A Nonlinear EOQ Model for Time-dependent Demand, Deterioration and Shortages with Inflation

Dr. MONAMI DAS ROY

Assistant Professor, Department of Mathematics,
Haldia Government College, Vidyasagar University,
Haldia, Purba Medinipur 721657, India.
E-mail: monamidasroy@gmail.com and mdasroy2009@yahoo.in.

Abstract

This research article deals with an Economic Order Quantity (EOQ) model for a single type of deteriorating product. The demand of the product is considered to be an increasing quadratic function of time. Deterioration follows a two parameter Weibull distribution. Shortage takes place and the shortage cost is assumed to be a non-linear function of time. The effect of inflation and salvage cost are also taken into account. The objectives of this research work are: (i) maximize the average profit and (ii) study the effect of deterioration and inflation on the average profit function. Numerical example with its graphical representation is provided to establish the model. Some Special cases together with comparative study are also furnished with the help of numerical results.

Keywords: EOQ, inventory, time-dependent demand, deterioration, shortage, salvage cost, inflation.

1. Introduction

It is quite obvious that the demand of an item may not be fixed throughout the year. Sometimes, it is very high and sometimes it is very low or average. The effect of time parameter in customers demand attracts researchers to investigate inventory models by considering time dependent demand pattern. Silver and Meal [1] first presented an EOQ model by introducing time-dependent demand rate. An exponential time-dependent demand pattern is taken into consideration by Hariga and Benkherouf [2] while Wu et al. [3] have developed an EOQ model for time varying demand rate together with deterioration and shortages. Manna et al. [4] have introduced time-dependent quadratic demand rate in their studies. The effect of trade credit on an inventory model is investigated by Tripathy and Pradhan [5]. They have considered two parameter time-dependent Weibull distributed demand pattern while a deteriorating inventory model with time-dependent demand and holding cost is discussed by Dutta and Kumar [6].

Deterioration of product and occurrence of shortages are another two major issues in any inventory study. Chang and Dye [7] have presented an inventory model for deteriorating item including the concept of permissible delay in parameters together with shortages while Lee and Wu [8] have investigated an EOQ model for time varying demand. They have assumed exponentially distributed deterioration and shortages. The concept of partial backlogging for deteriorating items is introduced by Dye et al. [9]. Valliathal and Uthayakumar [10] presented a production-inventory problem where non-linear shortage cost is taken into account while Mishra [11] have included salvage value along with deterioration and shortages. Das Roy and Sana [12] have discussed an imperfect production model with free repair warranty and shortages. They have considered random sales price sensitive demand pattern while a markdown policy is determined by Das Roy [13] for an economic production quantity model (EPQ) where deterioration of product and shortages are taken into consideration. Plenty of research articles are available in which researchers have implemented either the effect of deterioration or shortages or both of them together. A few of them are Skouri et al. [14], Roy et al. [15], Das Roy et al. ([16], [17]).

In early studies, the researchers have ignored the effect of inflation but now-a-days it cannot be overlooked. A number of countries are affected by inflation. Buzacott [18] has first introduced the concept of inflation. A deteriorating inventory model together with inflation and time-discounting is discussed by Chen [19] while Yang et al. [20] have studied an inventory model for deteriorating items with stock dependent demand and partial backlogging under inflation.

The present paper proposes an EOQ model for deteriorating items in conjunction with inflation and shortages. Demand is assumed to be influenced by time. It is an increasing quadratic function of time. Deterioration of item is also time-dependent which follows a two parameter Weibull distribution. Salvage value for deteriorating items are taken into consideration. Shortages occur at the end of the cycle and the shortage cost is taken as a non-linear function of time. The average profit function contains ordering cost, holding cost, deterioration cost, shortage cost, salvage cost and revenue cost. The purpose of this research work is to determine the optimal values of the decision variables by maximizing the average profit and observe the effect of deterioration and inflation on the average profit function.

The entire paper consists of 8 Sections. Section 1 presents introduction part whereas notations and assumptions of the proposed model are given in Section 2. Mathematical formulation and solution procedure of the model are described in Section 3 and Section 4 respectively. Section 5 provides numerical result and graphical representation. Some special cases are discussion in Section 6 while Section 7 contains comparative study. Finally, conclusion and further research proposal is given in Section 8.

