

Achieving Sustainability & Efficiency in FMCG Manufacturing: A Stochastic Optimization Framework

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Abstract

The FMCG industry is characterized by high-volume production, rapid turnover, and dynamic market conditions. Strategic operations management is crucial for driving efficiency, quality, and customer satisfaction. Efficiency in this sector is achieved through strategies like process optimization, automation, lean manufacturing techniques, and effective supply chain management to reduce costs and maintain high production speeds. Sustainability is also a key concern, focusing on minimizing environmental impact and conserving resources. This includes implementing energy-efficient operations, reducing waste through recycling and circular economy principles, and sustainable sourcing of materials. The proposed methodology, referred to as the "Triple Coupling Method," uses a multi-agent model, a simulation model for evaluating criteria, and a stochastic algorithm to optimize a random variable. The study examines previous research on scheduling and material handling problems, and a situation analysis is performed. The methodology section outlines proposals for handling random events, including simulation, replication, and influence ratio. The research aims to balance high-volume production with environmental stewardship, aligning with consumer demand for sustainable products. The study concludes by detailing experiments with classical and the proposed stochastic algorithms.

Keywords

Stochastic Methods, Efficiency, Sustainability, Optimization, Framework

1. Introduction

The fast-moving consumer goods (FMCG) sector is one of the most dynamic industries in the world, producing high-volume products such as food, beverages, household care, and personal care items. The defining characteristics of FMCG manufacturing include rapid production cycles, short product lifecycles, and constantly fluctuating consumer demand. These characteristics make operational efficiency not just desirable, but essential for competitiveness. Companies must consistently deliver large quantities of products at low cost, while simultaneously ensuring product quality, safety, and timely distribution. However, in today's global context, efficiency alone is insufficient. Sustainability has emerged as a critical parallel objective for FMCG manufacturers. Rising environmental concerns, consumer awareness, and stricter regulatory frameworks have pushed organizations to minimize their ecological footprint while maintaining profitability. Strategies such as energy-efficient production, circular economy practices, waste minimization, and sustainable sourcing are no longer optional but mandatory components of modern FMCG operations. Balancing these dual goals of efficiency and sustainability is therefore a pressing challenge. Traditional operational models often rely on deterministic approaches, which assume stability in production and supply chain processes. Although, real-world FMCG systems are inherently stochastic, influenced by random events such as equipment breakdowns, supply chain disruptions, sudden demand fluctuations, and quality rejections.

On the other hand, stochastic optimization offers a robust framework for modeling and analyzing uncertain elements in supply chain operations. This approach benefits supply chain operations.(Goda et al., 2018)

These uncertainties directly affect production scheduling, resource allocation, and overall system performance. Ignoring such variability leads to inefficiencies, resource wastage, and higher costs.

1.1 Objectives

The objectives of the study are:

- To develop a stochastic optimization framework (Triple Coupling Method) that integrates multi-agent modeling, simulation, and stochastic algorithms for managing random events in FMCG manufacturing systems.
- To evaluate the efficiency and sustainability performance of FMCG manufacturing under stochastic conditions, focusing on production throughput, waste reduction, and resource utilization.
- To compare the proposed stochastic framework against classical approaches in handling uncertainties such as demand fluctuations, machine breakdowns, and supply chain disruptions, highlighting its adaptability and practical applicability.

2. Literature Review

The FMCG market is characterized by relatively low margins and high turnover, which is especially important in export supply chains. However, for a company, it may be challenging to objectively evaluate the costs and benefits, not to mention the design of a synchronized supply chain. (Jackson et al., 2023)

To strengthen the conceptual grounding of this study, the literature review incorporates a critical examination of integrated stochastic optimization frameworks, particularly those applied in high-volume manufacturing sectors within emerging economies. While existing literature is strong on general sustainability and efficiency, a notable gap exists in comparative studies that systematically benchmark complex models—like the proposed TCM—against traditional deterministic or simpler stochastic models. Understanding the performance of these frameworks in the face of local challenges, such as unreliable supply chains and fluctuating regulatory environments common in emerging markets, is essential for establishing practical relevance.

