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"An Inventory Model of Repairable Items with Exponential Deterioration and Linear Demand Rate"

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Abstract: *In this paper an inventory model for deteriorating and repairable itemsis developed with linear demand. An Exponential distribution is used to represent the distribution of time for deterioration.In the model considered here, shortages are allowed to occur and defective items can be repaired. The model is solved analytically to obtain the optimal solution of the problem. The derived model is illustrated by a numerical example and its sensitivity analysis is carried out.*

I. Introduction

Deterioration means damage, spoilage, dryness, vaporization, etc. It is defined as decay or damage such that the item cannot be used for its original purposes. The effect of deterioration is very important in many inventory systems. The pioneering work of Harris [7] inventory models are being treated by mathematical techniques. He developed the simplest inventory model, the Economic Order Quantity (EOQ) model which was later popularized by Wilson [24]. Relaxation of some assumptions in the formulation of the EOQ model led to the development of other inventory models that effectively tackles several other inventory problems occurring in day-to-day life. Inventory of deteriorating items was first studied by Whitin [25] where he considered the deterioration of fashion goods at the end of prescribed storage period. Ghare and Schrader [5] extended the classical EOQ formula to include exponential decay, wherein a constant fraction of on hand inventory is assumed to be lost due to deterioration.

Datta, T. K. and Pal, A. K. [4]gave order level inventory system with power demand pattern for items with variable rate of deterioration. Mandal, B. N. and Ghosh, A. K. [14]wrote a note on an inventory model with different demand rates during stock in and stock out period. Mandal, B. N. and Pal A. K. [15]have given order level inventory system for perishable items with power demand pattern. Teng, J. T. [21]has worked on model with linear trend in demand.

Manna and Chiang [13] developed an EPQ model for deteriorating items with ramp type demand. Teng and Chang [22] considered the economic production quantity model for deteriorating items with stock level and selling price dependent demand. Jain et al. [8] developed an economic production quantity model with shortages by incorporating the deterioration effect and stock dependent demand rate. Roy and Chaudhary [17] developed two production rates inventory model for deteriorating items when the demand rate was assumed to be stock dependent. In the research of Sana et al. [18] shortages are allowed to occur at the end of a cycle. With the consideration of time varying demand and constant deteriorating rate, the optimal production inventory policy was studied. Raman Patel [16] developed a production inventory model for deteriorating items following Weibull distribution with price and quantity dependent demand and varying holding cost with shortages.

Both Skouri and Papachristos [20] and Chen et al. [2] developed a production inventory model in which the shortages are allowed at the beginning of a cycle. In contrast,Manna and Chaudhari [12] have allowed shortages to occur at the end of each cycle. Goyal[6] deals with production inventory problem of a product with time varying demand, production and deterioration rates in which the shortages occur at the beginning of the cycle.

There are four synonyms of reuse according to Thierry et al. [23]. They are: Direct Reuse, Repair, Recycling and Remanufacturing. Schrady[19] was the first to consider reuse in a deterministic model.Recently, Mabini et al. [11] extended Schrady's model to consider stock-out service level constraints and multi-item system sharing the same repair facility. In the policy, expressions for the optimal control parameter values were derived. Koh[10] developed a joint EOQ and EPQ model in which the stationary demand can be satisfied by recycled products and newly purchased products. The model assumes a fixed proportion of the used products that are collected from the customers.

Recently, Bhojak and Gothi [1] have developed inventory models for ameliorating and deteriorating items with time dependent demand and IHC. Kirtan Parmar and Gothi [9] have developed an EPQ model of deteriorating items using three parameter Weibull distribution with constant production rate and time varying holding cost.Devyani Chatterji and Gothi [3] have developed three-parametric Weibully deteriorated EOQ model with price dependent demand and shortages under fully backlogged condition.

R. K. Yadav and Rajeev Kumar [26] developed an inventory model for deteriorating and repairable items with linear demand.Here, we have tried to redevelop the same model and corrected most of the results.

II. Notations

The mathematical model in this paper is developed using the following notations:

1. k : Production rate (units/unit time).
2. D : Demand rate.
3. $\theta(t)$: The deterioration rate (units/unit time).
4. b :The decreasing rate of the demand (units/unit time).
5. c : Fraction of defective product.
6. r :Fraction of stock-out demand sales lost due to some stock-out demands.($0 < r < 1$)
7. Q(t) :The instantaneous state of the inventory level at any time t ($0 \le t \le T$).

