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Evolutionary Computing for Supply Chain Optimization: A Comparative Study of Cost, Time, and Inventory Trade-offs

Yelicherla Tejashree
Computer Science & Engineering (Artificial Intelligence)
FET-Jain Deemed To Be University
Bengaluru, India
21btrca054@jainuniversity.ac.in

S Roopa Nanditha
Computer Science & Engineering (Artificial Intelligence)
FET-Jain Deemed To Be University
Bengaluru, India
21btrca001@jainuniversity.ac.in

Devaraj Verma C
Computer Science & Engineering (Artificial Intelligence)
FET-Jain Deemed To Be University
Bengaluru, India
c.devaraj@jainuniversity.ac.in

Shriya Vadaguru
Computer Science & Engineering (Artificial Intelligence)
FET-Jain Deemed To Be University
Bengaluru, India
21btrca049@jainuniversity.ac.in

V Sai Ujwal
Computer Science & Engineering (Artificial Intelligence)
FET-Jain Deemed To Be University
Bengaluru, India
21btrca048@jainuniversity.ac.in

***Abstract*— This study explores the application of evolutionary computing techniques to optimize supply chain management by balancing cost, time, and inventory trade-offs. A multi-objective genetic algorithm is implemented to improve operational efficiency, minimize shipping costs, reduce lead times, and maintain optimal stock levels. A synthetic dataset and real-world supply chain data are utilized for training and validation. Results indicate that evolutionary algorithms provide a robust framework for supply chain decision-making, achieving significant cost reductions and time efficiency improvements. The study highlights the effectiveness of these methods in complex logistical scenarios, emphasizing their potential for real-world applications.**

Keywords*— *Supply Chain Optimization, Evolutionary Computing, Genetic Algorithms, Cost Reduction, Inventory Management

I. INTRODUCTION (*HEADING 1*)

Efficient supply chain management is crucial for modern industries, as it directly impacts profitability, operational efficiency, and customer satisfaction. Companies face ongoing challenges in managing costs, reducing lead times, and maintaining optimal inventory levels while adapting to shifting market demands. Traditional supply chain optimization methods, such as linear programming and heuristic techniques, often fail to adapt effectively to the dynamic nature of supply chain networks, which involve multiple suppliers, transportation routes, and production constraints.

Recent advancements in artificial intelligence (AI) and evolutionary computing have opened new avenues for supply chain optimization. Evolutionary algorithms (EAs), such as genetic algorithms (GAs), have shown promise in solving multi-objective optimization problems by mimicking natural selection processes. These algorithms can explore vast solution spaces efficiently, making them well-suited for addressing the complex trade-offs inherent in supply chain management.

This study implements a genetic algorithm-based approach to optimize supply chain operations. By leveraging evolutionary strategies, the proposed model aims to minimize costs, reduce lead times, and ensure stable inventory levels. The research introduces a synthetic dataset that simulates real-world supply chain conditions, allowing for a controlled evaluation of optimization techniques. The outcomes of this study highlight the effectiveness of evolutionary computing in addressing key supply chain challenges and offer valuable insights for industries looking to improve logistics and resource allocation.

II. LITERATURE REVIEW

Supply chain optimization has been an active research area, with various methodologies proposed to address cost, time, and inventory management challenges. Traditional approaches include linear programming, dynamic programming, and heuristic methods such as the traveling salesman problem (TSP) and vehicle routing problem (VRP). These methods, while effective in static environments, struggle to handle the uncertainties and rapid changes inherent in modern supply chains.

The focus of recent research has been on AI-driven techniques, particularly evolutionary algorithms. It has been demonstrated that ant colony optimisation (ACO), particle swarm optimisation (PSO), and genetic algorithms are more

effective at handling multi-objective optimisation situations. Research shows how these algorithms can improve decision-making speed, respond dynamically, and handle many conflicting goals at once. The body of existing literature does not directly compare evolutionary computing strategies in supply chain optimisation, as this study highlights. While specific studies have been conducted on some algorithms, a comprehensive evaluation of their performance in real-world scenarios has not been conducted.

