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An EOQ Model for Delayed Deteriorating Items with Linear Time Dependent Holding Cost and Backordering

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Abstract

An EOQ model for delayed deteriorating items with linear time dependent holding cost and backordering is considered in this paper. This is different from most inventory models that consider the holding cost to be constant. In this paper, permissible delay in payment is not considered rather the payment is made instantaneously. The optimal cycle length that gives the minimum total inventory cost was at the end determined and the maximum backorder level determined.

Keywords: Inventory, Delayed Deterioration, Backordering

1.0 Introduction

The determination of the optimal replenishment policy for an Inventory Economic Order Quantity (EOQ) model is achieved by considering several costs such as the ordering cost, inventory holding cost, cost of deteriorated items and so on. The decaying inventory model was first considered by Ghare and Shrader [1] who developed a model for exponential decaying inventory. Many extensions to the maiden model were developed over the years by researchers.

The first work on EOQ model with linear increasing demand was carried out by Donaldson [2]. Murdeshwar [3] developed an inventory replenishment policy model for linearly increasing demand with shortages. Goswami and Chaudhuri [4] constructed an EOQ model for inventory items with a linear trend in demand and finite replenishment considering shortages. Goh [5] developed a model on the generalized EOQ model for deteriorating items where the demand rate, deteriorating rate, holding cost and ordering cost are all assumed to be continuous functions of time. Giri et.al [6] constructed an EOQ model for deteriorating items with time varying demand and costs. Musa and Sani [7] constructed an inventory model of delayed deteriorating items under permissible delay in payments. Musa and Sani [8] developed an EOQ model for delayed deteriorating items with linear time dependent holding cost. Musa and Sani [9] constructed a model on the inventory of delayed deteriorating items where they developed in the model an alternative method for the determination of the best possible period to have the positive stock of the inventory and the best possible cycle length. Goyal [10] developed a heuristic for replenishment of trended Inventories considering shortages.

In this paper an inventory model for delayed deteriorating items with a linear time dependent holding cost and backordering is developed. The model is an extension of the paper developed by Musa and Sani [8]. The retailer in this situation does not allow for permissible delay in settling the replenishment account as in the case of some inventory deteriorating models. The customer is expected to pay for the items as soon as they are received in the inventory where the customer does allow for backordering. The items backordered are settled first when a new replenishment account is received.

2.0 Assumptions and Notation

The following notation and assumptions are considered in developing the mathematical model:

Assumptions

(i) Instantaneous Inventory replenishment (ii) Permissible delay in payment not allowed
(iii) Backordering allowed (iv) Lead time is zero

Notation

D_1 = The demand rate during the period before deterioration sets in

D_2 = The demand rate after deterioration sets in

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EOQ = Economic Order Quantity
T = The inventory cycle length
C = The unit cost of the item
T_1 = The time deterioration begins
T_2 = The length of time with positive stock of the item
T_3 = The length of time for which there is deterioration
A = The ordering cost per order
i = The inventory carrying charge
θ = The rate of deterioration
b_l = The maximum shortage (backorder) level permitted
C_b = The backorder cost per unit time
C_B = The total backorder cost per cycle
$N(d_t)$ = The number of items that deteriorate during the time T_3
q_1 = The quantity sold as at the time T_2
I_0 = The initial inventory
$I(t)$ = The inventory level at any time t before deterioration begins
I_d = The inventory level at the time deterioration begins
$I_d(t)$ = The inventory level at any time t after deterioration sets in
T_d = The total demand between T_1 and T_2
$C(D(T_2))$ = The cost of deteriorated items
$H(t)$ = The inventory holding cost, where $H(t)=\alpha_1+\alpha_2 t$
C_H = The total inventory holding cost in a cycle