8.Q_1 : The maximum inventory level of the product.

9. Q_2: The maximum inventory level during shortage period.

10. A : Ordering cost per order.

10. C_h :Inventory holding cost per unit per unit time.

11. C_d : Deterioration cost per unit per unit time.

12. C_s :Shortage costper unit.

13. C_p : The penalty cost of a lost sale including lost profit (unit time).

14. Pc : Purchase cost per unit.

15. TC : The average total cost for the time period [0, T].

III. Basic Assumptions

The model is derived under the following assumptions

1. The inventory system deals with single item.
2. The production rate is finite and constant, which is larger than the demand rate and is unaffected by the lot size.
3. Once a unit of the product is produced, it is available to meet the demand.
4. Once the production is started the product starts being deteriorated.
5. The annual demand rate is a linear function of time and it is $D = \alpha + \beta t$. ($\alpha, \beta > 0$).

6.Shortages are allowed and completely backlogged.

7. Replenishment rate is infinite and instantaneous.
8. All defective products can be repaired and reused.
9. The second and higher powers of θ, b and care neglected in the analysis of the derived model.
10. Total inventory cost is a real, continuous function which is convex to the origin.

IV. Mathematical Model And Analysis

Here, we consider a single commodity deterministic production inventory model with a time dependentlinear demand rate. The distribution of the time to deteriorate is random variable following the exponential distribution. The probability density function for exponential distribution is given by

$$f(t) = \theta e^{-\theta t} \qquad ; (t > 0 \text{ and } 0 < \theta < 1)$$

The instantaneous rate of deterioration $\theta(t)$ of the non-deteriorated inventory at time t can be obtained from $\theta(t) = \dfrac{f(t)}{1-F(t)}$, where F(t) = $1-e^{-\theta t}$ is the cumulative distribution function for the exponential distribution.Thus, the instantaneous rate of deterioration of the on-hand inventory is $\theta(t) = \theta$. The probability density function represents the distribution of the time to deteriorate which may have a decreasing, constant or increasing rate of deterioration.

Initially, inventory level is zero. At time t = 0, the production starts and simultaneously supply also beginsandthe production stops at $t = t_1$ when the maximum inventory level Q_1 is reached. In the interval $[0, t_1]$, before the production stops, the inventory is built up at a rate k – D and is depleted at the rate (θ – b + c). In the interval$[t_1, t_2]$ the inventory is depleted at the rate D and rate (θ – b). The inventory is finitely decreasing in the time interval $[t_1, t_2]$ until inventory level reaches zero. It is decided to backlog the demands up to Q_2 level which occurs during stock-out time. Thereafter, shortages can occur during the time interval $[t_2, t_3]$, and all of the demand during the period $[t_2, t_3]$ is completely backlogged. Thereafter, production is started at a rate (1– r)(k – D)so as to clear the backlog, and the inventory level reaches to 0 (i.e. the backlog is cleared) at t=T.

The pictorial presentation is shown in the **Figure – 1**.

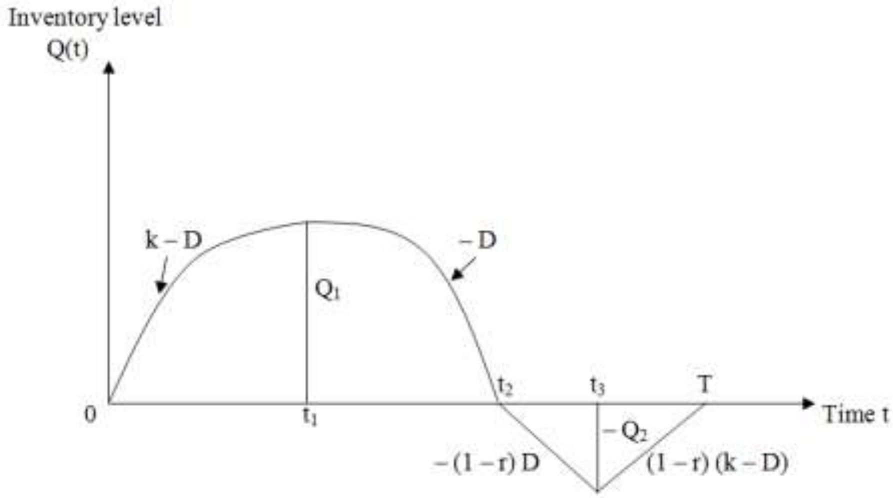

Figure – 1: Graphical presentation of the inventory system

The differential equations which govern 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] are given by

