International Journal of Mathematical Archive-6(2), 2015, 122-130
IJMA Available online through www.ijma.info ISSN 2229 – 5046

EOQPOLICIES FOR LINEARLY TIME DEPENDENT DETERIORATING ITEMS WITH POWER DEMAND AND PARTIAL BACKLOGGING

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(Received On: 16-01-15; Revised & Accepted On: 31-01-15)

ABSTRACT

The objective of the study is to develop a deterministic inventory model for linear time dependent deteriorating items with power demand pattern and backlogging of orders. The orders are partially backlogged and the backlogging rate is considered to be inversely proportional to the waiting time for the next replenishment. The optimal order quantity is obtained by minimizing the total cost per unit time. Numerical example is given to illustrate the model. Sensitivity analysis is carried out to study the effect of parameters.

Keywords*: Inventory, Deteriorating Items, Shortages, Power Demand, Partial Backlogging.*

1. INTRODUCTION

Deterioration of items in inventories is a common phenomenon. It is defined as decay or damage in the quality of the inventory. In some substances like foods, drugs, pharmaceuticals, and radioactive substances deterioration takes place during the normal storage period of the units and consequently this loss must be taken into account when analyzing the system**.** Since deterioration may lead to shortages care should be taken to keep it minimum. Study of deterioration inventory model began with Ghare and Schrader [5] who established the classical no shortage inventory model for constant rate of decay. Various types of inventory models for items deteriorating at a constant rate were discussed by Roychowdhury and Chaudhuri [12], Padmanabhan and Vrat [11], Balkhi and Benkherouf [1] and Yang [14] etc. In practice it can be observed that constantrate of deterioration occurs rarely. Most of the items deteriorate fast as the timepasses. Therefore, it is much more realistic to consider the variable deterioration rate.

Dave and Patel [3] developed the first deteriorating inventory model with linear trend in demand. He considers demand as a linear function of time. Goel and Aggarwal [6] formulated an order-level inventory system with power-demand pattern for deteriorating items. Dutta and Pal [4] presented an EOQ model with demand rate dependent on instantaneous stock displayed until a predefined maximum level of inventory L is achieved. After this level is reached, the demand rate becomes constant ($D(t)=\alpha[I(t)]^{\beta}$ for $I(t) > L$ and $D(t) = \alpha L^{\beta}$ for $0\leq I(t)\leq L$). Chang and Dye [2] developed an EOQ model with power demand and partial backlogging. He considered that if longer the waiting time smaller the backlogging rate would be. So the proportion of the customers who would like to accept backlogging at time tis decreasing with the waiting time for the next replenishment. In this situation the backlogging rate is defined as

$$B(t)=\frac{1}{1+\alpha\left(t_i-t\right)}$$

Where t_i is the time at which the i^{th}replenishment is being made and α is back logging parameter. Tarun Jeet Singh, Shiv Raj Singh and Rajul Dutt [13] developed EOQ model for perishable items with power demand and partial backlogging.

Many inventory control systems come across demand which increases with time during the development stages of the business. Hence power demand patterns are more suitable for such systems. In the present paper a deterministic inventory model with power demand pattern is developed in which inventory is depleted not only by demand but also by deterioration. Deterioration rate is assumed to be linearly time dependent. Shortages are allowed and partially backlogged. Two different cases of deterioration are dealt. The effect due to change in various parameters of the models are discussed with the help of numerical examples.

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1. ASSUMPTIONS AND NOTATIONS

The mathematical model is based on the following notations and assumptions.

Notations

A – The ordering cost per order.
C – The purchase cost per unit.
h – The inventory holding cost per unit per time unit.
π_b – The backordered cost per unit short per time unit.
π_l – The cost of lost sales per unit.
t_1 – The time at which the inventory level reaches zero, $t_1 \geq 0$.
t_2 – The length of period during which shortages are allowed, $t_2 \geq 0$.
T – ($=t_1+t_2$) The length of cycle time.
I_{MI} – The maximum inventory level during [0, T].
I_{MB} – The maximum backordered units during stock out period.
Q – ($=I_{MI}+I_{MB}$) The order quantity during a cycle of length T.
$I_1(t)$ – The level of positive inventory at time t, $0 \leq t \leq t_1$.
$I_2(t)$ – The level of negative inventory at time t, $t_1 \leq t \leq T$.
TCPT – The total cost per time unit.