2. Notation and assumptions

The notations and assumptions required to develop the proposed model are as follows.

2.1 Notation

K : Ordering cost per order.

$D(t)$: Demand at time $t \geq 0$.

$\theta(t)$: Deterioration rate at time $t > 0$.

$S(t)$: Shortage cost per unit per unit time.

C_p : Purchase cost (\$) per unit.

C_h : Inventory holding cost (\$) per unit per unit time.

S_p : Selling price (\$) per unit.

μ : Salvage value associated with deteriorating item.

t_1 : Time at which the inventory level reaches to zero, $t_1 \geq 0$ is a decision variable.

T : Cycle length is a decision variable.

q_1 : The level of positive inventory at time t, $0 \leq t \leq t_1$

q_2 : The level of negative inventory at time t, $t_1 \leq t \leq T$.

I_M : The maximum inventory level during $[0, T]$.

I_B : The maximum backlogging units during shortage period $[t_1, T]$.

Q : Inventory ordered lot-size in units during a cycle of length T where $Q = I_M + I_B$.

δ : Inflation per unit currency ($).

ψ : The total average profit ($).

2.2 Assumptions

1. The inventory model is investigated for a single item only.
2. Demand is considered to be influenced by time. It is a quadratic function in time t i.e., $D(t) = a + bt + ct^2; a > 0; b \neq 0; c \neq 0$. Here a denotes the initial rate of demand, b denotes the rate at which the demand rate changes and the rate of change in the demand rate itself changes at a rate c.
3. The deterioration rate follows a two parameter Weibull distribution i.e.,
$$\theta(t) = \alpha\beta t^{\beta-1}, \text{ where } 0 < \alpha << 1,\ \beta > 1.$$
Here α indicates the scale parameter and β indicates the shape parameter. Also, it is considered that deterioration increases with time t > 0.
4. Deteriorating items are not repaired or replaced.
5. The salvage value μ $(0 \leq \mu \leq 1)$ associated with deteriorating items per cycle is taken into account.
6. Shortages occur and shortage cost is assumed to be a non-linear function of time t i.e., $S(t) = l + mt + nt^2; l > 0; m \neq 0; n \neq 0.$
7. Replenish rate is infinite.
8. Lead time is zero or negligible.
9. The time horizon is finite.
10. The effect of inflation is considered.

3. Mathematical Formulation

Suppose at time t = 0 the on-hand inventory is Q. Deterioration starts from the beginning of the cycle. For the joint effect of demand and deterioration the on-hand stock depletes with time and reaches to zero after time t_1. Shortage takes place during the time span $[t_1, T]$. The inventory model is given in Figure 1.

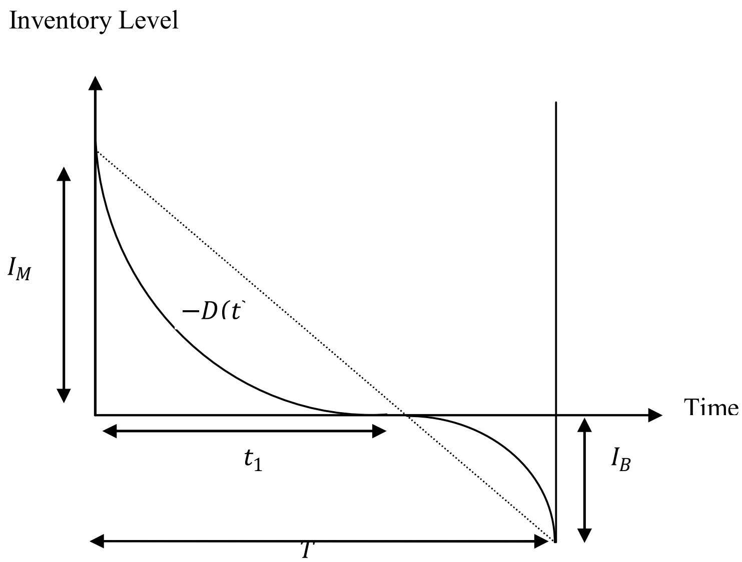

Figure 1. Inventory Versus Time

The governing differential equations of the system at any time t are

$$\frac{dq_1(t)}{dt} + \alpha\beta t^{\beta-1} q_1(t) = -(a + bt + ct^2),\ 0 \le t \le t_1,\ \ q_1(t_1) = 0 \tag{1}$$

