. At time $t = 0$ the production starts and simultaneously demand is also satisfied. The production stops at time $t = t_1$ where the maximum inventory level S_1 is attained. In the interval $[0, t_1]$ the inventory is accumulated at a rate $p - ae^{\theta t}$ as demand is following exponential distribution and there is a deterioration rate of two parameter Weibull distribution. The inventory level reaches zero level at time $t = t_2$. Thereafter, shortages occur during the time interval $[t_2, t_3]$ and there becomes a backlog of S_2 units, which is fully satisfied in the following time interval $[t_3, t_4]$.

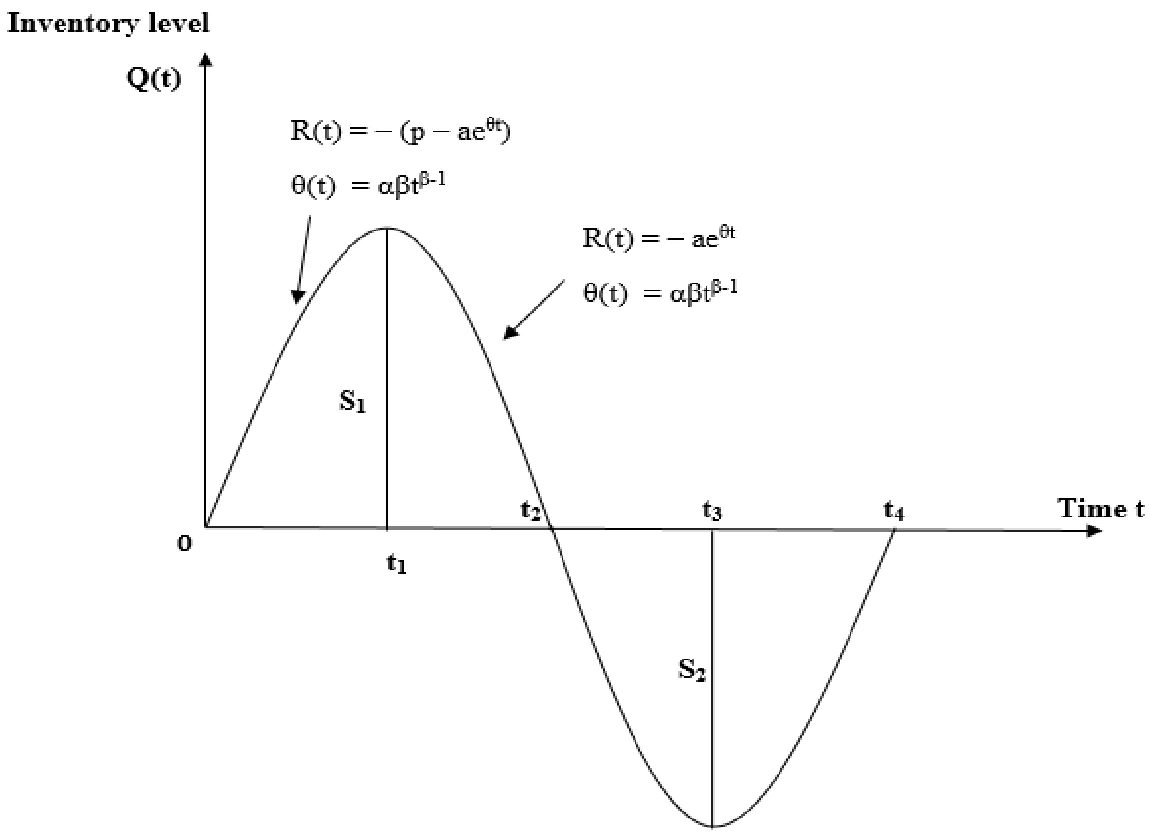

Figure 1: Graphical presentation of the inventory system

The differential equations which governs the instantaneous state of $Q(t)$ over the time intervals $[0,t_1]$, $[t_1,t_2]$, $[t_2,t_3]$ and $[t_3,t_4]$ are given by

