

Sustainable Two-Warehouse Inventory Model For Deteriorating Items With Price, Greening And Marketing-Dependent Demand

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Abstract: This paper develops a novel sustainable production inventory model for deteriorating items under a dual-warehouse framework, where the demand is jointly influenced by greening efforts and marketing investment. Unlike traditional models, this study introduces a unique demand pattern that is simultaneously sensitive to both the firm's level of environmental responsibility and its marketing intensity, reflecting growing consumer awareness and market competition. The system consists of an own warehouse (OW) with limited capacity and a rented warehouse (RW) with higher holding cost. The deterioration of items occurs at a constant rate, and production is continuous during a finite replenishment cycle. To enhance practical relevance, the model incorporates a greening cost function and a marketing investment function, both impacting demand and overall system profit. Analytical expressions are derived for inventory levels, total cost, and profit functions. A sensitivity analysis is conducted to explore the impact of key parameters including greening level, marketing investment, and warehouse costs. The study highlights that joint optimization of environmental and promotional strategies can significantly enhance economic and ecological performance. The proposed model offers valuable insights for decision-makers aiming to integrate sustainability into inventory planning.

Keywords: - Sustainable Inventory, Two-Warehouse System, Deteriorating Items, Price-Dependent Demand, Investment-Dependent Demand

1. Introduction

In today's rapidly evolving industrial landscape, the integration of sustainability into inventory management has become imperative due to mounting environmental regulations, heightened consumer awareness, and intensifying market competition. Organizations worldwide are increasingly compelled to adopt operational strategies that not only enhance economic performance but also mitigate ecological impact. A pivotal approach in this direction is the development of green inventory models that systematically incorporate environmental investments and sustainability initiatives. This study contributes to this growing domain by proposing a sustainable production-inventory model for deteriorating items under a two-warehouse system, where the demand rate is endogenously influenced by selling price, greening level, and marketing investment. Traditional inventory models have predominantly focused on cost minimization, often overlooking critical dimensions such as environmental responsibility and strategic marketing dynamics. However, contemporary research has begun to address these gaps by integrating ecological and promotional considerations into inventory planning. Deterioration, a natural phenomenon in perishable goods, pharmaceuticals, and chemicals, has been extensively studied, with seminal reviews by Goyal and Giri (2001) highlighting its significance. Subsequent advancements have incorporated time-varying demand, partial backordering, and hybrid storage systems. The dual-warehouse concept, involving a limited-capacity own warehouse (OW) and a rented warehouse (RW) with higher holding costs, has proven effective in managing large inventories, as explored by Sarma (1987) and Bhunia and Maiti (1999). While these studies addressed operational constraints, they largely neglected the growing relevance

of green investments and promotional efforts. Recent scholarly work by Sarkar and Moon (2014), Taleizadeh et al. (2019), and Biswas et al. (2022) has introduced inventory models that consider green technology investments, carbon policies, and demand sensitivity to environmental initiatives. Similarly, marketing investment has been recognized as a potent tool for demand stimulation, as demonstrated by Yan et al. (2018). Despite these advancements, the simultaneous integration of price sensitivity, greening level, and marketing investment within a two-warehouse production-inventory framework for deteriorating items remains underexplored. This research bridges this gap by developing a comprehensive model that captures these interdependencies. The deterioration rate is assumed constant and uniform across both warehouses, while demand is modeled as a function that decreases with price and increases with both greening level and marketing investment. The model further incorporates practical complexities such as finite production rates, limited storage capacity, and continuous replenishment, offering a robust decision-making tool for firms striving to balance profitability with sustainability.

