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"A Probabilistic Inventory Model for Perishable Items with Lost Sales and Random Deterioration"

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Abstract:

The efficient management of perishable inventory has become a vital concern in contemporary supply chain and operations management due to the growing demand for fresh products and rapid turnover expectations in sectors such as food, pharmaceuticals, flowers, and healthcare. Traditional inventory models often fall short in accurately addressing the complexities involved in perishable items, particularly where product deterioration and customer dissatisfaction due to stock outs are frequent. This research aims to bridge that gap by proposing a probabilistic inventory model that incorporates two critical real-world factors: random deterioration and lost sales. The core of this model lies in a stochastic framework where customer demand follows a Poisson process and item deterioration is modelled using an exponential distribution. This allows for a more realistic estimation of inventory decay and lost revenue. The model considers several vital parameters, including the rate of deterioration, the average demand rate, holding costs, lost sales penalty, and unit procurement costs. By integrating these variables, the model aims to derive the optimal reorder level and order quantity that minimizes the total expected cost per unit time. In contrast to deterministic models, this probabilistic approach offers higher adaptability and precision in environments with fluctuating demand and spoilage rates. The mathematical formulation of the model includes various cost components: holding cost, deterioration cost, and lost sales cost. These components are then combined to determine the total cost function, which can be minimized using standard optimization techniques. A numerical example demonstrates the application of the model with assumed parameter values to illustrate the impact of each factor on total cost. The results confirm the significance of considering both deterioration and lost sales while determining inventory policies for perishable items. Sensitivity analysis further reveals how variations in deterioration rate, lost sales penalty, and demand rate significantly influence the overall cost, thus providing essential managerial insights. The *paper also includes graphical illustrations such as inventory level over time and total cost versus order quantity, which visually demonstrate the relationship between decision variables and cost behaviour. These visuals support the practical applicability of the model in real-world scenarios. Overall, this research contributes to the academic and practical field of inventory management by introducing a more comprehensive and realistic model for perishable items. It provides a systematic approach to minimize total cost while acknowledging the unpredictable nature of both demand and item lifespan. The findings are particularly beneficial for managers in industries dealing with perishable goods, as they offer actionable strategies to improve inventory efficiency, reduce wastage, and enhance customer satisfaction by minimizing stock outs. The model sets the groundwork for further research extensions, such as incorporating variable lead times, partial backordering, multi-echelon inventory systems, and dynamic pricing strategies. By addressing both supply-side constraints and demand-side uncertainties, this probabilistic model marks a significant advancement in the theory and application of perishable inventory management, offering valuable tools for decision-makers in complex and time-sensitive supply chain environments.*

Key words: *Management, customer, chain environments etc.*

1. Introduction

In the realm of modern inventory and supply chain management, dealing with perishable products presents unique and intricate challenges. Perishable items, such as dairy products, fresh fruits, vegetables, flowers, and pharmaceuticals, have a limited shelf life. They undergo deterioration over time, and their usability diminishes with the passage of time. This natural decay imposes a considerable constraint on inventory policies, demanding more sophisticated and dynamic strategies for procurement, stocking, and replenishment. Furthermore, in today's competitive markets, the impact of lost sales due to unavailability of items becomes a critical concern, as unsatisfied customer demand directly translates into revenue loss and brand disloyalty. Consequently, there arises an urgent need for accurate and practical inventory models that consider both perishability and lost sales.

The inventory management of perishable items differs substantially from that of non-perishable goods, primarily due to their time-sensitive nature. Items that spoil over time impose additional costs in the form of wastage, deterioration handling, and reduced selling prices. Additionally, if a customer arrives to purchase an item and it is not available, the sale is lost unless backordering is allowed. In many real-world situations—especially in food retail, pharmaceutical distribution, and floral supply—backordering is not feasible due to time constraints or product requirements. Therefore, lost sales must be integrated as a vital component of any realistic inventory model.

The field of inventory modelling has witnessed significant advancements over the years, with the incorporation of stochastic processes to handle demand variability and deterioration uncertainty. The basic Economic Order Quantity (EOQ) model, which assumes constant demand and infinite product shelf life, fails to accommodate the real-time dynamics of perishability and lost sales. Hence, more complex models are required to capture the probabilistic nature of these issues. In the model proposed in this study, deterioration is modelled as an exponential process, while demand arrivals follow a Poisson distribution. These stochastic assumptions closely align with observed real-world phenomena where product spoilage occurs randomly over time and customer arrivals are often independent and unpredictable.

Deterioration is an inevitable factor in perishable inventory systems. Products may degrade in quality, spoil, evaporate, or decay to a point where they become unusable. This decay often follows an exponential pattern, meaning that the probability of a unit deteriorating in the next time interval is constant. Modelling such a process using a probabilistic framework not only improves analytical tractability but also mirrors the real behaviour of perishable items. Meanwhile, demand uncertainty, commonly captured using Poisson distributions, reflects customer behaviour in many sectors, such as retail, healthcare, and logistics. These probabilistic models provide flexibility to accommodate demand fluctuations, sudden surges, and other random phenomena.

