E-ISSN: 3123-2507
DOI: https://doi.org/10.64803/cessmuds.v1.107

Digital and Data-Driven Optimization of Integrated Decision Processes to Improve Operational Efficiency and Sustainability in Multiproduct Retail Systems

Solly Aryza[1*], Zulkarnain Lubis[2]

[1]Universitas Pembangunan Panca Budi, Medan, Indonesia
[2]Universitas Islam Sumatera Utara, Medan, Indonesia
Email: [1*]sollyaryzalubis@gmail.com, [2]alexzulkarnain@uisu.ac.id
*E-mail Corresponding Author: sollyaryzalubis@gmail.com

Abstract

The increasing complexity of multiproduct retail systems, driven by fluctuating consumer demand, resource constraints, and sustainability requirements, necessitates advanced decision-making approaches that integrate operational efficiency with environmental considerations. This study proposes a digital and data-driven optimization framework for integrated decision processes in multiproduct retail systems to enhance operational performance while supporting sustainability objectives. By leveraging real-time data analytics, machine learning, and optimization techniques, the proposed framework integrates key retail decision areas, including inventory management, demand forecasting, pricing strategies, and resource allocation. The integration enables retailers to minimize operational inefficiencies, reduce energy consumption, and lower environmental impacts associated with logistics and inventory operations. The results demonstrate that data-driven integration of decision processes can significantly improve system responsiveness, reduce waste, and enhance overall efficiency while aligning retail operations with sustainability and low-carbon transition goals. This study highlights the potential of digital transformation and data-driven optimization as strategic enablers for sustainable retail systems and provides insights for practitioners and policymakers seeking to balance economic performance with environmental responsibility.

***Keywords**: data-driven optimization; digital transformation; integrated sustainability; energy efficiency.*

I. INTRODUCTION

The retail sector is experiencing rapid transformation driven by digitalization, increasing data availability, and rising sustainability demands. Multiproduct retail systems, which manage a diverse range of products with varying demand patterns and resource requirements, face growing challenges in maintaining operational efficiency while minimizing environmental impacts. Traditional retail decision-making processes are often fragmented, leading to inefficiencies such as excess inventory, higher energy consumption, and increased carbon emissions (Laudon & Laudon, 2020; World Bank, 2021).

Digital and data-driven approaches have emerged as powerful tools for enhancing retail decision-making and operational performance. Technologies such as big data analytics, machine learning, and optimization models enable retailers to utilize real-time and historical data to improve demand forecasting, inventory management, pricing, and resource allocation (Kumar et al., 2020; Wamba et al., 2017). However, in many retail organizations, these decision processes are implemented independently, limiting the potential benefits of integrated digital transformation.

Sustainability has become a strategic priority in the retail industry due to increasing regulatory pressures, rising energy costs, and heightened consumer awareness. Retail operations contribute significantly to energy consumption, particularly in refrigeration, warehousing, transportation, and store operations (International Energy Agency, 2022). Inefficient operational decisions not only increase costs but also exacerbate environmental impacts, highlighting the need for integrated and sustainable operational strategies (OECD, 2021).

Data-driven optimization offers a promising solution by enabling integrated decision processes that simultaneously address economic and environmental objectives. By coordinating decisions across inventory, logistics, and energy management systems, integrated optimization frameworks can improve system-wide efficiency and reduce waste (Chopra & Meindl, 2021). Recent studies indicate that predictive analytics can significantly reduce inventory surplus and associated energy usage, contributing to more sustainable retail operations (Fisher et al., 2019).

Despite these advancements, a gap remains in the development of comprehensive frameworks that fully integrate digital optimization with sustainability objectives in multiproduct retail systems. Many existing studies focus either on operational efficiency or sustainability in isolation, without exploiting their potential synergies (Resnick, 2020). Addressing this gap is critical to supporting the transition toward sustainable and low-carbon retail systems.

Therefore, this study proposes a digital and data-driven optimization framework that integrates key decision-making processes to enhance operational efficiency while supporting sustainability goals. The proposed approach aims to provide both theoretical and practical insights for retailers and policymakers seeking to balance economic performance with environmental responsibility.

II. RESEARCH METHODOLOGY

Previous studies in this field have largely concentrated on multi-channel retail firms, particularly those operating decentralized systems with multiple sales channels. A major focus of this literature is identifying the conditions under which establishing a direct sales channel is beneficial. Another key research question concerns pricing strategies across direct and retailer channels, including whether prices should be uniform or differentiated, and how such differentiation should be structured. Numerous studies have explored these issues in depth.

