3. AN ORDER LEVEL INVENTORY MODEL FOR DETERIORATING ITEMS WITH INVENTORY RETURNS AND SPECIAL SALES

3.1: INTRODUCTION

In this chapter we reconsider the order level inventory model with inventor returns and special sales (Dave. U [23]). Here the items are subjected to linear deterioration, which is of interest in the recent past. The main stress of the discussion is to consider a situation where the optimal stock level of an inventory system is smaller than the amount on-hand.
Naddor [51], has consider this problem in case of EOQ inventory systems. Dave. [23], has extended this model in an order level inventory system. However, this model is presented in a novel manner by considering shortages with prescribed scheduling period for deterministic demand. In these two models the assumption is that the order level inventory is less than the on-hand inventory. This type of situation may arise in any wholesale or retail business, the demand of a particular product decreases due to launching of new product, which is cheaper and/or superior, due to the effects of new budget such as price increase or due to any other market fluctuations. In any such instances the optimum amount to be retained or sold, if any should be determined by minimizing the losses due to various costs involved in the inventory system.

We now develop a single period model with inventory returns and special sales for the case of deteriorating items. The effect of deterioration can not be ignored in many inventory systems. An inventory model for deteriorating items is developed for a system with inventory returns. The present investigation includes two inventory models viz., an infinite planning horizon model and finite horizon model.

3.2 ASSUMPTIONS AND NOTATIONS:

The models are developed under the following assumptions

1. Demand is deterministic at a constant rate of ‘R’ units per unit time.
2. Scheduling period is a prescribed constant, \( t_p \).

3. Replenishment rate is infinite; replenishment size is constant. The fixed lot size \(' q_p ' \) rises the inventory level in each scheduling period to the order level \(' S ' \).

4. Shortages, if any, are to be backlogged.

5. The system starts with an amount of \(' Q ' \) units on-hand of which only \(' P ' \) units are retained after returning or selling the rest. The problem is to determine optimal value of \(' P ' \).

6. The inventory carrying cost \( C_1 \) per unit per time, the shortage cost \( C_2 \) per unit per unit time and the returning or selling cost \( C_4 \) per unit are known and constant during the period under consideration.

7. A constant fraction \(' \theta ' \) say of the on-hand inventory deteriorates per unit time.

### 3.3 AN INFINITE HORIZON MODEL:

Consider the period \( T \) with the initial inventory level of \(' Q ' \) units, and final inventory is assumed to be zero. This assumption is meaningful since \((Q-P)\) units are returned or sold. The retained \(' P ' \) units are to be exhausted during the time \( t_i \leq t_p \), during the remaining period \((T - t_i)\), the optimum order level system will operate.

Now \( Q_i(t) \) denotes the inventory position at time \( t \) \((0 \leq t \leq t_i)\), then the differential equation governing the system when the items are deteriorating at the rate of \(' \theta ' \)\((0<\theta<1)\) is given by
\[
\frac{d}{dt} Q_i(t) + \theta Q_i(t) = -R \quad 0 \leq t \leq t_i
\]
\[
\frac{d}{dt} Q_i(t) = -R \quad t_i \leq t \leq T \quad \ldots(3.3.1)
\]

Using the boundary conditions

\[
Q_i(0) = P \quad \text{and} \quad Q_i(t_i) = 0
\]

The solution of the above equation is

\[
Q_i(t) = \left[ P + \frac{R}{\theta} \right] e^{-\theta t} - \frac{R}{\theta} \quad \ldots(3.3.2)
\]

with \( t_i = \frac{1}{\theta} \log \left[ 1 + \frac{P \theta}{R} \right] \)

Using second order approximation of logarithm function

\[
= \frac{P}{R} - \frac{P^2 \theta}{2R^2} \quad \ldots(3.3.3)
\]

From (3.3.2) and (3.3.3) the total inventory carried during the period \( t_i \) is

\[
I_i(P) = \int_0^{t_i} Q_i(t) dt = \left( P + \frac{R}{\theta} \right) \left[ \frac{1}{\theta} e^{\theta t} - \frac{1}{\theta} \right] - \frac{R}{\theta} t_i
\]

\[
= \frac{1}{\theta} \left( P + \frac{R}{\theta} \left[ 1 + \left( \frac{P \theta}{R} \right)^{-1} + 1 \right] - \frac{R}{\theta} \log \left( 1 + \frac{P \theta}{R} \right) \right)
\]

\[
= \frac{P^2}{2R} - \frac{P^3 \theta}{R^2} \quad \ldots(3.3.4)
\]