$$\frac{dQ(t)}{dt}+\alpha\beta t^{\beta-1}Q(t)=p-ae^{\theta t} \qquad (0\le t\le t_1) \qquad (1)$$

$$\frac{dQ(t)}{dt}+\alpha\beta t^{\beta-1}Q(t)=-ae^{\theta t} \qquad (t_1\le t\le t_2) \qquad (2)$$

$$\frac{dQ(t)}{dt}=-ae^{\theta t} \qquad (t_2\le t\le t_3) \qquad (3)$$

$$\frac{dQ(t)}{dt}=p-ae^{\theta t} \qquad (t_3\le t\le t_4) \qquad (4)$$

Using boundary conditions

$$Q(0)=Q(t_2)=Q(t_4)=0 \qquad (5)$$

$$Q(t_1)=S_1,\ \ Q(t_3)=-S_2 \qquad (6)$$

The solutions of equations (1), (2), (3) and (4) are given by

$$Q(t)=(p-a)\left(t-\frac{\alpha\beta}{\beta+1}t^{\beta+1}\right)-a\theta\frac{t^2}{2} \qquad (0\le t\le t_1) \qquad (7)$$

$$Q(t)=a(t_2-t)(1-\alpha t^{\beta})+\frac{a\alpha}{\beta+1}\left(t_2^{\beta+1}-t^{\beta+1}\right)+\frac{a\theta}{2}\left(t_2^2-t^2\right) \qquad (t_1\le t\le t_2) \qquad (8)$$

$$Q(t)=\frac{a(t_2-t)}{2}\left[2+\theta(t_2+t)\right] \qquad (t_2\le t\le t_3) \qquad (9)$$

$$Q(t)=(t-t_4)\left[(p-a)-\frac{a\theta}{2}(t_4+t)\right] \qquad (t_3\le t\le t_4) \qquad (10)$$

Putting $Q(t_1)=S_1$ in equation (7), we get

$$S_1=(p-a)\left(t_1-\frac{\alpha\beta}{\beta+1}t_1^{\beta+1}\right)-\frac{a\theta}{2}t_1^2 \qquad (11)$$

Putting $Q(t_1) = S_1$ in equation (8), we get

$$S_1=a(t_2-t_1)(1-\alpha t_1^{\beta})+\frac{a\alpha}{\beta+1}\left(t_2^{\beta+1}-t_1^{\beta+1}\right)+\frac{a\theta}{2}\left(t_2^2-t_1^2\right) \qquad (12)$$

Comparing (11) and (12) we get an expression which expresses t_1 in terms of t_2, and hence t_1 is not taken as the decision variable.

$$-\frac{\alpha\beta p}{\beta+1}t_1^{\beta+1}+pt_1=a\left[t_2(1-\alpha t_1^{\beta})+\frac{\alpha}{\beta+1}t_2^{\beta+1}+\frac{\theta}{2}t_2^2\right] \qquad (13)$$

Putting $Q(t_3)=-S_2$ in equation (9), we get

$$S_2=\frac{a(t_3-t_2)}{2}\left[2+\theta(t_2+t_3)\right] \qquad (14)$$

Putting $Q(t_3)=-S_2$ in equation (10), we get

$$S_2=(t_4-t_3)\left[(p-a)-\frac{a\theta}{2}(t_4+t_3)\right] \qquad (15)$$

Comparing (14) and (15) we get another expression which expresses t_3 in terms of t_2 and t_4, and hence t_3 is not taken as the decision variable.

$$t_3=\frac{at_2^2\theta-at_4^2\theta+2at_2-2at_4+2pt_4}{2p} \qquad (16)$$

Cost Components:
The total cost per replenishment cycle consists of the following cost components:

1. Operating Cost

The operating cost OC over the period $[0,t_4]$ is

$$OC=A \qquad (17)$$

2. Deterioration Cost

The deterioration cost DC over the period $\left[0,t_2\right]$ is

$$DC=C_d\left[\int_0^{t_1}\alpha\beta t^{\beta-1}Q(t)dt+\int_{t_1}^{t_2}\alpha\beta t^{\beta-1}Q(t)dt\right]$$

$$\therefore DC=C_d\alpha\beta\left[\left\{(p-a)\frac{t_1^{\beta+1}}{\beta+1}-\frac{a\theta}{2}\frac{t_1^{\beta+2}}{\beta+2}\right\}+a\left\{\begin{array}{l}\left(t_2+\frac{\theta}{2}t_2^2\right)\frac{1}{\beta}\left(t_2^{\beta}-t_1^{\beta}\right)-\frac{1}{\beta+1}\left(t_2^{\beta+1}-t_1^{\beta+1}\right)\\-\frac{\theta}{2(\beta+2)}\left(t_2^{\beta+2}-t_1^{\beta+2}\right)\end{array}\right\}\right] \quad (18)$$

3. Holding Cost

The holding cost for carrying inventory over the period $\left[0,t_2\right]$ is

$$\mathrm{IHC}=\left[\int_0^{t_1}(\mathrm{h}+\mathrm{rt})\mathrm{Q(t)dt}+\int_{t_1}^{t_2}(\mathrm{h}+\mathrm{rt})\mathrm{Q(t)dt}\right]$$

$$\therefore IHC=\left[\begin{array}{l}h\left\{(p-a)\frac{t_1^2}{2}-(p-a)\frac{\alpha\beta t_1^{\beta+2}}{(\beta+1)(\beta+2)}-\frac{a\theta}{6}t_1^3+\frac{a\alpha\theta\beta t_1^{\beta+3}}{(\beta+2)(\beta+3)}\right\}+r\left\{\begin{array}{l}(p-a)\frac{t_1^3}{3}-(p-a)\frac{\alpha\beta t_1^{\beta+3}}{(\beta+1)(\beta+3)}-\frac{a\theta}{8}t_1^4\\+\frac{a\alpha\theta\beta t_1^{\beta+4}}{(\beta+2)(\beta+4)}\end{array}\right\}\\+a\left[\begin{array}{l}\left\{t_2+\frac{\alpha}{\beta+1}t_2^{\beta+1}+\frac{\theta}{2}t_2^2+\frac{\alpha\theta}{\beta+2}t_2^{\beta+2}\right\}\left\{h(t_2-t_1)+\frac{r}{2}\left(t_2^2-t_1^2\right)\right\}\\-h\left\{\begin{array}{l}\frac{1}{2}\left(t_2^2-t_1^2\right)+\frac{\theta}{6}\left(t_2^3-t_1^3\right)-\frac{\alpha\beta}{(\beta+1)(\beta+2)}\left(t_2^{\beta+2}-t_1^{\beta+2}\right)-\frac{\alpha\beta\theta}{2(\beta+2)(\beta+3)}\left(t_2^{\beta+3}-t_1^{\beta+3}\right)\\+\alpha t_2\left(1+\frac{\theta}{2}t_2\right)\frac{1}{\beta+1}\left(t_2^{\beta+1}-t_1^{\beta+1}\right)\end{array}\right\}\\-r\left\{\frac{1}{3}\left(t_2^3-t_1^3\right)+\frac{\theta}{8}\left(t_2^4-t_1^4\right)-\frac{\alpha\beta}{(\beta+1)(\beta+3)}\left(t_2^{\beta+3}-t_1^{\beta+3}\right)\right\}\end{array}\right]\end{array}\right] \quad (19)$$