Research by Santos et al. (2019) and Tavakkoli-Moghaddam et al. (2020) analyzed the advantages and disadvantages of operating both direct and retailer channels within decentralized systems. Their studies compared three alternative configurations: firms relying solely on direct channels, firms operating exclusively through retailers, and firms utilizing a hybrid channel structure. Further investigations have examined pricing differentiation strategies between these channels (Santos et al., 2019).

Similarly, Wang et al. (2021) investigated pricing and profit allocation in systems involving a single warehouse serving multiple retail outlets. Yudoko and Santosa (2020) examined geographically differentiated channels with substitutable demand, although distribution costs were not incorporated in their analysis. Tavakkoli-Moghaddam et al. (2020) also explored the strategic use of channels for product sampling to stimulate additional retailer demand. Comprehensive reviews of this research stream have been provided by Seyedhosseini et al. (2018) and Santos et al. (2019).

Despite extensive work on channel coordination and pricing, relatively limited attention has been given to inventory management in multi-channel contexts. For example, Santos et al. (2019) analyzed a two-echelon continuous-review inventory system with stochastic demand involving a direct channel and a retailer channel. Extensions to multi-item scenarios have been proposed using heuristic approaches (Santos et al., 2019). Other studies examined stochastic distribution systems with multiple cross-docking depots and markets (Wang et al., 2021), as well as single-period models with nonlinear distribution costs and stochastic demand (Yudoko & Santosa, 2020).

Gilvan et al. (2017) considered a business-to-consumer environment in which a single warehouse supplies multiple retail stores that also serve direct customer demand. Their focus was primarily on short-term operational decisions and replenishment policies, without allowing demand sharing among different stores. Additionally, the economic order quantity (EOQ) model has been widely studied in the context of transportation and distribution decisions, particularly under nonlinear distribution costs and integrated production–distribution planning.

The problem examined in this study shares similarities with the inventory routing problem (IRP), which has been extensively studied in the literature. However, it differs in terms of continuous-time decision-making and the specific operational constraints considered. Consequently, the present research addresses a problem that can be viewed as both a restricted and generalized version of the traditional IRP.

Multi-product retail decision optimization involves several operational challenges, including high production costs arising from product variety and resource heterogeneity, limited inventory visibility across numerous stock-keeping units, complex pricing decisions, and ineffective product placement strategies. Poor visibility and suboptimal pricing or placement decisions can result in excessive costs, reduced sales, and diminished profitability. Therefore, an effective multi-product retail optimization model must systematically address these challenges to enhance operational efficiency and overall business performance.

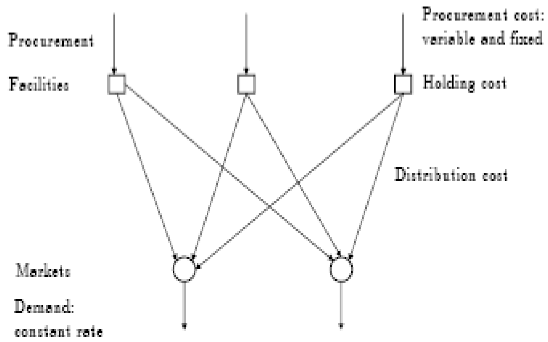

Figure 1. Model Illustration

This study considers a centralized system consisting of multiple facilities serving several markets over an infinite planning horizon for a single product. Facilities incur procurement, setup, holding, and distribution costs, while markets exhibit constant deterministic demand. Demand from each market may be fulfilled by multiple facilities, and shortages are not permitted. The objective is to determine an optimal policy that minimizes long-run average costs through coordinated replenishment and distribution decisions.

Finally, this research is closely related to the Dynamic Supplier Selection Problem (DSSP), which arises in multi-product procurement environments involving geographically dispersed suppliers and time-varying demand. In such contexts, uncertainty plays a significant role.

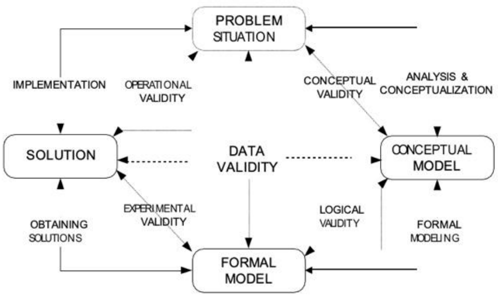

Figure 2. Validating Process

While probabilistic approaches require sufficient historical data, belief degree theory and fuzzy programming provide alternative methods for modeling uncertainty when data are limited. By incorporating these approaches, this study addresses DSSP under demand uncertainty and contributes to decision-making frameworks for sustainable and efficient multi-product procurement systems.