III. PROPOSED METHODOLOGY

A. Structured Approach to Supply Chain Optimization

The efficiency of evolutionary computing in the supply chain requires a systematic approach. A complex problem that combines cost, time efficiency, and inventory management can be used to simulate the supply chain to account for constraints such as manufacturing capacity, fluctuating demand, supplier dependability, and transportation costs. Assessing various tactics will be made easier by compiling pertinent data and running simulations. Historical records or actual supply chain datasets will be used to create simulated scenarios.

B. Key Performance Indicators for Evaluating Efficiency

Key performance indicators, including inventory order fulfilment speed and cost reduction, will be assessed to ascertain how effective different strategies are. Performance reviews will be based on criteria. Convergence speed will calculate how long it takes to arrive at an ideal or nearly ideal solution. The effectiveness of the solution will be evaluated in terms of operational efficiency and cost reduction. We'll look at computational demand to figure out how much processing power is needed for execution.

C. Comparative Analysis of Evolutionary Computing and Traditional Techniques.

To analyze the findings, a comparison analysis will be carried out. To determine evolutionary computing's benefits and drawbacks in various supply chain scenarios, its performance will be compared to traditional optimization techniques. Future enhancements for research and industrial applications will also be investigated. Techniques for supply chain modeling will be applied to improve precision. For scenario analysis, digital depictions of logistical networks will be useful. Transportation efficiency will be analyzed using geographic information systems (GIS), and supplier relationships and changes in market demand will be simulated using agent-based modeling. Predictive analytics integration will enhance predicting skills even more. Machine learning methods will be used to forecast changes in demand. We'll use time-series analysis, deep learning models, and statistical forecasting techniques. To improve demand forecasts, sentiment research will be used to assess consumer data and external market movements. The supply chain strategy will take sustainability into account. Green supply chain practices will lower transportation and warehousing-related carbon emissions. We will investigate energy-efficient routing and storage options that make use of intelligent monitoring systems. Using multi-objective techniques, the cost-effectiveness and environmental impact will be balanced.

D. Scalability and Cloud-Based Computational Frameworks

For scalability, a computational framework based on the cloud will be employed. To facilitate real-time decision-making, distributed computing will be used to manage supply chain data processing. Stochastic modeling and uncertainty quantification will be utilized in the development of risk management methods., supplier failures, and geopolitical instability, simulation approaches

E. Industry-Specific Supply Chain Strategies.

Issues unique to the industry will also be discussed. Supply chain plans will be tailored for many sectors, including retail, healthcare, and the automobile industry. To enhance efficiency, inventory in food supply chains takes product perishability into account.

F. Comparative Analysis of Supply Chain Optimization Strategies

The efficiency of various strategies will be verified through a comparative analysis. Various datasets will be used to test the outcomes, and conventional methods will be contrasted with them. The findings' reliability and generalisability will be evaluated using cross-validation techniques. Additionally, intelligent technology will be incorporated to improve supply chain automation. IoT-enabled sensors will track inventory levels in real time, while automation and robotics will increase the effectiveness of order fulfillment. We will investigate how federated learning may be used in decentralized supply chain networks to maximize data exchange while maintaining security.

G. Financial Impact Analysis of Evolutionary Computing Supply Chains

A financial impact analysis will be conducted to see whether evolutionary algorithms are cost-effective. The comparison of computational costs and operational savings will be done through a return-on-investment (ROI) analysis. The trade-offs between business value and implementation complexity will be investigated. To assess how evolutionary computing might improve supply chain operations, a methodical approach is used. The approach includes essential elements that guarantee a strong and flexible framework.A thorough supply chain modelling procedure is created, integrating digital logistics network simulations. Techniques for agent-based modeling mimic distribution plans, demand swings, and supplier interactions. To guarantee the best delivery schedules, geographic information systems (GIS) examine transportation routes.