4. Shortage Cost

The shortage cost SC over the period $\left[t_2,t_4\right]$ is

$$SC=-C_s\left[\int_{t_2}^{t_3}Q(t)dt+\int_{t_3}^{t_4}Q(t)dt\right]$$

$$\therefore SC=C_s\left\{\begin{array}{l}\frac{a}{6}(t_3-t_2)\left(t_3^2+3(t_3-t_2)+t_2t_3-2t_2^2\right)+\left(p-a-\frac{a\theta}{2}t_4\right)t_4(t_4-t_3)\\+\frac{1}{2}\left(a+\frac{a\theta}{2}t_4+t_4-p\right)\left(t_4^2-t_3^2\right)-\frac{1}{3}\left(t_4^3-t_3^3\right)\end{array}\right\} \quad (20)$$

5. Production Cost

The production cost PC during the period $\left[0,t_1\right]$ and $\left[t_3,t_4\right]$ is

$$PC=p_c\left(t_1+t_4-t_3\right) \quad (21)$$

Hence, the average total cost for the time period $[0, t_4]$ **is given by**

$$TC=\frac{1}{t_4}\left[OC+DC+IHC+SC+PC\right]$$

$$\therefore TC=\frac{1}{t_4}\left[\begin{array}{l} A+C_d\alpha\beta\left\{\begin{array}{l}\left[(p-a)\dfrac{t_1^{\beta+1}}{\beta+1}-\dfrac{a\theta}{2}\dfrac{t_1^{\beta+2}}{\beta+2}\right]+a\left[\left(t_2+\dfrac{\theta}{2}t_2^2\right)\dfrac{1}{\beta}\left(t_2^{\beta}-t_1^{\beta}\right)\right]\\ -\dfrac{1}{\beta+1}\left(t_2^{\beta+1}-t_1^{\beta+1}\right)-\dfrac{\theta}{2(\beta+2)}\left(t_2^{\beta+2}-t_1^{\beta+2}\right)\end{array}\right\}\\ +\left[\begin{array}{l} h\left\{(p-a)\dfrac{t_1^2}{2}-(p-a)\dfrac{\alpha\beta t_1^{\beta+2}}{(\beta+1)(\beta+2)}-\dfrac{a\theta}{6}t_1^3+\dfrac{a\alpha\theta\beta t_1^{\beta+3}}{(\beta+2)(\beta+3)}\right\}\\ +r\left\{\begin{array}{l}(p-a)\dfrac{t_1^3}{3}-(p-a)\dfrac{\alpha\beta t_1^{\beta+3}}{(\beta+1)(\beta+3)}-\dfrac{a\theta}{8}t_1^4\\ +\dfrac{a\alpha\theta\beta t_1^{\beta+4}}{(\beta+2)(\beta+4)}\end{array}\right\}\\ +a\left\{\begin{array}{l}\left[t_2+\dfrac{\alpha}{\beta+1}t_2^{\beta+1}+\dfrac{\theta}{2}t_2^2+\dfrac{\alpha\theta}{\beta+2}t_2^{\beta+2}\right]\left[h\left(t_2-t_1\right)+\dfrac{r}{2}\left(t_2^2-t_1^2\right)\right]\\ -h\left[\begin{array}{l}\dfrac{1}{2}\left(t_2^2-t_1^2\right)+\dfrac{\theta}{6}\left(t_2^3-t_1^3\right)-\dfrac{\alpha\beta}{(\beta+1)(\beta+2)}\left(t_2^{\beta+2}-t_1^{\beta+2}\right)\\ -\dfrac{\alpha\beta\theta}{2(\beta+2)(\beta+3)}\left(t_2^{\beta+3}-t_1^{\beta+3}\right)+\alpha t_2\left(1+\dfrac{\theta}{2}t_2\right)\dfrac{1}{\beta+1}\left(t_2^{\beta+1}-t_1^{\beta+1}\right)\end{array}\right]\\ -r\left[\dfrac{1}{3}\left(t_2^3-t_1^3\right)+\dfrac{\theta}{8}\left(t_2^4-t_1^4\right)-\dfrac{\alpha\beta}{(\beta+1)(\beta+3)}\left(t_2^{\beta+3}-t_1^{\beta+3}\right)\right]\end{array}\right\}\end{array}\right]\\ +C_s\left\{\begin{array}{l}\dfrac{a}{6}\left(t_3-t_2\right)\left(t_3^2+3\left(t_3-t_2\right)+t_2t_3-2t_2^2\right)+\left(p-a-\dfrac{a\theta}{2}t_4\right)t_4\left(t_4-t_3\right)\\ +\dfrac{1}{2}\left(a+\dfrac{a\theta}{2}t_4+t_4-p\right)\left(t_4^2-t_3^2\right)-\dfrac{1}{3}\left(t_4^3-t_3^3\right)\end{array}\right\}\\ +p_c\left(t_1+t_4-t_3\right)\end{array}\right] \tag{22}$$