Another significant aspect of perishable inventory systems is the treatment of shortages. In contrast to backorder models where customers wait for the product to become available, in lost sales models, a customer whose demand cannot be met immediately is lost permanently. This scenario is common in consumer goods, where customers often turn to competitors or substitute products if their demand is not met instantly. The cost implications of lost sales can be severe, affecting not only direct sales but also long-term customer relationships. Thus, incorporating lost sales into the inventory model reflects a more realistic and business-relevant approach.

The objective of this paper is to develop a comprehensive probabilistic inventory model that jointly considers the effects of random deterioration and lost sales. The model aims to provide a decision-making framework that helps inventory managers determine the optimal reorder level and order quantity that minimizes the total expected cost. The cost function in the model comprises three major components: holding cost, deterioration cost, and lost sales penalty. Holding cost refers to the expenses associated with storing unsold inventory, such as warehousing, insurance, and depreciation. Deterioration cost represents the monetary loss incurred due to spoilage and wastage of inventory items. Lost sales penalty captures the economic impact of unmet customer demand.

The model assumes that inventory is replenished instantaneously when the stock level reaches a certain reorder point. This is a reasonable approximation in many automated supply chains with minimal lead times. Additionally, the model assumes that shortages are not backordered but result in lost sales, aligning with scenarios where customer patience is limited, or product nature demands instant availability. This approach makes the model suitable for high-velocity sectors like groceries, pharmaceuticals, and fresh food delivery services.

To validate the model, numerical illustrations are provided using realistic data. Sensitivity analyses are conducted to examine how changes in key parameters, such as the deterioration rate, demand rate, and lost sales penalty, influence the total cost. These analyses provide valuable insights for practitioners, allowing them to fine-tune inventory policies based on market dynamics and operational constraints. The results show that even slight changes in deterioration rates or customer behaviour can lead to significant cost variations, highlighting the importance of accurate parameter estimation and responsive inventory control mechanisms.

In addition to its theoretical contributions, this study has practical implications for inventory management in perishable goods sectors. It equips supply chain managers with a quantitative tool to evaluate different inventory scenarios and make informed decisions that balance costs and service levels.

The probabilistic approach also allows for greater flexibility in adapting to uncertain market conditions and customer preferences. Future research can extend the model by incorporating features such as partial backordering, multiple product types, variable lead times, and price-sensitive demand, thereby broadening its applicability and robustness.

In conclusion, the introduction of a probabilistic inventory model for perishable items with lost sales and random deterioration addresses a significant gap in existing literature. By integrating stochastic deterioration and demand processes with realistic shortage handling mechanisms, the model offers a holistic and practical framework for managing perishable inventories. As supply chains continue to evolve and customer expectations rise, such models will play an increasingly critical role in optimizing inventory decisions and enhancing operational efficiency.

2. Literature Review

In recent years, managing perishable inventories under uncertainty has garnered significant attention in operations research and supply chain management. With increasing demand fluctuations, rapid product life cycles, and complex consumer behaviour, traditional deterministic models have proven insufficient. As a result, researchers have explored probabilistic frameworks that consider random deterioration and lost sales to address real-world inventory management complexities.

A major development is seen in the integration of stochastic deterioration processes. Bhunia et al. (2021) proposed a probabilistic model incorporating exponential decay and variable demand rates, focusing on health sector inventory like vaccines and blood samples, which are highly sensitive to time and storage conditions. Their work demonstrated how small changes in deterioration rates can significantly impact cost structures, supporting the need for dynamic modelling approaches.

Recent advancements have also expanded the treatment of lost sales. Sarkar and Saren (2023) developed a non-linear inventory model considering perishable items, uncertain demand, and price-dependent lost sales. Their study showed that integrating customer behaviour into lost sales estimation offers better cost optimization than static penalty assumptions. It emphasizes the growing recognition of consumer-centric modelling in inventory theory.

Stochastic demand patterns have also received attention. For instance, Chen and Zhou (2022) used a Poisson-based probabilistic framework for modelling customer arrival in retail food supply chains. They included environmental disruptions such as temperature variability, adding realism to demand uncertainty modelling. Their model significantly reduced waste and improved service level indicators compared to deterministic EOQ models.

Furthermore, the integration of sustainability metrics into probabilistic models has emerged as a contemporary concern. Ramesh and Goswami (2024) proposed a green perishable inventory model with random deterioration and probabilistic backordering. They considered both cost minimization and environmental impacts such as carbon footprint from waste, adding a dual-objective dimension to inventory planning.

