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A screening policy for an inventory model of decaying items with imperfect quality and price varying demand

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Abstract
The present paper considers the study of an imperfect quality and screening policy for an inventory model of decaying items with price-varying demand. All defective items are screened by the retailer. The screening of defective items plays an important role in the optimization of a retailer's total profit/cost. Therefore, the inspection process of defective products is implemented by retailers assuming Type-I and Type-II errors. The inspection errors of Type-I and Type-II refer to a good product being assumed as defective and a defective product being assumed as good. The objective is to optimize the retailer's total inventory cost in the considered cycle length. The applicability of the model characteristics is demonstrated by a numerical example.

Keywords: Inventory, defective products, screening policy and deterioration
Subject classification: MSC 2010 (90B05, 90B30).

1. Introduction
In the present day real world situations, every business firm faces extreme competition regarding quality production, nominal price, price discount and timely delivery. The production of defective products together with non-defective products cannot be ignored in any production system. It may occur due to imperfect manufacturing process, damages or many other reasons. The inspection of defective products is not 100% error free. Therefore in the inspection process two types of screening errors occur namely Type-I and Type-II. In Type-I error due to falsely screening some non-defective products are sent for rework. And in Type-II error due to unsuccessfully screening when some defective products are sold to customers then they incur penalty to retailer. The following scholars have been studied imperfect production in their respective inventory model.

Schrady [1] constructed a deterministic inventory model for repairable items in which he was determined the optimal procurement and repair quantities. Shih [2] developed an inventory model for deteriorating items and studied optimal inventory policies for defective products when stock out take place. Raouf *et al*. [3] studied the human error in inspection planning for a cost minimization inventory model with miss classification of multi-characteristic critical components. Rosenblatt and Lee [4] presented an imperfect production inventory model for decaying items with different production cycles. Salameh and Jaber [5] focused on an economic production quantity model for deteriorating items with imperfect quality. In his model they were considered that the poor quality products are sold after 100% screening policy assuming as a single batch. Hayek and Salameh [6] studied a lot-sizing nite production inventory model with re-working of imperfect quality products. In his inventory model they were minimize the total inventory cost. Chiu [7] analyzed a finite production inventory model with optimal lot sizing. They were considered the imperfect quality items that are reworked and partial backlogging in their inventory model. Flapper and Teunter [8] proposed a logistic planning of rework for an inventory model of deteriorating items with work in progress. Chiu *et al*. [9] constructed an imperfect production inventory model with lot sizing and rework. They were considered that some produced products have different service level constraint and scrap rate. Chung *et al*. [10] studied a two warehouse inventory model for perishable item that incorporating imperfect quality production. Cardenas [11] focused on economic production quantity model with rework process for a single stage manufacturing system and allowing back orders. Lin *et al.* [12] determined an optimal ordering policy for a production system of deteriorating items with rework. Yoo *et al.* [13] developed a profit maximization economic production quantity model incorporating inspection errors and sales returns. Chiu [14] considered robust planning for random machine breakdown in his production inventory model with failure in rework. Khan *et al.* [15] proposed an economic order quantity model for deteriorating items with inspection errors and imperfect quality. Widyadana and Wee [16] focused on an economic production quantity model for perishable products including multiple production setups and rework. Tai [17] analyzed an economic production quantity model for imperfect products incorporating service and rework. Krishnamoorthi and Panayappan [18] constructed an inventory model with rework of regular production and allowing shortages and sales return. Hsu and Hsu [19] developed two economic production quantity models and obtained the closed form of optimal lot size. They were considered imperfect production, screening errors, sales return, planned back ordered and partial backlogging in both the models. Chen *et al.* [20] studied an economic order quantity model for deteriorating items with carbon constrained. Sarkar *et al.* [21] proposed a single stage economic production quantity model for perishable items with random defective rate, rework process and assuming back orders. Hovelaque and Bironnean [22] constructed an economic order quantity model for deteriorating items with carbon emission dependent demand. Bhuniya and Chakraborty [23] analyzed an economic production quantity model for deteriorating items considering fuzzy type deterioration rate and inspection errors. Zhou *et al.* [24] focused on an economic order quantity model for decaying items with imperfect quality and inspection errors and allowing shortages. Khanna *et al.* [25] developed a production inventory model for defective items with imperfect inspection process and incorporating rework, two level trade credit and sales return. Pal and Mahapatra [26] determined a manufacturing based supply chain inventory model with stochastic demand and including imperfect quality, inspection errors, rework and allowing shortages. Sanjai and Periyasamy [27] considered a cost minimization production inventory model with planned back orders for a single product and incorporating imperfect production, rework and allowing shortages. Chayanika *et al.* [28] studied a type two fuzzy approach for an economic production quantity model of deteriorating items with imperfect production, inspection errors, rework and allowing shortages. Ganesan and Uthayakumar [29] proposed a cost minimization economic production quantity models for an imperfect manufacturing system considering warm-up production run, shortages during hybrid maintenance period and partial back ordering. Gautam *et al.* [30] focused on inventory and pricing decisions for an imperfect production system with quality inspection, rework and carbon emissions. In his inventory model they were maximized the profit function by optimizing both the mark-up price and production quantity.