Using the expressions (13) and (16), t_1 and t_3 are eliminated from equation (22) of total cost TC. Hence, TC remains a function of t_2 and t_4 only, which are the decision variables. t_2* and t_4* are the optimum values of t_2 and t_4 respectively, which minimize the cost function TC and they are the solutions of the equations $\frac{\partial TC}{\partial t_2} = 0$ & $\frac{\partial TC}{\partial t_4} = 0$ such that

$$\left.\begin{aligned} &\left[\left(\frac{\partial^2 TC}{\partial t_2^2}\right)\left(\frac{\partial^2 TC}{\partial t_4^2}\right) - \left(\frac{\partial^2 TC}{\partial t_2\, \partial t_4}\right)^2\right]_{t_2 = t_2^*,\, t_4 = t_4^*} > 0 \\ &\left[\frac{\partial^2 TC}{\partial\, t_2^2}\right]_{t_2 = t_2^*,\, t_4 = t_4^*} > 0 \end{aligned}\right\} \tag{23}$$

V. NUMERICAL EXAMPLE

Let us consider the following example to illustrate the above developed model. Taking A = 200, α = 0.0001, β = 2, h = 8, r = 4, p = 4, a = 2, θ = 0.0001, C_s = 8, p_c = 10 and C_d= 2 (with appropriate units).

The optimal values of t_2 and t_4 are t_2* = 2.913512467, t_4* = 5.827425183 units and the optimal total cost per unit time TC = 62.305118663 units.

VI. SENSITIVITY ANALYSIS AND GRAPHICAL ANALYSIS

Sensitivity analysis depicts the extent to which the optimal solution of the model is affected by the changes in its input parameter values. Here, we study the sensitivity for the cycle length t_4 and total cost per time unit TC with respect to the changes in the values of the parameters A, α, β,h, r, p, a, θ, C_s, p_c and C_d.

The sensitivity analysis is performed by considering variation in each one of the above parameters keeping all other remaining parameters as fixed. The last column of the **Table – 1** gives the % changes in TC as compared to the original solution for the relevant costs.

Table – 1: Partial Sensitivity Analysis

Parameter	Values	t_2	t_4	TC
A	–40	2.400759089	4.801810864	47.286215869
	– 20	2.678360813	5.357069557	55.155467312
	+ 20	3.119504969	6.239460943	68.932893173
	+ 40	3.304001469	6.608503862	75.158253213
α	– 40	2.913713010	5.827551306	62.304366555
	– 20	2.913612720	5.827488232	62.304756358
	+ 20	2.913412251	5.827362160	62.305481126
	+ 40	2.913312070	5.827299162	62.305845130
β	– 40	2.913911981	5.827683638	62.303854750
	– 20	2.913769587	5.827593269	62.304349790
	+ 20	2.913068220	5.827128865	62.306296110
	+ 40	2.912321632	5.826623452	62.308085190
h	– 40	3.246050876	5.985340787	59.739029352
	– 20	3.074483562	5.904104487	61.082814619
	+ 20	2.762855856	5.755344166	63.417589503
	+ 40	2.622138838	5.687815710	64.430977734

