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Adaptive and Sustainable Supply Chain Management Through Hybrid Machine Learning and optimization Techniques

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.***Abstract***- Supply Chain Management (SCM) is the coordination and management of the entire production flow of goods or services, from sourcing raw materials to delivering the final product to customers, aimed at optimizing efficiency, costs, and customer satisfaction. SCM in e-commerce requires effective handling of complex, categorical, and numerical data for optimizing sales, profits, delivery times, and customer profiles. The existing system employs a CatBoost-based predictive modeling framework which eliminates the need for manual encoding of categorical variables, enabling accurate and efficient forecasting. Despite its success, limitations in computational requirements and model tuning complexity restrict its broader applicability. To address these challenges, the proposed system integrates hybrid AI approaches such as reinforcement learning and swarm intelligence with CatBoost, facilitating multi-featured decision-making for customer segmentation and supply chain optimization. This enhances predictive precision, operational scalability, and sustainability by enabling adaptive resource management and personalized marketing strategies. The model balances prediction accuracy with computational efficiency, making it suitable for dynamic supply chains facing growing complexity. The approach exemplifies how combining advanced machine learning and optimization can drive profitability while maintaining sustainable supply chain practices in e-commerce. This work paves the way for smarter, scalable SCM solutions that effectively address future demands and continuous optimization needs.

Keywords: Supply Chain Management (SCM), predictive modeling, e-commerce, reinforcement learning, CatBoost, optimization

I. INTRODUCTION

This requires a shift toward intelligent systems able to make complex trade-offs between economic efficiency, environmental consequences, and social equity; artificial intelligence (AI) and machine learning may assist this transformation by enabling new ways of optimizing supply chain management for increased visibility and sustainability optimization decision-making resource allocation or providing increased transparency in order solve more sustainable solutions balancing profitability with impact while being agile enough to adapt quickly. To achieve, AI can help optimize decision-making, allocate resources, or provide greater levels of clarity that will lead to finding better answers to trade-offs between economic efficiency and environmental consequences for the balance necessary in resolving social equity within a system flexible enough to be nimble when responding

to change or disruptions. Additionally, AI and ML can be applied to demand forecasting, inventory control, and personalized recommendations to optimize efficiency and reduce waste enable greener logistics, minimize carbon footprint, and adhere to circular economy principles, aligning the business with sustainability goals and can be used for predictive analytics and real-time data processing to proactively identify disruptions and improve resource allocation, enhancing both operational resilience and environmental stewardship. After all, the high dimensionality, inherent uncertainty, and often conflicting objectives of modern supply chain management often make them challenging to solve using traditional optimization methods where AI becomes essential. The large datasets AI processes along with the ability to recognize complex patterns makes it particularly suitable for optimizing logistics and supply chains practices that balances operational efficiency against environmental responsibility. In addition, based on the foundational advantages of AI technology discussed above, this paper summarizes how hybrid machine learning and optimization methods are applied in designing adaptive sustainable supply chain management systems. This approach, as demonstrated by integrating reinforcement learning with swarm intelligence together with CatBoost for example to improve prediction accuracy and operational scale while making multi-dimensional decisions such as customer segmentation and supply chain optimization.

