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Quadratic demand, Variable holding cost with Time Dependent Deterioration without Shortages and Salvage Value

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***Abstract**: In this paper, an attempt has been made to study deterministic inventory models for deteriorating items with variable holding cost. This model has been developed considering demand function as quadratic with respect to time and salvage value is associated to the deteriorated items. At the end numerical example with sensitivity analysis also presented.*
***Key Words**: Variable holding cost, Deterioration, Quadratic demand, Inventory*

I. Introduction

Researchers developed exponentially increasing/decreasing growth in demand for any commodity. This phenomenon is not realistic for any item. Also the rate of linear-time varying demand has some limitations, i.e., uniform change in demand rate per unit time. This is not quite frequent in any case of items/commodity in business. In general for realistic situation, addressing demand rate in quadratic demand pattern (Khanra and Chaudhuri, 2003) is quite worthy than exponential demand rate or linear demand rate.

Hariga (1995) studied an EOQ model with time-varying demand with shortages for deteriorating items. Chakraborti and Choudhuri (1996) proposed an EOQ model in linear trend in demand with shortages in all cycles for deteriorating products. Giri and Chaudhuri (1997) presented an EOQ model for deteriorating items of time varying demand and costs. Shortages are considered in the demand rate. Goyal and Giri (2001) studied survey of recent trend in deteriorating inventory models considering various types of demand rate. Mondal et. al (2003) developed price dependent demand rate of an inventory model for ameliorating items. Ajanta Roy (2008) proposed an inventory model with and without shortages of price dependent demand for deteriorating items incorporating time varying holding cost. Mishra and Singh (2010) studied an inventory model with partial backlogging of time dependent demand rate for deteriorating items. Sushil Kumar and U.S. Rajput (2013) studied an inflationary inventory model with constant demand considering Weibull rate of deterioration and partial backlogging under permissible delay in payments. R. Amutha and Dr.E. Chandrasekaran proposed an inventory model for constant demand with shortages under permissible delay in payments. In this model they incorporated deterioration rate with respect to time. Venkateswarlu and Mohan (2013a) studied an EOQ model for price dependent quadratic demand with time varying deterioration under salvage value for deteriorating items. Venkateswarlu and Mohan (2013b) studied an EOQ model with Weibull deterioration (2-Parameter), time dependent quadratic demand and salvage value for deteriorating items. Mohan and Venkateswarlu (2013a) studied an EOQ models with holding cost as function of time and salvage value. Mohan and Venkateswarlu (2013b) proposed an inventory model for, quadratic demand as a function of time with salvage value for deteriorating products considering deterioration rate is time dependent. Recently, Mohan and Venkateswarlu (2013c) proposed an EOQ model with Quadratic Demand, considering Holding Cost as function of time with Salvage value.

In this paper, inventory models have been developed using variable holding cost when the demand rate is a quadratic function of time with time-dependent deterioration. Shortages are not allowed and the time horizon is infinite. The optimal total cost (TC) is obtained by considering the salvage value for deteriorated items. Numerical example and sensitivity analysis is also carried out.

II. Assumptions And Notations

The following assumptions and notations are used to develop in this mathematical model:

The rate of demand D(t) at time *t* is assumed to be $D(t) = a + bt + ct^2$, $a \geq 0, b \neq 0, c \neq 0$.

(i) Replenishment rate is infinite.
(ii) $\theta(t) = \theta t$ is the deterioration rate, $0 < \theta < 1$.
(iii) C, the cost per unit
(iv) $(h + \beta t)$, $0 < \beta < 1$, the carrying cost per unit
(v) *A* is the order cost per unit order.
(vi) *I(t)* is the inventory level at time *t.*
(vii) Lead time is zero.

(viii) Q_1 ,order quantity in one cycle

(ix) The salvage value γC, $0 \le \gamma < 1$ is associated with deteriorated units during a cycle time.

III. Mathematical And Solution Of The Model

The differential equation which governs the inventory level at time *t* is given by

$$\frac{dQ(t)}{dt} + \theta t\, Q(t) = -(a + bt + ct^2), \quad 0 \le t \le T \tag{1}$$

with the initial condition $Q(0) = Q_1$ and $Q(T) = 0$.

Equation (1) is a linear first order differential equation which can be written as

$$\left(Q(t) e^{\frac{\theta t^2}{2}} \right)' = -(a + bt + ct^2) e^{\frac{\theta t^2}{2}}$$

which on integration yields

$$Q(t) = -e^{-\frac{\theta t^2}{2}} \int (a + bt + ct^2) e^{\frac{\theta t^2}{2}} dt + k_1 e^{\frac{-\theta t^2}{2}}$$

where k_1 is an integral constant.