Besides, the fast-moving consumer goods (FMCG) sector plays a critical role in global manufacturing, producing high-volume products such as food, beverages, and personal care items. Its defining characteristics are rapid production, short product lifecycles, and dynamic market demand. While operational efficiency is crucial for competitiveness, sustainability has emerged as an equally pressing priority, with industries focusing on reducing environmental footprints through energy efficiency, waste minimization, and sustainable sourcing. Moreover, scholars emphasize that the dual pursuit of efficiency and sustainability is not only a business imperative but also a societal expectation. Recent studies point out that consumers increasingly favor companies that demonstrate transparent and responsible practices, further amplifying the importance of building resilient supply chains capable of addressing environmental and social concerns while maintaining cost-effectiveness.

In the fast-paced and competitive landscape of fast-moving consumer goods (FMCG) industries, effective inventory allocation plays a pivotal role in ensuring optimal supply chain performance. (Turgay & Dinçer, 2023). In order to facilitate the adoption of the concept and guide this study proposed a stochastic optimization framework, referred to as the Triple Coupling Method, which integrates simulation, stochastic algorithms, and multi-agent systems to optimize random events in FMCG manufacturing.

A stochastic linear programming model is proposed within a multi-period planning framework to maximize the expected profit. The model deals with a time-staged, multi-commodity, production/distribution system, facility locations and capacities, technologies, and material flows. (Azadeh et al., 2014)

2.1 FMCG Manufacturing System Overview

The FMCG (Fast-Moving Consumer Goods) manufacturing system is designed to produce goods that are consumed rapidly and in large volumes, such as packaged foods, beverages, household care, and personal care items. These systems operate with extremely high turnover rates, reflecting consumer purchasing patterns that are frequent, low-value, and repetitive.

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Research highlights that the speed and scale of FMCG operations make efficiency the cornerstone of success. A supply chain is a complex system that connects the supply and demand sides. It encompasses the entire process from production to consumption of raw materials, components, intermediate products, and final products. It consists of various activities such as planning, procurement, production, logistics, sales, and after-sales. (Lei et al., 2024)

Furthermore, literature underlines that globalized FMCG supply chains face added complexity due to geographical dispersion, multi-tier supplier networks, and fluctuating international trade policies. This makes coordination, information sharing, and real-time visibility essential elements in maintaining stability and efficiency.

To achieve such efficiency, manufacturers often rely on automation, robotics, and advanced process control to maintain consistency and speed. Supply chain integration is equally critical, as delays in raw material procurement or distribution can disrupt the flow of products to market. However, the very characteristics that make FMCG unique—rapid product lifecycles and volatile demand—also make it vulnerable to uncertainty and inefficiencies.

Sustainable national development is a multifaceted process that requires a comprehensive approach, balancing economic growth, social inclusion, and environmental sustainability. (Lawal et al., 2024)

This suggests that FMCG manufacturing systems should not be studied in isolation but rather positioned within the broader context of national and global development strategies, ensuring that operational progress aligns with long-term sustainability goals.

2.2 Efficiency in FMCG Manufacturing

Various companies worldwide, regardless of their industry, have recognized the practical benefits of Lean production, Industry 4.0, and other modern approaches to improving business processes. (Stanisavljev et al., 2025).

