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

R. Mohan
Dept. of Mathematics College of Military Engineering Pune-31-Maharastra -INDIA

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.


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.
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(viii) \( Q_i \), order quantity in one cycle
(ix) The salvage value \( \gamma C \), \( 0 \leq \gamma < 1 \) 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

\[
\frac{dQ(t)}{dt} + \theta t \ Q(t) = -(a + bt + c t^2), \quad 0 \leq t \leq T
\]  

(1)

with the initial condition \( Q(0) = Q_i \) and \( Q(T) = 0 \).

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

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

which on integration yields

\[
Q(t) = -e^{\frac{\theta t}{2}} \int (a + bt + c t^2) e^{\frac{\theta t}{2}} \ dt + k_i \ e^{\frac{-\theta t}{2}}
\]

where \( k_i \) is an integral constant.

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

\[
Q(t) = \left \{ \begin{align*}
\frac{a \ (T-t)}{2} + \frac{b(T^2-t^2)}{2} + \frac{c(T^3-t^3)}{3} \\
+ \theta \left \{ \frac{a \ (T^3-t^3)}{6} + \frac{b \ (T^4-t^4)}{8} + \frac{c \ (T^5-t^5)}{10} \right \} \\
+ \theta^2 \left \{ \frac{a \ (T^3-t^3)}{40} + \frac{b \ (T^4-t^4)}{48} + \frac{c \ (T^5-t^5)}{56} \right \} \\
- \theta \left \{ \frac{a \ (t^2T-t^2)}{2} + \frac{b \ (t^2T^2-t^2)}{4} + \frac{c \ (t^2T^3-t^3)}{6} \right \} \\
- \theta^2 \left \{ \frac{a \ (T^2T-t^2)}{12} + \frac{b \ (T^3T-t^3)}{16} + \frac{c \ (T^4T-t^4)}{20} \right \} \\
+ \theta^2 \left \{ \frac{a \ (T^2T-t^2)}{8} + \frac{b \ (T^3T-t^3)}{16} + \frac{c \ (T^4T-t^4)}{24} \right \}
\end{align*} \right \}
\]

(2)

Using \( Q(0) = Q_i \), we obtain

\[
Q_i = \left [ aT + \frac{bt^2}{2} + \frac{ct^3}{3} + \theta \left \{ \frac{aT^3}{6} + \frac{bT^4}{8} + \frac{cT^5}{10} \right \} + \theta^2 \left \{ \frac{aT^3}{40} + \frac{bT^4}{48} + \frac{cT^5}{56} \right \} \right ]
\]

(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) = \( Q(0)C = QC \) \hspace{1cm} (4)

Carrying cost/holding cost per cycle = \( (h + \beta t) \int_{0}^{T} Q(t) \ dt \) \hspace{1cm} (5)

Total Cost = Carrying cost + Ordering cost + Material cost

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\[
\frac{A}{T} + \frac{CQ(0)}{T} + \frac{(h + \beta T)^z}{T} \int_0^T Q(t) dt
\]

(6)

\[
\frac{A}{T} + C + \left[ \frac{bT^2}{2} + \frac{cT^3}{3} + \theta \left( \frac{aT^4}{6} + \frac{bT^4}{8} + \frac{cT^4}{10} \right) \right] +
\]

\[
\theta \left( \frac{aT^5}{40} + \frac{bT^5}{48} + \frac{cT^5}{56} \right)
\]

\[
= \left\{ \frac{aT^2}{2} + \frac{bT^3}{3} + \frac{cT^4}{4} + \theta \left( \frac{aT^5}{12} + \frac{2bT^5}{3} + \frac{7cT^5}{96} \right) \right\} +
\]

\[
\theta \left( 0.0111aT^3 + 0.00952bT^3 + 0.0083cT^3 \right)
\]

The necessary condition for minimizing the total cost is 

\[
\frac{\partial(TC)}{\partial T} = 0 \text{, i.e.,}
\]

\[
\left\{ \frac{b}{2} + \frac{2cT^3}{3} + \theta \left( \frac{aT^4}{3} + \frac{3bT^4}{8} + \frac{2cT^4}{5} \right) \right\} +
\]

\[
- \frac{A}{T} + C + \left[ \frac{aT^4}{10} + \frac{5bT^4}{48} + \frac{6cT^4}{56} \right] +
\]

\[
\theta \left( \frac{aT^5}{10} + \frac{5bT^5}{48} + \frac{6cT^5}{56} \right)
\]

\[
= 0
\]

\[
\left\{ \frac{a}{2} + \frac{2bT^4}{3} + \frac{3cT^5}{4} + \theta \left( \frac{aT^6}{4} + \frac{8bT^6}{3} + \frac{35cT^6}{96} \right) \right\} +
\]

\[
(h + \beta T) + \theta \left( 0.0111aT^4 + 0.00952bT^4 + 0.0083cT^4 \right)
\]