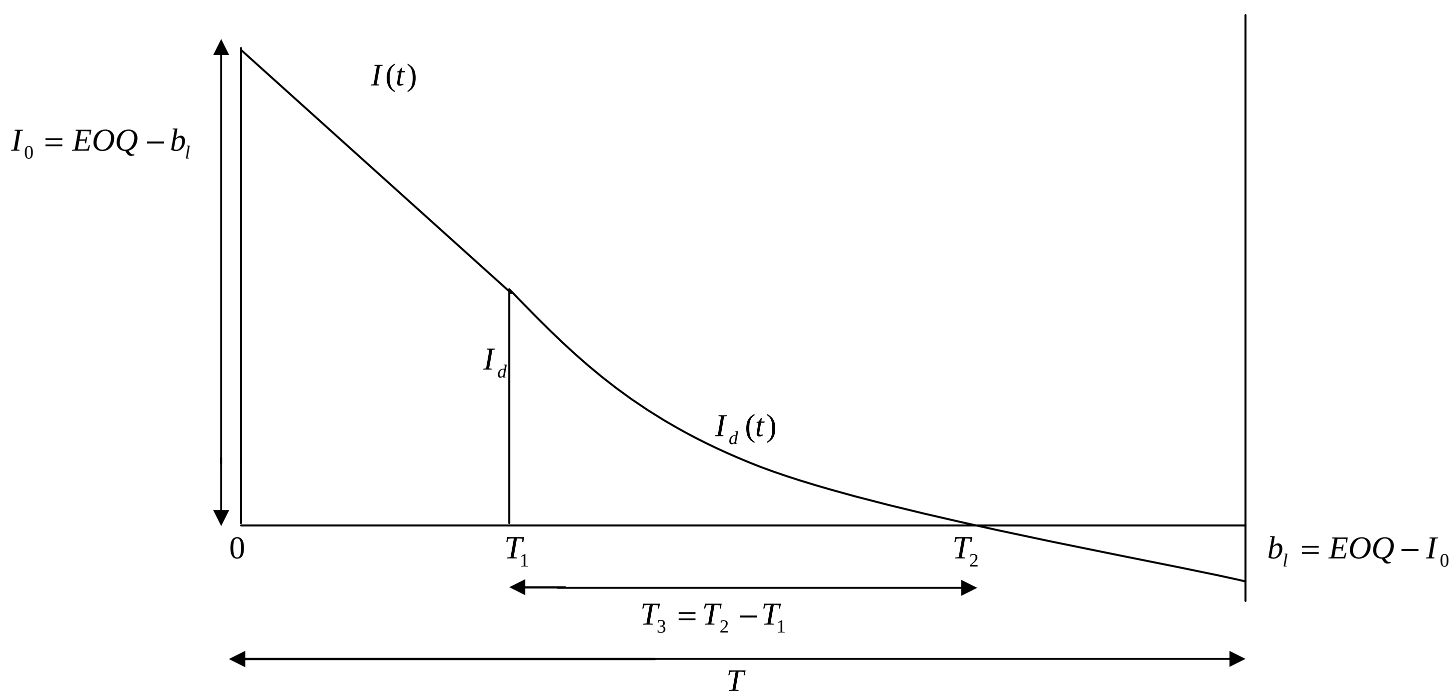

Figure I: Inventory depletion in a delayed deterioration situation with shortages

3.0 The Mathematical Model

The differential equation that represents the depletion of inventory due to demand only before deterioration sets in is given by:

$$\frac{dI(t)}{dt} = -D_1, \qquad 0 \le t \le T_1 \tag{1}$$

Separating the variables and solving equation (1) gives:

$$I(t) = -D_1 t + \lambda_1 \tag{2}$$

where λ_1 is an arbitrary constant. Now, at $t=0$, $I(t) = I_0$, equation (2) becomes $I_0 = \lambda_1$, so that from (2), we get:

$$I(t) = -D_1 t + I_0 \tag{3}$$

Also at $t=T_1$, $I(t) = I_d$, we obtain from equation (3)

$$I_0 = I_d + D_1 T_1 \tag{4}$$

Substituting equation (4) into equation (3), we have

$$I(t) = I_d + (T_1 - t)D_1 \tag{5}$$

The differential equation that represents the depletion of inventory after deterioration sets in which depends on both demand and deterioration is given by:

$$\frac{dI_d(t)}{dt} + \theta I_d(t) = -D_2, \qquad T_1 \le t \le T \tag{6}$$

The solution of equation (6) is given by:

$$I_d(t) = -\frac{D_2}{\theta} + \lambda_2 e^{-\theta t} \tag{7}$$

Where λ_2 is an arbitrary constant, applying the conditions at $t = T_1$, $I_d(t) = I_d$, we have from equation (7), $I_d = -\frac{D_2}{\theta} + \lambda_2 e^{-\theta T_1}$

$$\therefore \quad \lambda_2 = \left(I_d + \frac{D_2}{\theta} \right) e^{\theta T_1} \tag{8}$$

Substituting equation (8) into equation (7) gives,

$$I_d(t) = -\frac{D_2}{\theta} + \left(I_d e^{\theta T_1} + \frac{D_2}{\theta} e^{\theta T_1} \right) e^{-\theta t} = -\frac{D_2}{\theta} + \left(I_d + \frac{D_2}{\theta} \right) e^{(T_1 - t)\theta}$$

$$\therefore \quad I_d(t) = \frac{D_2}{\theta}\left(e^{(T_1-t)\theta} - 1\right) + I_d e^{(T_1-t)\theta} \tag{9}$$

Now at $t = T_2$ $I_d(t) = 0,$ equation (9) then becomes

$$I_d = \frac{-D_2}{\theta}\left(e^{(T_1-T_2)\theta-(T_1-T_2)\theta} - e^{(T_2-T_1)}\right) = \frac{-D_2}{\theta}\left(1 - e^{(T_2-T_1)\theta}\right) \tag{10}$$

Substituting equation (10) into (9) yields

$$I_d(t) = \frac{D_2}{\theta}\left(e^{(T_1-t)\theta} - 1\right) - \frac{D_2}{\theta}\left(1 - e^{(T_2-T_1)\theta}\right)e^{(T_1-t)\theta} = \frac{D_2}{\theta}\left(e^{(T_2-t)\theta} - 1\right) \tag{11}$$

Now, substituting equation (10) into (5) yields:

$$I(t) = -\frac{D_2}{\theta}\left(1 - e^{(T_2-T_1)\theta}\right) + (T_1 - t)D_1 \tag{12}$$

4.0 Computation of the Total Inventory Costs

The total inventory or variable cost is the sum of the inventory ordering cost, cost due to deterioration of inventory items, the total inventory carrying cost and the total backorder cost. The costs as computed individually before they are added together are given below:

(a) The inventory ordering cost is given as A

(b) To compute the cost due to deterioration of inventory, we take into cognizance that:

The total demand between T_1 and T_2 = the demand rate at the beginning of deterioration x the time period during which the item deteriorates. This is given as: $T_d = D_2 T_3 = D_2(T_2 - T_1)$

The number of items that deteriorate during the interval, $[T_1, T_2]$ is given as:

$$N(d_t) = I_d - D_2 T_3 = I_d - D_2(T_2 - T_1) \tag{13}$$

Substituting equation (10) into (13) to have

$$N(d_t) = -\frac{D_2}{\theta}(1 - e^{(T_2 - T_1)\theta}) - D_2(T_2 - T_1) = -\frac{D_2}{\theta}(1 - e^{(T_2 - T_1)\theta} + \theta(T_2 - T_1)) \tag{14}$$

and the total cost due to deterioration of inventory items is given as:

$$CN(d_t) = -\frac{CD_2}{\theta}(1 - e^{(T_2 - T_1)\theta} + \theta(T_2 - T_1)) \tag{15}$$

