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Application of Two-Stage Stochastic Programming for Multi-Product Inventory Optimization in a Nigerian Pharmaceutical Firm

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ABSTRACT

Inventory management remains a key challenge in pharmaceutical supply chains, especially in emerging markets like Nigeria. Unpredictable demand, poor infrastructure, and limited budgets often cause stock imbalances. Traditional inventory models work well in stable environments but struggle to manage demand and lead time uncertainties. This study uses a two-stage stochastic programming model to improve multi-product inventory management for Miracle Kudura Pharmacy, a Nigerian retail and wholesale distributor. Based on 37 months of sales, holding, and ordering cost data for over 100 products, the model incorporates uncertainty through probability distributions grounded in real figures. In the first stage, it sets preliminary order quantities without knowing actual demand. In the second, it updates these quantities as actual demand becomes clear. The initial stage reduced inventory costs to ₦1,224,000, demonstrating cost-effective efficiency. The second stage, however, reported a total cost of ₦1,435,000, showing a trade-off between cost savings and flexibility. Sensitivity analysis revealed that demand for products such as Clarten and Postinor varied widely, while items like Tribotan were more stable. These findings highlight the importance of stochastic models in managing costs, service levels, and risks which are crucial factors in pharmaceuticals where shortages impact public health. Overall, the study highlights how stochastic optimization offers practical, adaptable solutions for managing pharmaceutical inventory in resource-constrained environments.

Keywords: stochastic programming; pharmaceutical inventory; demand uncertainty; optimization; supply chain resilience.

1.0 INTRODUCTION

Inventory management is central to pharmaceutical supply chains, acting as the key process through which medicines are procured, stored, and delivered to patients. In this study, inventory management refers to the systematic process of balancing product availability against associated costs while ensuring that life-saving medicines reach end users promptly (George & Elrashid, 2023). Scholars have highlighted that inventory decisions in pharmaceuticals are not merely economic choices but also public health measures, since poor management can directly disrupt patient care. Pathy and Rahimian (2023) argue that resilience in pharmaceutical supply chains heavily depends on how inventory is managed during disruptions, as shortages in essential drugs immediately compromise service levels. This makes inventory management a multifaceted concept involving cost, service, risk, and responsiveness. However, existing research varies on the extent to which inventory practices should prioritize efficiency over resilience, with some advocates promoting deterministic, cost-minimizing models and others advocating stochastic, uncertainty-focused frameworks.

The issues of demand uncertainty, frequent stockouts, and waste dominate discussions in the Nigerian context, where infrastructural gaps and supply irregularities are common. Demand uncertainty in pharmaceutical supply chains can be understood as the unpredictable variation in product requirements caused by outbreaks, seasonal factors, and consumer behaviour (Ahmadi et al., 2022). In Nigeria, this uncertainty is worsened by macroeconomic factors such as exchange rate instability and reliance on imports, making forecasting unreliable. John and Margaret (2019) examined disruptions in Nigeria's oil and gas sector, drawing parallels to pharmaceutical supply chains, and found that weak institutional capacity worsens the impact of uncertain demand on supply stability. Similarly, Alvarez et al. (2020) show that stochastic fluctuations in both supply and demand have a compounding effect on inventory routing, increasing mismatches between product availability and actual needs. These findings highlight that Nigerian pharmaceutical systems cannot depend on deterministic models assuming stable conditions. Instead, an analysis of real-world complexity suggests that waste from expired stock and shortages caused by unmet demand are two sides of the same structural inefficiency.

Deterministic models, although useful in controlled settings, are still inadequate for capturing complex real-world scenarios. A deterministic inventory model assumes demand and lead times to be fixed and predictable, focusing decision-making on minimising known costs under certainty (Hooshangi-Tabrizi et al., 2021). Critics such as Stranieri et al. (2023) argue that while deterministic models are computationally convenient, they oversimplify dynamic environments. Hooshangi-Tabrizi et al. (2021) demonstrate that deterministic approaches in perishable inventory often incur significant order modification costs when demand deviates from projections. This limitation is especially critical in pharmaceuticals, where perishable products like vaccines demand precise replenishment planning. The differing viewpoints stem from some researchers valuing tractability, while others emphasise realism. From a critical perspective, the deterministic approach may be seen as incompatible with developing economies, where disruptions are routine rather than exceptional. Consequently, neglecting uncertainty in decision models ultimately diminishes their relevance for Nigeria.