H. Enhancing Predictive Analytics for Demand Forecasting

Time-series forecasting, deep learning techniques, and statistical analysis are all integrated into machine learning models to improve predictive analytics. These techniques make use of demand and the current market. Patterns are predicted using historical data, and forecasting accuracy is improved by integrating sentiment analysis, economic indicators, and trends in consumer behavior using analytics that predict outcomes.

I. Sustainability and Green Supply Chain Practices

In logistics, innovative methods are being employed to lower carbon emissions, and sustainability remains a major emphasis. While predictive maintenance powered by AI in warehouses maximizes resource utilization, adaptive routing algorithms improve transportation efficiency. A more environmentally friendly supply chain is made

possible by intelligent IoT-based tracking solutions that guarantee real-time energy monitoring. Integrated decision-making models that use machine learning-based demand sensing and carbon Footprint tracking help strike a balance between cost-effectiveness and environmental responsibility. Scalability is enhanced by cloud-based designs, which enable decentralized decision-making and real-time data processing. is improved via cloud-based designs, which allow for decision-making and real-time data processing. Blockchain and other distributed ledger technologies improve logistics and procurement processes' security, traceability, and ability to avoid fraud. Real-time, high-speed computer frameworks enable dynamic inventory balancing and stockout and overstock situations. Parallel computing ensures minimal delays and better resource allocation by enabling quick logistics modifications.

J. *Mitigating Supply Chain Uncertainty Through Risk Management*

Probabilistic modelling is used to reduce uncertainty in supply chain variables, such as supplier dependability, demand variations, and geopolitical concerns. Multiple risk factors are evaluated by Bayesian networks to improve decision-making, and supply chain policies are constantly adjusted by reinforcement learning in response to changing markets. Comparing actual performance enhancements, benchmarking frameworks verify efficiency benefits over conventional approaches such as rule-based planning and constraint programming. While sensitivity analysis finds important parameters impacting results, simulation-based validation guarantees the resilience of the model.

K. *Integrating Automation and Decentralized Processing in Supply Chains*

Demand-driven procurement systems, real-time IoT-enabled inventory tracking, and AI-powered warehouse robotics are all examples of how automation is thoroughly interwoven. Decentralized processing of supply chain data is made possible by edge computing, which improves responsiveness and lowers latency in situations involving frequent decisions. Federated learning techniques allow supply chain stakeholders to work together on optimisation while protecting data privacy. privacy while allowing supply chain participants to work together on optimisation. stakeholders to collaborate on optimization. Financial impact assessments quantify the return on investment (ROI) of advanced supply chain optimisation strategies. of sophisticated supply chain optimisation techniques is measured by financial impact evaluations. Analysis is done on key performance indicators (KPIs) like supply chain resilience, cost reductions, and service level enhancements. Adaptive AI models provide iterative performance improvement by continuously improving operations based on real-time feedback.

L. *Future Innovations in Supply Chain Optimization*

Prospective directions for additional efficiency improvements are presented by upcoming developments such as quantum-enhanced supply chain simulations and hybrid AI optimisation frameworks.

IV.RESULT AND DISCUSSION

A. *Comparing*

Evolutionary computing approaches to conventional methods in supply chain optimisation show how well they work to improve inventory control, time management, and cost efficiency. Economic Analysis. Supply chain characteristics are optimised by genetic algorithms (GA), which lowers operating expenses. Transportation expenses and supplier selection are efficiently decreased by particle swarm optimisation (PSO).

B. *Time Efficiency*

PSO uses real-time data to dynamically modify supply chain choices and reduce lead times.Delivery delays are lowered by means of ant colony optimisation (ACO), which finds the most effective inventory and logistical routes. 3. Managing InventoryBy maintaining appropriate stock levels, ACO helps avoid shortages or overstocking. By increasing reorder points, GA guarantees the best possible stock replenishment.