Assumptions

- The inventory system deals with single item.
- The demand rate follows a power demand pattern expressed as $\frac{dt^{(1-n)/n}}{nT^{1/n}}$ at any time t, where d is a positive constant, n may be any positive number denoting pattern index, T is the planning horizon.
- The variable deterioration rate is
  Case (i): $\theta(t) = \theta t,\ 0 < \theta << 1,\ t > 0$
  Case (ii): $\theta(t) = \theta + \phi t,\ 0 << \theta < 1,\ 0 << \phi < 1,\ t > 0.$
- The replenishment rate is infinite.
- The lead-time is zero or negligible.
- The planning horizon is infinite.
- During the stock out period, the backlogging rate is variable and is dependent on the length of the waiting time for the next replenishment. The proportion of the customers who would like to accept the backlogging at time "t" is with the waiting time ($T-t$) for the next replenishment i.e., for the negative inventory the backlogging rate is $B(t) = \frac{1}{1+\delta(T-t)}$; $\delta > 0$ denotes the backlogging parameter and $t_1 \leq t \leq T$.

2. MATHEMATICAL MODEL

Case (i): Deterioration rate is $\theta(t) = \theta t$

Inventory level before shortage period

Under above assumptions, the on-hand inventory level at any instant of time is exhibited in figure 1.

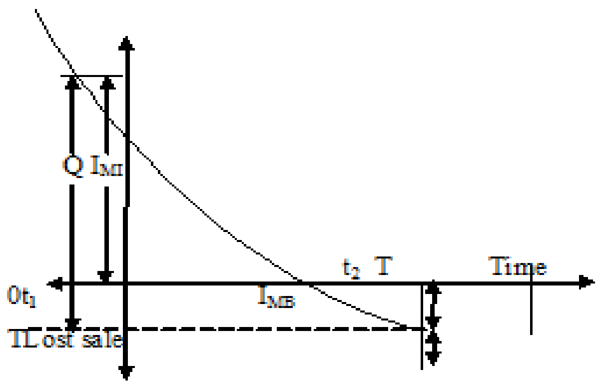

Figure 1. Representation of inventory system

During the period [0, t_1], the inventory depletes due to the deterioration and demand. Hence, the differential equation governing the inventory level $I_1(t)$ at any time t during the cycle [0, t_1] is given by

$$\frac{dI_1(t)}{dt}+\theta t I_1(t)=-\frac{dt^{\frac{1-n}{n}}}{nT^{\frac{1}{n}}},\quad 0\le t\le t_1 \tag{1}$$

with the boundary condition $I_1(t_1) = 0$ at $t = t_1$.

The solution of equation (1) is given by

$$I_1(t)=\frac{d}{T^{\frac{1}{n}}}\left[\left(1-\frac{\theta t^2}{2}\right)\left(t_1^{\frac{1}{n}}-t^{\frac{1}{n}}\right)+\frac{\theta}{2(1+2n)}\left(t_1^{\frac{1+2n}{n}}-t^{\frac{1+2n}{n}}\right)\right],\ 0\le t\le t_1 \tag{2}$$

The maximum positive inventory level during $0 \le t \le t_1$ is

$$I_{MI}=I_1(0)=\frac{d}{T^{\frac{1}{n}}}\left[t_1^{\frac{1}{n}}+\frac{\theta t_1^{\frac{1+2n}{n}}}{2(1+2n)}\right] \tag{3}$$

Inventory level during shortage period

During the interval [t_1, T] stock out situation arises and hence orders during this period are backlogged. The depletion of inventory is given in the figure 1. The state of inventory during [t_1, T] can be represented by the differential equation,

$$\frac{dI_2(t)}{dt}=-\frac{\left(\frac{dt^{(1-n)/n}}{nT^{(1/n)}}\right)}{1+\delta(T-t)},\quad t_1\le t\le T \tag{4}$$

with the boundary condition $I_2(t_1) = 0$ at $t = t_1$.