$$\frac{dQ(t)}{dt}+(\theta-b+c)Q(t)=k-(\alpha+\beta t), \qquad \left(0\le t\le t_1\right) \tag{1}$$

$$\frac{dQ(t)}{dt}+(\theta-b)Q(t)=-(\alpha+\beta t), \qquad \left(t_1\le t\le t_2\right) \tag{2}$$

$$\frac{dQ(t)}{dt}=-(1-r)(\alpha+\beta t), \qquad \left(t_2\le t\le t_3\right) \tag{3}$$

$$\frac{dQ(t)}{dt}+(1-r)c\cdot Q(t)=(1-r)\left\{k-(\alpha+\beta t)\right\}, \qquad \left(t_3\le t\le T\right) \tag{4}$$

Under the boundary conditions Q(0) = 0, Q(t_1) = Q_1, Q(t_2) = 0, Q(t_3) = – Q_2&Q(T) = 0, the solutions of equations(1) to (4)are given by

$$Q(t)=(k-\alpha)\cdot t \qquad \left(0\le t\le t_1\right) \tag{5}$$

$$Q(t)=-\alpha t+\left[\alpha(1-t\xi)\right]t_2+\left[\beta(1-t\xi)\right]t_2^2 \qquad \left(t_1\le t\le t_2\right) \tag{6}$$

$$Q(t)=(1-r)\left(\alpha(t_2-t)+\frac{1}{2}\beta(t_2^2-t^2)\right) \qquad \left(t_2\le t\le t_3\right) \tag{7}$$

$$Q(t)=(1-r)\left\{\left[\frac{k-\alpha}{\mu}-\beta\left(\frac{t}{\mu}-\frac{1}{\mu^2}\right)\right]+(1+\mu T)(1-\mu t)\left[-\frac{k-\alpha}{\mu}+\beta\left(\frac{T}{\mu}-\frac{1}{\mu^2}\right)\right]\right\}$$
$$\left(t_3\le t\le T\right) \tag{8}$$

[Where $\delta = \theta - b + c$, $\xi = \theta - b$ and $\mu = (1 - r)\cdot c$]

From (5), $$Q(t_1)=Q_1=(k-\alpha)\cdot t_1 \tag{9}$$

and from (6), $$Q(t_1)=Q_1=-\alpha t_1+\left[\alpha(1-\xi t_1)\right]t_2+\left[\beta(1-\xi t_1)\right]t_2^2 \tag{10}$$

Eliminating Q(t_1) from equations (9) and (10), we get

$$t_1=\frac{(\alpha+\beta t_2)t_2}{\alpha\xi t_2+\beta\xi t_2^2+k} \tag{11}$$

Thus, t_1 can be written in terms of t_2 and so t_1 is not a decision variable.

From (7), $$Q(t_3) = -Q_2 = (1-r)\left(\alpha(t_2 - t_3) + \frac{1}{2}\beta(t_2^2 - t_3^2)\right) \tag{12}$$

and from (8),

$$Q(t_3) = -Q_2 = (1-r)\left\{\begin{matrix}\left[\dfrac{k-\alpha}{\mu} - \beta\left(\dfrac{t_3}{\mu} - \dfrac{1}{\mu^2}\right)\right] \\ +(1+\mu T)(1-\mu t_3)\left[-\dfrac{k-\alpha}{\mu} + \beta\left(\dfrac{T}{\mu} - \dfrac{1}{\mu^2}\right)\right]\end{matrix}\right\} \tag{13}$$

Eliminating $Q(t_3)$ from equations (12) and (13), we get

$$t_2 = \frac{1}{\beta}\left\{-\alpha + \sqrt{\alpha^2 + 2\beta k t_3 + \beta^2 t_3^2 + \left[\left(2T\alpha\beta - 2T\beta k + 2T^2\beta^2\right)\left(1-\mu t_3\right)\right]}\right\} \tag{14}$$

Thus, t_2 can be written in terms of t_3 and so t_2 is alsonot a decision variable.