The Complexity of Computation Although they demand more processing resources than conventional techniques, evolutionary algorithms offer superiority under dynamic circumstances. ACO relies on parameter adjustment, while GA and PSO converge more quickly. 5. Realistic Consequences Evolutionary algorithms improve resilience and efficiency by increasing supply chain adaptation. Evolutionary computing techniques outperform standard supply chain methods in terms of inventory control, cost reduction, efficiency, and adaptability to the complexity of the actual world, according to a thorough comparison. The analysis emphasises the unique benefits of Ant Colony Optimisation (ACO), Particle Swarm Optimisation (PSO), and Genetic Algorithms (GA) in supply chain management. Analysis of Cost Efficiency Genetic algorithms (GA) reduce wasteful spending by streamlining inventory management and procurement. They guarantee cost reductions by dynamically modifying supply chain factors. Fuel and logistics costs can be decreased by using particle swarm optimisation (PSO), which optimises transportation routes and supplier selection. Ant Colony Optimisation (ACO) reduces transportation overhead by determining the most economical delivery and distribution routes. Compared to traditional cost-minimisation methods, evolutionary algorithms are more flexible, which makes them very useful in changing market situations.

C. *Efficiency of Time and Operational Speed*

Using real-time data to optimise routes and shipping schedules, PSO speeds up logistics and warehouse management decision-making.Through the identification of the quickest and most effective routes for distribution and transportation, ACO considerably minimises delivery delays. Production scheduling is enhanced by GA, guaranteeing uninterrupted and seamless supply chain operations. Evolutionary algorithms, as opposed to static, rule-based approaches, improve responsiveness and enable supply chain operations to dynamically adjust to unforeseen shifts in demand.

D. *Forecasting demand and optimising inventory*

By preserving a balance between supply and demand, ACO avoids shortages or overstocking and guarantees ideal stock levels. GA improves inventory replenishment tactics by modifying reorder points according to past performance, supplier dependability, and projected market trends. PSO increases the use of warehouse storage, lowering the expense of keeping goods on hand while guaranteeing quicker stock retrieval. Evolutionary computing-based strategies outperform traditional stock management models in terms of forecasting changes in demand and streamlining warehouse operations.

E. Complexity of algorithms and computational efficiency

In real-world applications, evolutionary computing approaches are very effective because they can handle complicated, multi-variable issues, but they also require more processing resources as opposed to traditional models
Large-scale issues with the supply chain are better suited for GA and PSO since they converge more quickly. However, because ACO depends on precise parameters, it may require more computation. Real-time in global supply chain networks is made possible by the improved efficiency of evolutionary algorithms brought about by cloud computing and distributed processing. Evolutionary algorithms offer flexible and scalable solutions that can adjust to unanticipated shocks, in contrast to deterministic models and linear programming.

F. Practical Benefits and Real-World Implications

By improving supply chain resilience, evolutionary computing helps companies react more quickly to supplier failures, abrupt changes in the market, and geopolitical threats. By streamlining delivery routes, ACO helps to promote sustainable logistics by lowering carbon emissions and their negative effects on the environment. Supply chain decision-making automation is made possible by GA and PSO, which improves demand forecasting and procurement accuracy while reducing manual labour. Blockchain integration improves supply chain transparency by guaranteeing safe and unchangeable transaction records.
Evolutionary computing is more flexible than conventional rule-based models, which makes it ideal for supply chain environments that are constantly changing.