(c) **Inventory Carrying Cost (or Holding Cost)**

The total inventory carrying is given as:

$$C_H = i\int_0^{T_1} H(t)I(t)dt + i\int_{T_1}^{T_2} H(t)I_d(t)dt$$

$$= i\int_0^{T_1}(\alpha_1 + \alpha_2 t)\left(-\frac{D_2}{\theta}(1 - e^{(T_2 - T_1)\theta}) + (T_1 - t)D_1\right)dt + i\int_{T_1}^{T_2}(\alpha_1 + \alpha_2 t)\left(\frac{D_2}{\theta}(e^{(T_2 - t)\theta} - 1)\right)dt$$

$$= \frac{-iD_2\alpha_1}{\theta}\int_0^{T_1} dt + \frac{iD_2\alpha_1 e^{(T_2 - T_1)\theta}}{\theta}\int_0^{T_1} dt + iD_1\alpha_1 T_1\int_0^{T_1} dt - iD_1\alpha_1\int_0^{T_1} tdt - \frac{iD_2\alpha_2}{\theta}\int_0^{T_1} tdt + \frac{iD_2\alpha_2 e^{(T_2 - T_1)\theta}}{\theta}\int_0^{T_1} tdt$$

$$+ iD_1\alpha_2 T_1\int_0^{T_1} tdt - iD_1\alpha_2\int_0^{T_1} t^2 dt + \frac{iD_2\alpha_1}{\theta}\int_{T_1}^{T_2} e^{(T_2 - t)\theta}dt - \frac{iD_2\alpha_1}{\theta}\int_{T_1}^{T_2} dt + \frac{iD_2\alpha_2}{\theta}\int_{T_1}^{T_2} te^{(T_2 - t)\theta}dt - \frac{iD_2\alpha_2}{\theta}\int_{T_1}^{T} tdt$$

$$= \frac{-iD_2\alpha_1}{\theta}[t]_0^{T_1} + \frac{iD_2\alpha_1 e^{(T_2 - T_1)\theta}}{\theta}[t]_0^{T_1} + iD_1\alpha_1 T_1[t]_0^{T_1} - \frac{iD_1\alpha_1}{2}[t^2]_0^{T_1} - \frac{iD_2\alpha_2}{2\theta}[t^2]_0^{T_1} + \frac{iD_2\alpha_2 e^{(T_2 - T_1)\theta}}{2\theta}[t^2]_0^{T_1}$$

$$+ \frac{iD_1\alpha_2 T_1}{2}[t^2]_0^{T_1} - \frac{iD_1\alpha_2}{3}[t^3]_0^{T_1} - \frac{iD_2\alpha_1}{\theta^2}[e^{(T-t)\theta}]_{T_1}^{T_2} - \frac{iD_2\alpha_1}{\theta}[t]_{T_1}^{T_2} + \frac{iD_2\alpha_2}{\theta}\left\{-\frac{1}{\theta}[te^{(T-t)\theta}]_{T_1}^{T_2} - \frac{1}{\theta^2}[e^{(T-t)\theta}]_{T_1}^{T_2}\right\}$$

$$- \frac{iD_2\alpha_2}{2\theta}[t^2]_{T_1}^{T_2}$$

$$= \frac{-iD_2\alpha_1 T_1}{\theta} + \frac{iD_2\alpha_1 T_1 e^{(T_2 - T_1)\theta}}{\theta} + \frac{iD_1\alpha_1 T_1^2}{2} - \frac{iD_2\alpha_2 T_1^2}{2\theta} + \frac{iD_2\alpha_2 T_1^2 e^{(T_2 - T_1)\theta}}{2\theta}$$