2. Notations

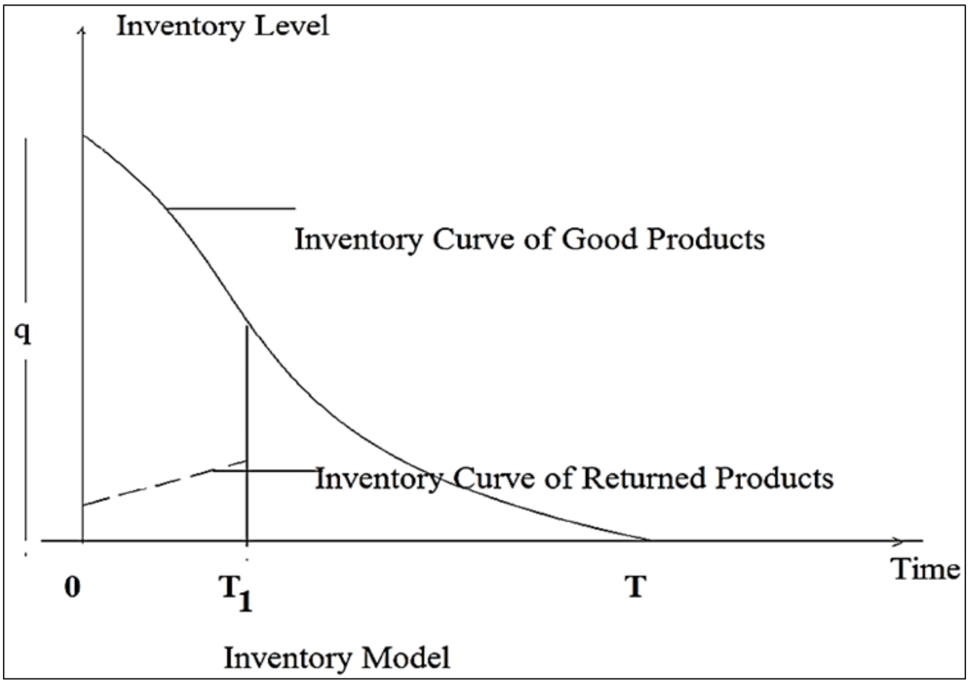
The developed model has the following notations:

1. The price dependent demand rate is $D(t) = (a + bs_p)$, where $a, b > 0$.
2. The constant deterioration rate is $\theta(t) = \theta$.
3. The screening rate is α.
4. The screening cost coefficient is λ.
5. The defect rate is γ.
6. The probability of Type-I error is p_1.
7. The probability of Type-II error is p_2.
8. The ordering cost per order is A.
9. The holding cost of good products per unit per unit time is h.
10. The holding cost of defective products per unit per unit time is h_d.
11. The purchasing cost per unit is c.
12. The screening period is T_1 (decision variable).
13. The replenishment cycle length is T (decision variable).
14. The initial order quantity is q.
15. The variable total inventory cost is $\pi(T_1, T)$.

1.2 Inventory model formulation

Suppose the retailer receives the maximum units q of the product at time $t = 0$. As the maximum units of the product are received then the screening of non-deteriorated units starts at $t = 0$ and ends at $t = T_1$. Let $y_d = (1 - y)p_1 + y(1 - p_2)$ be the defect rate of the product detected by the retailer incorporating two Types of error. The screening of defective units is completed together with returned units of the previous period at $t = T_1$.