and $$\frac{dq_2(t)}{dt} = -(a + bt + ct^2),\ t_1 \le t \le T. \tag{2}$$

The solutions of equations (1) and (2), are

$$q_1(t) = \left(1 - \alpha t^{\beta}\right)\Big[a(t_1 - t) + \frac{b}{2}({t_1}^2 - t^2) + \frac{c}{3}({t_1}^3 - t^3) + \alpha\Big\{\frac{a}{\beta+1}({t_1}^{\beta+1} - t^{\beta+1}) + \frac{b}{\beta+2}({t_1}^{\beta+2} - t^{\beta+2}) + \frac{c}{\beta+3}({t_1}^{\beta+3} - t^{\beta+3})\Big\}\Big], \qquad 0 \le t \le t_1$$

and $$q_2(t) = a(t_1 - t) + \frac{b}{2}({t_1}^2 - t^2) + \frac{c}{3}({t_1}^3 - t^3), \qquad t_1 \le t \le T.$$

The maximum level of inventory I_M is

$$I_M = q_1(0) = at_1 + \frac{b}{2}{t_1}^2 + \frac{c}{3}{t_1}^3 + \alpha\left\{\frac{a}{\beta+1}{t_1}^{\beta+1} + \frac{b}{\beta+2}{t_1}^{\beta+2} + \frac{c}{\beta+3}{t_1}^{\beta+3}\right\}$$

and the maximum level of back order inventory I_B is

$$I_B = -q_2(T) = a(T - t_1) + \frac{b}{2}(T^2 - {t_1}^2) + \frac{c}{3}(T^3 - {t_1}^3).$$

Thus, the ordered lot size is

$$Q = I_M + I_B = aT + \frac{b}{2}T^2 + \frac{c}{3}T^3 + \alpha\left\{\frac{a}{\beta+1}{t_1}^{\beta+1} + \frac{b}{\beta+2}{t_1}^{\beta+2} + \frac{c}{\beta+3}{t_1}^{\beta+3}\right\} \qquad (3)$$

Now the inventory related costs are as follows.

The ordering cost per cycle (OC) with the effect of inflation is $OC = K(T - \frac{\delta T^2}{2})$.

The inventory holding cost per cycle (HC) with the effect of inflation is

$$HC = C_h \int_0^{t_1} q_1(t)\, e^{-\delta t} dt$$

$$= C_h[\frac{1}{2}a{t_1}^2 + \frac{1}{6}(2b - a\delta){t_1}^3 + \frac{1}{8}(2c - b\delta){t_1}^4 - \frac{1}{10}c\delta{t_1}^5$$

$$+ \frac{a\alpha\beta}{(\beta+1)(\beta+2)}{t_1}^{\beta+2} + \frac{\alpha\beta\{2b(\beta+2) - a\delta(\beta+1)\}}{2(\beta+1)(\beta+2)(\beta+3)}{t_1}^{\beta+3}$$

$$+ \frac{\alpha\beta\{2c(\beta+2) - b\delta(\beta+1)\}}{2(\beta+1)(\beta+2)(\beta+4)}{t_1}^{\beta+4} - \frac{c\delta\alpha\beta}{2(\beta+2)(\beta+5)}{t_1}^{\beta+5}$$

$$- \frac{a\alpha^2}{(\beta+1)(2\beta+2)}{t_1}^{2\beta+2} - \frac{\alpha^2\{b(\beta+2) - a\delta(\beta+1)\}}{(\beta+1)(\beta+2)(2\beta+3)}{t_1}^{2\beta+3}$$

$$- \frac{\alpha^2\{c(\beta+2) - b\delta(\beta+1)\}}{(\beta+1)(\beta+2)(2\beta+4)}{t_1}^{2\beta+4} + \frac{c\delta\alpha^2}{(\beta+2)(2\beta+5)}{t_1}^{2\beta+5}].$$