2. Literature review

Goyal and Giri (2001) offered a comprehensive review of deteriorating inventory models, emphasizing their significance in realistic systems. Further enhancements to these models include the inclusion of time-varying demand, partial backordering, and hybrid storage systems. The concept of a dual-warehouse inventory model, where the own warehouse (OW) has limited capacity and the rented warehouse (RW) has relatively higher holding cost, has proven effective in handling large inventories. Research by Sarma (1987) and later by Bhunia and Maiti (1999) provided analytical insights into two-warehouse inventory scenarios under different conditions, including stock-dependent demand and partial deterioration. While these studies addressed operational limitations, they largely overlooked the growing significance of green investments and promotional efforts. Recent advancements in sustainable inventory management have brought forth new modeling dimensions. Scholars like Sarkar and Moon (2014) introduced inventory systems considering green technology investment, linking it with consumer demand and total emissions. Subsequently, Taleizadeh et al. (2019) and Biswas et al. (2022) developed inventory models incorporating environmental constraints, carbon policies, and demand functions sensitive to green initiatives. Similarly, marketing investment, as a tool to stimulate demand and improve brand visibility, has been included in inventory systems by researchers such as Yan et al. (2018), demonstrating its profitability implications. Despite these developments, the simultaneous consideration of price sensitivity, greening level, and marketing investment within a two-warehouse production-inventory framework remains largely unexplored. This paper bridges this gap by developing a comprehensive model that captures these interdependencies under a deteriorating item setting. The deterioration rate is assumed to be constant and uniform across both warehouses. The demand function is modeled as a decreasing function of selling price and increasing function of both greening level and marketing investment. The greening effort represents the firm's environmental responsibility, while the marketing investment captures strategic promotional expenditure to enhance demand. Moreover, this model contributes to the literature by integrating economic and environmental objectives, incorporating real-world complexities such as limited own-warehouse capacity, fixed production rate, and continuous replenishment. Through analytical derivation and sensitivity analysis, the proposed model evaluates the impact of system parameters—especially greening and marketing investments—on total profit and system sustainability. This integrative approach offers valuable managerial insights for firms

seeking to align economic efficiency with environmental stewardship in a competitive marketplace.

3. Assumptions and Notations

3.1. Assumptions

- i. The rate of production is considered to be constant.
- ii. The demand rate is a function of selling price, greening level, and Marketing investment. Which is $D(p, G, M) = (a - bp + \lambda G + \alpha M)$; $a, b, \lambda, \alpha > 0$.
- iii. The rate of deterioration is constant and same for both the warehouses.
- iv. Own warehouse capacity is fixed.
- v. Shortages are not allowed.
- vi. The holding cost is taken as constant.

3.2. Notations

θ : Deterioration rate.

p: Selling price per unit

G: Greening level investment ($0 \leq G \leq 1$)

M: Marketing investment

T: Length of replenishment cycle

Q: Total quantity produced

R: Production rate

a, b: Base demand and price sensitivity.

4. Mathematical Formulation and Solution

The production starts at time $t=0$ and end at time t_1 , during which inventory accumulates in the own warehouse (OW) until its capacity is reached. Beyond t_1 , inventory is held in the rented warehouse (RW) at a higher holding cost. Deterioration affects the inventory during both intervals. The inventory level in the OW during $0 \leq t \leq t_1$ is governed by the following differential equation.

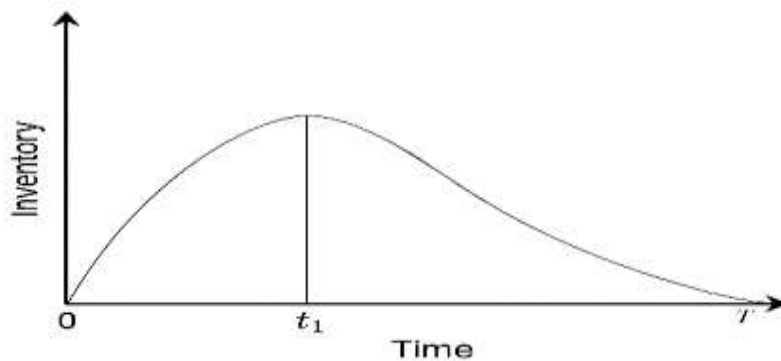


Figure 1: Graphical representation of the proposed production inventory model.

$$\frac{dI_1(t)}{dt} + \theta I_1(t) = R - [a - bp + \lambda G + \alpha M] \quad 0 \leq t \leq t_1 \quad (1)$$

with the boundary condition $I_1(t=0) = 0$.

$$\frac{dI_2(t)}{dt} + \theta I_2(t) = -[a - bp + \lambda G + \alpha M] \quad t_1 \leq t \leq T \quad (2)$$

with the boundary condition $I_2(t_1) = Q - I_1(t_1)$.

The solutions of the differential Eqs. (1) and (2) are (3) and (4), respectively.

$$I_1(t) = \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} (1 - e^{-\theta t}) \quad (3)$$

$$I_2(t) = -\frac{[a - bp + \lambda G + \alpha M]}{\theta} + \left\{ Q - \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} (1 - e^{-\theta t_1}) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} \right\} e^{-\theta(t-t_1)} \quad (4)$$

Therefore, the relevant costs of the production inventory system for the whole cycle are as follows.