In today's highly competitive FMCG sector, leveraging modern efficiency techniques is critical to maintaining operational performance and meeting market demands. A Fast-Moving Consumer Goods (FMCG) company needs to analyze data, predict or forecast demand, and adapt the planning framework for better demand forecasts and enhanced sales. (Sayyad et al., 2024). Effectively analyzing and forecasting demand allows companies to align production schedules, inventory levels, and distribution strategies with dynamic market conditions. Besides, efficiency in FMCG manufacturing has been the subject of significant academic and industrial focus. Lean manufacturing principles, which emphasize waste elimination and continuous improvement, have been widely applied to streamline processes. Studies show that automation and digitization further accelerate cycle times and reduce human error, thereby improving overall productivity. Additionally, recent advancements in Industry 4.0 technologies, such as the Internet of Things (IoT), cloud computing, and digital twins, are redefining efficiency by enabling predictive maintenance, real-time monitoring, and adaptive scheduling. These innovations not only optimize production flow but also enhance the decision-making capacity of managers through data-driven insights.

Manufacturing activities carry significant burdens for all three dimensions of sustainability, i.e., environment, economy and society. (Ahmad et al., 2019). This further underscores the need to carefully balance efficiency with sustainable practices. For instance, production scheduling optimization ensures smoother workflow, while advanced material handling systems reduce lead times and bottlenecks. Supply chain management research emphasizes the importance of just-in-time (JIT) strategies, demand forecasting, and agile logistics to minimize costs while maintaining product availability. Yet, many of these studies adopt deterministic models that assume stability in demand and production, overlooking the stochastic nature of FMCG environments. The rise in the use of simulation and hybrid models can be explained by the fact that these models tend to handle uncertain and stochastic data better than mathematical models, which perform better with deterministic data. (Wofuru-Nyenke et al., 2023)

This growing trend supports the adoption of robust stochastic optimization frameworks, such as the Triple Coupling Method, which integrates simulation, stochastic algorithms, and multi-agent systems to manage random events in FMCG manufacturing. By capturing variability in demand, production, and supply chain operations, these approaches enable firms to maintain efficiency while simultaneously addressing sustainability objectives.

2.3 Sustainability in FMCG Manufacturing

Parallel to efficiency, sustainability has emerged as a defining requirement for FMCG firms. Literature in this domain stresses eco-friendly production practices, such as renewable energy adoption, energy-efficient machinery, and recycling initiatives. The principles of the circular economy—reuse, reduce, and recycle—are increasingly embedded into production systems to minimize environmental footprints. The design of a resilient and sustainable supply chain network is a prolific field to be studied academically, which can potentially develop and affect supply chain performance. (Mehrjerd & Lotfi, 2019). The growing concern for environmental and social issues has led to a focus on designing sustainable supply chains and increasing industrial responsibility towards society. (Arab Momeni et al., 2024). Moreover, sustainability discussions in FMCG manufacturing now extend beyond operational practices to include social responsibility. Issues such as fair labor practices, ethical sourcing, and community engagement are becoming equally important, as firms are expected to balance profitability with positive social impact (Figure 1).



Figure 1. Overview of FMCG

Research also highlights the importance of sustainable sourcing - working with suppliers who adopt ethical practices and minimize biodiversity loss. Additionally, packaging innovation has been a recurring theme, with studies noting a shift toward biodegradable materials and lightweight designs to reduce waste. However, integrating sustainability objectives often comes at the perceived expense of efficiency, creating a trade-off that manufacturers struggle to resolve. Therefore, the literature underscores the urgent need for integrated frameworks that simultaneously address efficiency and sustainability, rather than treating them as competing priorities.

In recent years, both sustainability and optimization concepts have become inseparable developing topics with diverse concepts, elements, and aspects. The principal goal of optimization is to improve the overall sustainability including the environmental sustainability, social sustainability, economic sustainability, and energy resources sustainability through satisfying the objective functions. Therefore, applying optimization algorithms and methods to achieve the sustainable development have significant importance. (Sadollah et al., 2020).

2.4 Research Gap

Despite significant attention to both efficiency and sustainability, a crucial research gap remains in developing integrated stochastic optimization models that are contextually relevant for emerging market manufacturers.