The deterioration cost per cycle (DC) with the effect of inflation is

$$DC = C_p \int_0^{t_1} \theta(t) q_1(t)\, e^{-\delta t} dt$$

$$= C_p\alpha\beta[\frac{a}{\beta(\beta+1)}{t_1}^{\beta+1} + \frac{\{b(\beta+1) - a\beta\delta\}}{\beta(\beta+1)(\beta+2)}{t_1}^{\beta+2}$$

$$+ \frac{\{c(\beta+1) - b\beta\delta\}}{\beta(\beta+1)(\beta+3)}{t_1}^{\beta+3} - \frac{c\delta}{(\beta+1)(\beta+4)}{t_1}^{\beta+4}$$

$$+ \frac{a\alpha}{2\beta(2\beta+1)}{t_1}^{2\beta+1} + \frac{\{b\alpha(\beta+1)(2\beta+1) - 2a\alpha\beta^2\delta\}}{2\beta(\beta+1)(2\beta+1)(2\beta+2)}{t_1}^{2\beta+2}$$

$$+ \frac{\{c\alpha(\beta+1)(2\beta+1) - 2b\alpha\beta^2\delta\}}{2\beta(\beta+1)(2\beta+1)(2\beta+3)}{t_1}^{2\beta+3}$$

$$- \frac{c\alpha\beta\delta}{(\beta+1)(2\beta+1)(2\beta+4)}{t_1}^{2\beta+4}$$

$$\frac{a\alpha^2}{2\beta(3\beta+1)}{t_1}^{3\beta+1} \qquad \frac{\alpha^2\{b(2\beta+1) - 2a\beta\delta\}}{2\beta(2\beta+1)(3\beta+2)}{t_1}^{3\beta+2}$$

$$-\frac{\alpha^2\{c(2\beta+1)-2b\beta\delta\}}{2\beta(2\beta+1)(3\beta+3)}t_1^{3\beta+3}+\frac{c\alpha^2\delta}{(2\beta+1)(3\beta+4)}t_1^{3\beta+4}].$$

The salvage cost per cycle (SV) with the effect of inflation is $SV = \mu DC.$

The shortage cost per cycle (SC) with the effect of inflation is

$$SC = \int_{t_1}^{T} S(t)(-q_2(t))\, e^{-\delta t}dt$$

$$= l\left\{a\left(\frac{1}{2}T^2+\frac{1}{2}t_1^2-Tt_1\right)+b\left(\frac{1}{6}T^3+\frac{1}{3}t_1^3-\frac{1}{2}Tt_1^2\right)+c\left(\frac{1}{12}T^4+\frac{1}{4}t_1^4-\frac{1}{3}Tt_1^3\right)\right\}$$
$$+(m-l\delta)\left\{a\left(\frac{1}{3}T^3+\frac{1}{6}t_1^3-\frac{1}{2}T^2t_1\right)+b\left(\frac{1}{8}T^4+\frac{1}{8}t_1^4-\frac{1}{4}T^2t_1^2\right)\right.$$
$$\left.+c\left(\frac{1}{15}T^5+\frac{1}{10}t_1^5-\frac{1}{6}T^2t_1^3\right)\right\}$$
$$+(n-m\delta)\left\{a\left(\frac{1}{4}T^4+\frac{1}{12}t_1^4-\frac{1}{3}T^3t_1\right)\right.$$
$$\left.+b\left(\frac{1}{10}T^5+\frac{1}{15}t_1^5-\frac{1}{6}T^3t_1^2\right)+c\left(\frac{1}{18}T^6+\frac{1}{18}t_1^6-\frac{1}{9}T^3t_1^3\right)\right\}$$
$$-n\delta\left\{a\left(\frac{1}{5}T^5+\frac{1}{20}t_1^5-\frac{1}{4}T^4t_1\right)+b\left(\frac{1}{12}T^6+\frac{1}{24}t_1^6-\frac{1}{8}T^4t_1^2\right)\right.$$
$$\left.+c\left(\frac{1}{21}T^7+\frac{1}{28}t_1^7-\frac{1}{12}T^4t_1^3\right)\right\}.$$

