Research on Collaborative Optimization of Fresh Food E-commerce Distribution Routes and Inventory: An Analysis Based on the EOQ Model and Dynamic Constraints

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Abstract. Due to the perishable nature of products, the continuously expanding fresh food e-commerce industry is confronted with crucial inventory management challenges. This study examines the shortcomings of the traditional economic order Quantity (EOQ) model in this context, bringing to light its inability to cope with product spoilage, quality depreciation, and the ever - changing supply chain c. Our analysis discovers three fundamental issues: the model lacks the inclusion of perishability factors, Operational uncertainties regarding demand and lead times, Moreover, the integration with the route optimization system is not close enough. The inaccuracy of data and the separate decision-making process have greatly weakened the effectiveness of inventory management, resulting in greater waste and higher e. The paper explores extended EOQ forms that account for deterioration rates and uncertain demand, Propose a better decision-making framework. Effective inventory management requires a comprehensive solution that combines adaptive EOQ models, real-time data analysis, and collaborative optimization methods. This global strategy enables enterprises to strike a balance between cost efficiency and product freshness, ultimately advancing customer satisfaction and competitive dominance in the fast - expanding fresh food e-commerce market.

Keywords: Fresh food delivery, Path optimization, Inventory synergy, EOQ model, Joint ordering model, Data quality Timeliness.

1. Introduction

The fresh food e-commerce segment has witnessed remarkable g., By 2024, China's market transaction volume had exceeded 620 billion y. This quickly expanding market, But then again, it is encountering long-term operational difficulties arising from the inherent conflict between the perishable nature of the product and the efficiency of logistics. Industry data shows that over 70% of consumers prioritize "same-day delivery", "next-day delivery" and "product freshness guarantee" when making purchases. In the fresh food e-commerce sector, customer complaints caused by delivery delays and product damage account for more than 65% of total complaints. For customers encountering such problems, their repurchase intention drops by more than 40 percentage points, highlighting the essential role of efficient logistics management.

The core part of these challenges lies in the application of inventory management principles, notably the Economic Order Quantity (EOQ) model, which serves as an essential framework for deciding order quantities that reduce c. Initially put forward by Harris, The EOQ model has long been thought of as a core element in inventory m. Nevertheless, its direct use in fresh produce supply chains exposes significant d. The distinct traits of fresh produce, including high perishability, constrained shelf life, and continuous quality decline—significantly challenge the core assumptions of the m. For instance, Strawberries could soften and decay if left at room temperature for more than six h., and the quality of frozen meat deteriorates rapidly when the cold chain loses its i.

These product-specific constraints are exacerbated by dynamic operational factors [1]. Demand volatility influenced by seasonal patterns and promotional activities, coupled with uncertain lead times due to traffic congestion and logistical disruptions, creates complex challenges for inventory planning. The industry practice of locating warehouses in suburban areas to reduce costs has further

increased urban delivery distances, while vehicle capacity limitations and order dispersion add additional layers of complexity.

Despite technological advancements in big data, artificial intelligence, and Internet of Things (IoT) that theoretically enable real-time route optimization and condition monitoring, practical implementation faces significant hurdles. Temperature data loss rates of 8% to 12% due to sensor malfunctions, along with traffic information delays exceeding 15 minutes, compromise decision-making precision. Furthermore, the siloed approach separating inventory management from distribution optimization creates systemic inefficiencies, as evidenced by industry cases were disconnected decision-making leads to elevated spoilage rates and customer dissatisfaction.

This paper systematically scrutinizes these diverse challenges and explores integrated optimization tracks for fresh food. Through the analysis of product attributes, fluctuating limitations, and the interdependencies between data and models, we inquire into why the classical EOQ framework falls short in perishable goods management and how extended modeling methods can improve the precision of decision - m. The results are aimed at helping develop more all - around inventory management strategies that balance cost efficiency and product freshness well in this highly competitive market, ultimately helping enterprises curtail costs, Lift customer satisfaction degree, and elevate their competitive.

