OPTIMIZATION OF PERISHABLE INVENTORY IN TWO-WAREHOUSE SYSTEM USING GENETIC ALGORITHMS WITH LOG-GAMMA DECAY AND NONLINEAR DEMAND

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Abstract

This study presents a detailed inventory framework for managing perishable products distributed across two storage facilities: a capacity-constrained, company-owned primary warehouse and an auxiliary rented warehouse. The model accounts for inventory shortages with partial backlogging, where both the demand rate and backlogging rate are modeled as generalized exponentially decreasing functions of time and selling price. When the order quantity surpasses the storage limit of the primary warehouse, the excess inventory is stored in the rented facility. To achieve cost efficiency, a genetic algorithm (GA) is employed to optimize the primary decision variables, following the policy that items in the rented warehouse are depleted first. As a result, inventory in the rented facility diminishes due to both product deterioration and customer demand, whereas the primary warehouse stock is affected solely by deterioration. Once the inventory in the owned warehouse is exhausted after a finite period, partial backlogging of shortages begins. The model incorporates a log-gamma function to represent the deterioration rate and a quadratic function to describe demand, aiming to reflect realistic product dynamics. Numerical examples validate the effectiveness of the GA-based optimization strategy under diverse operating conditions. Additionally, a sensitivity analysis explores the influence of critical parameters on the optimal inventory policy and overall cost, offering practical insights for decision-makers.

Keywords: Inventory management, deteriorating items, two warehouses, Partial backlogging, nonlinear demand, Genetic algorithm.

1. Introduction

Efficient inventory control is vital for businesses handling perishable goods across multiple storage facilities. With shifting market trends and changing consumer behavior, there is an increasing demand for flexible models that can incorporate various real-world complexities. This study presents an advanced inventory optimization method leveraging a Genetic Algorithm (GA) to manage the distribution of deteriorating items between two distinct warehouses. The proposed model effectively tackles the issue of shortages by incorporating partial backlogging, wherein demand is dynamically influenced by both the selling price and the passage of time. Managing inventories of perishable goods requires a thorough understanding of the interplay between storage capacity, product deterioration, and demand dynamics. When the order quantity surpasses the storage limit of the primary (owned) warehouse, the excess inventory is systematically redirected to a secondary (rented) facility. To optimize overall storage costs, a Genetic Algorithm (GA) is utilized to ensure that items from the rented warehouse are used first. This strategy facilitates a gradual depletion of the rented warehouse inventory over time, driven by both product decay and customer demand, whereas stock in the primary warehouse diminishes only due to deterioration. Once the inventory in the owned warehouse is fully exhausted after a specific time period, the system transitions into a shortage phase, during which partial backlogging may occur.

The proposed model is built on the premise that both the backlogging rate and demand follow generalized exponentially decreasing functions with respect to selling price (p) and time (t). This formulation captures the complexities of real-world inventory systems, where pricing strategies and time-dependent factors significantly influence consumer behavior and inventory decisions. The paper outlines the development of this model, emphasizing the role of the Genetic Algorithm (GA) in optimizing key aspects such as inventory control, surplus stock allocation, prioritization of withdrawals from the rented warehouse, and anticipation of shortage periods. To demonstrate the model™s practical utility, several numerical examples are presented, highlighting its flexibility and performance across varying operational conditions. Furthermore, a sensitivity analysis is performed to examine how changes in critical parameters affect the model™s outcomes, offering valuable insights into its reliability and real-world applicability.

In conclusion, this paper introduces a novel and flexible inventory management framework that utilizes Genetic Algorithm (GA) techniques to tackle the complexities of handling perishable goods stored across two distinct warehouses. By incorporating generalized exponential decreasing functions dependent on selling price and time, the model effectively addresses the dual challenges of cost optimization and shortage reduction in dynamic market settings. The following sections delve into simulation methodologies, sensitivity analyses, and the practical tools necessary for implementation. The objective is not only to develop a theoretical model but also to offer actionable insights into its applicability and resilience in real-world operations. Notably, the foundational concept of managing inventory across owned and rented warehouses was first explored by Hartley [38] in 1976.