The instantaneous rate of change of retailer's inventory of goods products is given by the following differential equations



$$\frac{dI}{dt} + \theta I = -[(a + bs_p) + \alpha\, y_d], \quad 0 \le t \le T_1 \tag{1}$$

With boundary condition, $I(0) = q$

$$\frac{dI}{dt} + \theta I = -(a + bs_p), \qquad T_1 \le t \le T \tag{2}$$

With boundary condition, $I(T) = 0$

On solving the equation (1), we obtain

$$I = -[(a + bs_p) + \alpha y_d]\left(t + \frac{\theta}{2}t^2 - \theta t^2\right) + q(1 - \theta t) \tag{3}$$

(for the first order approximation of $e^{\theta t} = 1 + \theta t$)

The maximum units q of the product are obtained by putting $t = T_1$ in the equation (3), we obtain the value of q i.e.

$$q = (a + bs_p + \alpha y_d)\left(T_1 + \frac{\theta}{2}T_1^2\right) - (a + bs_p)\left(T_1 - T + \frac{\theta}{2}T_1^2 - \frac{\theta}{2}T^2\right) \tag{4}$$

The solutions of equations (1) and (2) are given by the equations (5) and (6) respectively.

$$I = -(a + bs_p + \alpha y_d)\left(t - \frac{\theta}{2}t^2\right) + (1 - \theta t)(a + bs_p + \alpha y_d)(T_1 + \theta T_1^2) - (a + bs_p)\left(T_1 - T + \frac{\theta}{2}T_1^2\right.$$

$$\left. - \frac{\theta}{2}T^2\right), \qquad 0 \le t \le T_1 \tag{5}$$

$$I = -(a + bs_p)\left(t - \frac{\theta}{2}t^2 - T - \frac{\theta}{2}T^2 + \theta t_1 T\right), \qquad T_1 \le t \le T \tag{6}$$

The total number of units of good products in $[0, T]$ is

$$I = \int_0^{T_1} I(t)dt + \int_{T_1}^{T} I(t)dt$$

Or

$$I = (a + bs_p + \alpha y_d)\left(\frac{1}{2}T_1^2 + \frac{\theta}{6}T_1^3\right) - \frac{1}{2}(a + bs_p)(2T_1^2 - 2TT_1 + \theta T_1^3 - \theta T_1 T^2) + \frac{1}{6}(a + bs_p)(3T^2 + 3T_1^2 - 6TT_1 + \theta T^3 - \theta T_1^3 - 3\theta T_1 T^2 + 3\theta T T_1^2) \quad (7)$$

The retailer's screened inventory of defective units of product in $[0, T_1]$

According to the assumption, the screening process is finished at $t = T_1$. Therefore, the variation in defective units incorporating deterioration quantity of some defective units is followed by the differential equation,

$$\frac{dI_d(t)}{dt} = \alpha y_d, \qquad 0 \le t \le T_1 \quad (8)$$

On solving, equation (8), we obtain the screened defective units,

$$I_d = \alpha y_d t \quad (9)$$

In the interval $[0, T_1]$, the screening process of retailer is not perfect (100%) because only the non-defective units are inspected. Therefore, the retailer's screening quantity is

$$\alpha T_1 = q - \int_0^{T_1} \theta(t) I(t)dt$$

Or

$$\alpha T_1 = (a + bs_p + \alpha y_d)\left(T_1 + \frac{\theta}{2}T_1^2\right) - (a + bs_p)\left(T_1 - T + \frac{\theta}{2}T_1^2 - \frac{\theta}{2}T^2\right) - \theta\left\{(a + bs_p + \alpha y_d)\left(\frac{1}{2}T_1^2 + \frac{\theta}{6}T_1^3\right) - (a + bs_p)\left(T_1^2 - TT_1 + \frac{\theta}{2}T_1^3 - \frac{\theta}{2}T_1T^2\right)\right\}$$

The retailer's screening rate in the interval $[0, T_1]$ is

$$\alpha = \frac{1}{T_1}\left[(a + bs_p + \alpha y_d)\left(T_1 + \frac{\theta}{2}T_1^2\right) - (a + bs_p)\left(T_1 - T + \frac{\theta}{2}T_1^2 - \frac{\theta}{2}T^2\right) - \theta\left\{(a + bs_p + \alpha y_d)\left(\frac{1}{2}T_1^2 + \frac{\theta}{6}T_1^3\right) - (a + bs_p)\left(T_1^2 - TT_1 + \frac{\theta}{2}T_1^3 - \frac{\theta}{2}T_1T^2\right)\right\}\right] \quad (10)$$