Cost Components:

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

1) Ordering Cost (OC)

The ordering cost OC over the period [0, T] is

OC = A (Fixed) (15)

2) Deterioration Cost (DC)

The deterioration cost DC over the period [0, t_1] and [t_3, T] is

$$DC = C_d \cdot c\left[\int_0^{t_1} Q(t)dt + (1-r)\int_{t_3}^{T} Q(t)dt\right]$$

$$\Rightarrow DC = C_d \cdot c\left\{\frac{1}{2}(k-\alpha)t_1^2 + (1-r)\left(\begin{matrix}\dfrac{1}{2}\left[-\dfrac{(1-r)\beta}{\mu} - (1+T\mu)(1-r)\left(-\dfrac{k-\alpha}{\mu} + \beta\left(\dfrac{T}{\mu} - \dfrac{1}{\mu^2}\right)\right)\mu\right](T^2 - t_3^2) \\ +(1-r)\left(\dfrac{k-\alpha}{\mu} + \dfrac{\beta}{\mu^2}\right)(T - t_3) \\ +(1+T\mu)(1-r)\left(-\dfrac{k-\alpha}{\mu} + \beta\left(\dfrac{T}{\mu} - \dfrac{1}{\mu^2}\right)\right)(T - t_3)\end{matrix}\right)\right\} \tag{16}$$

3) Inventory Holding Cost (IHC)

The inventory holding cost IHC over the period [0, t_2] is

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

$$\Rightarrow IHC = C_h\left[\frac{1}{2}(k-\alpha)t_1^2 - \frac{1}{2}(\beta\xi t_2^2 + \alpha\xi t_2 + \alpha)(t_2^2 - t_1^2) + \beta t_2^2(t_2 - t_1) + \alpha t_2(t_2 - t_1)\right] \tag{17}$$

4) Shortage Cost (SC)

Demand during the time [t_3, T] is satisfied at a time as the production hasalready started at time t = t_3 and so shortage cost during this interval is not taken into account.

The shortage cost SC over the period [t_2, t_3] is

$$SC = -C_s \int_{t_2}^{t_3} Q(t)dt$$

$$\Rightarrow SC = -C_s\left(1-r\right)\left[-\frac{1}{6}\beta\left(t_3^3-t_2^3\right)-\frac{1}{2}\alpha(t_3^2-t_2^2)+\left(\alpha t_2+\frac{1}{2}\beta t_2^2\right)(t_3-t_2)\right] \quad (18)$$

5) Lost Sale Cost (LSC)

The lost sale cost LSC over the period [t_2, t_3] is

$$LSC = C_p \cdot r\int_{t_2}^{t_3}(\alpha+\beta t)dt$$

$$\Rightarrow LSC = C_p r\left(\alpha(t_3-t_2)+\frac{1}{2}\beta\left(t_3^2-t_2^2\right)\right) \quad (19)$$

6) Purchase Cost (PC)

The purchase cost PC over the period [0, T] is

$$PC = P_c \cdot k(t_1+t_3-t_2)$$

$$PC = P_c \cdot k\left[\frac{(\alpha+\beta t_2)t_2}{\alpha\xi t_2+\beta\xi t_2^2+k}+t_3-\frac{1}{\beta}\left\{-\alpha+\sqrt{\alpha^2+2\beta k t_3+\beta^2 t_3^2+\left[\left(2T\alpha\beta-2T\beta k+2T^2\beta^2\right)\left(1-\mu t_3\right)\right]}\right\}\right] \quad (20)$$

Hence, the total cost per unit time for the time period [0, T] is given by

$$\mathrm{TC} = \frac{1}{\mathrm{T}}\left(\mathrm{OC}+\mathrm{DC}+\mathrm{IHC}+\mathrm{SC}+\mathrm{LSC}+\mathrm{PC}\right) \quad (21)$$

Now, our objective is to determine optimum values t_3^* and T* of t_3 and T respectively to minimize the total cost TC. Using mathematical software, the optimal values t_3^* and T* can be obtained by solving $\frac{\partial \mathrm{TC}}{\partial t_3} = 0$ and $\frac{\partial \mathrm{TC}}{\partial \mathrm{T}} = 0$ which can satisfy the following sufficient conditions:

$$\left.\begin{array}{l}\left[\left(\frac{\partial^2 \mathrm{TC}}{\partial t_3^2}\right)\left(\frac{\partial^2 \mathrm{TC}}{\partial \mathrm{T}^2}\right)-\left(\frac{\partial^2 \mathrm{TC}}{\partial t_3 \partial \mathrm{T}}\right)^2\right]_{t_3=t_3^*,\mathrm{T}=\mathrm{T}^*} > 0 \\ \left[\left(\frac{\partial^2 \mathrm{TC}}{\partial t_3^2}\right)\right]_{t_3=t_3^*,\mathrm{T}=\mathrm{T}^*} > 0\end{array}\right\} \quad (22)$$