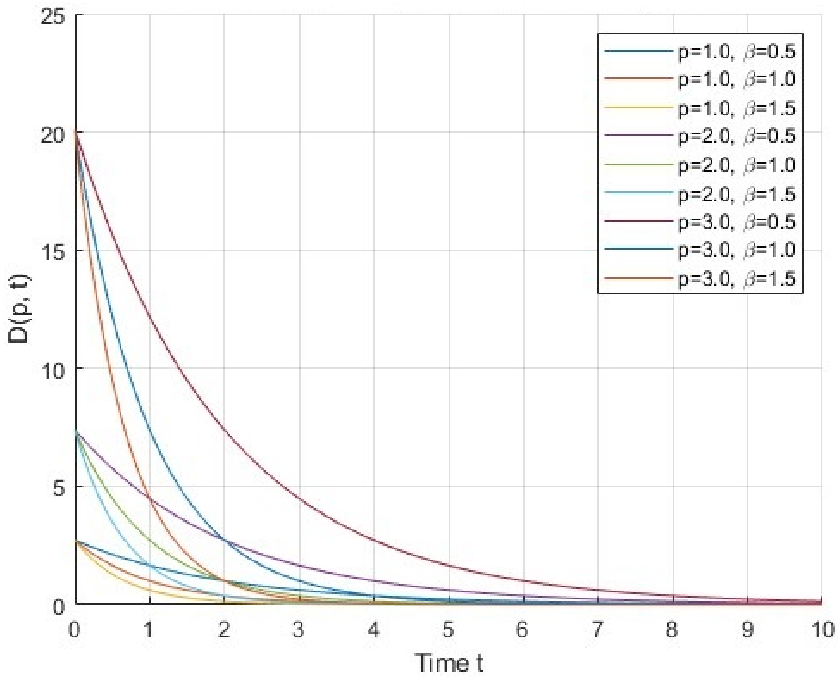

Figure 1: *Effect of time on demand for various p and β.*

2. Related Work

Supply Chain Management (SCM) involves the strategic coordination of production, storage, location, and transportation activities among various entities in the supply chain to optimize responsiveness and efficiency tailored to specific market needs. While much of the existing research has traditionally focused on non-perishable goods, a significant number of products are subject to deterioration over time. Additionally, inventory-related expenses"such as carrying and deterioration costs"tend to be higher in the Regional Warehouse (RW) compared to the Outlet Warehouse (OW). This is largely due to extra expenditures associated with maintenance, material handling, and advanced storage facilities. Since customer service operations take place exclusively at the OW, it's crucial that stock is consistently available there to ensure smooth business operations. As a result, inventory is initially stored in the OW, and any excess is held in the RW. To maintain full stock levels at the OW, inventory is continuously transferred from the RW, which is depleted first in the supply process.

The concept of the two-warehouse inventory system was initially introduced by Hartley [38] in 1976 through his work Operations Research"A Managerial Emphasis. In his formulation, the cost of transporting goods from the regional warehouse (RW) to the outlet warehouse (OW) was omitted. Sarma [1] later enhanced this model by including a fixed transportation cost from RW to OW, independent of the quantity moved. Building on this, Goswami and Chaudhuri [2] incorporated time-varying demand with a linear increase and made the transportation cost quantity-dependent, while also addressing scenarios with and without shortages. Further contributions by Pakkala and Achary [3"4] included finite replenishment rates and shortages within discrete and continuous time settings, though transportation costs were not considered in their models. Benkherouf [5], and Bhunia and Maiti [6"7], extended the framework to account for deteriorating items and time-dependent demand across dual storage locations. These earlier models generally assumed a continuous and direct release of inventory from both warehouses. Murdeshwar and Sathi [8], along with Pakkala and Achary [9], introduced a bulk release mechanism, where inventory is first transferred from RW to OW before being dispatched to customers. Despite these advancements, most models assumed an infinite planning horizon with demand parameters reset at the start of each cycle. Addressing this limitation, Kar et al. [10] proposed a two-warehouse model under a finite planning horizon with linearly time-dependent demand. Lee and Ma [11] later developed a heuristic-based approach for equal production cycle times under general time-dependent demand within a finite horizon. More recently, Lee and Hsu [12] extended this model by incorporating a finite replenishment rate and employing a variable production cycle time (VPCT) strategy to determine both the number and timing of production cycles over a finite planning period.