$$+\frac{iD_1\alpha_2T_1^3}{2}-\frac{iD_1\alpha_2T_1^3}{3}-\frac{iD_2\alpha_1e^{(T-T_2)\theta}}{\theta^2}+\frac{iD_2\alpha_1e^{(T-T_1)\theta}}{\theta^2}-\frac{iD_2\alpha_1T_2}{\theta}+\frac{iD_2\alpha_1T_1}{\theta}$$
$$+\frac{iD_2\alpha_2}{\theta}\left\{\frac{-T_2e^{(T-T_2)\theta}}{\theta}+\frac{T_1e^{(T-T_1)\theta}}{\theta}-\frac{e^{(T-T_2)\theta}}{\theta^2}+\frac{e^{(T-T_1)\theta}}{\theta^2}\right\}-\frac{iD_2\alpha_2T_2^{\ 2}}{2\theta}+\frac{iD_2\alpha_2T_1^{\ 2}}{2\theta}$$
$$=\frac{iD_2\alpha_1T_1e^{(T_2-T_1)\theta}}{\theta}+\frac{iD_1\alpha_1T_1^{\ 2}}{2}+\frac{iD_2\alpha_2T_1^{\ 2}e^{(T_2-T_1)\theta}}{2\theta}-\frac{iD_2\alpha_1e^{(T-T_2)\theta}}{\theta^2}+\frac{iD_2\alpha_1e^{(T-T_1)\theta}}{\theta^2}-\frac{iD_2\alpha_1T_2}{\theta}$$
$$-\frac{iD_2\alpha_2T_2e^{(T-T_2)\theta}}{\theta^2}+\frac{iD_2\alpha_2T_1e^{(T-T_1)\theta}}{\theta^2}-\frac{iD_2\alpha_2e^{(T-T_2)\theta}}{\theta^3}+\frac{iD_2\alpha_2e^{(T-T_1)\theta}}{\theta^3}-\frac{i\alpha_2D_2T_2^2}{2\theta}$$

$$\therefore\ C_H=\left\{e^{(T_2-T_1)\theta}+\frac{D_1T_1\theta}{2D_2}+\frac{\alpha_2T_1e^{(T-T_1)\theta}}{2\alpha_1}-\frac{e^{(T-T_2)\theta}}{\theta T_1}+\frac{e^{(T-T_1)\theta}}{\theta T_1}-\frac{T_2}{T_1}-\frac{\alpha_2T_2e^{(T-T_2)\theta}}{\alpha_1T_1\theta}+\frac{\alpha_2e^{(T-T_2)\theta}}{\alpha_1\theta}\right.$$
$$\left.-\frac{\alpha_2e^{(T-T_2)\theta}}{\alpha_1T_1\theta^2}+\frac{\alpha_2e^{(T-T_1)\theta}}{\alpha_1T_1\theta^2}-\frac{\alpha_2T_2^{\ 2}}{2\alpha_1T_1}\right\}\frac{iD_2\alpha_1T_1}{\theta} \qquad (16)$$

(d) **Total backorder cost**

The total backorder cost per cycle is given as: $C_B=C_b\int_0^{T-T_2}D_2tdt=\frac{C_bD_2}{2}\left[t^2\right]_0^{T-T_2}=\frac{C_bD_2}{2}(T-T_2)^2$

The Total Variable (Inventory) cost per unit time T is given as

$TC(T)=\frac{1}{T}$ (Inventory ordering cost + Cost due to deterioration of inventory items

+ Total inventory holding cost +Total backorder cost)

$$\therefore\ TC(T)=\frac{1}{T}(A+CN(d_t)+C_H+C_b)$$
$$=\frac{A}{T}-\frac{CD_2}{\theta T}(1-e^{(T_2-T_1)\theta}+\theta(T_2-T_1))+\left\{e^{(T_2-T_1)\theta}+\frac{D_1T_1\theta}{2D_2}+\frac{\alpha_2T_1e^{(T_2-T_1)\theta}}{2\alpha_1}-\frac{e^{(T-T_2)\theta}}{\theta T_1}\right.$$
$$\left.+\frac{e^{(T-T_1)\theta}}{\theta T_1}-\frac{T_2}{T_1}-\frac{\alpha_2T_2e^{(T-T_2)\theta}}{\alpha_1T_1\theta}+\frac{\alpha_2e^{(T-T_1)\theta}}{\alpha_1\theta}-\frac{\alpha_2e^{(T-T_2)\theta}}{\alpha_1T_1\theta^2}+\frac{\alpha_2e^{(T-T_1)\theta}}{\alpha_1T_1\theta^2}-\frac{\alpha_2T_2^{\ 2}}{2\alpha_1T_1}\right\}\frac{iD_2\alpha_1T_1}{\theta T}$$
$$+\frac{C_bD_2}{2T}(T-T_2)^2 \qquad (17)$$