Using initial conditions and expanding $e^{\frac{\theta t^2}{2}}$ by omitting the higher order terms involving θ (not more than 2nd power terms), the solution of the above equation is obtained as

$$Q(t) = \begin{cases} \left\{ a\,(T-t) + \frac{b(T^2 - t^2)}{2} + \frac{c(T^3 - t^3)}{3} \right\} \\ + \theta \left\{ \frac{a\,(T^3 - t^3)}{6} + \frac{b\,(T^4 - t^4)}{8} + \frac{c\,(T^5 - t^5)}{10} \right\} \\ + \theta^2 \left\{ \frac{a\,(T^5 - t^5)}{40} + \frac{b\,(T^6 - t^6)}{48} + \frac{c\,(T^7 - t^7)}{56} \right\} \\ - \theta \left(\frac{a\,(t^2 T - t^3)}{2} + \frac{b\,(t^2 T^2 - t^4)}{4} + \frac{c\,(t^2 T^3 - t^5)}{6} \right) \\ - \theta^2 \left(\frac{a}{12}(T^3 t^2 - t^5) + \frac{b}{16}(T^4 t^2 - t^6) + \frac{c}{20}(T^5 t^2 - t^7) \right) \\ + \theta^2 \left(\frac{a}{8}(t^4 T - t^5) + \frac{b}{16}(T^2 t^4 - t^6) + \frac{c}{24}(T^3 t^4 - t^7) \right) \end{cases} \tag{2}$$

Using $Q(0) = Q_1$, we obtain

$$Q_1 = \left[aT + \frac{bT^2}{2} + \frac{cT^3}{3} + \theta \left(\frac{aT^3}{6} + \frac{bT^4}{8} + \frac{cT^5}{10} \right) + \theta^2 \left(\frac{aT^5}{40} + \frac{bT^6}{48} + \frac{cT^7}{56} \right) \right] \tag{3}$$

IV. Inventory Models Without Shortages

The following costs are taken for consideration to calculate total cost of the system:

Ordering cost = A

Material cost per cycle

(Including Deterioration Loss) = $Q(0)C = Q_1 C$ (4)

Carrying cost/holding cost per cycle = $(h + \beta t) \int_0^T Q(t)\, dt$ (5)

Total Cost = Carrying cost + Ordering cost + Material cost

$$= \frac{A}{T} + \frac{CQ(0)}{T} + \frac{(h+\beta t)}{T}\int_0^T Q(t)dt \tag{6}$$

$$= \left\{ \begin{array}{l} \dfrac{A}{T} + C\left[\begin{array}{l} a + \dfrac{bT}{2} + \dfrac{cT^2}{3} + \theta\left(\dfrac{aT^2}{6} + \dfrac{bT^3}{8} + \dfrac{cT^4}{10}\right) + \\ \theta^2\left(\dfrac{aT^4}{40} + \dfrac{bT^5}{48} + \dfrac{cT^6}{56}\right) \end{array}\right] + \\ \\ (h+\beta t)\left[\begin{array}{l} \dfrac{aT}{2} + \dfrac{bT^2}{3} + \dfrac{cT^3}{4} + \theta\left(\dfrac{aT^3}{12} + \dfrac{2bT^4}{3} + \dfrac{7cT^5}{96}\right) + \\ \theta^2\left(0.0111aT^5 + 0.00952bT^6 + 0.0083cT^7\right) \end{array}\right] \end{array} \right.$$

The necessary condition for minimizing the total cost is $\dfrac{\partial(TC)}{\partial T} = 0$, i.e.,

$$\frac{\partial(TC)}{\partial T} = \left\{ \begin{array}{l} \dfrac{-A}{T^2} + C\left[\begin{array}{l} \dfrac{b}{2} + \dfrac{2cT}{3} + \theta\left(\dfrac{aT}{3} + \dfrac{3bT^2}{8} + \dfrac{2cT^3}{5}\right) \\ + \theta^2\left(\dfrac{aT^3}{10} + \dfrac{5bT^4}{48} + \dfrac{6cT^5}{56}\right) \end{array}\right] \\ \\ +(h+\beta t)\left[\begin{array}{l} \dfrac{a}{2} + \dfrac{2bT}{3} + \dfrac{3cT^2}{4} + \theta\left(\dfrac{aT^2}{4} + \dfrac{8bT^3}{3} + \dfrac{35cT^4}{96}\right) \\ + \theta^2\left(0.0111*5*aT^4 + 0.0092*6*bT^5 + 0.0083*7*cT^6\right) \end{array}\right] \end{array} \right\} = 0$$

