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An Order Model for Deteriorating Products with Time Dependent Demand

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Abstract:

An inventory model with ramp type demand rate is developed. The time varying deterioration rate is taken into consideration. Three different cases are discussed according to the variations of demand rate. The objective of this study is to find the optimal policy for the system developed. A numerical assessment is done to illustrate the proposed model and sensitivity analysis is also performed to validate the results.

1. Introduction

Most of the traditional research articles are developed with the assumption that the goods in inventory always conserve their physical attributes which is not true in general. In real life situations, many products like; fruits, vegetables, medicines etc. deteriorates over time. Initially, Ghare and Schrader (1963) proposed a model with exponentially decaying inventory. This model was extended by Covert and Philip (1973) by considering Weibull distributed deterioration rate. Later on, Raafat (1991) and Goyal and Giri (2001) provided assessments of literature on deteriorating inventory models. For more aspects one can refer to Teng et al. (2005), Wee et al. (2009), Yan et al. (2011) and Bakker et al. (2012).

Many practical experiences reveal that for fashionable or seasonal products demand increases with time, after some time it becomes constant and then it decreases with time. But, most of the classical inventory models are developed with constant demand pattern. Donaldson (1977) proposed an inventory model with linear trend in demand. Dave and Patel (1981) and Bahari-Kashani (1989) established inventory models with time proportional demand rate. Hill (1995) discussed inventory models for increasing demand followed by level demand. Later, Lin et al. (2000) discussed a model with time varying demand and allowing the model for shortages. Manna and Chaudhuri (2006), Skouri et al. (2009) provided inventory models with ramp-type demand rate. Recently, Singh and Sharma (2013) developed an inventory model with ramp-type demand pattern and two-level trade-credit financing.

2. Notation and Assumptions

The following notations and assumptions are used in developing the model:

Notations

T The constant scheduling period (cycle)

t_1 The time when the inventory level reaches zero

S The maximum inventory level at each scheduling period

c_1 The inventory holding cost per unit per unit time

c_2 The cost incurred from the deterioration of one unit

μ The time point that increasing demand becomes steady

γ The time point, after μ, until the demand is steady and then decreases $I(t)$ The inventory level at time t □ $[0, T]$.

Assumptions :

(1) The ordering quantity brings the inventory level up to the order level S. Replenishment rate is infinite.

(2) The deterioration of the item is distributed as Weibull (a, b); and is given by $\theta(t) = abt^{b-1} (a > 0, b > 0, t > 0)$. There is no replacement or repair of deteriorated units during the period T. For $b = 1$, $\theta(t)$ becomes constant.

(3) The demand rate $D(t)$ is a time dependent ramp-type function and is of the following form:

$$D(t) = \begin{cases} f(t) = a + bt, & 0 < t < \mu, \\ f(\mu) = a + b\mu = g(\gamma) & \mu \le t \le \gamma, \\ g(t) = a - bt & \gamma < t, \end{cases} \qquad \text{(I)}$$

where $f(t)$ is a positive, continuous, and increasing function of t, and $g(t)$ is a positive, continuous and decreasing function of t.

3. The Mathematical Formulation of the Model

The replenishment at the beginning of the cycle brings the inventory level up to S. During the period $(0, t_1)$ inventory level decreases due to demand and deterioration and falls to zero at $t=t_1$. Consequently, the inventory level, $I(t)$, during the time interval $0 \le t \le t_1$, satisfies the following differential equation:

$$\frac{dI(t)}{dt} + \theta(t)I(t) = -D(t), \quad 0 \le t \le t_1, \ I(t_1) = 0, \tag{1}$$

The solution of this differential equation is affected from the relation between t_1, μ, and γ through the demand rate function. Since the demand has three components in three successive time periods, the following cases: (i)$t_1<\mu<\gamma<T$, (ii) $\mu<t_1<\gamma<T$, and (iii) $\mu<\gamma<t_1<T$ must be considered to determine the total cost and then the optimal replenishment policy.