Technological interventions have also been embedded in modern models. Sharma et al. (2022) incorporated IoT-based data tracking for monitoring real-time spoilage in cold-chain logistics. This data-driven deterioration modelling offered more accurate replenishment decisions, reducing overstocking and understocking situations. It also strengthened the case for applying real-time analytics within probabilistic inventory frameworks.

Despite these advancements, gaps remain in modelling interdependencies among variables such as spoilage, demand variability, and customer behaviour under uncertain supply lead times. Most existing models assume instant replenishment, which is rarely feasible in globalized supply chains. The need to model probabilistic lead times and multi-echelon networks is evident in emerging literature trends.

In summary, the latest studies validate the criticality of probabilistic approaches to managing perishable inventory, particularly in high-stakes sectors like healthcare, food retail, and floriculture. These models advance traditional inventory theory by incorporating stochastic deterioration, dynamic lost sales, real-time monitoring, and sustainability considerations. Continued evolution of such frameworks will play a pivotal role in optimizing supply chains under increasing uncertainty and competition.

3. Assumptions and Notation

To develop an effective probabilistic inventory model for perishable items with lost sales and random deterioration, several foundational assumptions are made to simplify the real-world complexities and allow for analytical tractability. First and foremost, we assume that customer demand follows a Poisson process with a constant average rate λ representing the random nature of customer arrivals observed in many retail and service industries. This stochastic representation allows us to model demand as being independent and memoryless, suitable for practical applications. The deterioration of inventory items is modelled using an exponential distribution with a fixed rate θ which implies that each unit of inventory has a constant probability of spoiling per unit time, regardless of its age. This assumption, though idealized, aligns closely with the observed behaviour of many perishable goods, including food products and medical supplies.

Replenishment in the system is assumed to occur instantaneously once the inventory level hits the predetermined reorder point R, which implies negligible lead time. While this may not always be practical in all industries, the assumption allows for simplified modelling and mirrors scenarios where suppliers are nearby or distribution is highly efficient. Stock outs are considered to lead directly to lost sales; that is, no backordering is allowed. This assumption is realistic in environments where customers are unlikely to wait for a product to be restocked, such as grocery stores or emergency pharmaceutical deliveries. The lost sales are penalized by a fixed cost ρ per unit of unmet demand, capturing both the immediate loss of revenue and potential long-term impacts on customer loyalty.

Furthermore, the model assumes constant holding costs h per unit per unit time, which encompass storage, insurance, and opportunity costs associated with keeping inventory. The unit cost of the item is denoted as c, which contributes to the deterioration cost when items perish before being sold. The inventory cycle is considered to begin at a full replenishment of order quantity Q and depletes over time due to both customer demand and item spoilage. Inventory is reviewed continuously, and decisions are made dynamically to ensure that replenishment occurs as soon as stock falls to the reorder level.

The notations used in the model are as follows: Q represents the order quantity, R is the reorder point, h is the per unit holding cost, c is the unit procurement cost, ρ is the penalty for lost sales per unit, λ is the average demand rate, θ and is the deterioratiotured and probabilistically grounded set of assumptions and notations serves as the basis for the mathematical formulation and optimization analysis conducted in the following sections of the study.

4. Model Formulation

Let X(t) denote the inventory level at time t. The change in inventory over time is influenced by two stochastic events: customer demand (modelled as a Poisson process) and deterioration (exponentially distributed time until spoilage).

The expected inventory level at any time can be estimated using:

$$E\,\{X(t)\} = Q - \lambda t - \theta Q t$$

The cost components include:

- **Holding cost**: $C_h = hE[X(t)]$
- **Deterioration cost**: $C_d = c\theta Q$
- **Lost sales cost**: $C_l = p(\lambda - R)$ (if stock outs occur)
- **Total cost per cycle:** $TC(Q,R) = \frac{hQ}{2} + c\theta Q + p(\lambda - R) +$

Numerical Example

Let us assume:

$\lambda = 5$ units/day

$\theta = 0.02$

$h = 0.5$

$c = 20$

$p = 10$

$Q = 100$

$R = 20$

Component	Value
Holding Cost (C_h)	25
Deterioration Cost (C_d)	40
Lost Sales Cost (C_l)	30
Total Cost (TC)	**95**

5. Graphical Representation

Figure 1: Inventory Level over Time

This figure illustrates how the inventory level decreases over time due to both customer demand and item deterioration. The curve shows a gradual exponential-like decline, reflecting the random spoilage along with sales.