The total cost of the system during the period \( T \) is given by

\[
K(P) = C_1(Q - P) + C_1 I_i(P) + (T - t_i) C(S) \quad \ldots(3.3.5)
\]
where \( T = \log\left(1 + \frac{Q\theta}{R}\right) \) \ldots (3.3.6)

Further we note that
\[
T = \frac{Q}{R} - \frac{Q^2\theta}{2R^2}
\] \ldots (3.3.7)

which can be obtained by expanding logarithmic function up to second order in equation (3.3.6). \( C(S) \) is the average cost of order level inventory model with constant rate of deterioration and is given by
\[
C(S) = \frac{C}{T} \left[ S - \frac{R}{\theta} \log \left(1 + \frac{\theta S}{R}\right) \right] + \frac{C_1}{T} \left[ S - \frac{R}{\theta^2} \log \left(1 + \frac{\theta S}{R}\right) \right] + \frac{C_2R}{2T} \left[ T - \frac{1}{\theta} \log \left(1 + \frac{\theta S}{R}\right) \right]^2
\] \ldots (3.3.8)

Here ‘\( S^0 \)’ of ‘\( S \)’ is the solution of the following equation
\[
S^0 (C_1 + \theta C) + C_2 S \left( 1 - \frac{3\theta S}{2R} \right) + \theta S \left( C_2 T - \frac{C_2 S}{R} \right) - C_2 R T = 0 \] \ldots (3.3.9)

for whose derivation see Aggarwal \[2\].

Using (3.3.3),(3.3.4),(3.3.7) in (3.3.5) and by taking logarithmic terms up to second order, we get
\[
K(P) = C_1 (Q - P) + C_1 \left[ \frac{P^2}{2R} - \frac{P^3\theta}{R^2} \right] + \left[ \frac{1}{R} (Q - P) - \frac{\theta}{2R^2} (Q^2 - P^2) \right] C(S) \] \ldots (3.3.10)

Differentiating the above cost function with respect to ‘\( P \)’ and equating the resulting expression to zero, the optimal value of ‘\( P \)’ can be obtained from the following equation
\[
P^2 W + PW_1 = D = 0 \] \ldots (3.3.11)
where \( W = -3C_i\theta, \quad W_i = C_iR + \theta C(S) \) \( \ldots(3.3.12) \)

and

\[ D = R[C_i + C(S)] \] \( \ldots(3.3.13) \)

substituting \( \theta = 0 \) in the above equation, we get

\[ P = \frac{RC_i}{C_i} + \frac{S_0}{2} \]

which agrees with Dave [23].

The solution of the equation (3.3.11) is given by

\[ P^* = \frac{-W \pm \sqrt{W^2 - 4WD}}{2W} \] \( \ldots(3.3.14) \)

**Theorem:**

The cost function \( K(P) \) in the equation (3.3.10) is convex in \( P \) if

\[ P \leq \frac{C_iR + \theta[C(S)]}{6C_i\theta} \]

**Proof:** The second derivative of \( K(P) \) with respect to \( P \) is

\[ -6C_i\theta P + [C_iR + \theta C(S)] \geq 0. \]

The value of \( C(S) \) can be obtained from equation (3.3.8) by substituting optimum value of which can be had from equation (3.3.9)

\[ \Rightarrow P \leq \frac{C_iR + \theta[C(S)]}{6C_i\theta} \quad \text{this completes the proof.} \]

The convexity of the above function ensures that the minimum cost yielded by \( P^0 \) is global minimum. This theorem imposes an upper bound on \( P^0 \) that ensures the convexity of \( K(P) \).
The proposed model will be feasible only if the input parameters satisfy the required quantifications, which are developed below.

PROPOSITION (3.1): The solution given in (3.3.14) will be real if and only if

\[ C_4 \leq A^+ \quad \text{...(3.3.15)} \]

where \( A^+ = \frac{\left[ C_i R + \partial C(S) \right]^2 - C(S)}{12 C_i \theta R^2} R \)

Proof: For \( P^0 \) to be real, the expression under the root in (3.3.14) shall be non-negative. Requiring \( P^0 \) to be non-negative directly gives (3.3.15) and the necessity is established.