The revenue per cycle (RV) with the effect of inflation is

$$RV = S_p\int_0^T D(t)\, e^{-\delta t}dt = S_p[aT+\left(\frac{b-a\delta}{2}\right)T^2+\left(\frac{c-b\delta}{3}\right)T^3-\frac{c\delta}{4}T^4].$$

The average profit ($\psi(t_1,T)$) is

$$\psi(t_1,T)=\frac{1}{T}[RV-(OC+HC+DC+SC-SV)] \qquad (4)$$

4. Solution Procedure

The average profit function $\psi(t_1,T)$ is a non-linear function of decision variables. Therefore, it is not possible to examine the concavity nature of the function and determine the optimal solutions analytically. “MATHEMATICA 8.0" software is used to obtained the optimal stock-out point i.e., t_1^*, cycle length $T^*$and the optimum value of average profit $\psi(t_1^*,T^*)$. Also, with the help of “MATHEMATICA 8.0" the optimization conditions are verified i.e., at the optimal values of t_1 and T.

$$\frac{\partial^2\psi(t_1,T)}{\partial t_1^2}<0,\quad \frac{\partial^2\psi(t_1,T)}{\partial T^2}<0,\ \text{and}\ \frac{\partial^2\psi(t_1,T)}{\partial t_1^2}\times\frac{\partial^2\psi(t_1,T)}{\partial T^2}-\left(\frac{\partial^2\psi(t_1,T)}{\partial t_1\partial T}\right)^2>0.$$

5. Numerical Example

Example 1. Let us consider an inventory system where shortage occurs at the end of the cycle. The parameters values related to the model in appropriate units are as follows.

$K = \$50, \quad \alpha = 0.1, \quad \beta = 0.2, \quad \delta.03, \quad C_h = \$4, \quad C_p = \$30, \quad S_p = \$70,$
$a = 1720, \quad b = 100, \quad c = 40, \quad l = 0.1, \quad m = 0.3, \quad n = 0.9, \quad \mu = 0.1.$

Then the optimum solution obtained from equation (4) is: $t_1^* = 5.55441 \cong 5.55$ weeks, $T^* = 6.42573 \cong 6.43$ weeks and $\psi^* = \$123235$. Also, the optimal ordered lot size obtained from equation (3) is $Q^* = 18275.5$ units.

Since at the optimal solution $t_1^* = 5.55441$, $T^* = 6.42573$, $\frac{\partial^2\psi}{\partial t_1^2} = 15346.9 < 0$, $\frac{\delta^2\psi}{\partial T^2} = -19954.5 < 0$ and $H = \frac{\partial^2\psi}{\partial t_1^2} \times \frac{\partial^2\psi}{\partial T^2} - (\frac{\partial^2\psi}{\partial t_1 \partial T})^2 = 7.72878 \times 10^6 > 0$. Therefore, the Hessian matrix $H = \begin{pmatrix} \frac{\partial^2\psi}{\partial t_1^2} & \frac{\partial^2\psi}{\partial t_1 \partial T} \\ \frac{\partial^2\psi}{\partial T \partial t_1} & \frac{\partial^2\psi}{\partial T^2} \end{pmatrix}$ is negative definite.

Hence, the required optimal solution is $t_1^* = 5.55441 \cong 5.55$ weeks, $T^* = 6.42573 \cong 6.43$ weeks and $\psi^* = \$123235$ (see Figure 2).