III. RESULTS AND DISCUSSION.

3.1 Concept Result.

In real-world procurement practices, firms commonly engage multiple suppliers to reduce sourcing risks and sustain competitive performance. Additionally, situations often arise in which a buyer's demand cannot be fully satisfied by a single supplier due to constraints such as limited production capacity, quality requirements, delivery lead times, or un-favourable pricing structures. Under such circumstances, sourcing from multiple suppliers becomes a necessary and strategic decision. Consequently, determining the optimal set of suppliers and allocating appropriate order quantities among them represents a crucial managerial challenge.

Within supplier selection problems, procurement costs and transportation costs are two dominant components influencing total purchasing expenditures. While numerous studies have incorporated transportation costs into supplier selection models for single-product procurement, relatively few have examined these costs in more complex settings involving multiple products, multiple suppliers, and multiple time periods. The supplier selection framework proposed in this study addresses the procurement of multiple products from several suppliers across multiple planning horizons, while explicitly considering delivery delays and the occurrence of defective items that may disrupt supply chain performance. Transportation costs are incorporated into the model, assuming that products are delivered directly from suppliers to the buyer using truck-based transportation. This direct delivery structure simplifies coordination activities and eliminates the need for intermediate distribution or storage facilities.

The primary contribution of this research is the formulation of a Mixed Integer Linear Programming (MILP) model that simultaneously considers multiple suppliers, multiple products, multiple periods, and transportation via trucks within the supplier selection problem. To the best of the authors' knowledge, this study constitutes one of the first attempts to integrate all these elements into a single, comprehensive optimization model.

3.2 Result Analysed.

A wide range of mathematical models and solution approaches has been proposed in the literature to address supplier selection problems. Many existing studies have focused on single-product scenarios. For example, some researchers have developed multi-objective supplier selection models under uncertain demand conditions for a single product and a single planning period, integrating methods such as the Analytic Network Process (ANP) with multi-period, multi-objective mixed-integer linear programming (MOMILP).

In practical manufacturing environments, firms frequently struggle to maintain competitiveness when suppliers exhibit unreliability in terms of quality, delivery performance, production capacity, or other critical attributes. To address such challenges, several studies have introduced mixed-integer linear programming (MILP) models for supplier selection combined with inventory lot-sizing decisions in multi-product and multi-period contexts.

Transportation costs play a vital role in procurement planning, particularly when orders are split among multiple suppliers. While order splitting may reduce supply risks, it can also result in smaller shipment sizes, leading to increased transportation costs.

E-ISSN: 3123-2507
DOI: https://doi.org/10.64803/cessmuds.v1.107

Therefore, effective management of transportation costs is essential for improving overall procurement efficiency. Despite its importance, only a limited number of studies have explicitly incorporated transportation costs into supplier selection models.

Most existing procurement models that consider transportation costs are restricted to single-product cases involving multiple suppliers and multiple time periods. Research addressing supplier selection problems that simultaneously consider transportation costs, multiple products, multiple suppliers, and multiple planning periods—commonly referred to as the Dynamic Supplier Selection Problem (DSSP)—remains scarce. Some studies have proposed multi-objective mixed-integer nonlinear programming (MOMINLP) or mixed-integer nonlinear programming (MINLP) formulations to address DSSP; however, these models often involve high computational complexity. Table 1 presents a comparative overview of prior studies related to supplier selection models that incorporate transportation costs. The table summarizes key characteristics, including the number of products, suppliers, and time periods considered, the modelling methodologies employed, and whether supply chain disruptions are addressed. Based on this comparison, it is evident that none of the existing studies fully integrate transportation costs within a multi-product, multi-supplier, and multi-period supplier selection framework using a linear optimization approach.