(7)

Using MATHCAD the optimal value of T and the total cost (TC) is obtained from equation (7)

The following numerical example is taken to verify the sufficient condition i.e., $\frac{\partial^2 (TC)}{\partial T^2} > 0$. It is found that the optimality conditions are satisfied for all T in all the four cases viz.,

(i) $c > 0$ and $b > 0$ gives accelerated growth in demand model (M-1)

(i) $c > 0$ and $b < 0$ gives retarded growth in demand model (M-2)

(iii) $c < 0$ and $b > 0$, gives retarded decline in demand model (M-3)

(iv) $c < 0$ and $b < 0$, gives accelerated decline in demand model (M-4)

4.1 Numerical Example

We now consider an inventory system with the following hypothetical values for the parameters:

c = 4, b = 20, a = 500, h = 0.6

A = 150, C= 3, θ = 0.01, β = 0.3

The following tables indicate the MATHCAD output to compare our models with linear demand patterns:

Model-I: (a > 0, b > 0 and c > 0)

Table.1:

Model Type	T	TC	Q
Quad. Demand	0.79	1855.286	402.321
Linear Demand	0.801	1852.398 407.355	

Model-II: (a > 0, b > 0 and c < 0)

Table.2:

Model Type	T	TC	Q
Quad. Demand	0.814	1849.416	413.366
Linear Demand	0.801	1852.398	407.355

Model-III: (a > 0, b < 0 and c > 0)

Table.3:

Model Type	T	TC	Q
Quad. Demand	0.932	1797.017	459.053
Linear Demand	0.955	1792.847	469.086

Model-IV: (a > 0, b < 0 and c < 0)

Table.4:

Model Type	T	TC	Q
Quad. Demand	0.982	1788.434	480.857
Linear Demand	0.955	1792.847	469.086

Considering Model II and Model IV of these models the conditions of optimality is being satisfied. Hence we take Model II and Model IV for further discussions. The total cost (TC) of these two models is reduced when comparing with linear demand models and quadratic time dependent demand models. In comparison with linear models the lot size and re-order time are more .Thus we conclude that the re-orders become not so frequent and economic lot size will be higher and in both case (i.e., retarded growth and accelerated decline models.)

4.2 Sensitivity Analysis

We will analyze the cycle time (T), total cost (TC) and EOQ (Q) by changing the values of the parameters a, b, c, C, A , θ and altogether from 20% to 50% and -20% to -50% of model- II and model- IV.

The observations are as follows from table 5:

(i) TC and Q both decreases (increases) while T increases (decreases) with the decrease (increase) in the parameter values of ‘a’.

(ii) T and Q increase (decrease) when TC decreases (increases) with the decrease (increase) in the parameter values of ‘b’

(iii) T and Q decrease (increase) where as TC increases (decreases) with the decrease (increase) in the parameter ‘c’, In the above three cases the sensitivity is very marginal.

(iv) TC decrease (increases) while T and Q increases (decreases) when the parameter ‘C’ decrease (increase). The sensitivity is substantial in this case.

(v) All the three values T, TC and Q decreases(increases) with the

Decrease (increase) in the values of ‘A’. In this case the sensitivity rate considered to be high.

(vi) Decrease (increase) in the parameter θ, TC decreases (increases) and T and Q increase (decrease). In this case sensitivity is very negligible.

It is observed from table-6, the values of total cost (TC), cycle time T, and EOQ (Q) in accelerated decline model also noticed similar changes as earlier retarded growth model when all the parameters are decreased or increased.

It is also observed that the unit cost C of the commodity towards total cost (TC) is highly sensitive.

Finally the study of sensitivity analysis of both models exhibit similar behavior when the changes made in the parameter values of *a*, *c*, *A*, *C* and θ except for the parameter *b*.

Table.5: Model - II: (a > 0, b > 0 and c < 0)