(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)
(ii) $c > 0$ 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:

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

$A = 150, C= 3, \theta = 0.01, \beta = 0.3$

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>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.79</td>
<td>1855.286</td>
<td>402.321</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.801</td>
<td>1852.398</td>
<td>407.355</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.814</td>
<td>1849.416</td>
<td>413.366</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.801</td>
<td>1852.398</td>
<td>407.355</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.932</td>
<td>1797.017</td>
<td>459.053</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.955</td>
<td>1792.847</td>
<td>469.086</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.982</td>
<td>1788.434</td>
<td>480.857</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.955</td>
<td>1792.847</td>
<td>469.086</td>
</tr>
</tbody>
</table>

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 $a, b, c, C, A, \theta$ 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 $\theta$, 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 $\theta$ except for the parameter $b$.

<table>
<thead>
<tr>
<th>parameter</th>
<th>% change</th>
<th>T</th>
<th>TC</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>-50</td>
<td>1.051</td>
<td>1018.839</td>
<td>272.758</td>
<td>1.687</td>
<td>924.726</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.887</td>
<td>1519.92</td>
<td>362.216</td>
<td>1.13</td>
<td>1450.695</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.692</td>
<td>2663.293</td>
<td>523.766</td>
<td>0.781</td>
<td>2614.269</td>
</tr>
<tr>
<td>$b$</td>
<td>-50</td>
<td>0.847</td>
<td>1835.33</td>
<td>426.788</td>
<td>0.929</td>
<td>1804.976</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.827</td>
<td>1843.858</td>
<td>418.697</td>
<td>0.96</td>
<td>1795.178</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.785</td>
<td>1862.905</td>
<td>401.515</td>
<td>0.883</td>
<td>1787.5</td>
</tr>
<tr>
<td>$c$</td>
<td>-50</td>
<td>0.808</td>
<td>1850.92</td>
<td>410.627</td>
<td>0.968</td>
<td>1790.674</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.811</td>
<td>1850.021</td>
<td>411.963</td>
<td>0.976</td>
<td>1789.338</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.821</td>
<td>1847.887</td>
<td>414.767</td>
<td>0.988</td>
<td>1787.18</td>
</tr>
<tr>
<td>$A$</td>
<td>-50</td>
<td>0.593</td>
<td>1743.025</td>
<td>299.915</td>
<td>0.716</td>
<td>1700.277</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.736</td>
<td>1810.705</td>
<td>373.224</td>
<td>0.888</td>
<td>1756.351</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.883</td>
<td>1884.758</td>
<td>448.966</td>
<td>1.006</td>
<td>1817.723</td>
</tr>
<tr>
<td>$\theta$</td>
<td>-50</td>
<td>0.819</td>
<td>1848.395</td>
<td>415.709</td>
<td>0.992</td>
<td>1786.997</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.816</td>
<td>1849.01</td>
<td>414.304</td>
<td>0.986</td>
<td>1787.862</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.809</td>
<td>1850.425</td>
<td>412.427</td>
<td>0.978</td>
<td>1789</td>
</tr>
</tbody>
</table>

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

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

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

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

$$= \left( a T B + \frac{bT^2}{2} + \frac{cT^3}{3} \right) \left( \left( \frac{a T B + \frac{bT^2}{2} + \frac{cT^3}{3}}{T} \right) \right)$$

$$= \left( \frac{a T B}{T} + \frac{bT^2}{2T} + \frac{cT^3}{3T} \right)$$

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

\[
\begin{align*}
&= \left\{ \frac{a}{2} + \frac{2bT}{3} + \frac{3cT^2}{4} + \theta \left( \frac{aT^2}{4} + \frac{8bT^3}{3} + \frac{35cT^4}{96} \right) \\
&+ (h + \beta) \\
&+ \theta^2 \left( 0.0111 \times 5 \times aT^4 + 0.0092 \times 6 \times bT^5 + 0.0083 \times 7 \times cT^6 \right) \right\} \\
&+ \left( 1 - \gamma \right) C \left\{ \frac{b}{2} + \frac{2cT}{3} + \theta \left( \frac{aT}{3} + \frac{3bT^2}{8} + \frac{2cT^3}{5} \right) + \theta^2 \left( \frac{aT^3}{10} + \frac{5bT^4}{48} + \frac{6cT^5}{56} \right) \right\} = 0
\end{align*}
\]