V. Numerical Example

To illustrate the proposed model, an inventory system with the following hypothetical values is considered. By taking $\alpha = 40$, $\beta = 0.001$, $C_h = 0.8$, $C_d = 2$, $C_p = 5$, $Cs = 2$, $\theta = 0.01$, $b = 0.005$,$c = 0.06$, $r = 0.09$, $k = 60$ and $A = 300$(with appropriate units), optimal values of t_3 and T are $t_3^* = 8.664682800$,$T^* = 25.29411443$ units and the optimal total cost per unit time TC = 126.5618193 units.

VI. Sensitivity 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 and total cost per time unit TC with respect to the changes in the values of the parameters α, β, C_h, C_d, Cp, Cs, θ, b, c, r, k and A. The sensitivity analysis is performed by considering different values in each one of the above parameters keeping all other parameters as fixed. The results are presented in the **Table**.

Table:Partial Sensitivity Analysis

Parameter	%	t_3	T	TC	% change in TC
α	– 10	9.314694607	24.27554607	129.6847228	2.47
	– 05	9.060134527	24.87171030	128.6346419	1.64
	+ 05	9.575232049	22.83983430	129.1252431	2.03
	+ 10	6.795258895	24.21483912	118.1465409	-6.65
β	– 10	8.665547815	25.29378321	126.5682307	0.0051
	– 05	8.665114980	25.29398694	126.5649983	0.0025
	+ 05	8.664278055	25.29435706	126.5586179	-0.0025
	+ 10	8.663797766	25.29438876	126.5554025	-0.0051
C_h	– 10	8.826234244	25.52562423	125.6524724	-0.72
	– 05	8.746522473	25.41424588	126.1022482	-0.36
	+ 05	8.594913624	25.20151358	126.9561036	0.31
	+ 10	8.526715876	25.10923951	127.3363820	0.61
C_d	– 10	8.978771732	26.59655084	124.3731096	-1.73
	– 05	8.818701486	25.92256960	125.5009322	-0.84
	+ 05	8.516208777	24.70602428	127.5620582	0.79
	+ 10	8.372836499	24.15393468	128.5069043	1.54
C_p	– 10	8.489861457	24.42544911	118.6665614	-6.24
	– 05	8.578163592	24.86306834	122.6303315	-3.11
	+ 05	8.785634529	25.70576324	131.7545938	4.10
	+ 10	8.905227459	26.12744231	135.8244732	7.32
Cs	– 10	8.462429432	25.02492440	125.7057239	-0.68
	– 05	8.558090273	25.15990219	126.1572357	-0.32
	+ 05	8.763050331	25.41798970	126.9349913	0.29
	+ 10	8.854080565	25.53263895	127.2801727	0.57
θ	– 10	8.599404426	25.19846964	126.8592190	0.23
	– 05	8.631745684	25.24597991	126.7118618	0.12
	+ 05	8.698239772	25.34289637	126.4091007	-0.12
	+ 10	8.732442178	25.39235043	126.2535609	-0.24
b	– 10	8.698239772	25.34289637	126.4091007	-0.12
	– 05	8.681382244	25.31842297	126.4858711	-0.06
	+ 05	8.648138296	25.26996772	126.6371650	0.06
	+ 10	8.631745684	25.24597991	126.7118618	0.12
c	– 10	9.662043332	27.92445113	126.9326540	0.29
	– 05	9.136330092	26.53887670	126.7116551	0.12
	+ 05	8.239133850	24.16944489	126.4733083	-0.07
	+ 10	7.853216402	23.14806098	126.4381012	-0.10
r	– 10	8.544024187	24.92631588	126.6369017	0.06
	– 05	8.604072005	25.10915505	126.5995069	0.03
	+ 05	8.725865710	25.48123189	126.5237261	-0.03
	+ 10	8.787630053	25.67054617	126.4853834	-0.06
k	– 10	8.702424294	24.40578093	103.6354453	-18.11
	– 05	9.227624464	24.54624572	116.6792374	-07.81
	+ 05	9.017541849	24.77252051	134.3868513	06.18
	+ 10	9.227672496	24.16722090	141.2883776	11.64
A	– 10	8.559347452	24.90282843	126.5105357	-0.04
	– 05	8.615342424	25.11355351	126.0267357	-0.42
	+ 05	8.698004189	25.43623237	127.1532333	0.47
	+ 10	8.730462016	25.57552735	127.7412747	0.93