Table.6: Model - IV (a > 0, b < 0 and c < 0)*

parameter	% change	T TC	Q		T	TC	Q	
a	-50	1.051	1018.839	272.758		1.687	924.726	388.639
	-20	0.887	1519.92	362.216		1.13	1450.695	438.223
	20	0.757	2176.391	459.793		0.883	2121.189	521.757
	50	0.692	2663.293	523.766		0.781	2614.269	579.601
b	-50	0.847	1835.33	426.788		0.929	1804.976	459.773
	-20	0.827	1843.858	418.697		0.96	1795.178	472.166
	20	0.802	1854.879	408.472		1.006	1781.501	490.313
	50	0.785	1862.905	401.515		1.046	1770.711	505.968
c	-50	0.808	1850.92	410.627		0.968	1790.674	474.758
	-20	0.811	1850.021	411.963		0.976	1789.338	478.233
	20	0.817	1848.808	414.767		0.988	1787.518	483.472
	50	0.821	1847.887	416.604		0.997	1786.121	487.374
C	-50	0.837	1087.527	425.224		0.938	1053.553	459.768
	-20	0.823	1544.699	418.005		0.964	1494.57	472.235
	20	0.805	2154.084	408.729		1.002	2082.172	490.429
	50	0.792	2610.995	402.033		1.033	2522.526	505.246
A	-50	0.593	1743.025	299.915		0.716	1700.277	352.683
	-20	0.736	1810.705	373.224		0.888	1756.351	435.747
	20	0.883	1884.758	448.966		1.066	1817.723	520.995
	50	0.976 1933.147	497.081		1.178	1857.815	574.251	
θ	-50	0.819	1848.395	415.709		0.992	1786.997	485.251
	-20	0.816	1849.01	414.304		0.986	1787.862	482.618
	20	0.812	1849.821	412.427		0.978	1789	479.093
	50	0.809	1850.425	411.016		0.973	1789.842	476.919

*In table 6, the cycle time (T), Total Cost (TC) and Ordering quantity (Q) is calculated for the same parameter and percentage as considered in table 5

V. Inventory Models With Salvage

The number of deteriorated units (*NDU*) during this cycle time is

$$NDU = Q - \int_0^T D(t)dt, \text{ where } D(t)=(a+bt+ct^2) \qquad (8)$$

Total Cost (TC) = Inventory Holding cost+ Ordering cost + Cost due to deterioration –Salvage value

$$TC = \frac{(h+\beta t)}{T}\int_0^T I(t)dt + \frac{A}{T} + \frac{C}{T}\left[Q - (aT + \frac{bT^2}{2} + \frac{cT^3}{3})\right] - \frac{\gamma * C}{T}\left[Q - (aT + \frac{bT^2}{2} + \frac{cT^3}{3})\right]$$

$$= (h+\beta)\begin{pmatrix} \frac{aT}{2}+\frac{bT^2}{3}+\frac{cT^3}{4}+\theta\left(\frac{aT^2}{12}+\frac{bT^3}{3}+\frac{cT^4}{96}\right) \\ +\theta(0.1aT+0.05bT^2+0.03cT^3) \end{pmatrix} + \frac{A}{T}$$

$$+(1-\gamma)*C\left(a+\frac{bT}{2}+\frac{cT^2}{3}\right)+\theta\left(\frac{aT}{6}+\frac{bT^2}{8}+\frac{cT^3}{10}\right)+\theta\left(\frac{aT^3}{40}+\frac{bT^4}{48}+\frac{cT^5}{56}\right)-\left(a+\frac{bT}{2}+\frac{cT^2}{3}\right) \qquad (9)$$

The necessary condition for a minimum total cost per unit time is $\dfrac{\partial(TC)}{\partial T}=0$

$$=\left\{\begin{array}{l} +(h+\beta t)\left[\begin{array}{l}\dfrac{a}{2}+\dfrac{2bT}{3}+\dfrac{3cT^2}{4}+\theta\left(\dfrac{aT^2}{4}+\dfrac{8bT^3}{3}+\dfrac{35cT^4}{96}\right)\\ +\theta^2\left(0.0111*5*aT^4+0.0092*6*bT^5+0.0083*7*cT^6\right)\end{array}\right]+\dfrac{-A}{T^2}\\ +(1-\gamma)*C\left[\dfrac{b}{2}+\dfrac{2cT}{3}+\theta\left(\dfrac{aT}{3}+\dfrac{3bT^2}{8}+\dfrac{2cT^3}{5}\right)+\theta^2\left(\dfrac{aT^3}{10}+\dfrac{5bT^4}{48}+\dfrac{6cT^5}{56}\right)-\left(\dfrac{b}{2}+\dfrac{2cT}{3}\right)\right]\end{array}\right\}=0 \tag{10}$$

