



Effect of Selling price-based Inventory model with quadratic demand under maximum life time

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Abstract

This study proposes an inventory model for non-instantaneous decaying products with selling price under a time-dependent quadratic demand pattern. In contrast to conventional inventory models that assume a constant rate of deterioration, the present model considers products that instigate to deteriorate only after a assured period due to their limited shelf life and gradual aging process. Such an assumption makes the model more realistic for handling perishable and semi-perishable goods in modern supply chain systems. The model also incorporates time-dependent sales revenue to capture changing market conditions and customer purchasing behaviour over time. The developed mathematical framework aims to determine the optimal replenishment policy that maximizes the total profit of the inventory system while minimizing the effects of deterioration and holding costs. To demonstrate the applicability of the developed inventory model, a numerical example is presented for obtaining the optimal order quantity and corresponding total profit. Furthermore, investigate the influence of important inventory parameters on the overall performance of the model. The final results provide useful managerial insights for inventory decision-making under realistic market environments.

Received 25 May., 2026; Revised 03 June, 2026; Accepted 05 June, 2026 © The author(s) 2026.

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I. INTRODUCTION

In recent decades, deteriorating inventory models have attracted considerable interest in the area of the inventory management and operations research due to their wide applicability to perishable and time sensitive products. The origin of inventory can be drawn hindmost Harris (1915), who introduce the EOQ model. Wilson (1934) refined and generalized this concept through the development of the classical EOQ formula for optimal order quantity determination. Subsequently, Whitin (1957) expanded inventory theory by examining fashionable products that undergo deterioration at the end of their storage life.

The study of deterioration inventory systems formally began with the pioneering work of Ghare and Schrader (1963), who examine an EOQ model with exponentially decaying items under a constant deterioration rate without shortages. Their contribution laid the ground work for subsequent research in deterioration inventory modelling. Later Covert and Philip (1973) extended this work by introducing a variable deterioration rate based on a two-parameter Weibull distribution. This approach was further refined by Philip (1974), who incorporated a three-parameter Weibull distribution to provide greater flexibility in representing deterioration behaviour. Thereafter, Misra (1975) proposed an EPQ model for deteriorating under both constant and variable deterioration rates. Additional contributions by Shah and Jaiswal (1977), Dave and Patel (1987), and Chowdhury and Choudhuri (1983) focused on order-level inventory models for deteriorating products under constant deterioration assumptions, thereby advancing inventory control policies for perishable items.

Early studies primarily concentrated on constant deterioration rates and deterministic demand pattern. Important contribution in this category mainly included Kang and Kim (1983), Dave (1986), Goyal and Gunasekaran (1995), and Bhunia and Maiti (1998) which expanded these above models by integrating the more realistic operational assumptions as the time-dependent deterioration and linear deterioration functions. With increasing the practical relevance, researchers began emphasizing the bond amongst time and deterioration. Chang and Dye (1999) examined deteriorating inventory systems under quantity discount, pricing strategies, and partial backordering. Further developments by Shah and Shah (2000), Abad (2001), and Mukhopadhyay et al. (2004) explored alternative time-dependent deterioration functions and recent trends in deteriorating inventory modelling.

In practical situations, products often remain fresh for an initial period before deteriorating begins. This concept, known as non-instantaneous deterioration, gained considerable attention in inventory research. Ouyang et al. (2006) formally introduced the concept of “non-instantaneous deterioration under permissible delay in payments”. Subsequent studies by Zhou and Gu (2007), Liao (2008), Malik et al. (2008), and Singh and Malik (2009, 2010) incorporated factor such as two-warehouse systems, inflation, exponential backlogging, stock-dependent demand, and variable deterioration rates. Li et al. (2010) further provided a comprehensive review of deteriorating inventory literature and identified several emerging research parameters for future studies.

Recent research has increasingly focused on sustainability, environmental concerns, and advanced inventory strategies. Sana (2010), Sarkar (2012), and Sarkar and Sarkar (2013) incorporated probabilistic deterioration, stock-dependent demand, and partial backlogging into deteriorating inventory systems. Later studies by Ghoreishi et al. (2014), Sheng et al. (2015), and Malik et al. (2016) integrated trade credit financing, controllable lead time, quality improvement, and non-instantaneous deterioration into inventory frameworks. In recent years, researchers have emphasized on the sustainable inventory practices by integrating the carbon emissions, preservation technology, green investment, reverse logistics, and the circular supply chain concepts. Malik et al. (2017), Kumar et al. (2017), Mathur et al. (2019), Saxena et al. (2020), Malik et al. (2021), Bansal et al. (2021), Kumar et al. (2022), and Beniwal et al. (2022) developed the advanced models which considering the variable demand, trade credit, maximum lifetime constraints, fuzzy decision-making, and the green inventory practices. Furthermore, Yadav et al. (2022) reviewed the applications of fuzzy techniques in the inventory control systems under uncertainty.