Parameter	Values	t_2	t_4	TC
r	– 40	3.387116727	6.115678166	60.237631826
	– 20	3.119807137	5.950803370	61.375110824
	+ 20	2.747296931	5.730526590	63.088502858
	+ 40	2.609236599	5.651775371	63.762770670
p	– 20	3.331953360	5.773069850	62.645737661
	– 10	3.070895471	5.782882207	62.589990000
	+ 10	2.810035863	5.882406950	61.971953943
	+ 20	2.737782695	5.938392470	61.652702989
a	– 40	3.152471426	7.066487482	51.455294768
	– 20	2.973741761	6.295064458	57.714806965
	+ 20	2.962052124	5.551526597	65.390061065
	+ 40	3.156136751	5.436234385	66.868551529
θ	– 40	2.913728332	5.827972134	62.301778882
	– 20	2.913620385	5.827698622	62.303449215
	+ 20	2.913404578	5.827151818	62.306788117
	+ 40	2.913296717	5.826878525	62.308456899
C_s	– 40	2.596943334	6.577164345	55.550796129
	– 20	2.776947074	6.130311133	59.385035031
	+ 20	3.021706424	5.606403154	64.624216357
	+40	3.110034600	5.437010438	66.520654444
p_c	–40	2.913576975	5.827489446	60.304323374
	– 20	2.913544721	5.827457315	61.304720745
	+ 20	2.913480215	5.827393053	63.305515358
	+ 40	2.913447964	5.827360924	64.305914024
C_d	– 40	2.913549201	5.827446846	62.304947787
	– 20	2.913530834	5.827436015	62.305034108
	+ 20	2.913494102	5.827414353	62.305203971
	+ 40	2.913475736	5.827403522	62.305288967