The retailer's total defective units in $[0, T]$ are

$$I_D = \int_0^{T_1} I_d(t)dt$$

Or

$$I_D = \frac{\alpha}{2} y_d T_1^2 \quad (11)$$

The retailer's returned inventory of defective units of product in $[0, T_1]$

In the interval $[0, T_1]$ some unscreened defective units of product are saled by the retailer to the customers. The customers return these defective units to retailer and the retailer handles these units with screened defective units at the end of inspection. Therefore, the retailer's returned inventory follows the differential equation

$$\frac{dI_R}{dt} + \theta I_R = p_2 y(a + bs_p) \tag{12}$$

With boundary condition, $I_R(0) = 0$

On solving equation (12), we obtain

$$I_R(t) = p_2 y(a + bs_p)\left(t + \frac{\theta}{2}t^2 - \theta t^2\right) \tag{13}$$

The retailer's total returned inventory in $[0, T]$ is

$$I_R(t) = \int_0^T I_R(t)dt$$

Or

$$I_R = \frac{1}{6} p_2 y(a + bs_p)(3T^2 - \theta T^3) \tag{14}$$

In the replenishment cycle, retailer's total inventory cost per cycle is

$$\pi(T_1, T) = \frac{1}{T}[C_O + C_H + C_D + C_P + C_{SR} + C_{SRP}] \tag{15}$$

Where, $C_O, C_H, C_D, C_P, C_{SR}, C_{SRP}$ are the ordering cost, holding cost, deterioration cost, purchasing cost, screening cost and screening error cost per cycle which are determined as follows,

The ordering cost per cycle is

$$C_O = \frac{A}{T} \tag{16}$$

The holding cost per cycle is

$$C_H = \frac{1}{T}[hI + h_d(I_D + I_R)]$$

Or

$$C_H = \frac{h}{T}\Bigg[(a + bs_p + \alpha y_d)\left(\frac{1}{2}T_1^2 + \frac{\theta}{6}T_1^3\right) - \frac{1}{2}(a + bs_p)(2T_1^2 - 2TT_1 + \theta T_1^3 - T_1T^2)$$

$$+\frac{1}{6}(a + bs_p)(3T^2 + 3T_1^2 - 6TT_1 + \theta T^3 - \theta T_1^3 - 3\theta T_1T^2 + 3\theta TT_1^2\Bigg] \tag{17}$$

The deterioration cost per cycle is

$$C_D = \frac{c}{T}\Bigg[(a + bs_p + \alpha y_d)\left(T_1 + \frac{\theta}{2}T_1^2\right) - (a + bs_p)\left(T_1 - T + \frac{\theta}{2}T_1^2 - \frac{\theta}{2}T^2\right) - (a + bs_p)T^2$$

$$-\alpha y_d T_1 + \frac{y}{2} p_2 (a+bs_p)\theta T^2 \Bigg] \qquad (18)$$

The purchasing cost per cycle is

$$C_P = \frac{c}{T} q$$

Or

$$C_P = \frac{c}{T}\left[(a+bs_p+\alpha y_d)\left(T_1 + \frac{\theta}{2} T_1^2 \right) - (a+bs_p)\left(T_1 - T + \frac{\theta}{2} T_1^2 - \frac{\theta}{2} T^2 \right)\right] \qquad (19)$$

The cost of Type I products per cycle is

$$C_{SRE_1} = \frac{1}{T} c_1 \alpha (1-y) p_1 T_1 \qquad (20)$$

The cost of Type II products per cycle is

$$C_{SRE_2} = \frac{1}{T} c_2 \alpha y p_2 T_1 \qquad (21)$$

The screening cost per unit time is

$$C_{SR} = \left(\frac{1}{2}\right)\left(\frac{\lambda}{T}\right)\left(\frac{T^2}{T_1}\right) \qquad (22)$$