More recently, Sharma et al. (2023) examined the inventory model integrating the advertisement-dependent demand, while Tyagi et al. (2023) reviewed the fuzzy mathematical models for pharmaceutical and the cosmetic products. Malik et al. (2024), Singh and Goel (2024), Jayswal et al. (2024), and Verma et al. (2026) further extended the deteriorating inventory-based research by integrating the carbon emission policies, preservation technology, inflation, eco-sensitive demand, reverse logistics, and the sustainable supply chain practice. Although, extensive research has been conducted on the deteriorating inventory systems, comparatively the limited attention has been devoted to models that simultaneously incorporate the both non-instantaneous deterioration and time-varying deterioration rates, despite their significant practical relevance in the real-world inventory environments. Most of the existing studies focus on either deterioration timing or varying deterioration behaviour as independently. To shows the relevance and usefulness of the suggested model, numerical example accompanied by the graphical illustrations is presented. The analysis evaluates the influence of key inventory constraints on the optimal ordering policy, total system cost, and the overall inventory performance.

NOTATIONS AND ASSUMPTIONS

To formulate this inventory model in a perfect and structured way, the resulting notations and assumptions are defined. These describe the system parameters and help in developing the mathematical framework.

Notations

$D(t)$	Time varying demand, assumed to follow an exponential form with respect to time t .
C_0	Fixed ordering cost incurred for each order placed in the inventory system
C_h	Holding cost per unit item / unit time.
C_p	Purchasing cost per unit item paid to acquire goods.
C_d	Deterioration cost per unit item due to spoilage, decay, or loss in quality over time.
$S_1 - S_2(t)$	Time dependent selling price per unit item.
$\theta(t)$	Time-varying deterioration rate at time t , given by $\theta(t) = \frac{1}{1+R-t}$ where $0 \leq \theta(t) \leq 1$.
L	Maximum inventory level or storage capacity.
R	Maximum life time of the item before complete deterioration occurs.
$Z_1(t)$	Inventory level during $[0, t_1]$, when items remain fresh with no deterioration.
$Z_2(t)$	Inventory Level during $[t_1, T]$, when deterioration starts and continues.
t_1	Time point separating fresh and deteriorating phases of inventory.
T	Total length of the inventory replenishment cycle.
TP	Total profit of inventory model, used as objective function.

Assumption

- The demand is considered to follow a quadratically growth pattern over time, expressed as $D(t) = (d_1 + d_1t + d_3t^2)$.

- The inventory management system drives over the finite planning prospect which is divided into two distinct phases. In $[0, t_1]$, all items are considered fresh and no deterioration takes place. After t_1 , deterioration begins in the on-hand inventory. Once deterioration starts, no repair, replenishment is permitted. The deterioration rate is time-dependent and defined as

$$\theta(t) = \frac{1}{1 + R - t}$$

Where R represented the maximum usable lifetime of the item.

- The system is designed such that shortages are not allowed under any circumstances, ensuring full demand fulfilment throughout the cycle.

MATHEMATICAL MODEL

The illustrated mathematical model represents a two-phase non-instantaneous deteriorating inventory model in which inventory depletion occurs continuously due to customer demand, while deteriorating begins only after a specified time t_1 . The horizontal axis indicates time t , whereas the vertical axis denotes the inventory level $Z(t)$. At the starting of cycle ($t = 0$), and the inventory attains its maximum height, represented by $Z_{max} = L$ (Fig.1).

