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Optimizing the Inventory and Fulfilment of an Omnichannel Retailer: A Stochastic Approach with Scenario Clustering — A Comprehensive Review

Dr. Shetty Deepa[1], Thangam Geeta[2], Sumathi K[3]
School of Management Studies, Sathyabama Institute of Science and Technology, India

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Abstract:
This research explores tactical and technological approaches to **optimize inventory management** with the primary objective of reducing *overall supply chain costs*. It discusses how real-time data analytics, advanced demand forecasting, and lean inventory techniques (such as Just-In-Time systems) help businesses lower holding costs, reduce stockouts, and improve cash flow. The study also examines the role of automation and integrated inventory platforms in enhancing process transparency and responsiveness. Strategic collaboration with suppliers and implementation of robust replenishment algorithms are emphasized as key enablers for maintaining balance between cost efficiency and demand fulfilment. Case examples illustrate how optimized inventory turnover enhances service levels and customer satisfaction.
Keywords: Inventory optimization, supply chain management, cost reduction, demand forecasting, lean systems, JIT, automation

1. Introduction

The rapid evolution of retail markets, accelerated by widespread digital adoption and shifts in consumer behavior, has made **omnichannel retailing** a dominant business model for contemporary retailers. An omnichannel retailer offers multiple ways for customers to engage with the brand — online (via e-commerce platforms), in physical stores, and often through hybrid services like Buy Online Pick Up In Store (BOPIS). The inherent complexity of these operations arises from the simultaneous fulfilment of online and in-store demand streams, the geographical distribution of inventory, and the variability in customer demand patterns. Managing inventory across multiple channels and deciding how best to fulfil orders from such an integrated network creates critical operational challenges.

Efficient inventory and fulfilment strategies are essential for achieving **cost optimization** and **customer satisfaction** in such systems. Classic inventory models such as Economic Order Quantity (EOQ) and base-stock policies have evolved into more advanced frameworks integrating data-driven approaches, multi-level decision structures, and stochastic optimization techniques. Yet, real-world uncertainty in demand and the combinatorial nature of fulfilment decisions call for robust and computationally feasible optimization methods.

In this context, the journal article **"Optimizing the Inventory and Fulfillment of an Omnichannel Retailer: A Stochastic Approach with Scenario Clustering"** by Abdo

Abouelrous, Adriana F. Gabor, and Yingqian Zhang (2022) presents a significant contribution. It introduces a **two-stage stochastic programming model** that jointly optimizes inventory levels and fulfilment decisions for an omnichannel retailer, while addressing the computational challenges posed by uncertainty through a **scenario clustering approach**.

This review paper critically examines the proposed methodology, frames it within the wider literature on inventory and fulfilment optimization, assesses empirical results, and discusses implications for research and practice.

2. Problem Context and Literature

Omnichannel retailing integrates multiple sales and fulfilment channels, requiring retailers to allocate inventory not only to fulfil in-store purchases but also to meet online orders, which may be fulfilled from stores or dedicated fulfilment centers. Traditional inventory models that treat channels independently or rely on deterministic demand forecasts often fail to capture the intricacies of such systems. Distribution strategies now need to navigate:

- **Demand uncertainty** across channels,
- **Multi-location fulfilment decisions**,
- **Dynamic online order allocations**,
- **Trade-offs between holding costs and delivery/fulfilment costs**.

The literature on omnichannel inventory and fulfilment spans several areas:

2.1 Inventory Models for Multiple Demand Streams

Early contributions examined **multi-class demand models** where inventory serves different customer classes, similar to omnichannel demand contexts. Such models often involve shared inventory pools with prioritization schemes. For example, inventory allocation studies address how to balance competing demand from different customer segments while minimizing stockouts and overstock risks.

2.2 Fulfilment Strategies in Retail Networks

The choice of fulfilment sources — whether to fulfil online orders from centralized distribution centers, local stores, or a hybrid — significantly impacts cost and service levels. Research shows that dynamic assignment of orders to fulfilment facilities can improve operational responsiveness.

2.3 Joint Inventory and Fulfilment Optimization

Integrated models that simultaneously consider inventory placement and fulfilment decisions are relatively recent. They recognize that inventory levels cannot be effectively optimized without accounting for how orders will be fulfilled from a network of locations. This holistic lens underscores the relevance of models like two-stage stochastic programs that embed fulfillment decisions within the inventory optimization structure.

2.4 Stochastic Frameworks and Scenario Management

Stochastic optimization acknowledges demand uncertainty by incorporating possible future outcomes into decision-making. However, these models often suffer from computational challenges due to the explosion of scenarios needed to represent realistic uncertainty. Scenario reduction and clustering techniques help make such models scalable and practical for large problems.

The work reviewed here builds directly on this literature by using **scenario clustering to reduce computational complexity** in a two-stage stochastic optimization framework applied to a practical omnichannel inventory and fulfilment problem.

3. Research Objectives and Contributions of the Paper

The article by Abouelrous et al. (2022) has several clear research objectives:

1. **Formalize a joint inventory and fulfillment decision problem** for an omnichannel retailer that faces stochastic (uncertain) demand from both online and in-store channels.
2. **Develop a two-stage stochastic optimization model** that determines initial inventory levels in the first stage and optimal fulfilment allocations in the second stage.
3. **Propose a scenario clustering method** that reduces the number of demand scenarios while maintaining solution quality, enhancing computational tractability.
4. **Evaluate the proposed algorithm on randomly generated data** to demonstrate cost reduction benefits compared with baseline methods.