The solution of equation (4) is given by

$$I_2(t)=-\frac{d}{T^{\frac{1}{n}}}\left[(1-\delta T)\left(t^{\frac{1}{n}}-t_1^{\frac{1}{n}}\right)+\frac{\delta}{1+n}\left(t^{\frac{1+n}{n}}-t_1^{\frac{1+n}{n}}\right)\right],\quad t_1\le t\le T \tag{5}$$

The maximum backordered units are given by

$$I_{MB}=-I_2(T)=\frac{d}{T^{\frac{1}{n}}}\left[(1-\delta T)\left(T^{\frac{1}{n}}-t_1^{\frac{1}{n}}\right)+\frac{\delta}{1+n}\left(T^{\frac{1+n}{n}}-t_1^{\frac{1+n}{n}}\right)\right] \tag{6}$$

Hence, the order size during [0, T] is $Q = I_{MI} + I_{MB}$.

$$Q=\frac{d}{T^{\frac{1}{n}}}\left[T^{\frac{1}{n}}+\frac{\theta t_1^{\frac{1+2n}{n}}}{2(1+2n)}+\delta T t_1^{\frac{1}{n}}-\frac{\delta}{1+n}\left(nT^{\frac{1+n}{n}}+t_1^{\frac{1+n}{n}}\right)\right] \tag{7}$$

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

Ordering cost per cycle (I_{OC}):

$$I_{OC}=A \tag{8}$$

Inventory holding cost per cycle (I_{HC}):

$$I_{HC}=h\int_0^{t_1}I_1(t)dt=\frac{hd}{T^{\frac{1}{n}}}\left[\frac{t_1^{\frac{1+n}{n}}}{1+n}+\frac{\theta t_1^{\frac{1+3n}{n}}}{3(1+3n)}\right] \tag{9}$$

Backordered cost per cycle (I_{BC}):

$$I_{BC}=\pi_b\int_{t_1}^{T}-I_2(t)dt=\frac{\pi_b d}{T^{\frac{1}{n}}}\left[(\delta T^2-T)t_1^{\frac{1}{n}}+\frac{nT^{\frac{1+n}{n}}}{1+n}+\frac{(1-2\delta T)t_1^{\frac{1+n}{n}}}{1+n}-\frac{2\delta n^2 T^{\frac{1+2n}{n}}}{(1+n)(1+2n)}+\frac{\delta t_1^{\frac{1+2n}{n}}}{1+2n}\right] \tag{10}$$

Cost due to lost sales per cycle (I_{LS}):

$$I_{LS} = \pi_l \int_{t_1}^{T} \left[1-\frac{1}{1+\delta(T-t)}\right]\left(\frac{dt^{\frac{1-n}{n}}}{nT^{\frac{1}{n}}}\right)dt = \frac{\pi_l d\delta}{T^{\frac{1}{n}}}\left[\frac{nT^{\frac{1+n}{n}}}{1+n} - Tt_1^{\frac{1}{n}} + \frac{t_1^{\frac{1+n}{n}}}{1+n}\right] \tag{11}$$

Purchase cost per cycle (I_{PC}):

$$I_{PC} = C\times Q = \frac{Cd}{T^{\frac{1}{n}}}\left[T^{\frac{1}{n}} + \frac{\theta t_1^{\frac{1+2n}{n}}}{2(1+2n)} + \delta T t_1^{\frac{1}{n}} - \frac{\delta}{1+n}\left(nT^{\frac{1+n}{n}} + t_1^{\frac{1+n}{n}}\right)\right] \tag{12}$$