Case $(t_1 < \mu < \gamma < T)$. In this case, (1) becomes

$$\frac{dI(t)}{dt} + abt^{b-1}I(t) = -(a+bt), \quad 0 \le t \le t_1, \ I(t_1) = 0. \tag{2}$$

The solution of (2), is

$$I(t)=e^{-at^{b}}\left[a(t_1-t)+\frac{a^2}{b+1}\left(t_1^{b+1}-t^{b+1}\right)+\frac{b}{2}\left(t_1^2-t^2\right)+\frac{ab}{b+2}\left(t_1^{b+2}-t^{b+2}\right)\right] \quad (3)$$

$$0\le t\le t_1$$

The total amount of deteriorated items during [0, t_1] is

$$D=I(0)-\int_0^{t_1}(a+bt)\,dt$$

$$D=\left(at_1+\frac{a^2t_1^{b+1}}{b+1}+bt_1^2+\frac{abt_1^{b+2}}{b+2}\right)-\left(at_1+\frac{bt_1^2}{2}\right). \quad (4)$$

The cumulative inventory carried in the interval [0, t_1] is

$$I_1=\int_0^{t_1}I(t)\,dt$$

$$I_1=-\frac{1}{2}at_1^2+\frac{a^2}{b+1}t_1^{b+2}\left(\frac{1}{b+2}-1\right)-\frac{b}{3}t_1^3+\frac{ab}{b+2}t_1^{b+3}\left(\frac{1}{b+3}-1\right)$$

$$+a^2t_1^{b+2}\left(\frac{1}{b+1}-\frac{1}{b+2}\right)+\frac{a^3t_1}{2(b+1)^2}+\frac{ab}{2}t_1^{b+3}\left(\frac{1}{b+1}-\frac{1}{b+3}\right) \quad (5)$$

The total cost is the sum of holding and deterioration costs and is given by

$$TC_1(t_1)=c_1I_1+c_2D \quad (6)$$

Case 2 ($\mu<t_1<\gamma<T$). In this case, (1) reduces to the following two:

$$\frac{dI(t)}{dt}+abt^{b-1}I(t)=-(a+bt),\quad 0\le t\le\mu, I(\mu^-)=I(\mu^+) \quad (7)$$

$$\frac{dI(t)}{dt}+abt^{b-1}I(t)=-(a+b\mu),\quad 0\le t\le t_1, I(t_1)=0 \tag{8}$$

Their solutions are, respectively,

$$I(t)=e^{-at^b}\left[a(\mu-t)+\frac{a^2}{b+1}\left(\mu^{b+1}-t^{b+1}\right)+\frac{b}{2}\left(\mu^2-t^2\right)+\frac{ab}{b+2}\left(\mu^{b+2}-t^{b+2}\right)\right.$$

$$\left.+(a+b\mu)\left((t_1-\mu)+\frac{a}{b+1}\left(t_1^{b+1}-\mu^{b+1}\right)\right)\right] \tag{9}$$

$$I(t)=e^{-at^b}(a+b\mu)\left[(t_1-t)+\frac{a}{b+1}\left(t_1^{b+1}-t^{b+1}\right)\right] \tag{10}$$

The total amount of deteriorated items during

$$D=I(0)-\int_0^{t_1}D(t)\,dt=I(0)-\left(\int_0^{\mu}D(t)\,dt+\int_{\mu}^{t_1}D(t)\,dt\right)$$

$$=a\mu+\frac{a^2\mu^{b+1}}{b+1}+\frac{b\mu^2}{2}+\frac{ab}{b+2}\mu^{b+2}+(a+b\mu)\left[(t_1-\mu)+\frac{a}{b+1}\left(t_1^{b+1}-\mu^{b+1}\right)\right]$$

$$-\left(a\mu+\frac{b\mu^2}{2}\right)-(a+b\mu)(t_1-\mu) \tag{11}$$

The total inventory carried during the interval

$$I_1=\int_0^{t_1}I(t)dt=\int_0^{\mu}I(t)dt+\int_{\mu}^{t_1}I(t)dt$$

$$= a\frac{\mu^2}{2} + \frac{a^2}{b+1}\frac{\mu^{b+2}}{2} + \frac{b\mu^3}{3} + \frac{ab\mu^{b+3}}{b+3} + (a+b\mu)(t_1\mu - \mu^2) + \frac{(a+b\mu).a}{(b+1)}(t_1^{b+1}\mu - \mu^{b+2})$$