Provided $\dfrac{\partial^2(TC)}{\partial T^2}>0$ i.e.,

$$\frac{\partial^2(TC)}{\partial T^2}=\left\{\begin{array}{l} (h+\beta t)\left[\begin{array}{l}\dfrac{2b}{3}+\dfrac{3cT}{2}+\theta\left(\dfrac{aT}{2}+8bT^2+\dfrac{35*4cT^3}{96}\right)\\ +\theta^2\left(0.0111*20*aT^3+0.0092*30*bT^4+0.0083*42*cT^5\right)\end{array}\right]+\dfrac{2A}{T^3}\\ +(1-\gamma)C\left[\dfrac{2c}{3}+\theta\left(\dfrac{a}{3}+\dfrac{3bT}{4}+\dfrac{6cT^2}{5}\right)+\theta^2\left(\dfrac{3aT^2}{10}+\dfrac{20bT^3}{48}+\dfrac{30cT^4}{56}\right)-\dfrac{2c}{3}\right]\end{array}\right. \tag{11}$$

We solved the above two equations for a minimum of TC using MATHCAD. The optimum values of the total cost, re-order time, and lot size are calculated with a numerical example and are shown in the following tables:

5.1. Numerical example

To illustrate the model developed, we have taken the following data:

$a = 500$, $b = 20$, $c = 4$, $\gamma = 0.1$

$A = 150$, $C = 3$, $\theta = 0.01$, $i = 0.2$

Model-I: ($a > 0$, $b > 0$ and $c > 0$)

Table.7:

Model Type	T	TC	Q	NDU
Quad. Demand	0.849	327.882	433.049	0.525
Linear Demand	0.852	327.443	433.788	0.529

Model -II: ($a > 0$, $b < 0$ and $c > 0$)

Table.8:

Model Type	T	TC	Q	NDU
Quad. Demand	0.883	320.737	435.182	0.561
Linear Demand	0.887	320.24	436.199	0.567

Model -III: ($a > 0$, $b > 0$ and $c < 0$)

Table.9:

Model Type	T	TC	Q	NDU
Quad. Demand	0.855	327.001	434.51	0.533
Linear Demand	0.852	327.443	433.788	0.529

Model -IV: ($a > 0$, $b < 0$ and $c < 0$)

Table.10:

Model Type	T	TC	Q	NDU
Quad. Demand	0.891	319.736	437.19	0.572
Linear Demand	0.887	320.24	436.199	0.567

Model-III and Model-IV from above tables 7-10 it is clear they behave alike. Also it is observed that the changes are very small in both cases. Hence the sensitivity of model-IV is taken for consideration in the following sensitivity Analysis:

5.2. Sensitivity Analysis

MODEL IV ($a > 0$, $b < 0$ and $c < 0$)

Table.11: Sensitivity of the Salvage parameter γ

	T	TC	Q	NDU
$\gamma = 0.1$	0.891	319.736	437.19	0.572
$\gamma = 0.15$	0.891	319.736	437.19	0.572
$\gamma = 0.2$	0.892	319.543	437.671	0.574
$\gamma = 0.25$	0.892	319.543	437.671	0.574
$\gamma = 0.3$	0.892	319.543	437.671	0.574

Table.12: Sensitivity of the parameter θ

	T	TC	Q	NDU
$\theta = 0.01$	0.891	319.736	437.19	0.572
$\theta = 0.05$	0.851	327.721	419.943	2.507
$\theta = 0.1$	0.811	336.792	402.577	4.365
$\theta = 0.15$	0.779	345.092	388.633	5.832
$\theta = 0.2$	0.752	352.788	376.803	7.025

Table.13: Sensitivity of the parameter θ and γ

		T	TC	Q	NDU
$\theta = 0.01$	$\gamma = 0.1$	0.891	319.736	437.19	0.572
$\theta = 0.05$	$\gamma = 0.15$	0.852	327.279	420.432	2.516
0.79341.6743 94.1846.082 $\theta = 0.1$	$\gamma = 0.2$	0.817	335.165	405.561	4.463
$\theta = 0.2\gamma = 0.25$ $\theta = 0.15$	$\gamma = 0.3$	0.77	347.048	386.005	7.543

VI. Discussion

Special Case: In both cases as proposed without shortages and Salvage value in this paper When $\beta = 0$ i.e., when holding cost is constant the derived model reduces to that of R. Mohan and R. Venkateswarlu, (2014) *J.of the Indian math. Soc*. Vol 81, Nos 1-2 (2014), 135-146. Hence this model reflects extensive work on variable holding cost as mentioned above.

VII. Conclusions

The deterministic inventory models are studied for total cost(TC),cycle time T and economic purchase quantity(Q) for time dependent deterioration rate, time dependent holding cost and time dependent quadratic demand when shortages are not allowed. Here the salvage value is associated to number of deteriorated units during cycle time.

VIII. Scope For Further Research:

This study can consider further research using price dependent demand, Weibull rate of deterioration, constant deterioration, and linear demand rate and permissible delay in payments.

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