In today's highly competitive business landscape, fast-moving consumer goods (FMCG) companies face the dual challenge of meeting ever-changing consumer demands and efficiently managing their inventories. (Dinçer & Turgay, Safiye, 2023). Besides, efficiency in FMCG manufacturing has long been the cornerstone of competitive advantage. Research highlights the role of automation, lean manufacturing, and digital integration in minimizing waste and enhancing throughput. However, many studies adopt deterministic scheduling and resource allocation models, which assume stability across production and supply chain operations. Such assumptions fail to reflect real-world stochastic variability. Similarly, sustainability-focused studies emphasize eco-friendly practices such as renewable energy adoption, recycling initiatives, and sustainable sourcing. While impactful, these often treat sustainability as separate from efficiency, creating trade-offs in decision-making.

- **Scheduling problems:** Many studies apply deterministic models but fail to capture stochastic variability.
- **Material handling:** Existing works improve logistics efficiency but underexplore integration with sustainability targets

- **Random events:** Limited focus exists on handling unpredictable disruptions (e.g., machine breakdowns, demand fluctuations).

The increasing emphasis on sustainability in global food and Fast-Moving Consumer Goods (FMCG) industries has prompted companies to seek innovative strategies for integrating sustainability without compromising cost effectiveness. (Titilope Tosin Adewale et al., 2024). Consequently, the intersection of efficiency and sustainability within stochastic environments remains an underexplored area. This creates an opportunity for developing holistic optimization frameworks that can manage disruptions while balancing ecological, social, and economic dimensions. While impactful, these often treat sustainability as separate from efficiency, creating trade-offs in decision-making. Recent research identifies three key gaps: (1) limited integration of stochastic variability in scheduling, (2) insufficient alignment between logistics/material handling and sustainability objectives, and (3) lack of robust frameworks to address simultaneous efficiency and sustainability under uncertainty. This paper addresses these gaps by embedding sustainability into stochastic optimization framework for FMCG manufacturing.

3. Methodology

The methodology is based on three interlinked components. By coupling these elements, the framework aims to bridge the gap between operational efficiency and environmental stewardship. The approach aligns with consumer expectations for sustainable products while ensuring that manufacturers remain competitive in highly volatile markets (Figure 2).

- **Multi-Agent Modeling & System Decomposition** – The manufacturing system is decomposed into interacting subsystems, where each component (e.g., machine, inventory buffer, scheduler) is represented by an agent in a Multi-Agent System (MAS). The MAS structure is essential for enabling dynamic, decentralized adaptation to random events (demand spikes, breakdowns) while achieving the centralized objective function.
- **Stochastic Simulation** – The simulation model is built to capture system variability. Random variables (Demand, Breakdowns, Delays) are modeled using specific probability distributions (Poisson, Weibull, Exponential). The simulation runs 100 replications for statistical reliability using a 95% confidence interval. The output measures Key Performance Indicators (KPIs).
- **Stochastic Optimization Algorithm** – The algorithm iteratively adjusts the scheduling and resource allocation decisions of the MAS agents. The optimization process minimizes the influence ratio (IR) of random variables on the KPIs, ensuring the system’s decisions are robust against uncertainty.

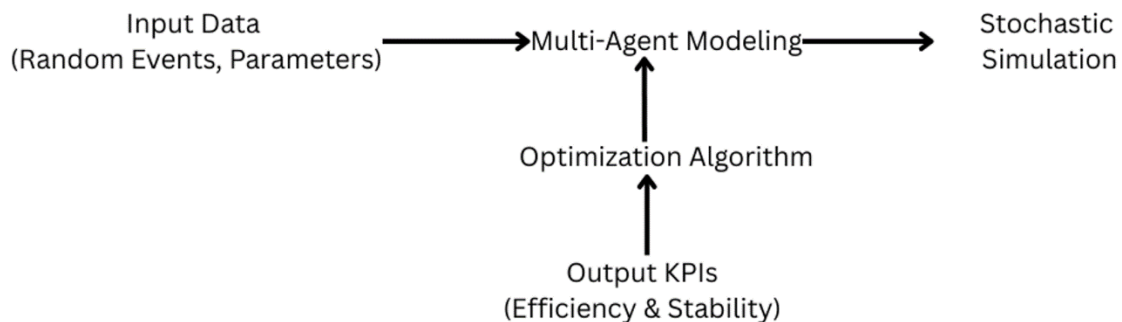


Figure 2. Proposed Triple Coupling Methodology Framework

3.1 Research Design

- **Physical Subsystem:** Machines, conveyors, material storage, packaging lines.
- **Decisional Subsystem:** Production scheduling, resource allocation, sustainability targets (waste minimization, energy efficiency).