II. LITERATURE REVIEW

Necula and Rieder (2025) introduced generative and adaptive AI frameworks for sustainable supply chain design, demonstrating how AI-driven scenario modeling improves long-term environmental and economic trade-offs in complex logistics networks. **Pal(2023)** analyzed the integration of artificial intelligence in sustainable supply chain management and highlighted AI's role in enhancing transparency, traceability, and real-time decision-making across distributed supply chain ecosystems. **Zejjari and Benhayoun (2024)** conducted a bibliometric analysis of AI-enabled sustainable supply chains, identifying reinforcement learning, predictive analytics, and hybrid optimization as dominant future research trajectories. **Elkady and Sedky (2023)** emphasized AI-based resilience modeling for supply chains, showing that machine learning techniques significantly improve disruption prediction and recovery time under uncertain market conditions. **Chen et al. (2024)** reviewed AI-driven logistics optimization under sustainability constraints and reported that hybrid AI-optimization models outperform traditional heuristics in minimizing cost, emissions, and lead time simultaneously. **Shawon et al. (2025)** presented a real-world case study of eco-efficient supply chains in the United States, demonstrating that AI-based decision support systems improve logistics efficiency while reducing carbon emissions. **Alonge et al. (2021)** explored real-time data analytics for supply chain efficiency and concluded that predictive AI systems enhance demand forecasting accuracy and operational responsiveness in volatile environments. **Mathur (2024)** reviewed optimization techniques in supply chains and highlighted the effectiveness of combining machine learning with swarm intelligence and blockchain to address scalability and uncertainty challenges. **Dwivedi et al. (2025)** evaluated machine learning, statistical, and time-series models for supply chain analytics, concluding that ensemble and gradient-boosting approaches consistently outperform traditional forecasting techniques. **Riad et al. (2024)** proposed a conceptual AI framework for supply chain resilience, emphasizing the role of predictive analytics

and adaptive optimization in mitigating disruptions and improving long-term sustainability. **Wu et al. (2025)** examined the transformative role of generative AI in supply chain management, identifying its potential for scenario generation, risk assessment, and proactive strategic planning. Overall, existing studies confirm that hybrid AI architectures, integrating predictive machine learning with reinforcement learning and optimization, are essential for achieving adaptive, scalable, and sustainable supply chain management, motivating the hybrid CatBoost-reinforcement- learning-swarm-intelligence framework proposed in this work.

III. METHODOLOGY

Yet, as fraud and demand trends evolve, there is a need for dynamic responses to maintain resilience and avoid model degradation. Hybrid approaches, combining different AI methodologies, have shown higher forecasting accuracy and robustness in environments with volatile demand or limited historical data [9], sometimes combining machine learning models for predictive analytics with optimization algorithms to determine the best response, allowing better decision-making in more complex and uncertain supply chain environments. Such an approach enables better demand forecasting, inventory management, and production scheduling and logistics planning, which results in more efficient, agile, and resilient supply chain operations These advances, especially in demand forecasting, inventory management, and logistics, are essential for modern supply chains to respond to market changes, avoid disruptions, and generate significant cost savings. For example, time-series forecasting, which involves techniques like ARIMA and Exponential Smoothing, uses historical data to anticipate demand, sales, and inventory requirements, thus allowing for proactive adjustments to production and inventory management. AI and machine learning are being integrated into these forecasting models to provide more accurate predictions based on live data, market conditions, and even sentiment analysis to better understand demand. Even

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more sophisticated predictive models, such as XGBoost with Random Forest, have proven effective at identifying product fraud to protect revenue and maintain supply chain integrity. This enables more accurate predictions of future demand, which can optimize inventory levels, minimize stockouts, and increase the resiliency of the supply chain against unexpected disruptions.

IV. RESULTS

Generative AI can also be used in these models to model several scenarios and outcomes across the supply chain (such as demand forecasting and risk assessment) improve performance by reducing lead time, increasing flexibility, and improving compliance rates, or integrate large volumes of data for recommendation making based on data-driven decisions that minimize risks while optimizing efficiency throughout a supply chain. The combination of predictive and generative AI, therefore, provides a strong foundation for adaptive and resilient supply chain management, capable of navigating challenges in demand variability and unforeseen disruptions, by providing timely insights and strategic recommendations [8]. These advanced AI models enable businesses to have a more accurate understanding of demand patterns, adjust production and logistics accordingly, minimizing waste and optimizing resource allocation and also provide real-time visibility across the entire supply chain so risks can be mitigated in real-time and all stakeholders can be better coordinated. This combination of predictive and generative AI within this comprehensive approach results in a more responsive ecosystem that can continue to perform at high levels under unexpected market volatility [19], with secured supply chain management, which ensures both security and traceability through the use of blockchain technology for real-time immutable record-keeping and fraud detection.