Stochastic programming has been developed as a more suitable approach to address the limitations of deterministic models. It can be defined as a mathematical optimisation framework that incorporates random variables into decision-making, thereby generating solutions that perform well across multiple scenarios rather than relying on a single forecast (Birge & Louveaux, 2011, cited in Stranieri et al., 2023). By structuring decisions in stages, stochastic models enable managers to make initial choices before uncertainty is revealed and then adapt once actual conditions are known. Fazli (2024) applies this approach to disaster relief supply chains, demonstrating how two-stage stochastic models enhance responsiveness to demand surges while maintaining efficiency. Similarly, Azizi et al. (2020) show that stochastic programming in reverse logistics introduces flexibility by allowing scenario-based lot-sizing adjustments, thus reducing overall costs. In contrast, deterministic models lack such adaptability. A critical review of these studies reveals that the strength of stochastic programming lies in its robustness across multiple futures, although some argue it increases computational complexity (Stranieri et al., 2023). The current study therefore positions stochastic programming as a pragmatic compromise between efficiency and resilience, particularly relevant for Nigerian pharmaceutical firms.

Miracle Kudura Pharmacy is the central case in this research, illustrating the challenges faced by Nigerian firms. Founded in 2018, the pharmacy operates both retail and wholesale distribution, managing over a hundred products. Despite its growth, the firm faces persistent stockouts of high-demand medicines and high holding costs for slower-moving drugs. Stockouts refer to inventory shortages that prevent meeting customer demand at the point of sale (Alvarez et al., 2020). Conversely, excess inventory results in wastage, especially for perishable drugs with short shelf lives (Ahmadi et al., 2022). George and Elrashid (2023), in their structural equation model of Bahraini hospital pharmacies, similarly noted that poor alignment between demand forecasts and replenishment practices leads to both shortages and waste. In Nigeria, where healthcare access is already fragile, these inefficiencies increase patient vulnerability. By focusing on Miracle Kudura Pharmacy, the study provides empirical insight into how stochastic programming can address the dual issues of scarcity and waste in a resource-limited environment.

The research begins with three distinct objectives, each highlighting a key aspect of inventory optimisation. The first aims to identify demand patterns across multiple products. Demand pattern analysis involves examining sales data to understand the frequency, variability, and seasonality of product consumption (Pathy & Rahimian, 2023). Scholars such as Ahmadi et al. (2022) argue that pattern recognition is essential for risk categorisation, as it differentiates between volatile and stable product lines. However, earlier studies often limited such analyses to developed markets, overlooking contexts where unstable infrastructure and weak logistics impair demand visibility. By analysing demand at Miracle Kudura Pharmacy, this study provides evidence from an under-researched environment.

The second objective is to model demand uncertainty using probability distributions. A probability distribution in this context refers to a statistical function that describes the likelihood of different demand levels occurring for each product (Azizi et al., 2020). Fazli (2024) employed probability distributions in disaster relief logistics, demonstrating how scenario construction enhances preparedness for extreme outcomes. Ramón-Lumbierres et al. (2020) also applied probabilistic modelling to additive manufacturing supply chains, illustrating its capacity to quantify uncertainty in design postponement strategies. Critics warn, however, that probability distributions derived from historical data may inadequately capture structural shocks such as pandemics or sudden regulatory changes. Nonetheless, as Hooshangi-Tabrizi et al. (2021) explain, scenario-based modelling remains superior to deterministic methods in its ability to provide managers with contingency strategies. The current study expands this approach by developing

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distributions for over one hundred pharmaceutical products in Nigeria.