Hence, the total cost per time unit is

$$TCPT = \frac{1}{T}\left[I_{OC} + I_{HC} + I_{BC} + I_{LS} + I_{PC}\right]$$

$$\begin{aligned} TCPT = \frac{1}{T}\Bigg\{ & A + \frac{hd}{T^{\frac{1}{n}}}\left[\frac{t_1^{\frac{1+n}{n}}}{1+n} + \frac{\theta t_1^{\frac{1+3n}{n}}}{3(1+3n)}\right] + \frac{\pi_b d}{T^{\frac{1}{n}}}\left[\left(\delta T^2 - T\right)t_1^{\frac{1}{n}} + \frac{nT^{\frac{1+n}{n}}}{1+n} + \frac{(1-2\delta T)t_1^{\frac{1+n}{n}}}{1+n} - \frac{2\delta n^2 T^{\frac{1+2n}{n}}}{(1+n)(1+2n)} + \frac{\delta t_1^{\frac{1+2n}{n}}}{1+2n}\right] \\ & + \frac{\pi_l d\delta}{T^{\frac{1}{n}}}\left[\frac{nT^{\frac{1+n}{n}}}{1+n} - Tt_1^{\frac{1}{n}} + \frac{t_1^{\frac{1+n}{n}}}{1+n}\right] + \frac{Cd}{T^{\frac{1}{n}}}\left[T^{\frac{1}{n}} + \frac{\theta t_1^{\frac{1+2n}{n}}}{2(1+2n)} + \delta T t_1^{\frac{1}{n}} - \frac{\delta}{1+n}\left(nT^{\frac{1+n}{n}} + t_1^{\frac{1+n}{n}}\right)\right] \end{aligned} \tag{13}$$

To minimize total average cost per unit time (*TCPT*), the optimal value of $t_1$can be obtained by solving the equation

$$\frac{dTCPT}{dt_1} = 0 \tag{14}$$

The condition $\frac{d^2TCPT}{dt_1^2} > 0$, (15)

is also satisfied for the above value of t_1. The value of t_1 obtained from equation (14) is used to obtain the optimal value of Q and *TCPT* respectively. Since the equation (14) is nonlinear, it is solved using MATLAB.

Case (ii): The deterioration rate is $\theta(t) = \theta + \phi t$

Inventory level before shortage period

In this case the differential equation governing the inventory level $I_1(t)$ at any time t during the cycle $[0, t_1]$ is given by

$$\frac{dI_1(t)}{dt} + (\theta + \phi t)I_1(t) = -\frac{dt^{\frac{1-n}{n}}}{nT^{\frac{1}{n}}},\ 0 \le t \le t_1 \tag{16}$$

with the boundary condition $I_1(t_1) = 0$ at $t = t_1$.

The solution of equation (16) is given by

$$I_1(t) = \frac{d}{T^{\frac{1}{n}}}\left[\left(1-\theta t - \frac{\phi t^2}{2}\right)\left(t_1^{\frac{1}{n}} - t^{\frac{1}{n}}\right) + \frac{\theta}{(1+n)}\left(t_1^{\frac{1+n}{n}} - t^{\frac{1+n}{n}}\right) + \frac{\phi}{2(1+2n)}\left(t_1^{\frac{1+2n}{n}} - t^{\frac{1+2n}{n}}\right)\right],\ 0 \le t \le t_1 \tag{17}$$

The maximum positive inventory level during $0 \le t \le t_1$ is

$$I_{MI}^{'} = I_1(0) = \frac{d}{T^{\frac{1}{n}}}\left[t_1^{\frac{1}{n}} + \frac{\theta t_1^{\frac{1+n}{n}}}{1+n} + \frac{\phi t_1^{\frac{1+2n}{n}}}{2(1+2n)}\right] \tag{18}$$

Hence, the order size during [0, T] is $Q = I_{MI}^{'} + I_{MB}$.

$$Q = \frac{d}{T^{\frac{1}{n}}}\left[T^{\frac{1}{n}} + \delta T t_1^{\frac{1}{n}} + \frac{1}{1+n}\left((\theta-\delta)t_1^{\frac{1+n}{n}} - n\delta T^{\frac{1+n}{n}}\right) + \frac{\phi t_1^{\frac{1+2n}{n}}}{2(1+2n)}\right] \tag{19}$$

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

Inventory holding cost per cycle (I'_{HC}):

$$I'_{HC} = h\int_0^{t_1} I_1(t)dt = \frac{hd}{T^{\frac{1}{n}}}\left[\frac{t_1^{\frac{1+n}{n}}}{1+n} + \frac{\theta t_1^{\frac{1+2n}{n}}}{2(1+2n)} + \frac{\phi t_1^{\frac{1+3n}{n}}}{3(1+3n)}\right] \tag{20}$$