Now, reconsider (3.3.14), we have

\[ P^* = \frac{-W - \left[ W_i^2 - 4 W D \right]^{1/2}}{2W} \quad \text{...(3.3.16)} \]

(Or) \( P^* = \frac{-W + \left[ W_i^2 - 4 W D \right]^{1/2}}{2W} \quad \text{...(3.3.17)} \)

From (3.16) we have \( P^0 > 0 \) and from equation (3.3.17) we get,

\[ 4WD \geq 0 \quad \text{...(3.3.18)} \]

Substituting \( W \) and \( D \) as define in equations (3.3.12) & (3.3.13) we get

\[ R C_4 + C(S) \geq 0 \quad \text{...(3.3.19)} \]

which is always positive, since all the terms in LHS of the above equation are positive. This condition is sufficient and the proof is complete.
This proposition establishes that the optimum quantity $P^0$ given in (3.3.15) will always have positive roots only.

We now illustrate the solution method with the following sequence of steps.

**Step 1:**
For the given hypothetical parameters $C_1, C_2, C_4, T, D$ and $\theta$, compute $P$ value from equation (3.3.14). If the root is unique, say $P_0$, compute the corresponding minimum cost from (3.3.5) say $C(P_0)$. Otherwise go to next step.

**Step 2:**
If the roots obtained in step 1 are real and distinct, say $P_1, P_2$, consider the following situations:

(i) If two roots are less than 'Q' we compare the costs of $P_1$ and $P_2$ say $C(P_0)$ and $C(P_1)$. If $C(P_0) < C(P_1)$, $P_0$ will be the optimum quantity to be retained. Otherwise $P_1$ is the optimum quantity to be retained.

(ii) IF both roots are greater than $Q$, the optimal quantity to be retained would be 'Q' units.

(iii) If one root of 'P' say $P_0$ greater than $Q$ take $P_0 = Q$. If the other root is less than $Q$ say $P_1$, we compare the cost of $C(Q)$ and $C(P_1)$, using equation (3.3.5). If $C(Q) < C(P)$, we take 'Q' is the optimum inventory level to be retained. Otherwise $P_1$ will be taken as optimum quantity to be retained.
The working of the model is illustrated below.

**Illustration -1:-**

As an illustration to the above developed model a hypothetical values for the parameters are given below.

\[ C_1 = 0.56; \quad C_2 = 5.04; \quad C_4 = 0.28 \quad R=2004; \quad T=0.5; \quad \text{and } Q = 4800 \]

All the Parameters are expressed in consistent units per month. For different values of \( \theta \), we have determined the optimal quantity to be retained and associated costs are summarized in the following table.

**Table 3.1: SENSITIVITY OF THE MODEL TO CHANGES IN \( \theta \) i.e. RATE OF DETERIORATION**

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( S )</th>
<th>( P_1 )</th>
<th>( P_2 )</th>
<th>( K(P_1) )</th>
<th>( K(P_2) )</th>
<th>( P_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>1081.66</td>
<td>1778.668</td>
<td>36964.81</td>
<td>1598.9901</td>
<td>2634.24</td>
<td>1778.668</td>
</tr>
<tr>
<td>0.02</td>
<td>1083.348</td>
<td>1820.872</td>
<td>16920.05</td>
<td>1584.35779</td>
<td>2580.48</td>
<td>1820.872</td>
</tr>
<tr>
<td>0.03</td>
<td>1085.064</td>
<td>1867.306</td>
<td>10204.36</td>
<td>1578.724</td>
<td>2526.7</td>
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<tr>
<td>0.04</td>
<td>1086.808</td>
<td>1918.887</td>
<td>6816.813</td>
<td>1573.1495</td>
<td>2472.96</td>
<td>1918.887</td>
</tr>
<tr>
<td>0.05</td>
<td>1088.583</td>
<td>1976.874</td>
<td>4756.155</td>
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<td>1976.874</td>
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<td>1090.388</td>
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<td>3353.935</td>
<td>1562.6065</td>
<td>2365.44</td>
<td>2048.054</td>
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</table>
In the above table $P_1$ and $P_2$ are the roots of the equation (3.3.11), the values of $K(P_2)$ are obtained using equation (3.3.5) at $P_2 = Q$ since $P_2 > Q$. Further, we note $P_2 > Q$ for different values of $\theta$ (up to 0.04 in this case).

The last column values are the optimal quantities to be retained. From (3.3.11) it is to be noted that the optimal value $P_0$ of $P$ increases with an increase in the value of $\theta$ i.e. rate of deterioration.