The third objective is to design and implement a two-stage stochastic programming model for optimal replenishment strategies. A two-stage model divides decision-making into an initial stage, where base orders are placed before demand is realised, and a second stage, where adjustments are made after actual demand is observed (Stranieri et al., 2023). In their study combining reinforcement learning with multi-stage stochastic programming, Stranieri et al. (2023) highlighted how staged models produce more adaptive and cost-effective inventory policies. Similarly, Hooshangi-Tabrizi et al. (2021) demonstrated the effectiveness of two-stage robust optimisation in managing perishables by minimizing over-ordering. Yet, Ramón-Lumbierres et al. (2020) caution that increased model complexity may raise implementation barriers for firms with limited analytical capacity. This tension suggests that while the theoretical benefits of two-stage models are significant, practical adoption in Nigeria must be accompanied by capacity-building initiatives. In this study, the two-stage framework is expected to reduce stockouts and waste through adaptive replenishment.

Finally, the contribution of this research extends beyond technical modelling to broader academic and practical fields. From an academic perspective, the study engages with debates about the relevance of stochastic programming in uncertain environments. Fazli (2024) and Azizi et al. (2020) demonstrate that stochastic approaches remain applicable across industries, but limited empirical work exists in Nigerian pharmaceuticals. By contextualising the analysis in this setting, the study addresses both methodological and empirical gaps. Practically, the findings are expected to support Nigerian managers in designing inventory systems that minimise waste while ensuring availability. As George and Elrashid (2023) argue, inventory management is directly linked to healthcare performance, and improvements have wider social implications. Therefore, the study aims to bridge the gap between theory and practice by providing a model that is both scientifically robust and relevant to the local context.

The structure of the article reflects this approach. After the introduction, a detailed methods section describes the data and model formulation. Results are presented emphasising both baseline and adaptive solutions. The discussion critically examines the findings, highlighting trade-offs between efficiency and robustness. The conclusion summarises contributions and proposes directions for future research. In this way, the article provides a comprehensive overview from problem identification to solution development.

2.0 METHODS

This study employs a quantitative modelling approach, using a two-stage stochastic programming framework to optimise inventory management at Miracle Kudura Pharmacy. Quantitative modelling involves the mathematical structuring of decision problems, where demand, cost, and resource constraints are represented as formal variables to guide optimisation (Stranieri, Fadda, & Stella, 2023). The dataset includes 37 months of historical sales records, covering monthly sales of over one hundred pharmaceutical products, as well as ordering, holding, and transportation costs, a budget cap of ₦1,500,000, and product-specific maximum order levels. Demand distributions were estimated using EasyFit to gauge the likelihood of different demand levels, a method commonly used in inventory management under uncertainty (Alvarez et al., 2020; Pathy & Rahimian, 2023). The two-stage model included a first-stage baseline ordering process, which set initial order quantities before demand was realised, and a second-stage adjustment process that amended orders after demand outcomes were observed (Hooshangi-Tabrizi, Doulabi, Contreras, & Bhuiyan, 2021; Fazli, 2024).

The Sample Average Approximation method was employed to estimate expected objectives, improving computational tractability by averaging outcomes across multiple simulated scenarios (Ramón-Lumbierres, Heredia, Minguella-Canela, & Muguruza-Blanco, 2020). The model was developed in Python using Pyomo and solved with Gurobi, a combination that has demonstrated effectiveness for large-scale stochastic optimisation (Forel & Grunow, 2023). This approach offers a robust framework for managing uncertainty in pharmaceutical demand and supports calls for resilient inventory strategies in healthcare systems (Ahmadi et al., 2022; George & Elrashid, 2023).

2.1 Model Formulation

The constraints in the model are typically defined as order quantity constraints and budget constraints.

Decision variable

x_i: Order quantity for the product i in both the first and second stage

Parameter

c_i: cost of ordering a unit product i

λ: parameter for the Poisson distribution representing the probability demand for the product under n scenario

B: Budget

d_i: demand for each product i

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First stage formulation

$$Minimze \sum_{i=1}^{n} c_i x_i + h_i x_i \qquad (1)$$

Subject to:

$x_i \leq B$

$x_i \geq 0$

Second stage model

$$Minimize \sum_{i=1}^{n} (c_i + h_i)\, \lambda \;\; x_i \qquad (2)$$

Subject to

$x_i \leq B$

$x_i \geq d_i$

$x_i \geq 0$

Sensitivity analysis conducted via Monte Carlo simulation to evaluate multiple demand scenarios.

