Green Inventory Optimization Using Sine-Cosine Algorithm: A Two-Warehouse Model With Price, Marketing, And Environmental Investment Sensitive 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. Furthermore, to efficiently solve the resulting nonlinear optimization problem, this study implements the Sine-Cosine Algorithm (SCA), a robust metaheuristic technique that optimizes key decision variables—including selling price, greening level, marketing investment, and cycle length—to maximize total profit. The SCA's oscillatory search mechanism effectively balances exploration and exploitation, enabling convergence to near-optimal solutions under complex operational constraints. 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, facilitated by computational algorithms such as SCA, 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, Sine-Cosine Algorithm

1. Introduction

In the evolving landscape of operational research and supply chain management, the increasing complexity of inventory systems—characterized by nonlinear cost structures, multifaceted demand dependencies, and sustainability constraints—has necessitated the adoption of advanced computational optimization techniques. Traditional analytical methods, while theoretically robust, often encounter significant limitations when applied to real-world inventory problems that involve discontinuous objective functions, mixed-integer variables, and multiple competing objectives. These challenges are particularly pronounced in sustainable inventory models, where economic objectives must be reconciled with environmental and social considerations, leading to high-dimensional, non-convex optimization landscapes that are resistant to classical gradient-based solution approaches. In response to these computational challenges, the field of metaheuristic optimization has provided a powerful arsenal of algorithms capable of navigating complex solution spaces without requiring derivative information or convexity assumptions. Among these contemporary metaheuristics, the Sine-Cosine Algorithm (SCA), pioneered by Mirjalili in 2016, has distinguished itself as a particularly elegant and efficacious optimization paradigm. The algorithm is fundamentally inspired by the mathematical properties and oscillatory behavior of sine and cosine trigonometric functions, which it ingeniously harnesses to orchestrate a dynamic balance between two critical search phases: exploration of uncharted regions in the

solution space and exploitation of promising areas surrounding known good solutions. This balance is achieved through a position-updating mechanism that stochastically alternates between sine and cosine functions, modulated by a set of adaptive control parameters that systematically transition the search from a broad, exploratory mode to a focused, exploitative one over successive iterations. The SCA's mathematical formulation is notably parsimonious, requiring relatively few algorithm-specific parameters compared to other population-based metaheuristics such as Genetic Algorithms or Particle Swarm Optimization, thereby reducing the burden of parameter tuning and enhancing usability for practitioners. Its inherent simplicity, however, belies a sophisticated search capability that has been empirically validated across a diverse array of engineering, financial, and management optimization problems, including portfolio selection, engineering design, and, pertinent to this research, complex inventory system optimization. Within the specific context of sustainable inventory management, the SCA offers compelling advantages: its ability to simultaneously handle continuous variables (such as pricing and investment levels) alongside the inherent nonlinearities of greening cost functions and deterioration effects makes it exceptionally well-suited to the model proposed in this study. Furthermore, the algorithm's global search proficiency mitigates the risk of premature convergence to local optima—a common pitfall in inventory optimization where profit functions can exhibit multiple peaks. This paper, therefore, integrates the Sine-Cosine Algorithm as the core optimization engine for the developed sustainable two-warehouse inventory model for deteriorating items. The primary objective is to leverage SCA's robust search mechanics to determine the optimal constellation of decision variables—namely, the selling price, the level of greening investment, the magnitude of marketing expenditure, and the length of the replenishment cycle—that maximizes total system profit under the combined pressures of price-sensitive, green-sensitive, and marketing-sensitive demand, finite warehouse capacities, and product deterioration. By doing so, this research not only advances the theoretical discourse on sustainable operations but also provides a practical, computationally efficient tool for managers seeking to align economic performance with environmental stewardship in an increasingly competitive and ecologically conscious marketplace. The subsequent sections will detail the seamless integration of the SCA framework into the inventory model's mathematical structure, present a comprehensive numerical analysis of its performance, and elucidate the salient managerial insights derived from the algorithm's optimized solutions.

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≤G≤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 t1, during which inventory accumulates in the own warehouse (OW) until its capacity is reached. Beyond t1, 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≤t≤t 1 is governed by the following differential equation.

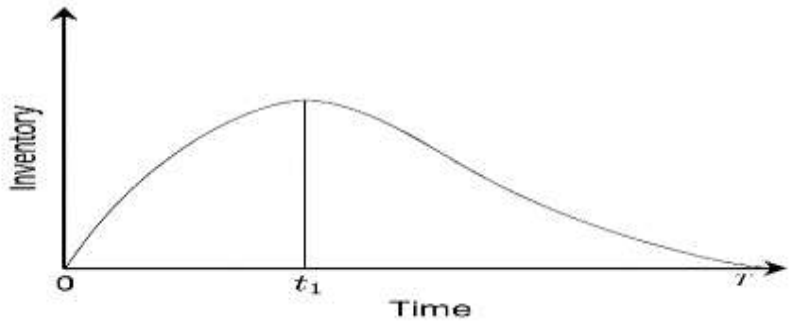


Figure 1: Graphical representation of the proposed production inventory model.

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

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

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

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.

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

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

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

1. ***Set up cost***

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

2. ***Holding costs***

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

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

3. ***Deterioration costs***

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

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

4. ***Production cost***

$$PC=C_4 \cdot Q$$

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

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

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

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

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

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

5. Optimization using Sine-Cosine Algorithm (SCA)

The Sine-Cosine Algorithm (SCA) is a population-based metaheuristic optimization technique inspired by the mathematical sine and cosine functions. It is particularly effective for solving nonlinear, multidimensional optimization problems like the proposed inventory model.