$$-\frac{a^2\mu^{b+2}}{(b+1)(b+2)} - \frac{a^3\mu^{2b+2}}{(b+1)(2b+2)} - \frac{ab\mu^{b+3}}{(b+1)(b+3)} - \frac{a^2b\mu^{2b+3}}{(b+1)(2b+3)} - \frac{at_1^{b+1}}{b+1}$$

$$(a+b\mu)(t_1-\mu) + \frac{a^2(a+b\mu)\mu^{2b+2}}{(b+1)(2b+2)} + (a+b\mu)\left[t_1(t_1-\mu) - \left(\frac{t_1^2}{2} - \frac{\mu^2}{2}\right) + \frac{a}{b+1}\left[t_1^{b+1}(t_1-\mu)\right.\right.$$

$$\left.\left. - \left(\frac{t_1^{b+2}}{b+2} - \frac{\mu^{b+2}}{b+2}\right)\right]\right] - \frac{at_1}{b+1}(t_1^{b+1} - \mu^{b+1}) + a\left(\frac{t_1^{b+2} - \mu^{b+2}}{b+2}\right) - \frac{a^2t_1^{b+1}}{b+1}(t_1^{b+1} - \mu^{b+1})$$

$$+\frac{a^2}{b+1}\left(\frac{t_1^{2b+2}}{2b+2} - \frac{\mu^{2b+2}}{2b+2}\right) \qquad (12)$$

The inventory cost for this case is

$$TC_2(t_1) = c_1I_1 + c_2D \qquad (13)$$

Case 3($\mu<\gamma<t_1<T$). In this case, (3.1) reduces to the following three:

$$\frac{dI(t)}{dt} + abt^{b-1}I(t) = -(a+bt), \quad 0 \le t \le \mu,\ I(\mu^-) = I(\mu^+), \qquad (14)$$

$$\frac{dI(t)}{dt} + abt^{b-1}I(t) = -(a+b\mu), \quad \mu \le t \le \gamma,\ I(\gamma^-) = I(\gamma^+), \qquad (15)$$

$$\frac{dI(t)}{dt} + abt^{b-1}I(t) = -(a-bt), \quad \gamma \le t \le t_1,\ I(t_1) = 0. \qquad (16)$$

Their solutions are, respectively,

$$I(t)=e^{-at^b}\left[\left[a(\mu-t)+\frac{a^2}{b+1}\left(\mu^{b+1}-t^{b+1}\right)+\frac{b}{2}\left(\mu^2-t^2\right)+\frac{ab}{b+2}\left(\mu^{b+2}-t^{b+2}\right)\right]\right]$$

$$+f(\mu)\left[(\gamma-\mu)+\frac{a}{b+1}\left(\gamma^{b+1}-\mu^{b+1}\right)\right]$$

$$+\left[a(t_1-\gamma)+\frac{a^2}{b+1}\left(t_1^{b+1}-\gamma^{b+1}\right)-\frac{b}{2}\left(t_1^2-\gamma^2\right)-\frac{ab}{b+2}\left(t_1^{b+2}-\gamma^{b+2}\right)\right] \qquad (17)$$

$$I(t)=e^{-at^b}\left[f(\mu)\left[(\gamma-t)+\frac{a}{b+1}\left(\gamma^{b+1}-t^{b+1}\right)\right]\right]+a(t_1-\gamma)+\frac{a^2}{b+1}\left(t_1^{b+1}-\gamma^{b+1}\right)$$

$$\frac{-b}{2}\left(t_1^2-\gamma^2\right)-\frac{ab}{b+2}\left(t_1^{b+2}-\gamma^{b+2}\right) \qquad (18)$$