3.0 RESULTS

Table 1 Optimal Solution Based on the Stochastic model 1 and 2

S/N	Product /Pharmaceutical item	Unit to order	
		Model 1	Model 2
1	Clarten	18	21
2	Clofena	9	17
3	Amoxil becan	13	24
4	Eintrin	17	20
5	Paracetamol	8	24
6	Flagyl	20	19
7	Boscopam	15	16
.	.	.	.
.	.	.	.
.	.	.	.
160	Gaviscon	16	16
161	Lazotan	14	18
162	Strepsil	10	20
	Total Cost	1,224,000	1,435,000

The outcomes of the two-stage stochastic programming model are shown in Table 1, comparing optimal solutions from the initial-stage baseline and the subsequent adjustment process. The initial-stage model reduced the total inventory cost to ₦1,224,000, establishing an effective baseline strategy that adhered to the budget constraint. This solution illustrates the economic benefit of committing to fixed order quantities across multiple products, as highlighted in earlier research on cost-efficient baseline inventory strategies (Alvarez et al., 2020).

In contrast, the second-stage model, which considered realised demand variability, resulted in a higher total cost of ₦1,435,000. Although more expensive, this solution demonstrated greater robustness by decreasing the probability of stockouts and aligning more closely with actual demand outcomes, in line with the trade-offs highlighted in Hooshangi-Tabrizi et al. (2021) and Fazli (2024). Product-specific results showed notable differences between the two models. For example, Clarten and Postinor required significant upward adjustments in the second stage due to high demand volatility, while Tribotan remained relatively stable across both models, echoing findings in Ahmadi et al. (2022) that some pharmaceutical products display consistent consumption patterns despite uncertainty.

Table 2 Monte-Carlo Simulation of Scenario with probabilities

S/N	Product /Pharmaceutical item	Scenario 1 (0.02)	Scenario 2 (0.03)	Scenario 3 (0.05)
1	Clarten	16	18	15
2	Clofena	15	16	18
3	Amoxil becan	19	17	15
4	Eintrin	19	15	18
5	Paracetamol	17	15	18
6	Flagyl	16	17	19
7	Boscopam	19	15	16
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
160	Gaviscon	16	15	15
161	Lazotan	18	18	19
162	Strepsil	15	17	17
	Total Cost	1,245,000	1,298,000	1,404,000

Monte Carlo simulations (Table 2) further assessed cost variability across probability-weighted scenarios. Total costs ranged from ₦1,245,000 to ₦1,404,000 depending on scenario outcomes. These results confirm that stochastic programming more effectively captures the uncertainty spectrum than deterministic approaches, while also pinpointing sensitive products that need adaptive ordering strategies (Pathy & Rahimian, 2023; Stranieri et al., 2023).

4.0 DISCUSSION

The results emphasise the key trade-off between cost reduction and resilience in pharmaceutical inventory management. The first-stage solution achieved the lowest total cost, but it was based on expected demand levels, leaving the system vulnerable to fluctuations. Conversely, the second-stage solution incurred higher costs, yet this increase reflects the cost of resilience. This aligns with Stranieri, Fadda, and Stella (2023), who assert that multi-stage stochastic models are more costly both computationally and financially but offer strategies that remain effective across varied demand conditions. For Nigerian pharmaceutical companies, the additional expense is compensated by the assurance of steady product availability, which is vital in healthcare systems where shortages have serious social implications.

The first-stage model produced optimal order quantities for all products within the budget constraint. Total cost was minimized to ₦1,224,000, reflecting an efficient baseline solution that reduced holding and ordering costs. While incorporating stochastic demand led to adjusted order decisions. The second stage of the stochastic programming model introduces a critical component by accounting for uncertainty in demand for each pharmaceutical item. This stage refines the initial optimal order quantities obtained in the first stage, providing a more robust and adaptable solution to the challenges of multi-product inventory management.