Putting the values of these costs in equation (15), we obtain the retailer's total inventory cost per cycle,

$$\pi(T_1,T) = \frac{1}{T}\Big[A + \{c\alpha y_d + c_1\alpha(1-y)p_1 + c_2\alpha y p_2\}T_1 + c(a+bs_p)T + \Big\{ c\alpha(a+bs_p) + \frac{1}{2}(a+bs_p)(h$$

$$+ h_d y p_2 + c\alpha p_2 y)\Big\}T^2 + \left(\frac{1}{2}(h+h_d)\alpha y_d + c\theta\alpha y_d\right)T_1^2 - \big(3h(a+bs_p) + 2h\alpha y_d\big)TT_1$$

$$+ \left(\frac{1}{6} h\theta(\alpha y_d - 3(a+bs_p)\right)T_1^3 + \frac{1}{6}(a+bs_p)(h - h_d p_2 y)\theta T^3 + \frac{1}{2} h\theta(a+bs_p)T_1T^2$$

$$+ \frac{1}{2} h\theta(a+bs_p)TT_1^2 + \left(\frac{\lambda}{2}\right)\left(\frac{T^2}{T_1^2}\right)\Big] \qquad (23)$$

Differentiating equation (23), we obtain the following equations

$$\frac{\partial \pi(T_1,T)}{\partial T_1} = \frac{1}{T}\Big[(c\alpha y_d + c_1\alpha(1-y)p_1 + c_2\alpha y p_2) + (\alpha y_d(h+h_d) + 2c\theta\alpha y_d)T_1 + \Big(\frac{h\theta}{2}(\alpha y_d - 3a$$

$$-3bs_p)\Big)T_1^2 + \frac{h\theta}{2}(a+bs_p)T^2 + h\theta(a+bs_p)TT_1 - \lambda\left(\frac{T^2}{T_1^3}\right)\Big] \qquad (24)$$

$$\frac{\partial \pi(T_1,T)}{\partial T} = \frac{1}{T}\Big[c(a+bs_p) + 2\Big(c\theta(a+bs_p) + \frac{1}{2}(a+bs_p)(h + h_d p_2 y + c\theta p_2 y\Big)T - \big(3h(a+bs_p)$$

$$+ 2h\alpha y_d\big)T_1 + \frac{1}{2}(a+bs_p)(h - h_d p_2 y)T^2 + 3h\theta(a+bs_p)TT_1 + \frac{h\theta}{2}(a+bs_p)T_1^2$$

$$+\left(\frac{\lambda}{2}\right)\left(\frac{T}{T_1^2}\right)\Bigg] - \frac{1}{T^2}\big[A + (c\alpha y_d + c_1\alpha(1-y)p_1 + c_2\alpha y p_2)T_1$$

$$+\Big\{c\alpha(a+bs_p) + \frac{1}{2}(a+bs_p)(h + h_d y p_2 + c\alpha p_2 y)\Big)T^2 + \left(\frac{1}{2}(h+h_d)\alpha y_d + c\theta\alpha y_d\right)T_1^2$$

$$-\big(3h(a+bs_p) + 2h\alpha y_d\big)TT_1 + \left(\frac{1}{6}h\theta(\alpha y_d - 3(a+bs_p)\right)T_1^3 + \frac{1}{6}(a+bs_p)(h$$

$$-h_d p_2 y)\theta T^3 + \frac{1}{2}h\theta(a+bs_p)T_1T^2 + \frac{1}{2}h\theta(a+bs_p)TT_1^2 + \left(\frac{\lambda}{2}\right)\left(\frac{T^2}{T_1^2}\right)\Bigg] \quad (25)$$

For the optimum values of $\pi(T_1,T)$, the necessary conditions are

$$\left(\frac{\partial\pi(T_1,T)}{\partial T_1}\right) = 0 \quad (26)$$

And

$$\left(\frac{\partial\pi(T_1,T)}{\partial T}\right) = 0 \quad (27)$$

On solving the equations (26) and (27), we obtain the optimum values of T_1 and T for which the total inventory cost $\pi(T_1,T)$ is minimum.

For the optimum values of $\pi(T_1,T)$, the sufficient conditions are

$$\left(\frac{\partial^2\pi(T_1,T)}{\partial T_1^2}\right)\left(\frac{\partial^2\pi(T_1,T)}{\partial T^2}\right) - \left(\frac{\partial^2\pi(T_1,T)}{\partial T_1\partial T}\right)^2 > 0 \quad (28)$$