VII. GRAPHICAL PRESENTATION

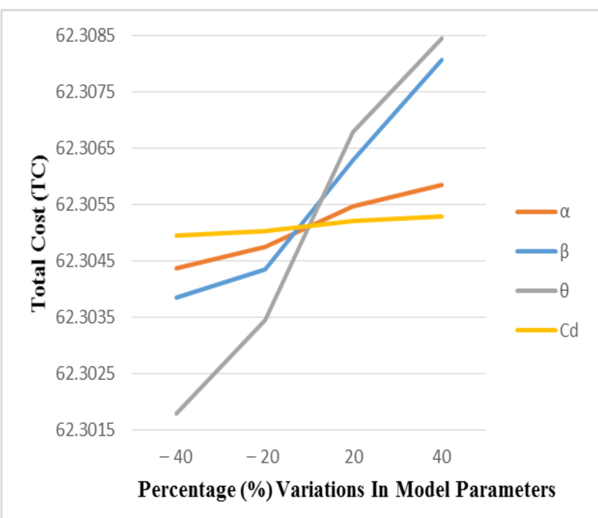

Figure – 2

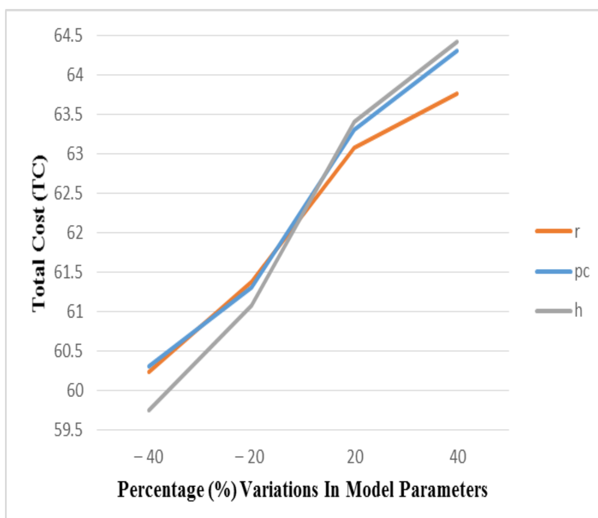

Figure – 3

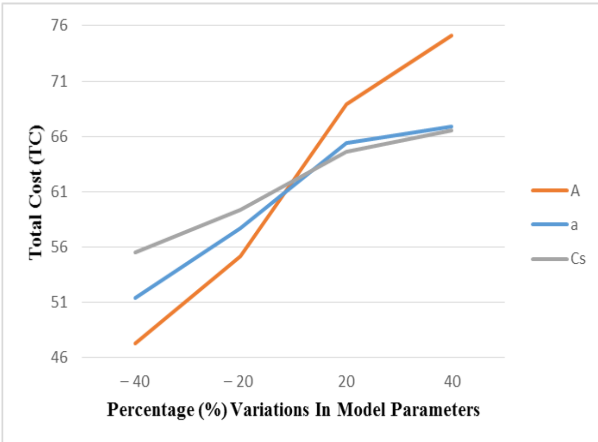

Figure – 4

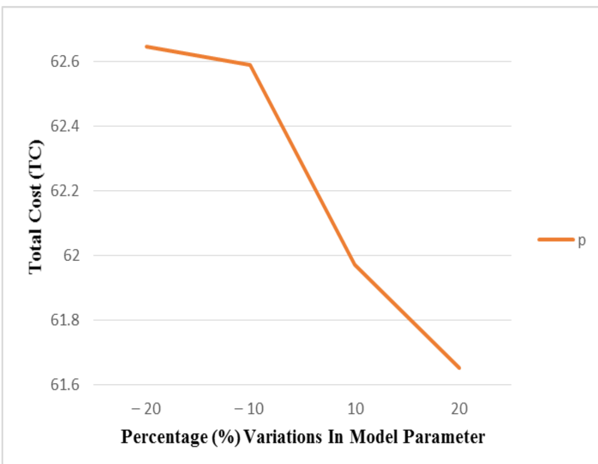

Figure – 5

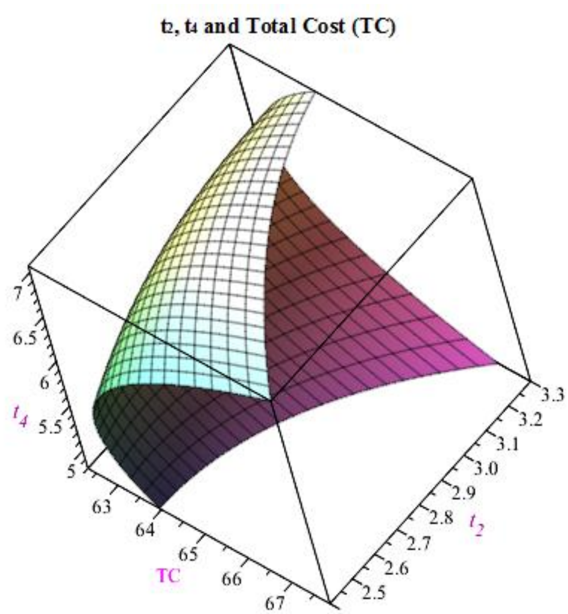

Figure – 6

VIII. CONCLUSION

From partial sensitivity analysis and graphical analysis we can conclude that as scale parameter α, shape parameter β, deterioration rate θ, deterioration cost C_d, linear constants of inventory holding cost r and h, production cost p_c, operating cost A, initial rate of demand a and shortage cost C_s increase , total cost TC increases. But we have also observed the following points:

- From Figure 4 it is observed that total cost TC is highly sensitive to change in operating cost A, initial rate of demand a and shortage cost C_s .
- From Figure 3 it is observed that total cost TC is moderately sensitive to the change in the linear constants r and h of inventory holding cost and production cost p_c .
- From Figure 2 it is observed that there is a mild change in the total cost TC towards the change in scale parameter α, shape parameter β, deterioration rate θ and deterioration cost C_d .
- Again from the partial sensitivity analysis and graphical analysis, from Figure 5 it can be said that as the rate of production p increases, total cost TC decreases.
- Also from the 3-D plotting in Figure 6 of t_2, t_4 and TC, it can be concluded that as t_2 and t_4 increase, total cost TC always increases.

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