In further studies, Yadav and Kumar [13] investigated inventory control for electronic storage devices, integrating environmental concerns and network-based logistics. Yadav, A.S. [13-15] explored seven performance metrics in supply chain management aimed at enhancing inventory efficiency, using optimization tools like Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). This research also addressed economic aspects of transportation and stock replenishment through computational intelligence techniques. Swami et al. [16-18] developed inventory strategies that incorporate factors such as payment delays and credit terms, presenting a depreciation model that relates to a variety of goods and services, particularly under inflationary conditions. Similarly, Gupta et al. [19-20] proposed multi-objective optimization frameworks using GA and PSO to balance supply sufficiency and inflation control, introducing models to assess scenarios of scarcity and low inflation. Singh et al. [21,22] examined inventory systems involving two different stock types, analyzing asset depreciation and storage costs using soft computing approaches. Their study also considered the effects of inflation and property risk in dual-inventory setups. Kumar et al. [23-25] focused on managing the supply of alcoholic beverages, developing environmentally friendly supply chain models and leveraging genetic algorithms for inventory and distribution improvements. Chauhan and Yadav [26-28] provided models for managing stock depreciation across two storage sites, utilizing vehicle routing and genetic inventory strategies to address fluctuating demand and inflation across distribution networks. Pandey et al. [29] applied genetic and multi-particle techniques to enhance the management of industrial marble reserves. Meanwhile, Ahlawat et al. [30] studied SCM in the white wine industry, utilizing neural networks to optimize operations. Singh et al. [31] proposed policies for efficiently importing damaged goods and managing payment deferrals within two-warehouse frameworks.

Yadav et al. [32-33] focus on enhancing inventory management for perishable goods by incorporating green technology investments. Their study evaluates the influence of selling price, carbon emissions, and time-sensitive demand, aiming to develop sustainable and efficient inventory strategies. In a related study, Yadav, Yadav, and Bansal [34, 39], Sinha, et at. [35], Hazer [36], Negi and Singh [37] are applied an interval number approach to model a two-warehouse inventory system for perishable items, effectively addressing uncertainties in both demand and cost parameters. Their findings suggest that investments in preservation technologies not only mitigate product waste but also improve inventory utilization. Adak and Mahapatra [40] developed a multi-item inventory model incorporating reliability, time-dependent demand, and deterioration, while allowing shortages with partial backlogging to enhance decision-making under complex inventory scenarios. Mebarek-Oudina, F [41-44] are also used the advanced techniques for enhancement and some other factors. These models highlight the significance of managing degradation-related expenses to optimize inventory levels and enhance overall system performance.

3. Notations and assumptions

3.1. Notations

The following notations are used in this model.

Parameters	Descriptions
A	Ordering cost coefficient
h_1	Coefficient of holding cost of Rented Warehouse (RW).
h_2	Coefficient of holding cost of Owned Warehouse (OW).
C_P	Purchasing cost.
C_S	Shortage cost.
C_L	Coefficient of cost of lost sale.
θ	Constant rate of deterioration
C_D	Deterioration cost per unit.
R	Inflation factor
q_1	Positive height of inventory of (RW) with $I(t=0)$
q_2	Positive height of inventory of (OW) with $I(t=0)$
q_3	The Negative height of inventory with $I(t=T)$
Q	Total order quantity of order.
T	Total cycle time (Total cycle length).
t_1	The time where inventory height of rented Warehouse becomes zero.
t_2	The time where inventory height of Owned Warehouse becomes zero.
$I_1(t)$	The height of inventory in rented warehouse between time intervals $[0, t_1]$
$I_2(t)$	The height of inventory in owned warehouse between time intervals $[0, t_1]$
$I_3(t)$	Height of inventory in owned warehouse between the time intervals $[t_1, t_2]$
$I_4(t)$	Level of inventory in owned Warehouse between the time intervals $[t_2, T]$
PC	Cost of purchasing
HC	Cost of holding of inventory.
SC	Cost of shortage of the inventory.
LC	Cost of lost sale cost of inventory.
TAC	Present total Average cost.