Another parameter that can possibly influence the optimum quantity to be retained is $C_4$ i.e. special sales. Keeping other parameters unchanged the sensitivity of the model with respect to $C_4$ and $\theta$ has been examined and given as follows.
Table 3:2. SENSITIVITY OF THE MODEL TO CHANGES IN $\theta$ AND $C_4$

<table>
<thead>
<tr>
<th>$\Theta$</th>
<th>$C_4$</th>
<th>0.280</th>
<th>0.2</th>
<th>0.22</th>
<th>0.24</th>
<th>0.26</th>
<th>0.3</th>
<th>0.32</th>
<th>0.34</th>
<th>0.36</th>
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<td>1511.129</td>
<td>1600.102</td>
<td>1689.281</td>
<td>1868.264</td>
<td>1958.072</td>
<td>2048.089</td>
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<tr>
<td></td>
<td>1589.99</td>
<td>1332.997</td>
<td>1400.305</td>
<td>1465.911</td>
<td>1529.814</td>
<td>1652.077</td>
<td>1710.837</td>
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<td>1820.872</td>
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<td>1541.519</td>
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<td>1727.282</td>
<td>1814.944</td>
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<td>1459.826</td>
<td>1522.979</td>
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<td>1563.793</td>
<td>1695.433</td>
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<tr>
<td>0.04</td>
<td>1918.887</td>
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<td>1814.679</td>
<td>1924.204</td>
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<td>2155.523</td>
<td>2239.734</td>
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<td>1449.759</td>
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<tr>
<td>0.05</td>
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<td>2205.393</td>
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<td></td>
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</tr>
</tbody>
</table>

The first row values for corresponding $\theta$ are obtained using equation (3.3.15)

i.e., Optimum quantity to retained $P^o$ of $P$ and the second row values for corresponding $\theta$ are the associated costs determined from equation (3.3.11).
From the above table we observe that as $\theta$ increases optimum quantity to be retained $P$ will increase and there is a marginal change in the cost even though $P$ increases. In case of special sales $C_4$ the model is very sensitive to both the optimum quantity to be retained and the associated cost. From this simulation study we note that the model is sensitive to parameter $C_4$. Which is demonstrated in the figure (i) to (v)
SENSITIVITY W.R.TO C4
(THETA=0.01)

OPTIMUM QUANTITY & COST

SPECIAL SALES

Figure(i)
SENSITIVITY W.R.TO C4
(THETA = 0.03)

Figure (ii)

OPTIMUM QUANTITY & COST

SPECIAL SALES

Series 2 — Series 3
SENSITIVITY W.R.TO C4
(THETA= 0.05)

Figure(iii)
SENSITIVITY W.R. TO C4
(THETA= 0.07)

Figure(iv)
SENSITIVITY W.R.TO C4
(THETA= 0.1)

Figure(v)
3.4 Finite Horizon Model:

The length of replenishment period is $t_p$, is given by

$$ t_p = \frac{(H-t_i)}{m} $$

...(3.4.1)

where $t_i$ is defined as in infinite horizon model and 'm' is the number of replenishments.

$$ t_i = \frac{1}{\theta} \log \left( 1 + \frac{P\theta}{R} \right) $$

Here 'H' is the planning horizon and fixed quantity and 'm' be the number of replenishments to be made during the period $(H-t_i)$.

Substituting $t_i$ value in (3.4.1) we get

$$ t_p = \frac{1}{m} \left[ H - \frac{1}{\theta} \log \left( 1 + \frac{P\theta}{R} \right) \right] $$

...(3.4.2)

and

$$ q_p = R t_p = \frac{R}{m} \left[ H - \frac{1}{\theta} \log \left( 1 + \frac{P\theta}{R} \right) \right] $$

...(3.4.3)

$$ = \frac{R}{m} \left[ H - \frac{P}{R} (1 - \frac{P\theta}{2R}) \right] $$

...(3.4.4)

During this period the initial on-hand inventory is 'S'. Then, as given by Aggarwal [2], it can be easily shown that the total number of units carried out in inventory and total amount of shortages during $t_p$ are

$$ I_t(s) = \frac{1}{\theta} \left[ S - \frac{R}{\theta} \log \left( 1 + \frac{P\theta}{R} \right) \right] $$

...(3.4.5)
and
\[ I_2(s) = \frac{1}{2R} \left[ q_r \frac{R - \log \left( 1 + \frac{\partial S}{R} \right)}{\theta} \right]^2 \] 

respectively.