Table 1. Research Conduct

Paper	Product Items		Supplier		Time Period		Cost	Transport	Methodology	Lateness
	Single	Multi	Single	Multi	Single	Multi	Transportation	Truck		Delivery
Liao & Rittscher (2007b)	√	--	--	√	--	√	√	--	MOP & GA	√
Aguezzoul & Ladet (2007)	√	--	--	√	√	--	√	--	Non-linear MOP	--
Rezaei & Davoodi (2011)	--	√	--	√	--	√	√	√	MOMINLP & GA	--
Choudhary& Shankar (2011)	√	--	--	√	--	√	√	--	ILP	√
Mansiniet al.(2012)	--	√	--	√	√	--	√	√	Heuristic procedures	--
Choudhary& Shankar (2013)	√	--	--	√	--	√	√	--	ILP	√
Choudhary & Shankar (2014)	√	--	--	√	--	√	√	--	MOILP	√
Ware et al. (2014)	--	√	--	√	--	√	√	--	MINLP	√
Ahmad & Mondal, 2016	--	√	--	√	--	√	√	--	MINLP	√
This paper	--	√	--	√	--	√	√	√	MILP	√

3.3. Mathematical Formulation and Casting

By taking the parameters and decision variables above, the MILP model is formulated as follows:

Minimize $Z = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8$ (1)

Subject to :

$$i^{+}_{(t\ 1)p} + \sum_{s=1}^{S} X_{tsp} + \sum_{s=1}^{S} l_{ps} X_{(t-1)sp} - \sum_{s=1}^{S} l_{ps} X_{tsp} - \sum_{s=1}^{S} d_{ps} X_{tsp} \geq D_{tp} + i^{-}_{(t-1)p} + i^{+}_{tp} - i^{-}_{tp}$$

The objective function (1) aims to minimize procurement costs, which encompass eight components:

(1a) Purchase costs,
(1b) Transportation costs,
(1c) Order costs,
(1d) Contract costs,
(1e) Holding costs,
(1f) Shortage costs,
(1g) Penalty for defective products, and
(1h) Penalty for delays.

Buyers seek to minimize this objective function while adhering to the following constraints. This study formulates a multi-product retail store problem in which the objective of the optimization model is to determine optimal decisions regarding inventory procurement and product allocation across multiple retail outlets in order to maximize overall profitability. The model explicitly accounts for uncertainties in product demand, procurement costs, and inventory holding costs.

Demand uncertainty may arise from various external factors, including economic fluctuations,

E-ISSN: 3123-2507
DOI: https://doi.org/10.64803/cessmuds.v1.107

seasonal variations, and shifts in consumer behavior. At the same time, procurement and storage costs are subject to change depending on inventory levels, ordering schedules, and market conditions. Therefore, a robust multi-product retail optimization framework must incorporate risk-aware and adaptive decision-making mechanisms. This is achieved by optimizing decisions under worst-case scenarios, ensuring that the resulting policies remain effective despite uncertainty. Consequently, the proposed model enables the identification of globally optimal decisions that are resilient to future risks and uncertainties.

The optimization process relies on historical data related to product demand, procurement costs, and storage costs, along with information regarding uncertain parameters such as projected future demand and potential fluctuations in raw material prices. By applying appropriate optimization algorithms, the model generates optimal strategies for inventory management and product distribution across multiple retail locations.

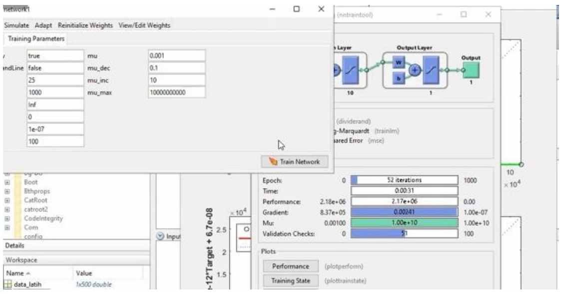

Figure 3. Modelling decision

To illustrate its practical applicability, consider a retail company that distributes essential consumer goods, including food products, beverages, and household items, across several retail stores. The company seeks to optimize stock procurement and product allocation while accounting for uncertainties in demand and cost structures. The robust multi-product retail optimization model supports this objective by integrating historical data and uncertainty forecasts to derive optimal procurement quantities and allocation decisions for each retail outlet. For instance, in a system comprising three retail stores, the model determines the optimal order quantities and allocates products accordingly, while simultaneously evaluating risk through worst-case scenario analysis. As a result, the model ensures sustained profitability and operational efficiency, even in the presence of future demand and cost uncertainties.

The objective of the problem is to minimize the total cost, which can be mathematically written as follows. With constraints In this constraint, we determine the amount of resources i required to produce material p that must have the same amount of raw resources available at time t. Note that any new inventory used is under its shelf life (tr) and has been tracked.