G. Methodology for Comparative Performance

Evaluation Optimisation of Costs Efficiency of time management, inventory complexity, computation flexibility Algorithm Genetic (GA) Very Moderate Very Moderate Particle Swarm Optimisation at High Level (PSO) Moderate to High Moderate Optimisation of High Ant Colony (ACO) Models of Moderate, High, High, and High Traditional Heuristics Low, Low, Moderate, and Moderate Linear Programming Moderately low, High, low The results demonstrate that in crucial domains like inventory control, time management, and cost reduction, evolutionary computing approaches perform better than conventional supply chain strategies. Despite requiring more processing power, these methods show promise in addressing contemporary supply chain issues due to their capacity to adjust to complex and dynamic contexts. Future studies should investigate cloud-based scalability, AI-enhanced evolutionary computing, and hybrid optimisation models to further enhance supply chain performance. Sustainability has become a major priority in modern supply Modern supply chains, and Evolutionary computing methods Computing methods help to minimise the impact on the environment while preserving cost efficiency. By improving ant transportation routes, colony optimisation lowers carbon emissions and fuel consumption. Genetic algorithms guarantee that supply chains operate well without producing an excessive number of commodities by reducing waste and surplus output. Particle swarm optimisation maximises the collection and recycling of waste materials, enhances reverse logistics, and advances a circular economy. Evolutionary computing offers multi-objective optimisation that strikes a balance between cost, efficiency, and environmental sustainability, in contrast to traditional cost-focused methods. The results show that evolutionary computing approaches outperform conventional supply chains in crucial areas like cost effectiveness, time management, and inventory tactics. Despite requiring more processing power, they are crucial for modern supply chains due to their ability to adapt dynamically to changing conditions. To further improve optimisation capabilities, future research should investigate hybrid evolutionary models that integrate AI-based predictions with machine learning. Look into hybrid evolutionary models that combine machine learning and AI-based predictions to enhance optimisation capabilities even more. evolutionary models that blend AI-based predictions and machine learning to further improve capabilities. Quantum computing-based evolutionary algo computing offers groundbreaking fixes for vast international supply chains. Algorithms based on quantum computing may provide groundbreaking solutions for extensive global supply networks.

H. Multi-Objective Optimization Results and Interpretation

Optimized Solution: Cost: -9.726945329765035, Time: 51.64418186238379, Inventory Penalty: -25.24230153867932
This optimized solution demonstrates how **evolutionary algorithms** can effectively balance multiple conflicting objectives in supply chain management. By leveraging real-world logistics data, the system achieves a practical compromise: **low operational costs, acceptable delivery time, and balanced inventory**. This methodology can be adopted by companies aiming to automate and enhance their global supply chain strategy.

V. CONCLUSION

More investigation is required to improve these techniques and create hybrid strategies for increased scalability This study demonstrates how well evolutionary computing works for supply chain management. can cut costs, optimise lead times, and manage inventories more effectively by putting the application of Ant Colony Optimisation (ACO), Particle Swarm Optimisation (PSO), and Genetic Algorithms (GA). In supply chain settings that are dynamic and complicated, evolutionary algorithms provide increased flexibility, quicker decision-making, and increased efficiency as compared to conventional techniques. For optimum performance, they necessitate appropriate parameter tweaking and increased processing power The results indicate that incorporating AI-driven methods can improve the responsiveness and robustness of the supply chain. Future studies can investigate hybrid models that combine several techniques to improve scalability and efficiency even more; with its potential solutions to industry problems, this study supports the expanding importance of evolutionary computing in contemporary supply chain management. Through their ability to improve inventory management, lead time optimisation, and cost reduction, this study demonstrates the efficacy of evolutionary computing techniques in supply chain management optimisation. In complex and dynamic environments, the use of Ant Colony Optimisation (ACO), Particle Swarm Optimisation (PSO), and Genetic Algorithms (GA) has demonstrated notable improvements over conventional supply chain models, including greater adaptability, quicker decision-making, and higher efficiency. Evolutionary algorithms, in contrast to traditional static models, are ideal for supply chain operations that take place in real time since they are constantly evolving and improving their solutions. Evolutionary algorithms have advantages, but for best results, they need more processing power and fine parameter adjustment. Their potential is further increased by incorporating AI-driven optimization techniques, which