3.2. Assumptions

The following assumptions are used in this paper.

1. The demand rate is generalized exponential function of selling price and time and taken as the following form : $D(p,t) = e^{p-\beta t};\ \ p > 0,\ \beta > 0$.
2. The decaying rate is $\theta(t) = \alpha\beta e^{\beta t};\ \ \alpha, \beta > 0$.
3. Infinite Time horizon is considered.
4. Lead time is zero with Infinite Replenishment rate is taken.
5. Warehouse (OW) has the limited space is allowed. On other hand the unlimited space area for rented warehouse has been permitted.
6. The holding cost (h_1) of the of Rented Warehouse is greater than the holding cost (h_2) of Owned Warehouse.
7. The charges for transportation and time between Rented Warehouse and Owned Warehouse are completely ignored.

4. FORMULATION AND SOLUTION OF THE MODEL

The issue which we have discussed here is the means by which retailers know whether or not to take a rented warehouse to hold the things. If the order quantity. The following is the formulation of the proposed model:

$$\frac{dI_r}{dt} + \alpha\beta e^{\beta t} I_r = -t^2, \qquad 0 \le t \le t_1 \tag{1}$$

$$\frac{dI_o}{dt} + \alpha\beta e^{\beta t} I_o = -t^2, \qquad 0 \le t \le t_1 \tag{2}$$

The solutions of differential equations (1), (2) are as follows:

$$I_r(t) = e^{-\theta(t_1-t)}\left(\frac{Ke^{a+bt_1}}{b+\theta}\right) - \frac{Ke^{a+bt}}{b+\theta} \tag{3}$$

$$I_o(t) = q_2 e^{-\theta t} \tag{4}$$

Positive inventory level of rented warehouse with $I_r(0) = q_1$and Eqs. (5) given by

$$q_1 = e^{\theta t_1}\left(\frac{Ke^{a+bt_1}}{b+\theta}\right) - \frac{Ke^{a}}{b+\theta} \tag{5}$$

Negative inventory level with $I_o(T) = -q_3$ and Eqs. (8) given by

$$q_3 = \left(\frac{Ke^{a+(b-\delta)T}}{b-\delta}\right) - \frac{Ke^{a+(b-\delta)t_2}}{b-\delta} \tag{6}$$

Next, we calculate all the associated inventory costs as follow:

1. Ordering Cost (OC):
$$OC = A \tag{7}$$
2. Purchasing Cost (PC):
$$PC = C_P\left[e^{\theta t_1}\left(\frac{Ke^{a+bt_1}}{b+\theta}\right) - \frac{Ke^{a}}{b+\theta} + q_2 + \left(\frac{Ke^{a+(b-\delta)T}}{b-\delta}\right) - \frac{Ke^{a+(b-\delta)t_2}}{b-\delta}\right] \tag{8}$$

3. Shortage Cost (SC):

$$SC = -C_S \int_{t_2}^{T} I_o(t) \cdot e^{-Rt} dt$$

$$SC = -C_S \int_{t_2}^{T} \left[\frac{Ke^{a+(b-\delta)t_2}}{b+\delta} - \frac{Ke^{a+(b-\delta)t}}{b+\delta} \right] .e^{-Rt} dt$$

$$SC = -\frac{KC_S}{(b-\delta)} \left[\frac{e^{a+(b-\delta)t_2-RT}}{-R} - \frac{e^{a+(b-\delta-R)T}}{b-\delta-R} - \frac{(b-\delta)e^{a+(b-\delta-R)t_2}}{R(b-\delta-R)} \right] \quad (9)$$

4. Lost sales Cost (LC):

$$LC = -C_L \int_{t_2}^{T} (1 - B(t)) \cdot D(t) \cdot e^{-Rt} dt$$

$$LC = -KC_L \left[\left(\frac{e^{a+(b-R)T}}{b-R} - \frac{e^{a+(b-\delta-R)T}}{b-\delta-R} \right) - \left(\frac{e^{a+(b-R)t_2}}{b-R} - \frac{e^{a+(b-\delta-R)t_2}}{b-\delta-R} \right) \right] \quad (10)$$