And

$$\left(\frac{\partial^2\pi(T_1,T)}{\partial T_1^2}\right) > 0 \quad (29)$$

After differentiating equation (23), we obtain the second order derivatives

$$\frac{\partial^2\pi(T_1,T)}{\partial T_1^2} = \frac{1}{T}\Big[\{\alpha y_d(h+h_d) + 2c\theta\alpha y_d\} + \{h\theta(\alpha y_d - 3a - 3bs_p)\}T_1 + \theta(a+bs_p)T + 3\lambda\left(\frac{T^2}{T_1^4}\right)\Big] \quad (30)$$

$$\frac{\partial^2\pi(T_1,T)}{\partial T_1\partial T} = \frac{1}{T}\Big[-\{3h(a+bs_p) + 2h\alpha y_d\} + h\theta(a+bs_p)T_1 - \lambda\left(\frac{T}{T_1^3}\right)\Big]$$

$$-\frac{1}{T^2}\big[(c\alpha y_d + c_1\alpha(1-y)p_1 + c_2\alpha y p_2) + (\alpha y_d(h+h_d) + 2c\theta\alpha y_d)T_1$$

$$-\{3h(a+bs_p) + 2h\alpha y_d\}T + \left(\frac{1}{2}h\theta(\alpha y_d - 3(a+bs_p)\right)T_1^2 + \frac{1}{2}(a+bs_p)h\theta T^2$$

$$+(a+bs_p)h\theta TT_1-\left(\frac{\lambda}{T_1^3}\right)T^2\Bigg] \quad (31)$$

$$\frac{\partial^2\pi(T_1,T)}{\partial T^2}=\frac{1}{T}\Big[(a+bs_p)\{2c\theta+(h+h_d p_2 y+c\theta)\}+(a+bs_p)(h-h_d p_2 y)T+h\theta(a+bs_p)T_1$$

$$+\left(\frac{1}{2}\right)\left(\frac{\lambda}{T_1^2}\right)\Big]-\frac{1}{T^2}\Big[2c(a+bs_p)+2(a+bs_p)\big(c\theta+h+h_d p_2 y+c\theta p_2 y\big)T$$

$$-\{6h(a+bs_p)+4h\alpha y_d\}T_1+(a+bs_p)(h-h_d p_2 y)T^2+2h\theta(a+bs_p)TT_1$$

$$+h\theta(a+bs_p)T_1^2+\left(\frac{3\lambda}{2}\right)\left(\frac{T}{T_1^2}\right)\Big]+\frac{2}{T^3}\Big[A+\{c\alpha y_d+c_1\alpha(1-y)p_1+c_2\alpha y p_2\}T_1$$

$$+h_d y p_2+c\alpha p_2 y)\big)T^2+c(a+bs_p)T+\Big\{c\alpha(a+bs_p)+\frac{1}{2}(a+bs_p)(h$$

$$+\left(\frac{1}{2}(h+h_d)\alpha y_d+c\theta\alpha y_d\right)T_1^2-\big(3h(a+bs_p)+2h\alpha y_d\big)TT_1$$

$$+\left(\frac{1}{6}h\theta(\alpha y_d-3(a+bs_p)\right)T_1^3+\frac{1}{6}(a+bs_p)(h-h_d p_2 y)\theta T^3+\frac{1}{2}h\theta(a+bs_p)T_1T^2$$

$$+\frac{1}{2}h\theta(a+bs_p)TT_1^2+\left(\frac{\lambda}{2}\right)\left(\frac{T^2}{T_1^2}\right)\Big] \quad (32)$$

Numerical example: To validate the model, Let us consider a numerical example having the following parameters in appropriate units,

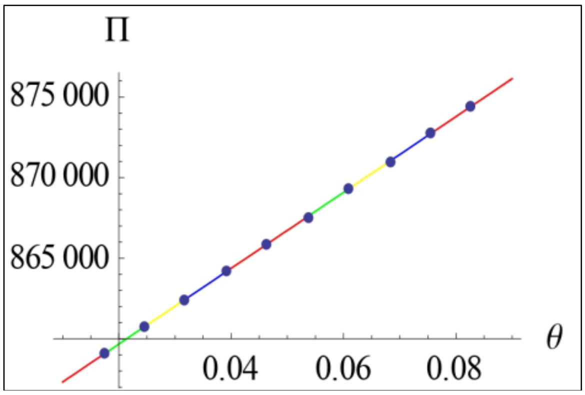
$a=1000, b=50, c=100, \alpha=0.6,\ s_p=150, \theta=0.01, A=200, h=10, h_d=4, y=0.04, c_1=5,$

$c_2=0.4, p_1=7, p_2=0.2, \lambda=20,\ y_d=6.752$

Table 1: Variation in $\pi(T_1,T)$ w.r.to deterioration parameter θ

θ	T_1	T	$\pi(T_1,T)$
0.01	0.0456	1.2088	857325.09719
0.03	0.0502	1.6266	861326.71984
0.05	0.0541	2.0493	865550.98131
0.07	0.0574	2.4775	869990.06543
0.09	0.0603	2.9116	874647.12262

The sensitivity analysis based on the results of table 1, shows that as the deterioration parameter θ increased then both the cycle length and total inventory cost are increased. The reason is that the screening cost is increased because the screening period is increased. Hence the retailer's total cost depends upon the number of units of good products.