2. Traditional economic order quantity model and its challenges

The Economic Order Quantity (EOQ) model was first formulated by Harris in 1913 [2], The Economic Order Quantity (EOQ) model acts as a key element in inventory management by figuring out the order quantity that minimizes., where total cost comprises both ordering and holding p. Yet, The special traits of fresh produce present substantial hurdles to the direct application of this classical.

Fresh consumables—encompassing fruits, cultivated vegetables, meats and seafood—has the characteristic of high perishability and a confined shelf life, making it very likely to experience quality decline under less than - ideal storage or transportation conditions [3]. A clear example is that strawberries and other berries tend to spoil within hours at room temperature, while fresh fish fast loses its sought - after texture and flavor without correct h. Consequently, the inventory holding costs of these goods surpass conventional elements like storage and c., to take in considerable costs emerging from product spoilage and quality loss [4].

The traditional EOQ model operates according to the assumptions of a stable demand rate and negligible product degradation during the holding p. However, these assumptions greatly deviate from the characteristics of fresh p. Actually, the demand for these products varies as a result of seasonal alterations—like the greater consumption of watermelons in the summer—and promotional e., while their spoilage rate is in essence non - t. Thus, Employing the unaltered EOQ model brings about suboptimal order q., as it omits to include the higher holding costs attributable to high rates of product spoiling [5].

What is more, fresh produce goes through a continuous degradation of quality as time p., indicating a continuous reduction in product value even when there isn't complete spoilage. For instance, slightly wilted lettuce is still edible., yet its market value is considerably lower than that of fresh lettuce. The typical EOQ model framework doesn't factor in this gradual quality decline and the associated drop in product v., which is a vital consideration in the case of perishable goods [6]. Such neglect may result in a mismatch between the ordered amounts and the real - time market value of the products at the time of sale, thus resulting in decreased profitability or heightened.

3. Dynamic constraints on the EOQ model in fresh product distribution

The application of the EOQ model in the context of fresh product distribution is subject to a range of dynamic constraints, which significantly complicate its practical implementation. These

constraints primarily manifest in demand volatility and lead time uncertainty, often rendering the model's foundational assumptions of stability inadequate.

Unlike the constant demand presumed in the classic EOQ framework, demand for fresh produce exhibits considerable fluctuation driven by multiple factors. Seasonality is a critical determinant; for instance, demand for pumpkin-flavored products surges during Halloween and Thanksgiving, while the consumption of hot pot ingredients rises markedly in winter [7]. Similarly, holiday periods such as Christmas and the Chinese New Year trigger sharp increases in demand for premium items like lobsters and high-quality fruits. Furthermore, promotional activities, like "buy one get one free", can induce sudden demand spikes or troughs, creating forecasting challenges that deviate fundamentally from the EOQ's stable demand postulate.

Another pivotal constraint is the inherent uncertainty in delivery lead time. The EOQ model depends on a fixed lead time to determine the reorder point. In practice, however, lead times are frequently disrupted by factors such as pervasive urban traffic congestion, which can delay deliveries for hours during peak periods [8], adverse weather conditions like blizzards or hurricanes, and unforeseen logistical failures including vehicle breakdowns or warehouse operational errors. As illustrated by the case of the fresh food e-commerce firm "Green Fresh," traffic-induced route inefficiencies exacerbate product spoilage and disrupt EOQ-based inventory planning. Delayed deliveries cause actual inventory levels to fall below the model's planned thresholds, potentially resulting in stockouts. This compels firms to initiate costly emergency replenishments, thereby inflating ordering costs and undermining the cost-equilibrium objective of the EOQ model [9].

Moreover, the capacity constraints of delivery vehicles impose additional limitations on the model's efficacy. The optimal order quantity derived from the EOQ model must align with the physical capacity of the distribution vehicles. Should the EOQ exceed this capacity, the order must be split into multiple consignments. This segmentation not only elevates ordering costs—as each batch incurs separate administrative expenses—but also increases transportation costs due to the need for multiple trips or larger vehicles. Consequently, this violation of the EOQ's singular shipment assumption contravenes its core cost-minimization objective [10]. For example, if a company's EOQ for a vegetable is 1,000 cases, but its vehicle capacity is limited to 800 cases, the requirement for two shipments effectively doubles the ordering cost and raises overall transportation expenses.