5. Holding Cost (HC):

$$HC = \left[h_1 \int_0^{t_1} I_r(t).e^{-Rt} dt + h_2 \int_0^{t_1} I_o(t) \cdot e^{-Rt} dt + h_3 \int_0^{t_2} I_o(t).e^{-Rt} dt \right]$$

$$= \left\{ \frac{h_1 k}{(b+\theta)} \left[\frac{-(b+\theta)e^{a+(b-R)t_1}}{(\theta+R)(b-R)} + \frac{e^{a+(b-R)t_1}}{(\theta+R)} + \frac{e^a}{(b-R)} \right] + \frac{h_2 q_2}{(R+\theta)} \left(1 - e^{-(R+\theta)t_1} \right) \right.$$
$$\left. + \frac{h_2 k}{(b+\theta)} \left[\frac{-(b+\theta)e^{a+(b-R)t_2}}{(\theta+R)(b-R)} + \frac{e^{a+(b+\theta)t_2-(\theta+R)t_1}}{(\theta+R)} + \frac{e^{a+(b-R)t_1}}{(b-R)} \right] \right\} \quad (11)$$

6. Deterioration Cost (DC):

$$DC = C_D \left[\theta \int_0^{t_1} I_r(t) \cdot e^{-Rt} dt + \theta \int_0^{t_1} I_o(t) \cdot e^{-Rt} dt + \theta \int_0^{t_2} I_o(t) \cdot e^{-Rt} dt \right]$$

$$= C_D \left\{ \frac{\theta k}{(b+\theta)} \left[\frac{-(b+\theta)e^{a+(b-R)t_1}}{(\theta+R)(b-R)} + \frac{e^{a+(b-R)t_1}}{(\theta+R)} + \frac{e^a}{(b-R)} \right] + \frac{\theta q_2}{(R+\theta)} \left(1 - e^{-(R+\theta)t_1} \right) \right.$$
$$\left. + \frac{\theta k}{(b+\theta)} \left[\frac{-(b+\theta)e^{a+(b-R)t_2}}{(\theta+R)(b-R)} + \frac{e^{a+(b+\theta)t_2-(\theta+R)t_1}}{(\theta+R)} + \frac{e^{a+(b-R)t_1}}{(b-R)} \right] \right\} \quad (12)$$

$$TAC = \frac{1}{T} \left[OC + PC + HC + DC - SC + LSC \right] \quad (13)$$

5. Genetic Algorithm Optimization (GAO) Methodology

Chromosomes (Genotypes): In a genetic algorithm, a potential solution to the optimization problem is encoded as a chromosome or genotype. The chromosome is typically represented as a string of symbols, often binary digits (0s and 1s), but it can be adapted to handle other representations.
Population: A population is a collection of individuals, where each individual represents a potential solution to the problem. The population evolves over generations, with each generation consisting of a set of individuals.
Fitness Function: The fitness function evaluates how well an individual solves the problem. It assigns a numerical value (fitness score) to each individual based on its performance. The goal is to maximize or minimize this fitness score, depending on the nature of the optimization problem.
Selection: Individuals are selected from the current population based on their fitness scores. High-fitness individuals have a higher probability of being selected. This mimics the process of

natural selection, where individuals with better adaptability have a higher chance of reproducing.
Crossover (Recombination): Crossover involves taking two parent individuals and creating new offspring by combining their genetic material. This is inspired by genetic recombination in biological reproduction. Different crossover techniques, such as one-point crossover or uniform crossover, can be used.
Mutation: Mutation introduces small random changes in an individuals chromosome. This helps to explore the search space more extensively, preventing the algorithm from getting stuck in local optima.
Termination Criteria: The algorithm stops when a certain condition is met, such as reaching a maximum number of generations, achieving a satisfactory solution, or a combination of factors.