At this stage, demand uncertainty is addressed by considering demand scenarios for each pharmaceutical item. The varying demand possibilities capture the pharmaceutical market's real-world unpredictability. These scenarios range from the minimum to maximum possible demand, enabling the model to generate a more resilient and flexible ordering strategy. Total cost increased to ₦1,435,000, reflecting the trade-off between robustness and cost minimization. The adaptive strategy reduced stockout risks and aligned inventory with real demand fluctuations.

The ability of the second-stage model to reduce stockouts highlights the value of adaptive strategies. By adjusting orders after demand is realised, the model better aligned inventory levels with market fluctuations. Similar findings were reported by Hooshangi-Tabrizi et al. (2021), who demonstrated that two-stage optimisation for perishables significantly decreases unmet demand.
Sensitivity analysis and Monte Carlo simulation revealed variation across products, capturing potential variations in demand for different pharmaceutical items. It also assigns a probability weight to each scenario generated through the Monte Carlo simulation, indicating the likelihood of each scenario occurring. It will capture the results of running the two-stage stochastic programming model for each Monte Carlo scenario. It also includes total costs and optimal order quantities for each pharmaceutical item.
In the current case, high sensitivity to demand shocks for Clarten and Postinor, while Tribotan remained relatively stable across scenarios. Total costs ranged from ₦1,245,000 to ₦1,404,000 depending on scenario probabilities. Adjustments for high-variability products such as Clarten and Postinor prevented shortages that would have been unavoidable under baseline planning. Conversely, products like Tribotan, with stable demand, confirmed the efficiency of the first-stage solution. This emphasises the importance of differentiated inventory policies across product categories rather than uniform strategies.

From a managerial perspective, understanding product-specific sensitivity is crucial. Sensitivity analysis shows which medicines are vulnerable to demand shocks and which remain steady, offering valuable guidance for pharmacy managers in allocating financial and storage resources. Pathy and Rahimian (2023) highlight that resilience in supply chains depends not only on overall system design but also on targeted strategies for critical products. Therefore, focusing managerial attention on volatile items ensures both efficiency and resilience.
More broadly, these findings confirm the relevance of stochastic programming in emerging economies. Frequent demand shocks, infrastructural limitations, and financial constraints in Nigeria reflect the uncertain environments analysed in previous studies (Fazli, 2024; George & Elrashid, 2023). While deterministic models simplify decision-making, they fail to capture these realities. Stochastic programming, by explicitly incorporating uncertainty, offers a framework that balances cost control with service reliability. The Nigerian pharmaceutical context shows that resilience is not an optional enhancement but a necessity, and the higher costs linked to adaptive inventory strategies are justified by their capacity to safeguard public health.

5.0 CONCLUSION

This study confirms that two-stage stochastic programming offers an effective framework for pharmaceutical inventory optimisation under uncertainty. By combining baseline order decisions with adaptive second-stage adjustments, the model balances efficiency with robustness and shows clear advantages over traditional deterministic approaches.

The practical advantages of this framework are clear in the reduced occurrence of stockouts, less wastage, and better alignment between demand and replenishment. Although the second-stage solution involved higher overall costs, the improvements in resilience made this trade-off worthwhile, as maintaining a consistent pharmaceutical supply is vital in healthcare delivery.

At the theoretical level, the findings confirm the use of stochastic programming models in the Nigerian pharmaceutical sector, an area where limited empirical evidence has existed. This advances operations research

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by broadening the use of stochastic methods in resource-limited environments where demand fluctuations and infrastructural issues are widespread.

From a practical standpoint, the study emphasises the importance of adopting data-driven optimisation tools to improve decision-making in healthcare supply chains. Encouraging managers to invest in stochastic approaches will bolster resilience and enhance patient access to vital medicines.

Future research should expand this framework by investigating multi-echelon supply chains, incorporating dynamic pricing strategies, and exploring how real-time demand forecasting can enhance pharmaceutical inventory performance.

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