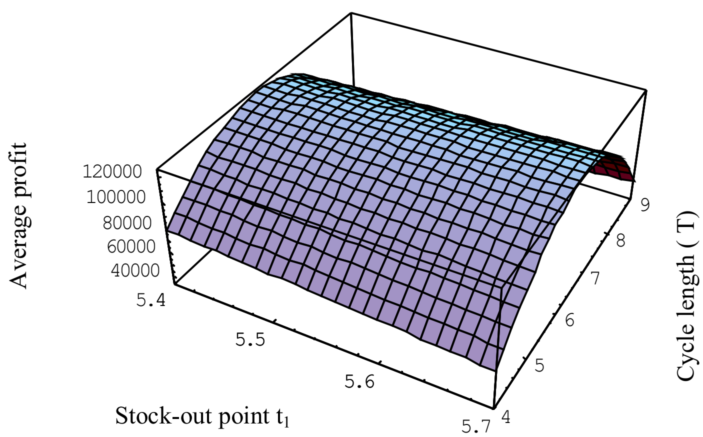

Figure 2. Graphical Representation of Average Profit Function Versus Stock-out Point (t_1) and Cycle Length (T) for Example 1

6. Special cases

In this section, some special cases are discussed separately.

6.1 Case-I: Deterioration without inflation

In this case, $\delta = 0$. Substituting $\delta = 0$ while keeping all the other parameters values as same as they are stated in Example 1, then the optimal values of stock-out point t_1, cycle length T, ordered lot size Q and average profit ψ obtained from equation (4) are: $t_1^* = 11.7242 \cong 11.72$ weeks, $T^* = 12.1183 \cong 12.12$ weeks, $Q^* = 58981.9$ units and $\psi^* = \$156000$ (See Figure 3).

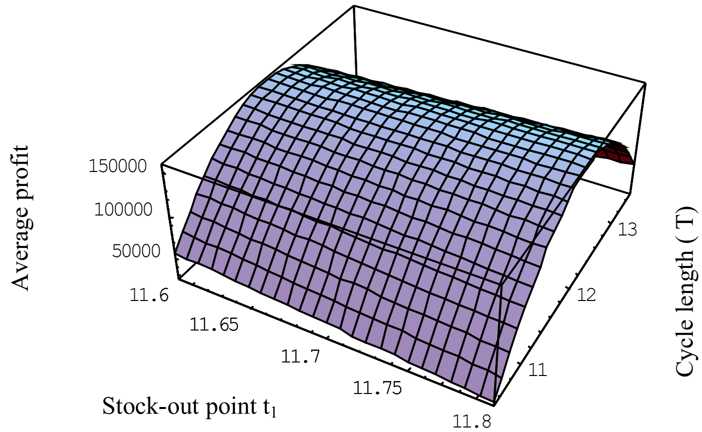

Figure 3. Graphical Representation of Average Profit Function Versus Stock-out Point (t_1) and Cycle Length (T) for Case - I

6.2 Case-II: Inflation without deterioration

In this subsection, $\alpha = 0$. Using $\alpha = 0$ in equation (4) when all the other parameters values of Example 1 remains same. Then the optimal solutions determined from equation (4) are $t_1^* = 7.67614 \cong 7.68$ weeks, $T^* = 8.27392 \cong 8.27$ weeks, $Q^* = 25206.2$ units and $\psi^* = \$132065$ (See Figure 4).

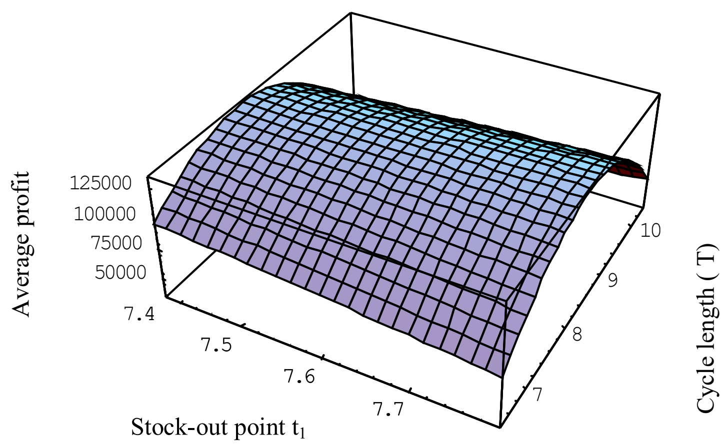

Figure 4. Graphical Representation of Average Profit Function Versus Stock-out Point (t_1) and Cycle Length (T) for Case - II

6.3 Case-III: Without deterioration and inflation

Here, $\alpha = 0$ and $= 0$. To get the optimal solutions for this case putting $\alpha = 0$ and $\delta = 0$ in equation (4) when all the other parameters values remain unaltered. Thus, the optimal solutions are: $t_1^* = 13.2286 \cong 13.23$ weeks, $T^* = 13.5484 \cong 13.55$ weeks, $Q^* = 65640.3$ units and $\psi^* = \$175066$ (See Figure 5).