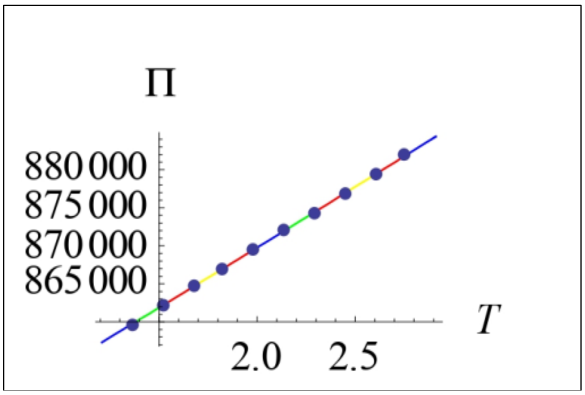
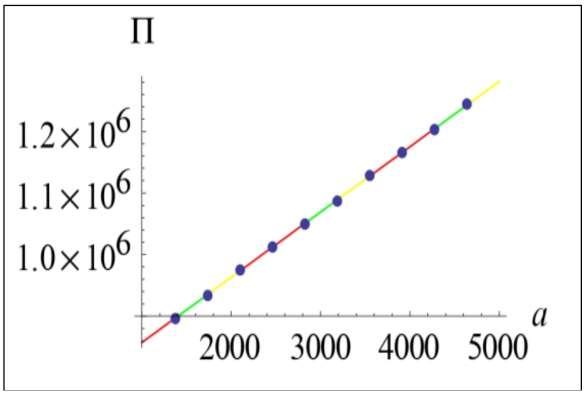


Fig 2: Variation in total cost w.r.to θ **Fig 3:** Variation in total cost w.r.to T

Table 2: Variation in a $\pi(T_1, T)$ w.r.to demand parameter

a	T_1	T	$\pi(T_1, T)$
1000	0.0456	1.2088	857325.09719
2000	0.0439	1.2092	964209.41937
3000	0.0425	2.2095	1.07106×10^{6}
4000	0.0412	2.2097	1.17798×10^{6}
5000	0.0401	2.2099	1.28486×10^{6}

The sensitivity analysis formed by the results of table 2, has the impact on demand parameter, screening period, cycle length and total inventory cost. The increase in the demand parameter a increases the cycle length and total inventory cost. The reason is that the holding cost is increased, because the screening cost is decreased. Hence the retailer's should sell the maximum number of units of the product after completing the inspection.



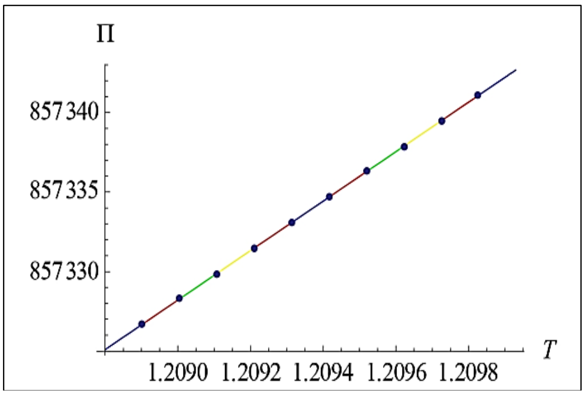


Fig 4: Variation in total cost w.r.to a **Fig 5:** Variation in total cost w.r.to T

1.3 Concluding remarks: In the present study, we consider a cost minimization inventory model of decaying items with imperfect quality and price varying demand in which the inspection process is not perfect. The retailer can optimize the total inventory cost either by improving the product quality or by reducing the defective items on completing the 100% inspection process. Therefore, the screening process and quality of products play an important role in the optimization of retailer's total cost. Further, the present work can be extended by incorporating some complicated assumptions on demand, deterioration and.

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