Equation (17) is differentiated to determine the value of T which minimizes the total variable cost per unit time as follows:

$$\frac{dTC(T)}{dT}=\frac{-A}{T^2}-\frac{CD_2}{\theta}\left\{-\frac{1}{T^2}+\frac{e^{(T_2-T_1)\theta}}{T^2}-\frac{\theta(T_2-T_1)}{T^2}\right\}+\left\{\frac{-e^{(T_2-T_1)\theta}}{T^2}-\frac{D_1T_1\theta}{2D_2T^2}-\frac{\alpha_2T_1e^{(T_2-T_1)\theta}}{2\alpha_1T^2}\right.$$
$$-\frac{(T\theta-1)e^{(T-T_2)\theta}}{\theta T_1T^2}+\frac{(T\theta-1)e^{(T-T_1)\theta}}{\theta T_1T^2}+\frac{T_2}{T_1T^2}-\frac{\alpha_2T_2(T\theta-1)e^{(T-T_2)\theta}}{\alpha_1T_1\theta T^2}+\frac{\alpha_2(T\theta-1)e^{(T-T_1)\theta}}{\alpha_1\theta T^2}$$
$$\left.-\frac{\alpha_2(T\theta-1)e^{(T-T_2)\theta}}{\alpha_1T_1\theta^2T^2}+\frac{\alpha_2(T\theta-1)e^{(T-T_1)\theta}}{\theta^2\alpha_1T_1T^2}+\frac{\alpha_2T_2^2}{2\alpha_1T_1T^2}\right\}\frac{iD_2\alpha_1T_1}{\theta}$$
$$+\frac{C_bD_2(2T(T-T_2)-(T-T_2)^2)}{2T^2}=0 \qquad (18)$$

Simplifying further and multiplying equation (18) through by T^2 yields:

$$-A-\frac{CD_2}{\theta}[-1+e^{(T_2-T_1)\theta}-\theta(T_2-T_1)]+\left\{-e^{(T_2-T_1)\theta}-\frac{D_1T_1\theta}{2D_2}-\frac{\alpha_2T_1e^{(T_2-T_1)\theta}}{2\alpha_1}-\frac{(T\theta-1)e^{(T-T_2)\theta}}{\theta T_1}\right.$$
$$+\frac{(T\theta-1)e^{(T-T_1)\theta}}{T_1\theta}+\frac{T_2}{T_1}-\frac{\alpha_2T_2(T\theta-1)e^{(T-T_2)\theta}}{\alpha_1T_1\theta}+\frac{\alpha_2(T\theta-1)e^{(T-T_1)\theta}}{\alpha_1\theta}-\frac{\alpha_2(T\theta-1)e^{(T-T_2)\theta}}{\alpha_1T_1\theta^2}$$
$$\left.+\frac{\alpha_2(T\theta-1)e^{(T-T_1)\theta}}{\alpha_1T_1\theta^2}-\frac{\alpha_2T_2^2}{2\alpha_1T_1}\right\}\frac{iD_2\alpha_1T_1}{\theta}+\frac{C_bD_2}{2}(T^2-T_2^2)=0 \qquad (19)$$

we can use equation (19) with other parameters provided to determine the best cycle length T which minimizes the total variable cost per unit time.

5.0 Computation of the Economic Order Quantity (EOQ)

The EOQ corresponding to the best cycle length T can be obtained thus:

$$EOQ = D_1T_1 + D_2T_3 + N(d_t) + b_l$$
$$= D_1T_1 + D_2(T_2-T_1) - \frac{D_2}{\theta}\left[(1-e^{(T_2-T_1)\theta}) + (T_2-T_1)\theta\right] + D_2(T-T_2)$$
$$= D_1T_1 - \frac{D_2}{\theta}(1-e^{(T_2-T_1)\theta}) + D_2(T-T_2) \qquad (20)$$

6.0 Numerical Examples

Table 1 gives the solutions of seven different numerical examples having different parameters where values used in the model developed by Musa and Sani [8] together with values of new parameters are used to show the application of the model and the effect of backordering. Table 2 represents the results obtained by Musa and Sani [8] and when the two tables are compared one can easily notice the increase in total variable (inventory) cost in the existing model as compared to the earlier model by Musa and Sani [8].