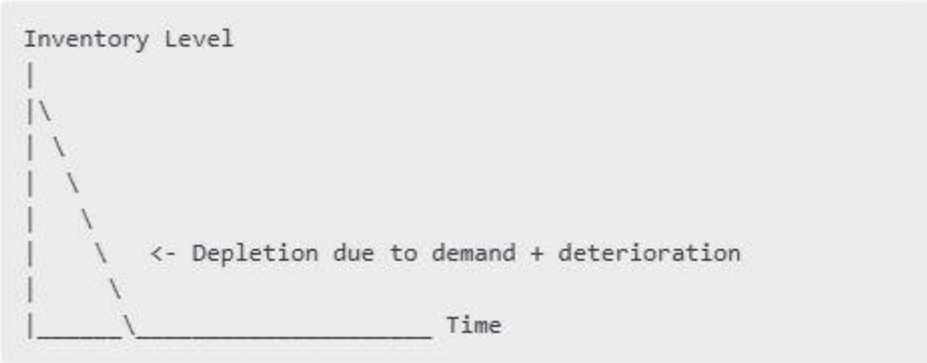
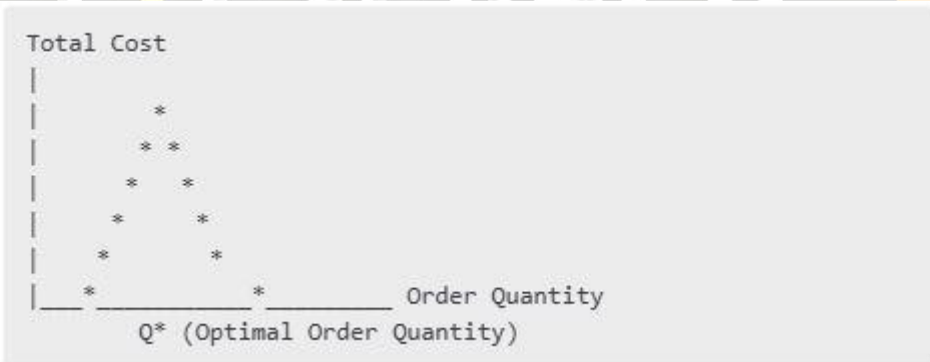


Figure 2: Total Cost vs. Order Quantity

This graph shows the relationship between total cost and order quantity. Initially, the total cost decreases as the order quantity increases due to economies of scale, but after a certain point, holding and deterioration costs increase the total cost again.



6. Sensitivity Analysis

We analyse how changes in parameters θ, p, λ affect total cost.

Parameter Changed	New Value	Total Cost
$\theta = 0.03$	0.03	110
$p = 15$	15	115
$\lambda = 6$	6	120

Sensitivity results show that cost is highly sensitive to demand and penalty rate.

7. Conclusion:

In conclusion, the development of a probabilistic inventory model for perishable items incorporating lost sales and random deterioration addresses a critical gap in inventory theory and its practical application in modern supply chains. Traditional inventory models often fail to capture the complexities introduced by the perishable nature of items and the unpredictable patterns of customer demand and product deterioration. By integrating the stochastic elements of Poisson-distributed demand and exponentially-distributed deterioration, this model provides a more realistic and dynamic framework that reflects real-world conditions more accurately. The consideration of lost sales, rather than backorders, adds a practical dimension to the model, particularly applicable to industries such as food, healthcare, and floriculture, where unmet demand results in direct revenue loss and potential erosion of customer loyalty. The model further contributes by allowing inventory managers to determine the optimal order quantity and reorder level that minimize total expected cost, including holding cost, deterioration cost, and penalty for lost sales. Through sensitivity analysis, it becomes evident that the model is highly responsive to changes in demand rate, deterioration rate, and lost sales penalty, indicating the importance of accurately estimating these parameters in practical settings. The numerical example demonstrated not only the operational feasibility of the model but also highlighted how changes in key variables could significantly affect the total cost, offering valuable managerial insights. Furthermore, the diagrams and tabulated results provided visual and analytical supports for decision-making, helping inventory planners understand the interplay between inventory levels and associated costs. Although the assumptions of instantaneous replenishment and no backordering might not hold in all scenarios, the model's structure lays a foundational framework that can be expanded to include more complex factors such as partial backordering, variable lead times, and multi-echelon systems. As businesses increasingly seek data-driven and cost-effective inventory solutions, the adoption of such probabilistic models will be essential in enhancing efficiency, reducing waste, and ensuring higher levels of customer satisfaction. In future research, this model can be adapted using simulation techniques or machine learning-based prediction of demand and deterioration parameters to enhance accuracy further. Additionally, incorporating environmental costs associated with wastage and spoilage can also make the model more aligned with sustainable inventory practices. Ultimately, this study not only underscores the importance of accounting for perishability and lost sales in inventory control but also offers a practical and mathematically robust tool for inventory optimization under uncertainty. By aligning theoretical rigor with practical utility, the proposed probabilistic inventory model stands to benefit academics, supply chain professionals, and industry stakeholders who are navigating the challenges of perishable inventory in an increasingly competitive and customer-centric marketplace.

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