6. Graphical Representation

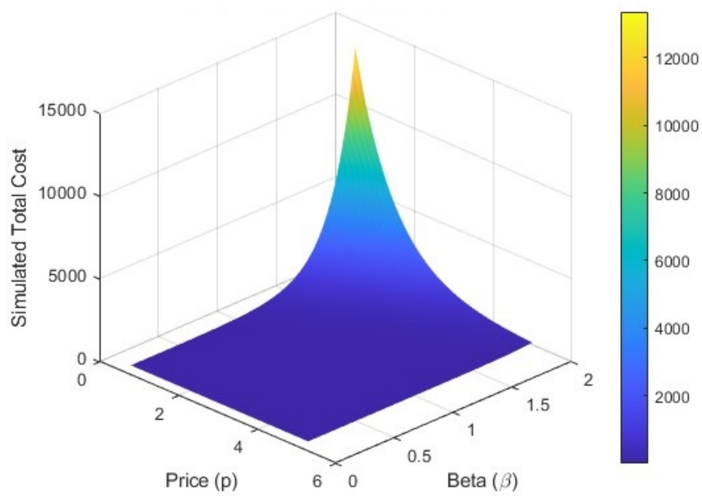

Figure 2: *Optimization with respect to decision variables.*

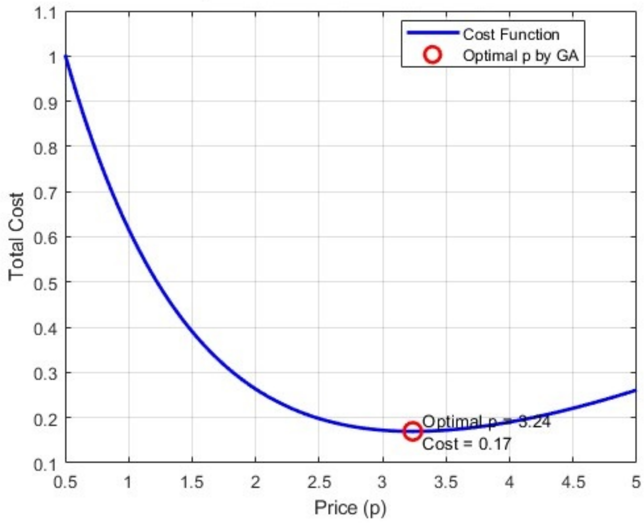

Figure 3: *Variation between total cost and price.*

The graphical depictions in this part provide a comprehensive grasp of the dynamics within the deteriorated inventory model of two-warehouses. Figure 2 and Figure 3 explains the link between demand rates and time, while Figure 2 illustrates how shortage impacts inventory management using different type of functions of time together with the adjustments needed to effectively balance demand, shortage, and time.

7. Conclusion

In conclusion, this paper introduces a novel Genetic Algorithm-based inventory management model tailored for businesses dealing with deteriorating items stored in two warehouses. The model addresses the complexities of shortages through a dynamic approach to partial backlogging, where demand is intricately linked to both selling price and time. The integration of the Genetic Algorithm provides a sophisticated optimization tool for strategic decision-making in the allocation and release of stock, emphasizing cost-effectiveness and adaptability to evolving market dynamics.

The models foundation on generalized exponential decreasing functions for backlogging rate and demand, considering selling price (p) and time (t), enhances its realism and applicability to real-world scenarios. This reflects the understanding that pricing dynamics and temporal considerations are integral factors influencing inventory management decisions. Throughout this paper, we have explored the models development, elucidating the genetic algorithms role in optimizing inventory management, handling excess stock, prioritizing rented warehouse releases, and predicting the onset of shortages. Numerical examples have been presented to showcase the practical implementation of the model, emphasizing its adaptability and efficacy in diverse business contexts. Furthermore, a comprehensive sensitivity analysis has been conducted to assess the models robustness and behavior under varying parameters. This analysis contributes valuable insights into the models performance and its suitability for different operational conditions.

In summary, the presented Genetic Algorithm-based inventory management model offers a sophisticated and adaptive solution for businesses seeking effective strategies in the face of deteriorating item inventories. By incorporating cutting-edge optimization techniques and considering influential factors such as selling price and time, the model provides a valuable framework for businesses to minimize storage costs and navigate the challenges of shortages in dynamic market environments. Future research may focus on further refining the model, expanding its applicability to diverse industries, and incorporating additional factors for a more comprehensive understanding of inventory dynamics.

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