4. The Interdependence of Data Integrity and Model Integration for EOQ Efficacy in Fresh Supply Chains

The efficacy of the Economic Order Quantity (EOQ) model within the fresh product supply chain is critically contingent upon high-quality data and synergistic collaboration with complementary operational models, such as those for distribution route optimization. The EOQ framework's reliance on precise inputs for demand, ordering costs, and holding costs establishes data accuracy as a foundational prerequisite. Nevertheless, enterprises in the fresh food sector frequently encounter significant impediments to procuring reliable data.

Historical order data, essential for demand forecasting, is often compromised by multiple factors. In small and medium-sized enterprises with limited automation, manual recording errors are prevalent. Furthermore, systemic issues, including data corruption or erroneous entries within inventory management software, introduce defects into historical datasets. The challenge is exacerbated for new product introductions or during periods of volatile market shifts, where the insufficiency of relevant historical data starkly reveals the limitations of the EOQ model's dependence on such information [11].

Traffic data, a critical input for route planning, represents another domain plagued by quality concerns. Outdated sensor networks or incomplete feeds from traffic monitoring systems can yield erroneous condition reports. Inaccuracies in this domain, exemplified by a 20% deviation in estimated transit time, directly impair the calibration of EOQ parameters. An underestimation of travel time, for instance, leads to a foreshortened lead time assumption within the EOQ calculation. This

miscalculation propagates to an erroneous order cycle, potentially causing either excessive inventory—elevating holding and spoilage costs—or inventory shortages, resulting in stockouts and lost sales [12].

Beyond data quality, a salient issue is the insufficient integration between the EOQ model and distribution route optimization algorithms. Predominant research and practice often treat inventory management and routing decisions as isolated silos. Consequently, route optimization tends to prioritize timeliness to meet delivery windows, while neglecting the integration of core EOQ considerations, namely product perishability and the associated costs of spoilage [13].

A case in point is Meituan Pinduoduo, where a lack of dynamic synchronization between the underlying inventory model (implicitly EOQ-based) and the route optimization engine—compounded by disconnected data streams for real-time warehouse inventory, in-transit goods, and order fulfillment—resulted in suboptimal delivery routing. These routes failed to prioritize time- and condition-sensitive items, such as imported fruits, leading to prolonged transit times and elevated spoilage rates. This case underscores that without robust data-model coordination, the EOQ model cannot effectively minimize inventory costs, nor can route optimization ensure product freshness, thereby inflating total supply chain costs [14].

The paradigm of data-model collaboration must also extend to the real-time updating of the EOQ model. While emerging technologies like the Internet of Things (IoT) enable the collection of real-time data on product freshness, inventory levels, and ambient conditions, many enterprises have been slow to leverage this capability for dynamic EOQ recalibration. For example, if IoT sensors in a cold chain logistics unit detect a temperature increase, indicating an accelerated spoilage rate, the holding cost parameter in the EOQ model should be adjusted upwards. The failure to integrate such real-time data streams results in the continued use of outdated parameters, generating suboptimal order quantities [15].

Finally, the collaborative scope must encompass other inventory models that explicitly address perishability. The Newsvendor Model, designed for products with short lifecycles and stochastic demand, is highly pertinent to fresh produce. However, achieving a functional integration between the cost-minimization focus of the EOQ model and the profit-maximization objective of the Newsvendor model for perishable goods is a complex undertaking, requiring meticulous data sharing and model coordination [16]. In the absence of such integration, firms face conflicting operational objectives, leading to systemic inefficiencies in inventory management.

5. Extensions and refinements of the EOQ model for perishable supply chains

In response to the documented limitations of the traditional EOQ model in managing perishable inventories, a substantial body of research has been dedicated to developing various extensions and refinements. These advanced models seek to enhance applicability and decision-making accuracy by incorporating the defining characteristics of fresh produce.