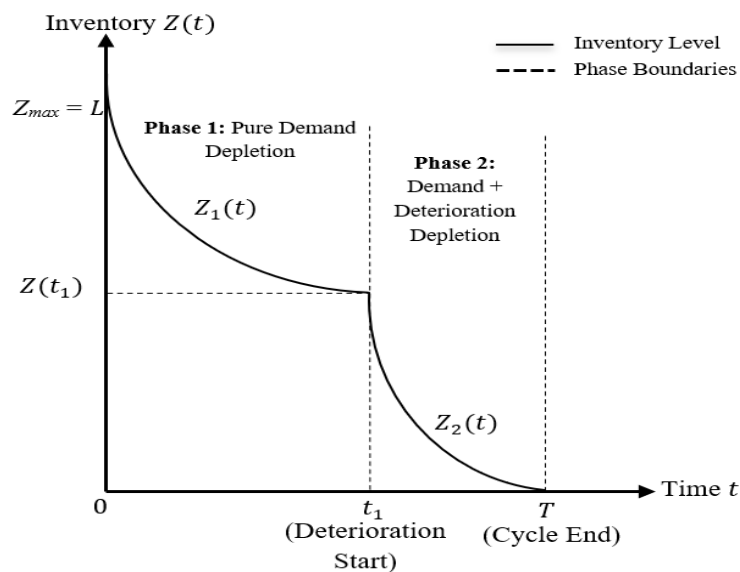


Fig.1. Graphically presentation of the developed inventory model

During Phase 1 ($0 \leq t \leq t_1$), the inventory declines exclusively because of market demand. In this interval, the items are assumed to retain their original quality and remain free from deterioration. Since, demand rate is considered time-varying and quadratic, inventory decreases as nonlinear manner, producing the smooth convex curve denoted by $Z_1(t)$. The stage is therefore mentioned to as the pure demand depletion phase and the ongoing reduction in the stock reflects the increasing impact of quadratic demand over the time. The instant $t = t_1$ marks the arrival of movement of deterioration and acts as the critical transition point separating the two phases of the inventory cycle. At this movement, the inventory level inception continuous and is represented by $Z(t_1)$.

In Phase 2 ($t_1 \leq t \leq T$), inventory depletion follows under the united influence of the demand and deterioration rate. Unlike the first phase, the products/ items are now begun to lose their efficacy or perish over time. Furthermore, the deterioration rate is presumed to be time-dependent and suggesting that the deterioration effect intensifies as time progresses. Consequently, the inventory level declined more rapidly, as illustrates by the steeper curve $Z_2(t)$. The stock eventually reaches zero at the time T , which represents the end of the refill cycle. Mathematically, the proposed model is governed by the two separate differential equations corresponding to the two phases: one describing demand-only depletion and the other integrating the both demand and deterioration effects. This inventory structure is particularly suitable for the deteriorating products as fresh food, pharmaceuticals, blood products, medicine. fashionable items, and other perishable commodities where the deterioration does not start immediately after refill but starts after the certain storage duration. Hence, the governing differential equations for interval ($0 \leq t \leq t_1$)

$$\frac{dZ_1(t)}{dt} = -(d_1 + d_2t + d_3t^2) \quad \dots (1)$$

And for another interval ($t_1 \leq t \leq T$)

$$\frac{dZ_2(t)}{dt} + \theta(t)Z_2(t) = -(d_1 + d_2t + d_3t^2) \quad \dots (2)$$

To obtain the inventory functions for the two phases of the replenishment cycle, the governing differential equations are solved subject to the boundary conditions $Z_1(0) = L$ and $Z_2(T) = 0$. Here, L represent the maximum initial inventory available at the creation of the cycle, whereas the condition $Z_2(t) = 0$ signifies that the inventory is completely exhausted at the terminal time T . by applying these boundary conditions to the respective differential equations, the analytical expressions describing the inventory levels during both the non-deterioration and deterioration phases over the entire planning horizon are derived as follows.

Solution of equation (1)

$$\int dZ_1(t) = - \int (d_1 + d_2t + d_3t^2) dt$$

$$Z_1(t) = - \left(d_1t + d_2 \frac{t^2}{2} + d_3 \frac{t^3}{3} \right) + C \quad \dots (3)$$

Now using boundary condition $Z_1(0) = L$,

$$Z_1(t) = - \left(d_1t + d_2 \frac{t^2}{2} + d_3 \frac{t^3}{3} \right) + L \quad \dots (4)$$

Solution of equation (2)

$$\frac{dZ_2(t)}{dt} + \left(\frac{1}{1+R-t} \right) Z_2(t) = -(d_1 + d_2t + d_3t^2)$$

Now the solution is

$$Z_2(t) \left(\frac{1}{1+R-t} \right) = - \int (d_1 + d_2t + d_3t^2) \left(\frac{1}{1+R-t} \right) dt$$

$$Z_2(t) \left(\frac{1}{1+R-t} \right) = (d_1 + d_2(1+R) + d_3(1+R)^2) (\log(1+R-t)) - (d_2 + d_3(1+R)) (1+R-t) + d_3 \frac{(1+R-t)^2}{2} + C \quad \dots (5)$$