Purchase cost per cycle (I'_{PC}):

$$I'_{PC} = C\times Q = \frac{Cd}{T^{\frac{1}{n}}}\left[T^{\frac{1}{n}} + \delta T t_1^{\frac{1}{n}} + \frac{1}{1+n}\left((\theta-\delta)t_1^{\frac{1+n}{n}} - n\delta T^{\frac{1+n}{n}}\right) + \frac{\phi t_1^{\frac{1+2n}{n}}}{2(1+2n)}\right] \tag{21}$$

Hence, the total cost per time unit is

$$TCPT = \frac{1}{T}\left[I_{OC} + I'_{HC} + I_{BC} + I_{LS} + I'_{PC}\right]$$

$$\begin{aligned} TCPT = \frac{1}{T}\Bigg\{ & A + \frac{hd}{T^{\frac{1}{n}}}\left[\frac{t_1^{\frac{1+n}{n}}}{1+n} + \frac{\theta t_1^{\frac{1+2n}{n}}}{2(1+2n)} + \frac{\phi t_1^{\frac{1+3n}{n}}}{3(1+3n)}\right] + \frac{\pi_b d}{\mathrm{T}^{\frac{1}{n}}}\Bigg[\left(\delta T^2 - T\right)t_1^{\frac{1}{n}} + \frac{nT^{\frac{1+n}{n}}}{1+n} \\ & + \frac{(1-2\delta T)t_1^{\frac{1+n}{n}}}{1+n} - \frac{2\delta n^2 T^{\frac{1+2n}{n}}}{(1+n)(1+2n)} + \frac{\delta t_1^{\frac{1+2n}{n}}}{1+2n}\Bigg] + \frac{\pi_l d\delta}{\mathrm{T}^{\frac{1}{n}}}\left[\frac{nT^{\frac{1+n}{n}}}{1+n} - Tt_1^{\frac{1}{n}} + \frac{t_1^{\frac{1+n}{n}}}{1+n}\right] \\ & + \frac{Cd}{T^{\frac{1}{n}}}\left[T^{\frac{1}{n}} + \delta T t_1^{\frac{1}{n}} + \frac{1}{1+n}\left((\theta-\delta)t_1^{\frac{1+n}{n}} - n\delta T^{\frac{1+n}{n}}\right) + \frac{\phi t_1^{\frac{1+2n}{n}}}{2(1+2n)}\right]\Bigg\} \end{aligned} \tag{22}$$

To minimize total average cost per unit time (*TCPT*), the optimal value of $t_1$can be obtained by solving the equation

$$\frac{dTCPT}{dt_1} = 0 \tag{23}$$

The condition $\frac{d^2TCPT}{dt_1^2} > 0$, (24)

is also satisfied for the above value of t_1. The value of t_1 obtained from equation (23) is used to obtain the optimal value of *Q* and *TCPT* respectively. Since the equation (23) is nonlinear, it is solved using MATLAB.

To illustrate and validate the proposed model, appropriate numerical data is considered and the optimal values are found in the following section. Sensitivity analysis is carried out with respect to backlogging parameter and deterioration rate.

NUMERICAL EXAMPLE AND SENSITIVITY ANALYSIS

The following parametric values are considered for an inventory system with appropriate units. d = 50 units, n = 2 units, T = 1 year, A = \$250 per order, C = \$8.0 per unit, h = \$0.50 per unit per year, π_b = \$12.0 per unit per year, π_l = \$15.0 per unit.

Optimal Solution
Case (i): θ(t) = θt

For the above numerical values, when deterioration parameter θ is 5%, the optimum time t_1 at which positive inventory is zero is 0.973038 time units and stock out period t_2 is of length is 0.026962 time units. This advices the retailer to buy 50 units which will cost a minimum of \$ 658.43.

Effect of backlogging parameter (δ):

The backlogging parameter has initially been taken as 2. Now varying the backlogging parameter from 1 to 3 the following table is obtained.

Table-1: Variation in backlogging parameter ‘δ’

Parameter value (δ)	% Change	t_1 (Year)	Q (Units)	TCPT ($)
1.0	-50	0.963639	50.211159	660.07
1.5	-25	0.969014	50.212891	660.12
2.0	0	0.973038	50.215149	660.15
2.5	+25	0.976152	50.217445	660.18
3.0	+50	0.978632	50.219612	660.20

The above table reveals that increment in backlogging parameter results in increase in inventory period and also increase in order quantity and total cost per unit time.