$$I(t)=e^{-at^b}\int_t^{t_1}(a-bx)\left(1+ax^b\right)dx,\ \mu\le t\le t_1$$

$$=e^{-at^b}\left[ax+\frac{a^2x^{b+1}}{b+1}-\frac{bx^2}{2}-\frac{abx^{b+2}}{b+2}\right]_t^{t_1}$$

$$=e^{-at^b}\left[a(t_1-t)+\frac{a^2}{b+1}\left(t_1^{b+1}-t^{b+1}\right)\frac{-b}{2}\left(t_1^2-t^2\right)-\frac{ab}{b+2}\left(t_1^{b+2}-t^{b+2}\right)\right] \qquad (19)$$

The total amount of deteriorated items during $[0,t_1]$ is

$$D=I(0)-\int_0^{t_1}D(t)dt=I(0)-\left(\int_0^{\mu}(a+bt)\,dt+\int_{\mu}^{\gamma}(a+b\mu)\,dt+\int_{\gamma}^{t_1}(a-bt)\,dt\right)$$

$$= a\mu + \frac{a^2\mu^{b+1}}{b+1} + \frac{b\mu^2}{2} + \frac{ab\mu^{b+2}}{b+2} + (a+b\mu)\left[(\gamma-\mu) + \frac{a}{b+1}\left(\gamma^{b+1} - \mu^{b+1}\right)\right]$$

$$+ a(t_1-\mu) + \frac{a^2}{b+1}\left(t_1^{b+1} - \mu^{b+1}\right) - \frac{b}{2}\left(t_1^2 - \mu^2\right) - \frac{ab}{b+2}\left(t_1^{b+2} - \mu^{b+2}\right)$$

$$-\left(a\mu + \frac{b\mu^2}{2}\right) - (a+b\mu)(\gamma-\mu) - \left(a(t_1-\gamma) - \frac{b}{2}\left(t_1^2 - \gamma^2\right)\right) \qquad (20)$$

The total inventory carried during the interval $[0,t_1]$, using (17), (18) and (19) is given by

$$I_1 = \int_0^{t_1} I(t)\,dt = \int_0^{\mu} I(t)\,dt + \int_{\mu}^{\gamma} I(t)\,dt + \int_{\gamma}^{t_1} I(t)\,dt.$$

$$= a\left(\frac{\mu^2}{2}\right) + \frac{a^2}{b+1}\left(\mu^{b+2} - \frac{\mu^{b+2}}{b+2}\right) + \frac{b}{3}\mu^3 + \frac{ab}{b+2}\left(\mu^{b+3} - \frac{\mu^{b+3}}{b+3}\right) + (a+b\mu)(\gamma-\mu)$$
$$+ \frac{a(a+b\mu)}{b+1}\left(\gamma^{b+1} - \mu^{b+1}\right)\mu + a(t_1-\gamma)\mu + \frac{a^2}{b+1}\left(t_1^{b+1} - \gamma^{b+1}\right)\mu - \frac{b}{2}\left(t_1^2 - \gamma^2\right) - \frac{ab}{b+2}$$
$$\left(t_1^{b+2} - \gamma^{b+2}\right) - \frac{a^3\mu^{b+2}}{b+1} + \frac{a^3\mu^{b+2}}{b+2} - \frac{a^3}{(b+1)^2}\mu^{2(b+1)} + \frac{a^3\mu^{2b+2}}{(b+1)(2b+2)} - \frac{ab\mu^{b+3}}{2(b+1)}$$