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

\[
\frac{\partial^2 (TC)}{\partial T^2} = \left\{ \frac{2b}{3} + \frac{3cT}{2} + \theta \left( \frac{aT}{2} + \frac{8bT^2}{2} + \frac{35cT^3}{96} \right) \right\} + \left( h + \beta \right) + 2A \left( \frac{aT}{2} + \frac{8bT^2}{2} + \frac{35cT^3}{96} \right) \left( \frac{aT}{2} + \frac{8bT^2}{2} + \frac{35cT^3}{96} \right) \]

\[
\left( \frac{2b}{3} + \frac{3cT}{2} + \theta \left( \frac{aT}{2} + \frac{8bT^2}{2} + \frac{35cT^3}{96} \right) \right) + \theta^2 \left( 0.0111 \times 5 \times aT^4 + 0.0092 \times 6 \times bT^5 + 0.0083 \times 7 \times cT^6 \right) + \left( 1 - \gamma \right) C \left\{ \frac{2c}{3} + \theta \left( \frac{3aT^2}{4} + \frac{6cT^3}{5} \right) + \theta^2 \left( \frac{3aT^2}{10} + \frac{20bT^3}{48} + \frac{30cT^4}{56} \right) \right\} = 0
\]

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:

\[ \begin{align*}
a &= 500, & b &= 20, & c &= 4, & \gamma &= 0.1, \\
A &= 150, & C &= 3, & \theta &= 0.01, & i &= 0.2
\end{align*} \]

Model-I: \( (a > 0, b > 0 \text{ and } c > 0) \)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
<th>NDU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.849</td>
<td>327.882</td>
<td>433.049</td>
<td>0.525</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.852</td>
<td>327.443</td>
<td>433.788</td>
<td>0.529</td>
</tr>
</tbody>
</table>

Model -II: \( (a > 0, b < 0 \text{ and } c > 0) \)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
<th>NDU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.883</td>
<td>320.737</td>
<td>435.182</td>
<td>0.561</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.887</td>
<td>320.24</td>
<td>436.199</td>
<td>0.567</td>
</tr>
</tbody>
</table>

Model -III: \( (a > 0, b > 0 \text{ and } c < 0) \)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
<th>NDU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.855</td>
<td>319.736</td>
<td>434.51</td>
<td>0.533</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.852</td>
<td>327.443</td>
<td>433.788</td>
<td>0.529</td>
</tr>
</tbody>
</table>

Model -IV: \( (a > 0, b < 0 \text{ and } c < 0) \)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>T</th>
<th>TC</th>
<th>Q</th>
<th>NDU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. Demand</td>
<td>0.891</td>
<td>319.736</td>
<td>437.19</td>
<td>0.572</td>
</tr>
<tr>
<td>Linear Demand</td>
<td>0.887</td>
<td>320.24</td>
<td>436.199</td>
<td>0.567</td>
</tr>
</tbody>
</table>

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** \( (a > 0, b < 0 \text{ and } c < 0) \)

**Table.11:** Sensitivity of the Salvage parameter \( \gamma \)

\[
\begin{array}{cccc}
\gamma = 0.1 & 0.891 & 319.736 & 437.19 & 0.572 \\
\gamma = 0.15 & 0.891 & 319.736 & 437.19 & 0.572 \\
\gamma = 0.2 & 0.892 & 319.543 & 437.671 & 0.574 \\
\gamma = 0.25 & 0.892 & 319.543 & 437.671 & 0.574 \\
\gamma = 0.3 & 0.892 & 319.543 & 437.671 & 0.574 \\
\end{array}
\]

**Table.12:** Sensitivity of the parameter \( \theta \)

\[
\begin{array}{cccc}
\theta = 0.01 & 0.891 & 319.736 & 437.19 & 0.572 \\
\theta = 0.05 & 0.851 & 327.721 & 419.943 & 2.507 \\
\theta = 0.1 & 0.811 & 336.792 & 402.577 & 4.565 \\
\theta = 0.15 & 0.779 & 345.092 & 388.633 & 5.832 \\
\theta = 0.2 & 0.752 & 352.788 & 376.803 & 7.025 \\
\end{array}
\]

**Table.13:** Sensitivity of the parameter \( \theta \) and \( \gamma \)

\[
\begin{array}{cccc}
\theta = 0.01 & \gamma = 0.1 & 0.891 & 319.736 & 437.19 & 0.572 \\
\theta = 0.05 & \gamma = 0.15 & 0.852 & 327.279 & 420.432 & 2.516 \\
0.79341.6743 & \theta = 0.1 & \gamma = 0.2 & 0.817 & 335.165 & 405.561 & 4.463 \\
0.941846.082 & \theta = 0.25 & \gamma = 0.3 & 0.77 & 347.048 & 386.005 & 7.543 \\
\end{array}
\]
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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