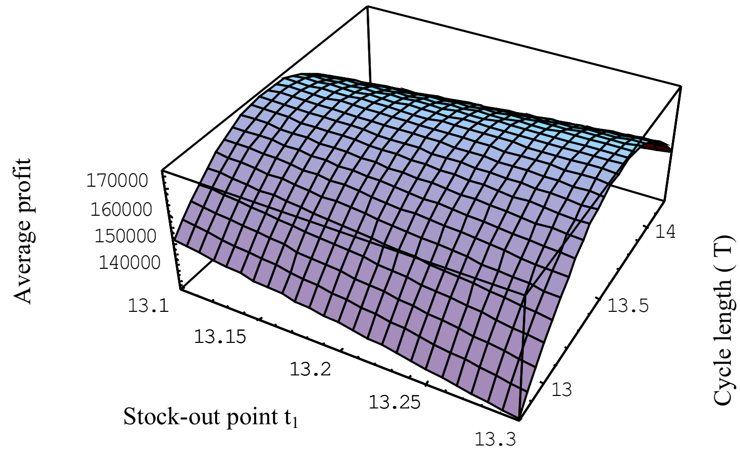

Figure 5. Graphical Representation of Average Profit Function Versus Stock-out point (t_1) and Cycle Length (T) for Case - III

7. Comparative study

In this section, a comparison has been made between the models mentioned in the above three cases with the present model. The percentage of increment or decrement in the optimal solutions in Case-I, Case-II and Case-III with respect to propose model are calculated and furnished in Table 1.

Table 1. Comparison Table

SPECIAL CASES	t_1^*(IN %)	T^*(IN %)	Q^*(IN %)	ψ^*(IN %)
CASE-I	+111.08	+88.59	+222.74	+26.59
CASE-II	+38.20	+28.76	+37.92	+7.17
CASE-III	+138.16	+110.85	+259.17	+42.06

From Table 1, it is observed that in all the three cases the optimal values of stock-out point (t_1^*), cycle length (T^*), ordered lot size (Q^*) and optimum average profit (ψ^*) increases as compared to the optimal values of t_1^*, T^*, Q^* and ψ^* of the present study. Also, it is noted that the increment in t_1^*, T^*, Q^* and ψ^* for Case III is higher than the other cases.

8. Conclusion and Further Research

In reality, demand, deterioration and shortage are not constant. They must vary with time. In this study, an EOQ model is framed for deteriorating items under the effect of inflation along with shortages in which demand, deterioration and shortage cost are assumed to be influenced by time. It is considered that demand is time dependent and quadratically increased, deterioration follows Weibull distribution and shortage cost is a non-linear function of time. Generally, researchers prefer constant shortage cost but here time dependent nonlinear shortages cost is taken because of two reasons. Firstly, the demand function is assumed to be increased qudratically so shortage cost will also increase proportionally. Secondly, stock-out for a long time causes financial loss as well as loss of goodwill. Therefore, assumption of non-linear shortage cost is more convenient.

Numerical example helps to establish the model and also helps to perform a comparison between the present model and the special cases. In comparative study, it is observed that the average profit is increased for all of the three cases but the increment is maximum for Case III i.e., the case of without deterioration and inflation and minimum for Case II i.e., the case which considered inflation without deterioration. Clearly, the effect of inflation is significantly high in any inventory system. Thus, inclusion of the effect of deterioration and inflation to develop the model is very much realistic in contemporary inventory studies.

This article has considered time dependent quadratic demand for single item. In future, it may be developed for other demand pattern and also for multiple items.

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