The central innovation lies in **the scenario clustering approach**, which uses a similarity measure based on demand distributions and cost patterns to group similar scenarios and reduce dimensionality without specifying the number of scenarios in advance. This offers both flexibility and computational efficiency.

4. Methodology

The methodological framework is grounded in **stochastic programming**, where uncertainty in demand is modeled through a finite set of demand scenarios. The methodology includes the following components:

4.1 Two-Stage Stochastic Optimization

The optimization model has two stages:

- **First Stage (Inventory Decisions):** The retailer decides initial inventory levels at each location based on expected demand across all scenarios.
- **Second Stage (Fulfillment Decisions):** For each realized demand scenario, the model determines how orders will be fulfilled (which locations, how much inventory to allocate to online vs. in-store orders) to minimize total costs, including holding, transportation, and penalties for unmet demand.

This framework reflects a realistic decision sequence: inventory levels are set before demand is observed, and then fulfilment decisions respond to actual demand realizations.

4.2 Scenario Representation and Reduction

A major challenge in stochastic programs is the **curse of dimensionality**, where the number of scenarios required to model uncertainties grows exponentially with the problem size. The authors introduce:

- A **similarity measure** to compare scenarios based on both demand distributions and resulting cost implications.
- A **clustering method** that groups similar scenarios and selects representative ones, drawing from Good–Turing sampling techniques and linear programming to maintain balance between representativeness and reduction.

This hybrid method lowers the number of scenarios included in the optimization without requiring a fixed predetermined count of clusters.

4.3 Solution Approach

With a reduced scenario set, the two-stage model is solved using the **L-shaped method** (a decomposition algorithm suited to stochastic problems):

- The first stage master problem generates candidate inventory decisions.
- The second stage subproblems evaluate fulfilment decisions under each scenario cluster.
- Iterative cuts are added to refine the master problem until an optimal solution is reached.

This approach ensures tractable problem solving even for larger problem sizes.

5. Numerical Experiments and Results

The article's empirical section evaluates the proposed strategy on **randomly generated demand scenarios**. Key findings include:

- The scenario clustering method leads to **significant cost savings** compared to benchmark algorithms used in previous literature.
- For **short selling horizons** with large proportions of in-store demand, the algorithm achieves an average cost reduction of up to 11.81%.
- Even for longer horizons, the proposed approach maintains a cost advantage (on average 3.93% lower costs) compared to state-of-the-art approaches.

These results confirm both the **effectiveness of the scenario clustering method** and the **value of integrated inventory and fulfilment optimization** in an omnichannel context.

6. Discussion and Implications

This research has several important implications:

6.1 Theoretical Implications

- It demonstrates the feasibility and effectiveness of **joint optimization models** that integrate inventory and fulfilment decisions under uncertainty — an area where much of the literature previously focused on isolated decisions.
- The scenario clustering technique contributes a scalable approach to handling uncertainty in stochastic optimization, which is broadly applicable beyond retail contexts.

6.2 Practical Implications

- **Retail Decision-Makers** can adopt similar models to optimize cost and service levels, particularly in complex omnichannel systems where inventory can be held at multiple accounting units and fulfilment options.
- The model highlights the importance of tailoring inventory strategies not only to expected demand but also to likely fulfilment pathways and their associated costs, including transportation and penalties.
- The algorithm's flexibility means it can be adapted to real company data, enabling data-driven inventory placement that reduces total operating cost.

7. Limitations and Future Research

Despite its contributions, the study also has limitations:

- The numerical experiments are based on **simulated demand data**, and real-world implementations may introduce additional complexities such as dynamic pricing, lead time uncertainty, and returns processing.
- The model assumes fixed selling seasons and does not address continuous review systems.
- The fulfilment cost model is simplified and may not capture detailed logistics costs such as last-mile delivery or capacity constraints.

Future research could extend the model in several ways:

1. **Empirical Applications:** Test the model on real company data from major omnichannel retailers to validate performance in operational contexts.
2. **Dynamic Demand and Pricing:** Integrate dynamic demand forecasting and pricing decisions with stochastic inventory optimization.
3. **Multi-Product Extensions:** Expand the model to handle multiple SKUs and inventory interactions.
4. **Risk-Averse Optimization:** Incorporate risk preferences (e.g., Conditional Value at Risk) to ensure better service performance under extreme demand variations.

8. Conclusion

The paper **"Optimizing the Inventory and Fulfillment of an Omnichannel Retailer: A Stochastic Approach with Scenario Clustering"** contributes significantly to the literature on inventory and fulfilment optimization by:

- Proposing a joint inventory and fulfilment stochastic optimization model,
- Introducing a novel scenario clustering technique to manage uncertainty,
- Demonstrating measurable cost benefits via empirical tests.

This work enhances our understanding of how modern omnichannel retailers can manage inventory and fulfilment under uncertainty, offering both theoretical advancements and practical decision-making frameworks.

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