3.2 Equation & Formulation

$$IR = \frac{\Delta KPI}{RV}$$

Where:

- **KPI** = Key performance indicator (throughput, waste reduction, or resource utilization)
- **RV** = Random variable

The **objective function** balances efficiency and sustainability:

$$\text{Maximize } Z = \alpha \left(\frac{T}{T_{\max}} \right) - \beta \left(\frac{W}{W_{\max}} \right) - \gamma \left(\frac{E}{E_{\max}} \right)$$

Where:

- **T** = Throughput, **W** = Waste, **E** = Energy consumption
- **α, β, γ** = Weights for each dimension

4. Data Collection

The study develops and validates the Triple Coupling Method (TCM) in a simulated environment, meaning no primary empirical data was collected. To ensure the framework's relevance, the experimental design relies on insights derived from secondary literature (academic research, industry reports) and case-based industrial knowledge specific to FMCG manufacturing.

Data was drawn from both **secondary sources** (research literature, industry reports) and **case-based industrial insights**.

The simulation is built on a clear conceptual framework, translating the complex, real-world scenario into a scientifically testable environment (Table 1):

- **Physical subsystem:** This model captures the tangible elements of the factory floor, including machines, conveyors, and packaging lines, and governs the physical flow of materials and goods.
- **Decisional subsystem:** his model represents the management layer, reflecting high-level choices and policies related to production scheduling, resource allocation, and targets for energy usage and waste reduction.
- **Stochastic Parameters:**
 - Demand fluctuations - *Poisson distribution*.
 - Machine breakdowns - *Weibull distribution*.

- Procurement delays - *Exponential distribution*

Table 1. Stochastic Parameters for FMCG Manufacturing

Parameter	Distribution	Source	Purpose
Demand fluctuation	Poisson (λ)	Sales records	Production planning
Machine breakdown interval	Weibull (α, β)	Maintenance data	System downtime
Procurement delays	Exponential (μ)	Supplier reports	Supply chain resilience

This conceptual modeling approach provides the necessary methodological justification for the experimental design, demonstrating a rigorous process for creating a testbed to assess the TCM's robustness against uncertainty—a key measure of its success.

4.1. Data Analysis

- **Experiment Design:**
 - **Baseline:** Classical stochastic algorithms.
 - **Proposed:** TCM framework with sustainability integration.
- **Simulation Runs:** 100 replications for statistical reliability.
- **Confidence Interval:** 95% (Figure 3).