Now applying boundary condition $Z_2(T) = 0$, put $t = T$ in equation (5)

$$Z(T) \left(\frac{1}{1+R-T} \right) = 0$$

$$0 = \left[\begin{array}{l} (d_1 + d_2(1+R) + d_3(1+R)^2) \log(1+R-T) \\ - (d_2 + 2d_3(1+R)) (1+R-T) \\ + \frac{d_3}{2} (1+R-T)^2 \end{array} \right] + C$$

By incorporating boundary condition $Z_2(T) = 0$ into the derived inventory model and determined the unknown constant C . The condition represents the depletion inventory stock at the end of refill cycle, thereby ensuring the validity and completeness of the obtained solution.

$$Z_2(t) = \left[\begin{array}{l} (d_1 + d_2(1+R) + d_3(1+R)^2)(1+R-t) \log \left(\frac{1+R-t}{1+R-T} \right) \\ + (d_2 + 2d_3(1+R)) (t-T)(1+R-t) \\ + d_3(1+R)(T-t)(1+R-t) \end{array} \right] \quad \dots (6)$$

Assuming that the inventory level function $Z(t)$ satisfies the continuity condition through critical time point $t = t_1$. Now inventory expressions corresponding to the two phases of the model become identical at this transition instant. Consequently, by applying Equations (4) & (6), the analytical expression for the maximum inventory level L is derived as follows.

$$Z_1(t) = Z_2(t)$$

Now from equation (4) & (6)

$$L = d_1 \left[t_1 + (1+R-t_1) \log \left(\frac{1+R-t_1}{1+R-T} \right) \right] + d_2 \left[\begin{array}{l} \frac{t_1^2}{2} + (1+R-t_1) \\ \left[(1+R) \log \left(\frac{1+R-t_1}{1+R-T} \right) + (t_1-T) \right] \end{array} \right]$$

$$+ d_3 \left[\frac{t_1^3}{3} + (1+R-t_1)(1+R) \left[(1+R) \log \left(\frac{1+R-t_1}{1+R-T} \right) + (t_1-T) \right] \right] \quad \dots (7)$$

The optimum profit per cycle consists of the resulting cost components. The ordering Cost incurred in each cycle is given by

$$OC = C_o \quad \dots (8)$$

The deterioration cost represents the loss incurred due to the spoilage or decay of items during the inventory cycle. Hence, the total deterioration cost per cycle is given by

$$DC = C_d \int_{t_1}^T \theta(t)I_2(t)dt$$

$$DC = C_d \left[\begin{aligned} &(d_1 + d_2(1 + R) + d_3(1 + R)^2) \\ &((1 + R)\log\left(\frac{1 + R - t_1}{1 + R - T}\right) + (t_1 - T)) \\ &+(d_2 + d_3(1 + R))(Tt_1 - \frac{t_1^2}{2} - \frac{T^2}{2}) \end{aligned} \right] \quad \dots (9)$$

The purchasing cost associated with acquiring inventory items during a single cycle is expressed as follows:

$$PC = C_p * L$$

From equation (7), we get

$$PC = C_p * \left[\begin{aligned} &d_1 \left[t_1 + (1 + R - t_1) \log\left(\frac{1 + R - t_1}{1 + R - T}\right) \right] \\ &+d_2 \left[\frac{t_1^2}{2} + (1 + R - t_1) \left((1 + R) \log\left(\frac{1 + R - t_1}{1 + R - T}\right) \right) + (t_1 - T) \right] \\ &d_3 \left[\frac{t_1^3}{3} + (1 + R - t_1)(1 + R) \left((1 + R) \log\left(\frac{1 + R - t_1}{1 + R - T}\right) \right) + (t_1 - T) \right] \end{aligned} \right] \quad \dots (10)$$

The Total Sales Revenue Cost Per Cycle is

$$SRC = C_s \int_0^T (d_1 + d_2t + d_3t^2) dt$$

$$SRC = S_1d_1T + (S_1d_2 - S_2d_1)\frac{T^2}{2} + (S_1d_3 - S_2d_2)\frac{T^3}{3} - S_2d_3\frac{T^4}{4} \quad \dots (11)$$