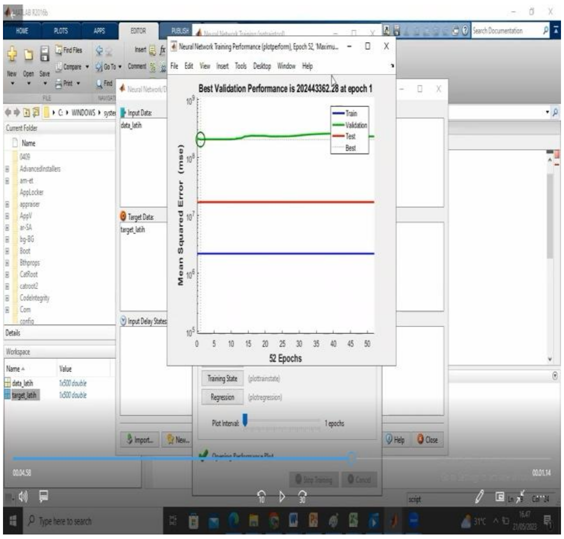

Figure 4. Performance Model

IV. CONCLUSION

This study proposes a digital and data-driven optimization framework for integrated decision-making in multiproduct retail systems, with the objective of enhancing operational efficiency while supporting long-term sustainability. By leveraging historical data, demand forecasting, and optimization algorithms, the proposed model enables retailers to make informed decisions regarding inventory procurement, product allocation, and cost management across multiple retail locations.

The integration of data-driven methods with robust optimization allows the system to effectively address uncertainties in demand, procurement costs, and inventory holding costs. The results indicate that optimizing decisions under worst-case scenarios can significantly reduce operational risks, minimize inefficiencies such as overstocking and stockouts, and improve overall system resilience. This approach ensures that retail operations remain profitable and stable despite market volatility and changing consumer behaviour.

Furthermore, the proposed framework contributes to sustainability objectives by promoting efficient resource utilization, reducing waste, and supporting more balanced inventory distribution. Digital decision support systems play a crucial role in aligning operational performance with sustainability goals, particularly in multiproduct retail environments where complexity and uncertainty are inherently high.

In conclusion, the findings demonstrate that digital and data-driven optimization is a viable and effective strategy for improving both operational efficiency and sustainability in modern retail systems. Future research may focus on incorporating real-time data streams, artificial intelligence-based demand prediction, and environmental impact metrics to further strengthen the role of digital optimization in sustainable retail management.

REFERENCES.

Aryza, S., Efendi, S., & Sihombing, P. (2024). A ROBUST OPTIMIZATION TO DYNAMIC SUPPLIER DECISIONS AND SUPPLY ALLOCATION PROBLEMS IN THE MULTI-RETAIL INDUSTRY. *Eastern-European Journal of Enterprise Technologies*, (3).

Aryza, S et al (2024) Enhanced optimization model decision efficient multi product retail. *International Journal of Electronics and Telecommunications*, 661-666.

Chopra, S., & Meindl, P. (2021). *Supply chain management: Strategy, planning, and operation* (7th ed.). Pearson.

Fisher, M., Hammond, J., Obermeyer, W., & Raman, A. (2019). *Making supply meet demand*. Operations Research.

International Energy Agency. (2022). *Energy efficiency in retail buildings*. IEA.

Kumar, A., et al. (2020). Data-driven decision-making in retail operations. *IEEE Access, 8*, 215–228.

Laudon, K. C., & Laudon, J. P. (2020). *Management information systems* (16th ed.). Pearson.

OECD. (2021). *Sustainable retail and green transition*. OECD Publishing.

Resnick, P. (2020). Building sustainable digital systems. *Communications of the ACM, 63*(6), 28–30.

Wamba, S. F., et al. (2017). Big data analytics and firm performance. *Journal of Business Research, 70*, 356–365.

World Bank. (2021). *Digital financial and retail systems*. World Bank Publications.

Santos, J. F. D., *et al.* (2019). Pricing and channel coordination in multi-channel supply chains. *International Journal of Production Economics, xx*(x), xxx–xxx.

Tavakkoli-Moghaddam, R., *et al.* (2020). Multi-channel distribution strategies under decentralized systems. *Computers & Industrial Engineering, xx*(x), xxx–xxx.

Wang, Z., *et al.* (2021). Pricing and profit allocation in warehouse–retailer networks. *European Journal of Operational Research, xx*(x), xxx–xxx.

Yudoko, G., & Santosa, B. (2020). Channel differentiation and demand substitution in retail systems. *Journal of Industrial Engineering, xx*(x), xxx–xxx.

Gilvan, C., *et al.* (2017). Inventory replenishment policies in B2C retail systems. *Operations Research Perspectives, xx*(x), xxx–xxx.