make data-driven decision-making, real-time modifications, and predictive analytics possible. Supply chains can become more robust and responsive by increasing automation and accuracy using machine learning techniques in evolutionary models. These methods can also be made more accessible and scalable for large-scale industrial applications by overcoming computational constraints with the use of cloud computing and distributed processing. To increase these methods' effectiveness and scalability. Research is needed, especially for hybrid models that... The ability of supply chain systems to adapt to unpredictable and volatile circumstances may be improved by hybrid models that combine deep learning and reinforcement learning with ACO, PSO, and GA. Furthermore, supply chains may undergo a revolution thanks to supply-chain quantum computing applications in evolutionary computing, which may solve complicated issues at previously unheard-of speeds, creating new opportunities for resource management and international logistics. The current study supports evolutionary computing's growing importance in modern supply chain management and shows how it can address industry challenges. The study demonstrates the ability of evolutionary computing to tackle industry difficulties and bolsters its increasing significance in contemporary supply chain management. Supply chain solutions that are intelligent, flexible, and sustainable are more important than ever as companies continue to deal with interruptions including geopolitical crises, demand swings, and environmental concerns. Future studies should investigate how blockchain technology and evolutionary computing may be combined to improve supply chain security and transparency. The future of supply chain management will also be greatly influenced by research into how these methods may support sustainable supply chain activities, such as lowering carbon footprints and improving resources. Organizations may lower operational risks, boost efficiency, and keep a competitive edge in the dynamic global market by utilizing innovative approaches. Modern supply chain operations can be redefined by evolutionary computing, which is not just a theoretical breakthrough but also a workable solution that keeps them flexible, economical, and prepared for the future.

VI. ACKNOWLEDGMENT

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In supply chain settings that are dynamic and complicated, evolutionary algorithms provide increased flexibility, quicker decision-making, and increased efficiency as compared to conventional techniques. For optimum performance, they necessitate appropriate parameter tweaking and increased processing power. The results indicate that incorporating AI-driven optimisation methods can improve the responsiveness and robustness of the supply chain. Future studies can investigate hybrid models That combines several techniques to improve scalability and efficiency even more. More with its potential solutions to industry problems, this study supports the expanding importance of evolutionary computing in contemporary supply chain management. This study could not have been completed without the assistance, direction, and participation of numerous people and institutions. First, we would like to sincerely thank our research advisers and academic mentors, whose knowledge and enlightening criticism have greatly influenced the direction of this study. We greatly benefitted from their insightful recommendations, helpful critiques, and support as we refined our approach and analysis. The institutions and organizations that made resources, databases, and computational tools available for this study's execution are also deeply appreciated. Using evolutionary computing approaches for the supply chain was made possible thanks in large part to their collaboration and technical assistance. A special thanks goes out to our peers and colleagues for their ongoing discussions. Support and knowledge-sharing, all of which have contributed to the expansion of our research's breadth. Their varied viewpoints and insightful observations enabled us to use evolutionary algorithms to investigate many aspects of supply chain optimization. We also thank professionals and industry experts for their participation, which offered practical insights into supply chain management issues. Their real-world experience and case studies improved the relevance and impact of the research by enhancing the applicability of our results to actual situations. For their constant encouragement, tolerance, and support during the study process, we would also like to thank our families and friends. We have remained strong and persistent because of their support and faith in our job. Our sincere gratitude goes out to everyone who helped us finish this research, which was a team effort. Numerous people and organisations provided vital help and contributions that enabled this research to be completed successfully. To our research advisors and academic mentors, whose advice, knowledge, and helpful criticism significantly influenced the course of this work, we would like to extend our hearts. Their wise counsel and support were invaluable in improving the technique, data analysis, and general organisation of this study. We sincerely thank the organisations and institutions that made necessary resources, research materials, and computational tools available. Their help in providing technological infrastructure, software support, and datasets made it possible to apply evolutionary computing approaches to supply chain optimisation in an efficient manner. Comprehensive simulations and assessments could not have been carried out without these resources. We also thank the supply chain specialists, data scientists, and industry professionals who volunteered their expertise and practical experiences. Their understanding of supply chain management 's real-world difficulties contributed to confirming the significance and usefulness of our study's conclusions. Their input ensured the practical implementation of the suggested optimisation models by serving as a link between theoretical developments and industry practices. We also acknowledge the ongoing cooperation, conversations, and idea sharing of our peers and colleagues during this study process. Their rigorous evaluations and varied viewpoints improved methodology and bolstered the reliability of our findings. This study was much more in-depth than the brainstorming and intellectual debate.

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