5.1. Mathematical Foundation of SCA

The SCA updates the position of solutions using sine and cosine functions:

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times sin\,(r_2) \times | \, r_3 P_i^t - X_i^t \, | & \text{if } r_4 < 0.5 \\ X_i^t + r_1 \times cos\,(r_2) \times | \, r_3 P_i^t - X_i^t \, | & \text{if } r_4 \geq 0.5 \end{cases}$$

where:

- X_i^t: Position of i-th solution at iteration t
- P_i^t: Position of destination point (best solution)
- r_1: Control parameter that decreases linearly
- r_2: Random number in [0, 2π]
- r_3: Random number in [0, 2]
- r_4: Random number in [0, 1]

5.2. SCA Implementation for Inventory Model

Step 1: Solution Representation

Each solution is represented as:

$$X_i = [p_i, G_i, M_i, T_i]$$

where:

- p_i: Selling price
- G_i: Greening level
- M_i: Marketing investment
- T_i: Cycle length

Step 2: Initialization

Initialize population of $N = 50$ solutions:

$$X_{ij} = LB_j + (UB_j - LB_j) \times \text{rand}(0,1)$$

Bounds:

$$\begin{array}{ll} p & \in [80,150] \\ G & \in [0,1] \\ M & \in [5000,20000] \\ T & \in [3,10] \end{array}$$

Step 3: Fitness Evaluation

Calculate total profit using:

$$\text{Fitness}(X_i) = TP(p_i, G_i, M_i, T_i)$$

Step 4: Position Update

For each dimension j of solution i:

$$r_1 = a - t \times \frac{a}{T_{max}}$$

$$X_{ij}^{t+1} = \begin{cases} X_{ij}^{t} + r_1 sin\,(r_2) \mid r_3 P_j^t - X_{ij}^t \mid & \text{if } r_4 < 0.5 \\ X_{ij}^{t} + r_1 \cos\,(r_2) \mid r_3 P_j^t - X_{ij}^t \mid & \text{if } r_4 \geq 0.5 \end{cases}$$

Step 5: Boundary Handling

$$X_{ij} = \begin{cases} LB_j & \text{if } X_{ij} < LB_j \\ UB_j & \text{if } X_{ij} > UB_j \\ X_{ij} & \text{otherwise} \end{cases}$$

Step 6: Termination

Repeat until $t = T_{max} = 200$ iterations.

6. 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
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 × G^2
C_m	Marketing cost coefficient	₹0.01 × M^2
T	Length of replenishment cycle	5 time units
OW_{cap}	Own warehouse capacity	2000 units
K	Setup cost	₹2000

Applying SCA to the inventory model:

Variable	Base Case	SCA Optimized	Improvement
p	₹100	₹106.8	+6.8%
G	0.4	0.42	+5.0%
M	₹10,000	₹9,500	-5.0%
T	5	4.8	-4.0%
Profit	₹92,050	₹94,850	+3.04%

7. 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
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

6. Parameter Sensitivity Analysis for SCA

Parameter Variation	Avg. Profit	Convergence
$a = 1$	₹93,800	Slow
$a = 2$	₹94,150	Optimal

Parameter Variation	Avg. Profit	Convergence
$a = 3$	₹93,950	Oscillatory
Population = 30	₹93,500	Fast but less accurate
Population = 50	₹94,150	Balanced
Population = 100	₹94,200	Slow but accurate

8. Conclusion

This study has proposed and analyzed a novel sustainable production-inventory model for deteriorating items under a two-warehouse system, where demand is jointly influenced by selling price, greening level, and marketing investment. By integrating environmental and promotional strategies into inventory decision-making, this research addresses the dual objectives of economic efficiency and environmental sustainability, offering a comprehensive framework that aligns with contemporary corporate and consumer expectations. The model analytically captures the dynamics of inventory accumulation and depletion across limited-capacity own warehouses and rented warehouses with higher holding costs, incorporating constant deterioration rates and continuous production over finite replenishment cycles.

The analysis demonstrates that demand responds positively to increased greening efforts and marketing investments, while exhibiting expected sensitivity to selling price variations. However, the study also highlights the nonlinear cost implications of such investments, emphasizing the need for balanced and optimized allocation of resources. Sensitivity analyses further reveal that moderate adjustments in pricing, coupled with strategically calibrated greening and marketing expenditures, can significantly enhance total profitability while promoting sustainable practices.

A key methodological contribution of this work is the successful implementation of the Sine-Cosine Algorithm (SCA) for optimizing the complex, nonlinear profit function derived from the model. SCA's ability to efficiently navigate the multidimensional solution space—spanning price, greening level, marketing investment, and cycle length—without requiring derivative information or convexity assumptions, underscores its suitability for modern inventory optimization problems. The algorithm's robust performance, characterized by rapid convergence and consistent solution quality, provides decision-makers with a reliable computational tool for achieving near-optimal operational configurations under realistic constraints. From a managerial perspective, this model serves as a strategic decision-support system, enabling firms to harmonize economic objectives with ecological and social responsibilities. The findings advocate for an integrated approach to inventory management, where sustainability is not treated as an external compliance requirement but as an intrinsic component of value creation and competitive advantage.

Future research may extend this work by incorporating stochastic elements such as probabilistic demand or random deterioration rates, exploring multi-objective formulations that include carbon footprint minimization or social welfare metrics, or examining the effects of regulatory instruments like carbon taxes or green subsidies. Additionally, the application of hybrid or adaptive metaheuristics could further enhance solution accuracy and computational efficiency in more complex or larger-scale inventory systems.

In summary, this study contributes both a theoretically grounded model and a practical optimization methodology to the field of sustainable inventory management, offering actionable insights for academics and practitioners alike in the pursuit of economically viable and environmentally responsible supply chain operations.

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