$$+ \frac{abt^{b+3}}{2(b+3)} - \frac{a^2b}{(b+2)}\frac{\mu^{2b+3}}{(b+1)} + \frac{a^3b}{(b+2)}\frac{\mu^{2b+3}}{(2b+3)} + \frac{a^2b}{b+2}\frac{t^{2b+3}}{(2b+3)} - \frac{a\mu^{b+1}}{b+1}(a+b\mu)(\gamma-\mu)$$
$$-a^2\frac{\mu^{b+1}}{(b+1)^2}(a+b\mu)\left(\gamma^{b+1} - \mu^{b+1}\right)\mu - a^2(t_1-\gamma)\frac{\mu^{b+1}}{b+1} - a^3\frac{\mu^{b+1}}{(b+1)^2}\left(t_1^{b+1} - \gamma^{b+1}\right)$$
$$-\frac{ba\mu^{b+1}}{2(b+1)}\left(t_1^2 - \gamma^2\right) - \frac{a^2b}{b+2}\frac{\mu^{b+1}}{(b+1)}\left(t_1^{b+2} - \gamma^{b+2}\right) + (a+b\mu)\gamma(\gamma-\mu) - \frac{(a+b\mu)}{2}$$
$$\left(\gamma^2 - \mu^2\right) + \frac{a(a+b\mu)}{b+1}\gamma^{b+1}(\gamma-\mu) - \frac{a(a+b\mu)\left(\gamma^{b+2} - \mu^{b+2}\right)}{(b+1)(b+2)} + a(t_1-\gamma)(\gamma-\mu) + \frac{a^2}{b+1}$$
$$\left(t_1^{b+1} - \gamma^{b+1}\right)(\gamma-\mu) - \frac{b}{2}\left(t_1^2 - \gamma^2\right)(\gamma-\mu) - \frac{ab}{b+2}\left(t_1^{b+2} - \gamma^{b+2}\right)(\gamma-\mu) - \frac{\gamma(a+b\mu)a}{b+1}$$
$$\left(\gamma^{b+1} - \mu^{b+1}\right) + \frac{(a+b\mu)a}{(b+2)}\left(\gamma^{b+2} - \mu^{b+2}\right) - \frac{a^2(a+b\mu)\gamma^{b+1}}{(b+1)^2}\left(\gamma^{b+1} - \mu^{b+1}\right) + \frac{a^2(a+b\mu)}{b+1}$$

$$\left(\frac{\gamma^{2b+2}-\mu^{2b+2}}{2b+2}\right)-\frac{a^2}{(b+1)}\left(\gamma^{b+1}-\mu^{b+1}\right)(t_1-\gamma)-\frac{a^3t_1^{b+1}\left(\gamma^{b+1}-\mu^{b+1}\right)}{(b+1)^2}$$

$$+\frac{a^3\gamma_1^{b+1}}{(b+1)^2}\left(\gamma^{b+1}-\mu^{b+1}\right)+\frac{ab}{2}\frac{t_1^2}{(b+1)}\left(\gamma^{b+1}-\mu^{b+1}\right)-\frac{ab}{2}\gamma^2\frac{\left(\gamma^{b+1}-\mu^{b+1}\right)}{b+1}$$

$$+\frac{a^2b}{(b+2)}t_1^{b+2}\frac{\left(\gamma^{b+1}-\mu^{b+1}\right)}{(b+1)}-\frac{a^2b}{b+2}\gamma^{b+2}\left(\gamma^{b+1}-\mu^{b+1}\right)+at_1(t_1-\gamma)$$

$$-\frac{a}{2}\left(t_1^2-\gamma^2\right)+\frac{a^2}{(b+1)}t_1^{b+1}(t_1-\gamma)+\frac{a^2\left(t_1^{b+2}-\gamma^{b+2}\right)}{(b+1)(b+2)}-\frac{b}{2}t_1^2(t_1-\gamma)+\frac{b}{2}$$

$$\frac{\left(t_1^3-\gamma^3\right)}{3}-\frac{ab}{b+2}t_1^{b+2}(t_1-\gamma)+\frac{ab\left(t_1^{b+3}-\gamma^{b+3}\right)}{(b+2)(b+3)}-\frac{a^2t_1}{(b+1)}\left(t_1^{b+1}-\gamma^{b+1}\right)+\frac{a^2}{(b+2)}$$