Graphical Interpretation:

The three dimensional total cost per time unit graph is shown in Figure 2 by plotting t_1 in the range of [0.963639, 0.978632] and t_2 in the range of [0.021368, 0.036361]. Figure 2 indicates that total cost per time unit is strictly convex.

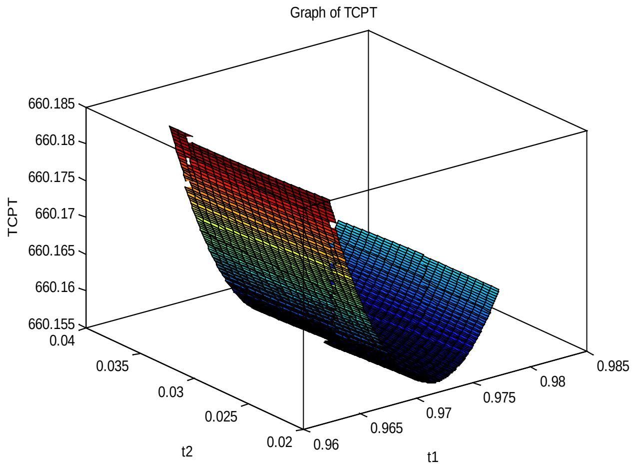

Figure 2. Total cost per time unit

Effect of deterioration parameter (θ):

Initially the deterioration parameter has been taken as 0.05. The following table is obtained with the variation in deterioration parameter from 0.025 to 0.075.

Table-2: Variation in deterioration parameter ‘θ’

Parameter value (θ)	% Change	t_1 (Year)	Q (Units)	TCPT ($)
0.0250	-50	0.976900	50.104462	659.19
0.0375	-25	0.974965	50.160183	659.67
0.0500	0	0.973038	50.215149	660.15
0.0625	+25	0.971120	50.269367	660.63
0.0750	+50	0.969209	50.322845	661.11

The above table reveals that increment in deterioration parameter results in decrease in inventory period and increase in order quantity and total cost per unit time.

Graphical Interpretation:

The three dimensional total cost per time unit graph is shown in Figure 3 by plotting t_1 in the range of [0.969209, 0.976900] and t_2 in the range of [0.023100, 0.030791]. Figure 3 indicates that total cost per time unit is strictly convex.

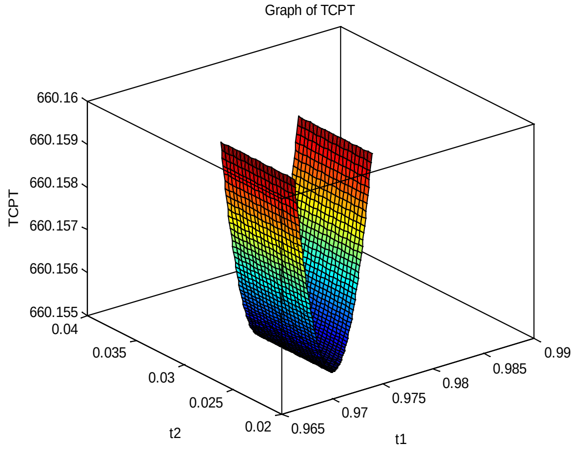

Figure 3. Total cost per time unit

Case (ii): $\theta(t) = \theta+\phi t$

For the above numerical values, the optimum time t_1 at which positive inventory is zero is 0.961960 time units and stock out period t_2 is of length is 0.038040 time units. This advices the retailer to buy 51 units which will cost a minimum of $ 666.75.

Effect of backlogging parameter (δ):

The backlogging parameter has initially been taken as 2. Now varying the backlogging parameter between 1 to 3 the following table is obtained.

Table-3: Variation in backlogging parameter 'δ'

Parameter value (δ)	% Change	t_1 (Year)	Q (Units)	TCPT ($)
1.0	-50	0.948869	50.824692	665.31
1.5	-25	0.956332	50.832500	665.41
2.0	0	0.961960	50.840355	665.48
2.5	+25	0.966338	50.847591	665.53
3.0	+50	0.969824	50.854027	665.57

The above table reveals that increment in backlogging parameter results are increase in inventory period and increase in order quantity and total cost per unit time.