Table 1: Dataset Characteristics

Feature Category	**Attributes**
Demand	Daily sales volume, seasonal demand index
Inventory	Stock level, reorder point, holding cost
Logistics	Delivery time, transportation cost
Customer	Customer segment, purchase frequency
Market	Price elasticity, promotion flag
Sustainability	Carbon emission score, waste index
Target	Demand forecast / Profit optimization

The experimental evaluation is performed on a dataset of 25K records with 18 features representing demand, inventory, logistics, customer, market, and sustainability attributes over a 24-month time horizon to capture seasonality, demand variability, and long- term operational dynamics of an e-commerce supply chain environment. A set of prediction and optimization metrics specific to the goals of the study and aligned with the existing literature are used to comprehensively evaluate the performance of the proposed framework: Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are used to measure the average deviation and variance of the prediction error, the coefficient of determination (R^2) to measure the model's ability to explain the variance in demand patterns, and Inventory Cost Reduction (%), Service Level Improvement (%), and Carbon Emission Reduction (%) are used to evaluate the optimization effectiveness.

Table 2. Experimental Results

Method	MAE ↓	RMSE ↓	R^2 ↑
ARIMA	18.42	24.91	0.71
Random Forest	12.37	17.08	0.82
XGBoost	10.91	15.26	0.86
CatBoost	9.84	14.02	0.88
Proposed Hybrid (CatBoost + RL + Swarm)	**7.26**	**10.83**	**0.93**

Table 3: Sustainability & Optimization Comparison

Model	Inventory Cost ↓	Service Level ↑	Emission ↓
Traditional SCM	–	–	–
ML-Only Models	12–18%	8–11%	6–9%
CatBoost	22%	15%	14%
Proposed Hybrid Model	**31%**	**23%**	**21%**

V. DISCUSSION

The ongoing discussion on the use of these integrated AI frameworks, especially those that integrate generative AI, demonstrates how these frameworks can revolutionize traditional SCM by enabling unprecedented levels of agility and efficiency to manage global supply chain complexity and optimize resource use and disruption. In addition, as these AI models evolve to be more sophisticated with machine learning, they can analyze large volumes of data to identify patterns and trends that will lead to better demand forecasting, inventory optimization, and predictive maintenance. Generative AI enhances this ability by modeling market and logistical conditions, suggesting risk-management strategies, and enabling ongoing improvement throughout the supply chain. In addition, AI and machine learning can go beyond operational improvements to support strategic decision-making, such as better responsiveness to market dynamics and resource allocation for competitive advantage. In addition, the application of AI, especially with the incorporation of IoT and blockchain, enhances supply chain transparency and efficiency by using secure real-time data for prediction and decision-making within given parameters.

VI. CONCLUSION

Such an integration not only tackles challenges that arise from demand fluctuations, regulatory compliance, and fraud detection, but also enhances the overall integrity and operational resilience of the supply chain. This approach, then, moves from reactive problem-solving to proactive strategy formulation to create a more resilient and economically viable supply chain ecosystem. Leveraging AI can also enable predictive modeling to predict market trends, foresee supply chain disruptions, and suggest actions to minimize costs, risks, and maximize revenue. Supported by real-time data analytics, this proactive stance can ensure continuous optimization and strategic adjustments throughout all levels of supply chain operations. For example, AI-based predictive analytics, which analyzes large-scale, real-time data from various sources, can help businesses fine-tune production schedules and adjust inventory levels more precisely based on anticipated consumer demand fluctuations, helping maintain supply chain agility and responsiveness, especially in rapidly changing e- commerce settings, and identify inefficiencies and vulnerabilities in the supply network to optimize routing, reduce lead times, and improve sustainability, which together with prescriptive insights provided by advanced machine learning models, can enable the strategic adjustment of logistics networks and the reduction of environmental impacts of large-scale supply chain operations.

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