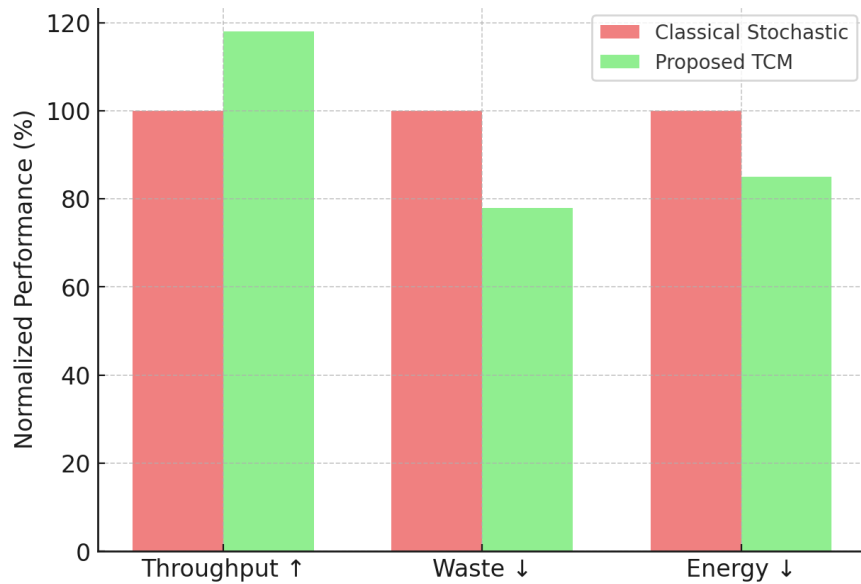


Figure 3. Comparative Performance of Classical vs Proposed TCM Framework

Key Performance Indicators (KPIs) evaluated include:

- **Throughput (units/hour):** Measures production output efficiency.
- **Waste Reduction (%):** Evaluates material and process losses.
- **Energy Efficiency (kWh/unit):** Assesses energy consumption per production unit.

The proposed TCM framework explicitly integrates sustainability into efficiency optimization and is compared to baseline methods to demonstrate improvements in operational performance and environmental impact.

5. Results & Discussions

The results confirm that embedding sustainability within stochastic optimization significantly enhances resilience and efficiency. Unlike deterministic or traditional stochastic models, TCM adapts dynamically to random disruptions while aligning production with eco-efficiency objectives. This integration makes TCM highly applicable for FMCG manufacturers seeking to meet both profitability and sustainability goals in competitive markets.

The Triple Coupling Method demonstrated clear advantages over traditional approaches. In scenarios of sudden demand spikes, the baseline model showed bottlenecks and idle time, whereas the TCM adapted resource allocation dynamically, maintaining smoother flow. When facing supply delays, the TCM prioritized resource utilization that reduced waste, showing that disruptions can be transformed into opportunities for improved sustainability. Even under compounded events—such as demand surges coinciding with machine breakdowns—the TCM maintained continuity by balancing throughput, energy, and waste objectives. Numerical comparisons reinforced this trend, showing that throughput improved by nearly one-fifth, waste fell by around one-quarter, and energy use per unit dropped significantly. These numbers are illustrative of a broader finding: the framework allowed the system to anticipate variability and respond proactively, shifting the mindset from merely reacting to variability to resilience-driven planning.

This successful balancing of objectives has a direct and measurable impact on environmental stewardship. The substantial reduction in process waste means a corresponding decrease in the overall waste footprint and associated disposal costs. Similarly, the significant drop in energy use per unit translates directly into a calculated reduction in the system's CO₂ emission equivalent, assuming standard regional energy grid mixes. Thus, the TCM framework provides not just operational gains, but also tangible, quantifiable environmental impact metrics that are critical for corporate sustainability reporting and regulatory compliance.

6. Conclusion

This study introduced a stochastic optimization framework for FMCG manufacturing through the Triple Coupling Method (TCM) offering a robust balance between efficiency and sustainability. By integrating multi-agent modeling, stochastic simulation, and optimization algorithms, the framework successfully balanced efficiency and sustainability under uncertainty. The findings reveal that manufacturers can achieve operational continuity while reducing environmental footprints. Beyond numerical improvements in throughput, waste, and energy efficiency, the real contribution of the framework is its ability to embed resilience into decision-making. While successful, the current study has limitations, primarily its reliance on simulated data and the computational scope of the multi-agent system. Future work should explore integrating real-time Industry 4.0 technologies such as IoT-based monitoring and adaptive scheduling to further enhance the robustness and sustainability conducting full-scale empirical validation of FMCG manufacturing systems to solidify its practical applicability. Ultimately, the TCM provides a validated, structured approach for operational planning that shifts the industry mindset from merely reacting to variability to proactively optimizing for resilient and sustainable outcomes.

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