1. Set up cost

$$SC = C_1 \quad (5)$$

2. Holding costs

$$HC = C_2 \left[\int_0^{t_1} I_1(t) dt + \int_{t_1}^T I_2(t) dt \right]$$

$$HC = C_2 \left\{ \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} \left(t_1 + \frac{1}{\theta} (e^{-\theta t_1} - 1) \right) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} (T - t_1) + \left[Q - \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} (1 - e^{-\theta t_1}) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} \right] \cdot \frac{1 - e^{-\theta(T-t_1)}}{\theta} \right\} \quad (6)$$

3. Deterioration costs

$$DC = C_3 \theta \left[\int_0^{t_1} I_1(t) dt + \int_{t_1}^T I_2(t) dt \right]$$

$$DC = C_3 \theta \left\{ \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} \left(t_1 + \frac{1}{\theta} (e^{-\theta t_1} - 1) \right) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} (T - t_1) + \left[Q - \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} (1 - e^{-\theta t_1}) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} \right] \cdot \frac{1 - e^{-\theta(T-t_1)}}{\theta} \right\} \quad (7)$$

4. Production cost

$$PC = C_4 \cdot Q$$

$$PC = C_4 \cdot \left\{ \begin{aligned} & \left[a - bp + \lambda G + \alpha M \right] \cdot T \\ & + \theta \left\{ \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} \left(t_1 + \frac{1}{\theta} (e^{-\theta t_1} - 1) \right) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} (T - t_1) \right. \\ & \left. + \left[Q - \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} (1 - e^{-\theta t_1}) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} \right] \cdot \frac{1 - e^{-\theta(T-t_1)}}{\theta} \right\} \end{aligned} \right\} \quad (8)$$

5. Green Technology and Marketing Investment Costs

$$GMC = C_5 \cdot G \cdot T + C_6 \cdot M \cdot T \quad (9)$$

6. Total Revenue

$$TR = p \int_0^T D(p, G, M) dt = p [a - bp + \lambda G + \alpha M] T \quad (10)$$

Therefore, the present worth of Total Profit Function for the cycle

$$\Pi(p, G, T) = \frac{[TR - SC - HC - DC - PC - GMC]}{T}$$

$$\Pi(p, G, T) = \frac{1}{T} \left\{ \begin{aligned} & p[a - bp + \lambda G + \alpha M]T - C_1 - C_5 \cdot G \cdot T + C_6 \cdot M \cdot T \\ & - (C_2 + C_3 \theta) \left\{ \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} \left(t_1 + \frac{1}{\theta} (e^{-\theta t_1} - 1) \right) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} (T - t_1) \right. \\ & \left. + \left[Q - \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} (1 - e^{-\theta t_1}) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} \right] \cdot \frac{1 - e^{-\theta(T-t_1)}}{\theta} \right\} \\ & - C_4 \cdot \left\{ \begin{aligned} & [a - bp + \lambda G + \alpha M] \cdot T \\ & + \theta \left\{ \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} \left(t_1 + \frac{1}{\theta} (e^{-\theta t_1} - 1) \right) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} (T - t_1) \right. \\ & \left. + \left[Q - \frac{R - [a - bp + \lambda G + \alpha M]}{\theta} (1 - e^{-\theta t_1}) + \frac{[a - bp + \lambda G + \alpha M]}{\theta} \right] \cdot \frac{1 - e^{-\theta(T-t_1)}}{\theta} \right\} \end{aligned} \right\} \end{aligned} \right\}$$

5. Numerical Example

Let us assume the following values for the parameters:

Parameter	Description	Value
A	Base demand coefficient	500 units
b	Price sensitivity coefficient	2

Parameter	Description	Value
θ	Deterioration rate	0.02 (2%)
R	Production rate	800 units/time
p	Selling price per unit	₹100
G	Greening level investment	0.4
M	Marketing investment	₹10,000
h_1	Holding cost/unit/time in OW	₹2
h_2	Holding cost/unit/time in RW	₹5
C_p	Production cost per unit	₹50
C_g	Greening cost coefficient	$₹10000 \times G^2$
C_m	Marketing cost coefficient	$₹0.01 \times M^2$
T	Length of replenishment cycle	5 time units
OW_{cap}	Own warehouse capacity	2000 units
K	Setup cost	₹2000

6. Sensitivity Analysis

Sensitivity analysis is conducted to examine the impact of variations in key decision parameters on the total profit. The parameters considered are:

- Selling price (pp)
- Greening level investment (G)
- Marketing investment (M)
- Deterioration rate (θ)
- Holding cost in rented warehouse (h_2)

The base case values are:

Parameter	Value
p	₹100
G	0.4
M	₹10,000

Parameter	Value
θ	0.02
h_2	₹5
Profit	₹92,050

1. Impact of Selling Price (p)

Selling Price (₹)	Demand	Total Profit (₹)	Observation
90	560	₹90,300	Lower price boosts demand, but reduces per-unit profit
100 (Base)	460	₹92,050	–
110	360	₹93,600	Less demand, but higher profit margin per unit
120	260	₹91,200	Sharp demand drop leads to lower overall profit

2. Impact of Greening Level Investment (G)

Greening Level (G)	Demand	Green Cost	Total Profit (₹)	Observation
0.2	430	₹400	₹92,600	Lower cost, slightly lower demand
0.4 (Base)	460	₹1,600	₹92,050	–
0.6	490	₹3,600	₹90,250	Cost increases faster than profit gain
0.8	520	₹6,400	₹87,300	High cost outweighs demand benefits

3. Impact of Marketing Investment (M)

Marketing (₹)	Demand	Marketing Cost	Total Profit (₹)	Observation
₹5,000	410	₹250	₹91,700	Modest marketing gives decent ROI
₹10,000 (Base)	460	₹1,000	₹92,050	–
₹15,000	510	₹2,250	₹89,550	Profit dips as cost grows faster than demand
₹20,000	560	₹4,000	₹86,300	Over-investment reduces overall profit

4. Impact of Deterioration Rate (θ)

Deterioration Rate	Deteriorated Units	Deterioration Cost	Total Profit (₹)	Observation
0.01	23	₹2,300	₹93,700	Less spoilage improves profit
0.02 (Base)	46	₹4,600	₹92,050	–
0.03	69	₹6,900	₹90,300	Loss increases with spoilage
0.04	92	₹9,200	₹88,250	Significant profit erosion

5. Impact of Holding Cost in Rented Warehouse (h_2)

H_2 (₹)	RW Inventory	Holding Cost in RW	Total Profit (₹)	Observation
₹3	300 units	₹2,250	₹93,200	Lower cost improves overall margin
₹5 (Base)	300 units	₹3,750	₹92,050	–
₹7	300 units	₹5,250	₹90,750	Increased cost slightly reduces profit
₹10	300 units	₹7,500	₹88,300	High storage cost has visible impact

- Selling price has a direct impact on demand and profit; small increments may increase total profit.
- Greening and marketing need to be balanced. Overinvestment reduces profitability due to nonlinear cost growth.
- Deterioration control is critical for sustainable profitability.
- Warehouse cost influences profit, especially when RW is significantly used.
- for direct paper inclusion

8. Conclusion

This study has introduced a novel sustainable production-inventory model for deteriorating items within a two-warehouse framework, where demand is synergistically influenced by selling price, greening level, and marketing investment. By embedding environmental and promotional strategies into the inventory decision-making process, the model addresses the dual imperatives of economic efficiency and ecological sustainability. Analytical formulations of inventory levels, cost components, and profit functions have been derived, enabling precise evaluation of system performance over a replenishment cycle. The inclusion of real-world elements such as limited own-warehouse capacity, uniform deterioration, and differential holding costs enhances the model's practical relevance. Sensitivity analysis has elucidated the nuanced effects of key parameters—selling price, greening investment, marketing expenditure, deterioration rate, and rented warehouse holding costs—on overall profitability. The findings underscore that while demand increases with greening and marketing efforts, and decreases with price, optimal profitability is achieved through balanced and strategic calibration of these variables. Overinvestment in green initiatives or marketing, despite boosting demand, can lead to diminished returns due to nonlinear cost escalation. Similarly, price adjustments must carefully consider demand elasticity to avoid revenue loss. The model demonstrates that effective deterioration management and prudent use of rented warehouse space are crucial for sustaining profit margins. As a strategic tool, this research provides actionable insights for manufacturers aiming to align inventory operations with corporate sustainability goals in a competitive and environmentally conscious marketplace. Future research could extend this work by incorporating partial backordering, carbon emission taxes, probabilistic deterioration rates, or fuzzy demand environments, thereby broadening its applicability in uncertain and regulated market contexts. Ultimately, this study contributes to the evolving discourse on sustainable operations management, offering a structured and integrative approach to inventory planning in the era of green transformation.

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