$$\left(t_1^{b+2}-\gamma^{b+2}\right)-\frac{a^3t_1^{b+1}}{b+1}\frac{\left(t_1^{b+1}-\gamma^{b+1}\right)}{(b+1)}+\frac{a^3}{(b+1)}\frac{\left(t_1^{2b+2}-\mu^{2b+2}\right)}{2(b+1)}+\frac{abt_1^2}{2(b+1)}\left(t_1^{b+1}-\gamma^{b+1}\right)$$

$$-\frac{ab}{2}\frac{\left(t_1^{b+1}-\mu^{b+1}\right)}{b+3}+\frac{a^2bt_1^{b+2}}{b+2}\frac{\left(t_1^{b+1}-\mu^{b+1}\right)}{b+1}-\frac{a^2b}{b+2}\frac{\left(t_1^{2b+3}-\gamma^{2b+3}\right)}{2b+3} \quad (21)$$

The inventory cost for this case is

$$TC_3(t_1)=c_1I_1+c_2D \quad (22)$$

Finally the total cost function of the system takes the following form:

$$TC(t_1) = \begin{cases} TC_1(t_1), & \text{if } t_1 \le \mu, \\ TC_2(t_1), & \text{if } \mu < t_1 < \gamma, \\ TC_3(t_1), & \text{if } \gamma \le t_1. \end{cases} \quad (23)$$

Now, our objective is to minimize the total cost (TC (t_1)) of the system. The optimal total cost (TC (t_1)) is $\min\{TC_1(t_1), TC_2(t_1), TC_3(t_1)\}$.

4. Numerical Example

The example, which follow, illustrate the results obtained.

Example: The input parameters are c_1 = \$4 per unit per year, c_2 = \$4.5 per unit, μ = 0.11 year, γ = 0.85, a = 20, b = 2, T = 1 year, Again t_1^* = 0.8 the optimal ordering quantity is Q^* = 35.59 and the minimum cost is $TC(t_1^*)$ = 2312.805. The convexity of the total cost is shown graphically in Fig. 1

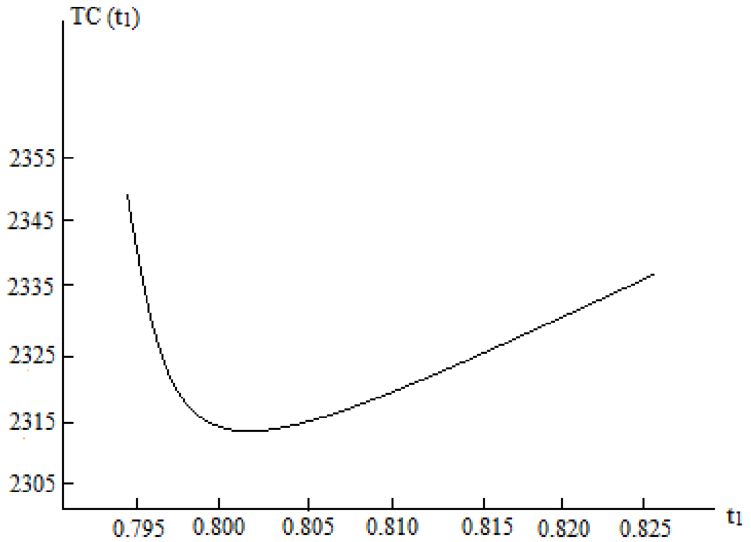

Fig. 1: Convexity of the total cost TC w.r.t. t_1.

Table 1 : Sensitivity analysis.

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Parameter	% Change	t_1^*	Q^*	$TC(t_1^*)$
c_1	-50	0.844	35.52	2267.686
	-20	0.823	35.51	2294.868
	+20	0.783	35.44	2344.073
	+50	0.764	35.38	2364.638
c_2	-50	0.800	35.59	2311.758
	-20	0.800	35.59	2312.015
	+20	0.800	35.59	2313.270
	+50	0.800	35.59	2313.985

Concluding Remarks

In this paper, an inventory model for decaying items has been studied. It is assumed that the demand rate is time dependent and a ramp type pattern of three branches has been used. The model is more realistic as Weibull distributed deterioration rate is taken into account. The whole concept of this model is illustrated with a numerical example and sensitivity analysis is also performed.

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