A primary stream of research integrates perishability directly into the model's structure by accounting for the product spoilage rate. These extended models, building on the foundational work of scholars [17, 18], operate on the premise that the deterioration rate is either constant or time-variant. Consequently, the holding cost is recalibrated to internalize the cost of deteriorated items. For example, under a constant deterioration rate assumption, the effective holding cost is computed as the sum of conventional storage costs and the financial loss attributable to spoiled products throughout the inventory cycle.

Beyond mere spoilage, another significant extension addresses the continuous decline in the quality of fresh produce over time. Moving beyond a binary perspective of product state (usable or perished), these models [19], conceptualize quality degradation as a gradual process that erodes market value. By embedding a quality function that maps storage duration to product value, the EOQ framework can be optimized to determine order quantities that maximize expected revenue, thereby explicitly balancing procurement and holding costs against the diminishing value of the inventory.

Furthermore, to contend with the pervasive uncertainties in demand and lead time within fresh food supply chains, stochastic EOQ models have been formulated [20]. These models employ probability distributions to represent key uncertain parameters, enabling the calculation of an optimal order quantity that strategically balances the costs of stockouts against those of excess inventory. For instance, an inventory policy for fresh seafood might be derived from a model that simulates demand using a normal distribution and lead times via a lognormal distribution, thus offering a more robust and realistic approach to inventory management under uncertainty.

6. Conclusion

This study has systematically examined the challenges and potential pathways for optimizing the application of the EOQ model within the fresh food e-commerce supply chain. Our analysis reveals that the classical EOQ model, while a cornerstone of inventory theory, faces significant limitations when directly applied to perishable goods due to the unique product characteristics, dynamic operational constraints, and critical interdependencies with data quality and other decision-making models.

The inherent perishability of fresh produce, characterized by rapid spoilage and continuous quality degradation, fundamentally challenges the model's core assumptions of negligible deterioration and stable demand. These product-specific issues are compounded by dynamic external constraints prevalent in distribution, including volatile demand influenced by seasonality and promotions, uncertain lead times due to traffic and logistical disruptions, and vehicle capacity limitations. As evidenced by cases such as "Green Fresh," these factors collectively disrupt EOQ-based inventory planning, leading to increased spoilage, stockouts, emergency replenishments, and ultimately, elevated supply chain costs.

Furthermore, the efficacy of the EOQ model is critically dependent on high-quality data and synergistic integration with other operational systems. Inaccuracies in historical demand data and real-time traffic information propagate through the model, resulting in suboptimal order cycles and quantity decisions. More profoundly, the siloed application of the EOQ model, disconnected from distribution route optimization and other pertinent models like the Newsvendor model, creates systemic inefficiencies. The case of "Meituan Pinduoduo" illustrates how a lack of dynamic synchronization between inventory and routing decisions fails to prioritize time-sensitive goods, undermining both cost minimization and freshness preservation. The underutilization of IoT data for real-time model recalibration further represents a missed opportunity for enhancing responsiveness.

In an attempt to tackle these challenges, Scholars' endeavors have polished the EOQ framework via extensions that contain spoilage r., Present quality decay as a function causing value depreciation, and employ stochastic programming to cope with demand and lead time u. These progressions mark a considerable shift from the deterministic, cost - dominated classic model toward more comprehensive and realistic.

Briefly speaking, attaining effective inventory management in the fresh food e - commerce arena necessitates a departure from the old - fashioned, Independent EOQ a. Future strategies ought to embrace an integrated approach that melds advanced, Customizable EOQ derivatives integrated with real - time data analytics and collaborative models for distribution and inventory o. For industry practitioners, this implies devoting capital to digital infrastructure for data integrity and fostering cross-functional model integration. For researchers, it underscores the need to further develop unified decision-support frameworks that seamlessly balance cost, timeliness, and product freshness. Only through such a holistic paradigm can enterprises effectively navigate the complexities of the fresh produce supply chain, thereby reducing waste, enhancing customer satisfaction, and securing a sustainable competitive advantage in this rapidly growing market.

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