VII. Graphical Presentation

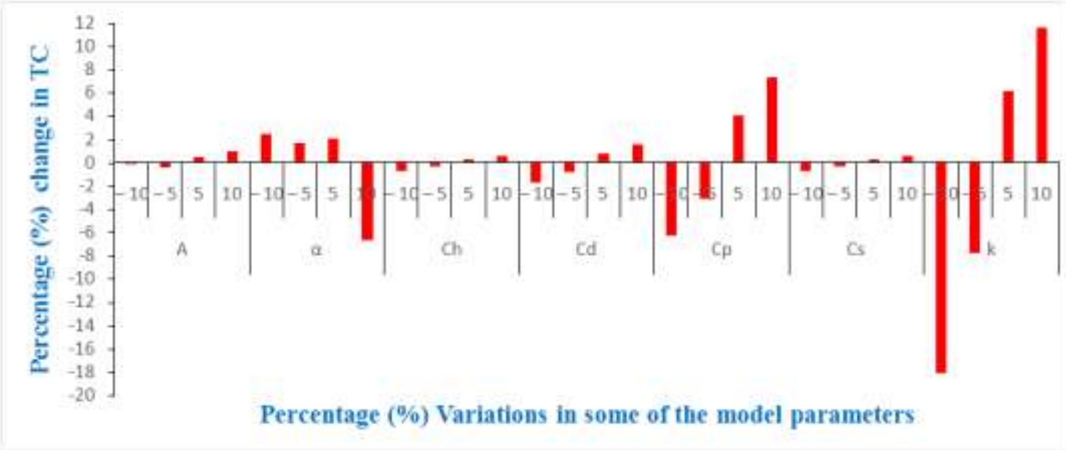

Figure – 2

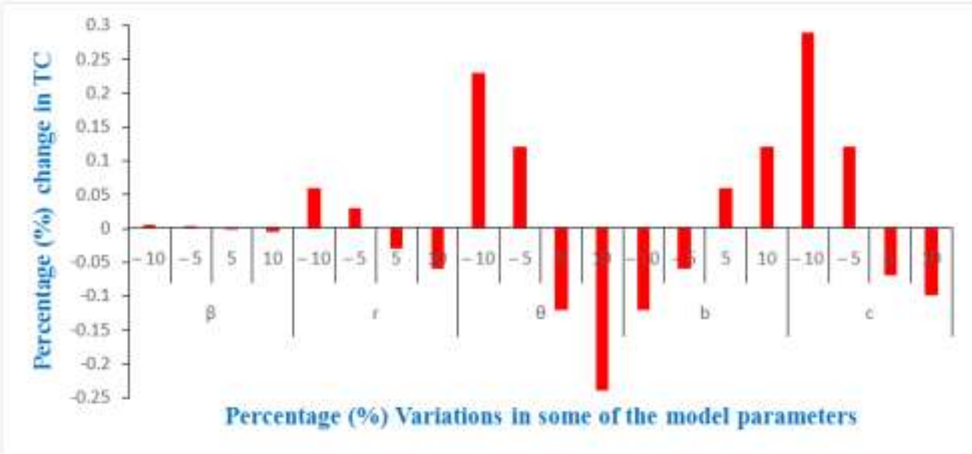

Figure – 3

VIII. Conclusions

- From the **Table**we can conclude that TC is highly sensitive to the change in C_p and k, moderately sensitive to the change in α and C_d and less sensitive to change in β, C_h, Cs, θ, b, c, A and r.
- It is observed from **Figure – 2** that the effect of increase or decrease in the values of α does not affectthe total cost TC much.
- It is observed from**Figure – 2** that when the values of A, C_h, C_d, Cp Cs and k increase simultaneously the average total cost TC also increases.
- It is observed from **Figure – 3** that when the values of b increase then TC also increases and when the values of β, θ, c and r increase, TC decreases.

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