There is also a significant decrease in the Economic Order Quantity (EOQ) in the model with backordering as compared with the earlier model. On comparing the best inventory cycle from the two tables, one can see clearly, the sharp decrease of the cycle length in this paper as compared to the cycle length in Musa and Sani [8]. The reduction in the cycle length will give the customer the opportunity to replenish frequently since his cycle lengths are reduced and loosing no orders since requests in excess of available stock are always backordered. Based on the above listed advantages of the model developed in this paper, the customer stands to benefit more by adopting the model in this paper.

Table 1: Parameter values and the optimal cycle length, T for the inventory model with linear time dependent holding cost and backordering

S/N	A (N)	C	C_b	D_1 (Units)	D_2 (Units)	i	T_1	θ	α_1	α_2	T_2	T	$TC(T)$	EOQ (Units)	I_0	b_i
1	100	30	150	500	200	0.04	0.0384 (14 days)	0.60	0.02	8.00	0.0575 (21 days)	0.1014 (37 days)	1277.82	32	23	09
2	150	60	200	600	300	0.06	0.0575 (21 days)	0.50	1.00	6.00	0.0767 (28 days)	0.1068 (39 days)	1674.23	48	40	08
3	200	100	250	500	300	0.07	0.0767 (28 days)	0.30	-0.50	5.00	0.0959 (35 days)	0.1233 (45 days)	1863.35	51	44	07
4	300	80	300	700	400	0.08	0.0959 (35 days)	0.40	0.03	9.00	0.1151 (42 days)	0.1342 (49 days)	2416.55	83	75	08
5	500	150	350	1000	600	0.09	0.1151 (42 days)	0.20	-0.04	-11.00	0.1343 (49 days)	0.1507 (55) days	3524.58	137	127	10
6	700	250	400	1500	1000	0.11	0.1343 (49 days)	0.25	-0.05	6.00	0.1534 (56 days)	0.1644 (60 days)	3866.61	232	221	11
7	1000	200	450	3000	1500	0.14	0.1534 (56 days)	0.35	0.09	0.07	0.1726 (63 days)	0.1808 (66 days)	5766.58	501	489	12

Table 2: Parameter values and the optimal cycle length, T for the inventory model with linear time dependent holding cost

S/N	A (N)	C	β_1 (Units)	β_2 (Units)	i	T_1	θ	α_1	α_2	T	$TC(T)$	*EOQ* *(Units)*
1	100	30	500	200	0.04	0.0384(14 days)	0.60	0.02	8.00	0.2328 (85 days)	734.08	99
2	150	60	600	300	0.06	0.0575(21 days)	0.50	1.00	6.00	0.1918 (70 days)	1217.12	116
3	200	100	500	300	0.07	0.0767(28 days)	0.30	-0.50	5.00	0.2219 (81 days)	1334.76	126
4	300	80	700	400	0.08	0.0959(35 days)	0.40	0.03	9.00	0.2356 (86 days)	1816.49	181
5	500	150	1000	600	0.09	0.1151(42 days)	0.20	-0.04	-11.00	0.2521 (92) days	2856.62	285
6	700	250	1500	1000	0.11	0.1343(49 days)	0.25	-0.05	6.00	0.2027 (74 days)	4182.57	339
7	1000	200	3000	1500	0.14	0.1534(56 days)	0.35	0.09	0.07	0.2082 (76 days)	5567.06	626

7.0 Conclusion

In this paper, we present a mathematical model on the inventory of delayed deteriorating items with backordering. The model is built on the assumption that the holding cost for the inventory items is a linear time dependent function.

The model considers a situation where the customer is expected to pay for the items as soon as they are received in the inventory which means that the retailer's capital is not constrained.

The optimal cycle length *T* that gives the minimum total inventory or variable cost, the maximum backorder level allowed and the backorder cost were determined in each of the seven examples given in Table 1.

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