The holding cost associated with storing inventory items over a single cycle is expressed as follows:

$$HC = C_h * \left(\int_0^{t_1} Z_1(t)dt + \int_{t_1}^T Z_2(t)dt \right)$$

$$HC = C_h * \left[\begin{aligned} &\left\{ Lt_1 - \frac{d_1t_1^2}{2} - \frac{d_2t_1^3}{6} - \frac{d_3t_1^4}{12} \right\} \\ &+ \left\{ (d_1 + d_2(1 + R) + d_3(1 + R)^2) \frac{(1+R-t_1)^2}{2} \log\left(\frac{1+R-t_1}{1+R-T}\right) \right\} \\ &+ (T - t_1) \left\{ \left(\frac{d_1+d_2(1+R)+d_3(1+R)^2}{4} \right) (T + t_1) - 2K \right\} \\ &+ (T - t_1)(d_2 + d_3(1 + R)) \left\{ -\frac{1}{3}(T^2 + t_1^2 + Tt_1) + Kt_1 + \frac{T}{2}(T + t_1) \right\} \\ &- (d_2 + d_3(1 + R)) \frac{KT^2}{2} \end{aligned} \right] \quad \dots (12)$$

Optimum profit TP/cycle/unit time is

$$TP = \frac{1}{T} [SRC - OC - HC - DC - PC] \quad \dots (13)$$

To obtain the optimal cycle T^* , total present value of profit must be maximized and achieve this, profit function TP is differential with respect to T ,

$$\frac{dTP}{dT} = 0 \quad \dots (14)$$

The second-order condition for a maximum requires that:

$$\frac{d^2TP}{dT^2} < 0 \dots (15)$$

Since profit function is vastly non-linear, optimal solution of inventory model cannot be obtained analytically. Therefore, a developed solution procedure is employed to determine the maximum profit.

NUMERICAL EXAMPLE

To demonstrate the proposed solution procedure, consider the following numerical illustration: $C_o = 1000$, $S_1 = 180$, $S_2 = 1.1$, $C_p = 140$, $C_h = 0.12$, $C_d = 0.08$, $R = 50$, $t_1 = 0.5$, $d_1 = 2000$, $d_2 = 100$, $d_3 = 10$. By employing the developed optimization technique, the optimal ordering cycle is obtained as $T^* = 4.64$. Consequently, the corresponding optimal values of profit and inventory level are evaluated as $TP^* = 82,436$ and $L^* = 38956$ respectively. These results, obtained under varying parameter settings, are systematically presented in Table 1 for comparison and analysis. The following graph represents the relation between Total profit and time t_2 (Fig.2).

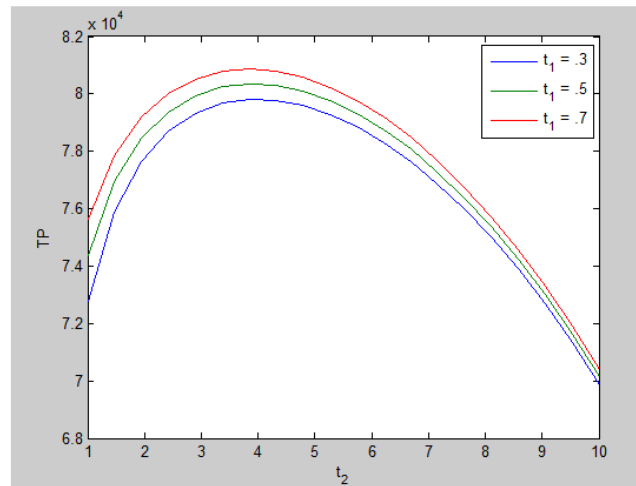


Fig. 2 Graphical representation of TP with t_2

II. CONCLUSION

The present study develops a mathematical model with non-instantaneous declining products through a time-varying deterioration rate under a quadratic demand pattern varying with time. Unlike conventional inventory models that assume a constant deterioration rate, the suggested model reflects more realistic inventory situation in which products deteriorate gradually over time due to their finite shelf life and aging characteristics. The proposed model incorporates varying demand and deterioration behaviour to obtain an effective replenishment policy for maximizing system performance. Numerical illustration is supported to examine the possessions of significant inventory constraints on the optimum inventory decisions and total system profit. The further findings show that the proposed model provides more applied and efficient tactics for inventory decision-making under realistic market conditions. Also, the developed model can be prolonged by integrating the additional factors as AI driven demand, inflation, probabilistic deterioration, partial backlogging, two-warehouse systems, and trade credit policies to augment its applicability in the modern supply chain and inventory management systems.

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