Graphical Interpretation:

The three dimensional total cost per time unit graph is shown in Figure 4 by plotting t_1 in the range of [0.948869, 0.969824] and t_2 in the range of [0.030176, 0.051131]. Figure 4 indicates that total cost per time unit is strictly convex.

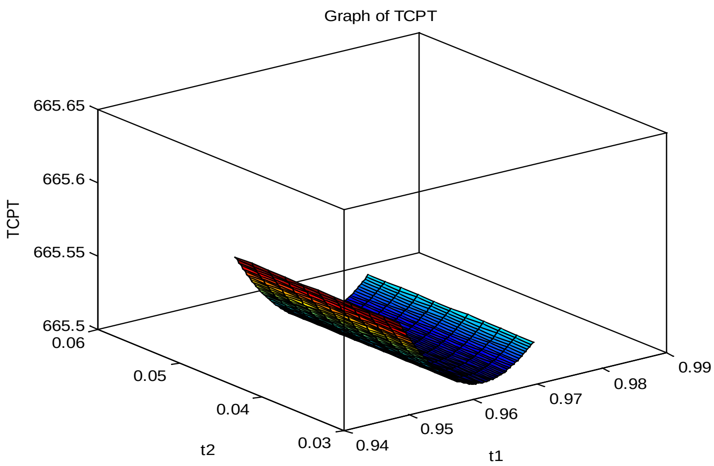

Figure 4. Total cost per time unit

Effect of deterioration parameter (ϕ):

The following table is obtained with the variation in deterioration parameter from 0.01 to 0.03.

Table-5: Variation in deterioration parameter 'ϕ'

Parameter value (ϕ)	% Change	t_1 (Year)	Q (Units)	TCPT ($)
0.010	-50	0.963484	50.799919	665.10
0.015	-25	0.962720	50.820190	665.29
0.020	0	0.961960	50.840355	665.48
0.025	+25	0.961201	50.860401	665.66
0.030	+50	0.960438	50.880318	665.85

The above table reveals that increment in deterioration parameter results in decrease in inventory period and increase in order quantity and total cost per unit time.

Graphical Interpretation:

The three dimensional total cost per time unit graph is shown in Figure 6 by plotting t_1 in the range of [0.960438, 0.963484] and t_2 in the range of [0.036516, 0.039562]. Figure 6 indicates that total cost per time unit is strictly convex.

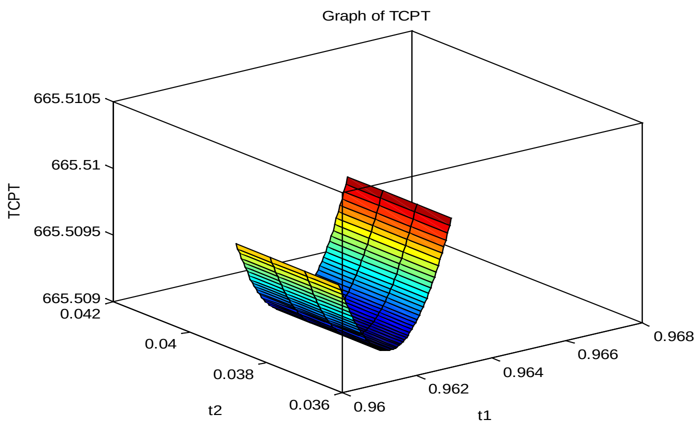

Figure 6. Total cost per time unit

Effect of deterioration parameter (θ):

θbeing an additive term has a similar effect as **ϕ.** That is, change in **θ** results in decrease in inventory period and increase in order quantity and total cost per unit time.

CONCLUSION

In this paper, we have developed a deterministic inventory model with power pattern demand and variable linear time dependent deterioration rate. Shortages have been allowed and are assumed to be partially backlogged in this model. The optimal order quantity has been computed by minimizing the total inventory cost. The cost function is strictly convex. It is obtained with the help of MATLAB. The models are illustrated numerically. Sensitivity analysis is also carried out and it can be inferred that the variation in the total cost is directly linked to variation in backlogging and deterioration parameters.

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Source of support: Nil, Conflict of interest: None Declared