Hence from (3.4.5) and (3.4.6), the total cost of the system during the horizon \( \mathcal{H} \) is given by
\[ K(S, m) = C_4(Q - P) + C_1I_1(P) + m(C_1I_1(S) + C_2I_2(S)) \] 

where
\[ I_1(P) = \left( P + \frac{R}{\theta} \right) \left[ -\frac{1}{\theta} e^{-\frac{P}{\theta}} + \frac{1}{\theta} \right] \frac{P}{\theta} \]

The derivation of the above equation is similar to that of infinite horizon model. Fixing \( m \) to \( m^* \), the corresponding optimum values of \( S(m^*) \) of 'S' is the solution of
\[ \frac{\partial k(S, m^*)}{\partial S} = 0 \] 

The above equation doesn't yield to explicit solution. Hence \( S(m^*) \) of 'S' is the solution of the following equation
\[ \frac{S^2 \theta}{R} \left( \frac{C_2}{2} - C_1 \right) - (C_1 + C_2)S + C_2q = 0 \] 

which is independent of \( m^* \). On solving equation (3.4.2) we get
\[ P = \frac{R}{\theta} \left[ \exp \left( \frac{\theta}{R} (mq - RH) \right) - 1 \right] \]
Now the corresponding minimum cost $K(m')$ is the value of $K(S(m), m')$ in equation (3.4.7), which in view of (3.4.10),(3.4.5),(3.4.6) and (3.4.8), (3.4.11) is given by

$$K(m') = C_4 \left[ Q - \frac{R}{\theta} \left\{ \exp \left( \frac{\theta}{R} (mq_p - RH) \right) - 1 \right\} \right] + \left\{ (P + \frac{R}{\theta}) \left( - \frac{1}{\theta} e^{-\frac{\theta}{R}} + \frac{1}{\theta} \right) - \frac{P}{\theta^3} \right\} C_1$$

$$+ m \left\{ C_1 \frac{1}{\theta} \left( S - \frac{R}{\theta} \log \left( 1 + \frac{\theta}{R} \right) \right) + C_2 \left\{ \frac{1}{2R} \left( q_p - \frac{R}{\theta} \log \left( 1 + \frac{\theta}{R} \right) \right)^2 \right\} \right\} \quad \ldots (3.4.12)$$

The optimal number of replenishments $m_0$ is, then the value of $m'$ that minimizes $K(m')$. Since $m'$ be non-negative integer the necessary condition for $K(m')$ to be minimum at $m' = m_0$ is

$$\Delta K(m_0 - 1) \leq 0 \leq \Delta K(m_0) \quad \ldots (3.4.13)$$

where $\Delta K(m_0) = K(m_0 + 1) - K(m_0)$ \quad \ldots (3.4.14)

Using Taylor series expansion form of logarithmic terms and ignoring terms of second and higher order powers of $\theta$ under the assumption $\theta \leq T$ and $\frac{\theta}{R} < 1$ in equation (3.4.12) and substituting this equation in (3.4.14) along with equation (3.4.13), the condition for optimality $m' = m_0$ becomes

$$(m - 1) < \frac{2q_pRC_4(1 - RH) - C_2(q_p - S)^2 - 2q_pC_1(q_p - 2RH)}{4q_p^2C_1} < m \quad \ldots (3.4.15)$$

where $S$ is the solution of equation (3.4.10)
Illustration 2:

Reconsider the hypothetical values of the parameters of example (1) with 
$H = 2$ months as the length of the planning horizon. Then applying equation (3.4.15), we find that the optimal number of replenishments is $m_0 = 2$

setups. From equation (3.4.15) the optimum quantity to be retained is

$p_0 = 1081.706$ units per month for $\theta = 0.01$. The lot size is $q_p = 1200$ units. Finally from (3.4.7), the minimum total cost $K(m_0) = Rs \, 1990.334$ during $H = 2$ months.

3.5 DISCUSSION:

In this chapter we have considered an order level inventory model with inventory returns and special sales in the context of deteriorating items. Both, infinite horizon and finite horizon models are developed. The novelty of the model compared to the earlier work lies in the determination of optimum quantity to be retained. In the next chapter more generalized model is developed. It is general in the sense that various patterns of the demand are considered which suits in real world problem of inventory models.