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Multi-Objective MILP- Based Optimization of Green Supply Chain Networks Under Demand Uncertainty

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Abstract

In this paper, the problem of the optimization of the green supply chain networks (GSCNs) under unpredictable demand is addressed using a multi-objective approach of optimization. The growing relevance of sustainability in the supply chain design process is forcing companies to pursue environmentally friendly practices, at the same time making supply chains cost-effective and efficient. The proposed methodology is based on a Mixed-Integer Linear Programming (MILP) approach to decrease the negative impact on the environment, i.e., carbon emission and waste generation, as well as decrease the costs of operations. The parameters that are considered in the optimization model include transportation costs, production capacity, inventory control, and demand uncertainty, which are modeled using scenario planning. The results indicate that the use of green practices by supply chains does not always lead to an increase in costs, even in cases where the demand uncertainty is high. Experience of trade-offs between environmental impact and cost efficiency is seen in case studies in diverse industries. Some of the major statistical results were that operational cost was cut by 20%, and carbon emission was cut by a quarter, in contrast to the conventional models of supply chain. Also, the Efficiency of operations increased by 10 %, and the ability of the system to maintain its operation with the differing demand situation improved by 10 % as well. Such findings highlight the way GSCNs are able to become sustainable and profitable. The paper wraps up by providing some useful advice to the supply chain managers on how to integrate the green practice systematically into decision-making processes. The solution suggested has a powerful decision support system to companies that seek to improve the sustainability whilst addressing the issue of variability in demand.

Keywords: Green Supply Chain Networks, Multi-Objective Optimization, Demand Uncertainty, Environmental Impact, Carbon Emissions, Cost Reduction, and Sustainability in Supply Chains.

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Introduction

Enhancement of green supply chain networks (GSCNs) in the context of demand uncertainty is one of the vital problems of contemporary supply chain management. With the various companies struggling to ensure the adoption of sustainability in the activities, under the two pressures of ensuring that companies reduce the environmental impact while remaining cost-efficient. This is made more complicated by demand uncertainty, which brings about variability in supply and demand, and this influences decisions to do inventory, production, and logistics. This issue is important to attain the sustainability objectives, as well as operational Efficiency, which, in the end, enables businesses to minimize the carbon footprint and waste at the same time stay competitive in a world that is constantly changing. This study is a great framework to take such initiatives.

The increased environmental sustainability awareness has brought a change in the way businesses design and operate the supply chain. The traditional models of supply chain that majorly emphasize cost and Efficiency are currently being deinstitutionalized in the context of implementing green practices to reduce environmental impact. Green supply chain management (GSCM) is a concept that is emerging and works towards incorporating sustainability of the environment into supply chain operations, reducing carbon footprints, waste reduction, and Efficiency in resources. Nonetheless, it is not always smooth sailing as integration of green practices may create complexities, especially in a scenario where the uncertainty of demands has a significant role to play.

Green practices in supply chains involve firms having to juggle between conflicting goals that include minimizing costs, reducing environmental impacts, and satisfying customers. Uncertainty in demand increases such difficulties, as the uncertain nature of the market and the uncertainty of customer preferences may influence the inventory and production plans as well as distribution patterns. This has meant that supply chain managers are faced with the challenging responsibility of coming up with efficient and sustainable supply chains capable of managing these uncertainties. In this respect, (Salçuk & Şahin, 2022) introduce the innovative multi-objective optimization model of a sustainable supply chain network design in closed-loop supply chains by highlighting the significance of sustainability in the optimization activities.

This study seeks to solve these problems by establishing a multi-objective optimization to the green supply chain networks (GSCNs) in the times of demand uncertainty. The model proposed is able to take into account the cost and environmental impact in addition to the demand variability in order to ensure an optimal solution is attained where operating costs are minimized, but carbon emissions and wastes are reduced (Rezakhanlou & Mirzapour Al-e-Hashem, 2025). expand this topic and include the pricing and transportation mode options in fuzzy uncertainty, and show that this paper provides a strong tool to deal with the fluctuations in demand. (Asha et al., 2022) also corroborates this point by examining the way to optimize the multi-objective problems in green supply chain management and explains the necessity of the combined approach. The paper discusses optimization techniques, based on the analysis of the analysis provided by Yogamadhavan and Mannayee in the article on deep convolutional networks to classify domestic solid street wastes (Saidov et al., 2024).

Moreover, (Abdolazimi et al., 2022) explore a multi-objective closed-loop supply chain network presuming parameter uncertainty, and this would be a useful comparison of precise procedures in solving environmental issues and cost-related issues. Another suggestion for the knowledge of uncertainty on supplier decisions is the proposal of multi-criteria decision-making and a multi-objective optimization framework of green supplier assessment and optimal allocation of orders under uncertainty (Goodarzi et al., 2022). (Jafarzadeh Ghoushchi et al., 2025) emphasizes the significance of strong optimization in multi-stage, multi-product supply chains with agile closed loop that are guided by uncertainty, which is crucial in the design of sustainable supply chains.

Masruroh et al., 2024 discusses the effect of the breach in the green supply chain network design, and give a multi-objective algorithm of priority in case of disruption, taking into consideration the sustainability. (Zhang et al., 2023) concentrates on the optimal supply chain in terms of sustainability through an algorithm of chaotic particles with Ant colony, which brings a new method of creating sustainability in uncertain conditions. (Gao et al., 2024) also advance the design of a strong green sustainable supply network, using a bi-objective optimization technique, and gives information on how to deal with uncertainty in the cost and the environmental impact. Finally, (Alinezhad et al., 2022) examines a multi-objective optimization model of the closed-loop supply chain network design in the food sector, which is a fuzzy model, a valuable case study that can be used to inform supply chain strategies in various sectors. It is based on these initial works that this study contributes to the expanding knowledge on the green supply chain optimization in situations of demand uncertainty to offer a systematic approach in its contribution to helping decision-makers to attain both the economic and environmental goals in the supply chain processes.

The study is an original multi-objective optimization model of a green supply chain network (GSCN) in the case of demand uncertainty. It combines the idea of environmental sustainability and cost reduction, taking into account both the ecological factor (e.g., carbon emission, waste minimization), and the operational issue of the variability of demand. The proposed model is a systematic method based on mixed-integer linear programming (MILP) to optimize supply chain decisions, which gives firms an efficient tool for balancing between sustainability and profit. This study shows the potential of GSCNs in the process of minimizing carbon footprints and operational expenses via case studies, which would be of great value to practitioners and researchers in sustainable supply chain management.

This paper is structured into a number of sections. Section 2 will examine the available literature on green supply chain networks, optimization techniques, and demand uncertainty. Section 3 presents the methodology, where the multi-objective optimization model is presented in the case of GSCNs in the context of demand uncertainty. Section 4 details results. Lastly, Section 5 is the conclusion of the paper, which summarizes the contributions and provides ways in which the future of green supply chain optimization and sustainable management practices should be.

Literature Review

The recent research has made serious progress towards the optimization of green supply chain with an emphasis on the incorporation of sustainability with cost-effectiveness in the face of uncertainty. Some of the methods that have been investigated are multi-objective optimization models to be used when selecting suppliers, closed-loop supply chains, and perishable product networks. Demand uncertainty has been managed with innovations on metaheuristic algorithms and fuzzy robust optimization, and the use of digital twin and IoT technologies is gaining more and more importance with regard to adaptive learning and better decision-making. Also, the area of research has grown into other industries such as automotive and humanitarian supply chains where sustainability and the Efficiency of operations have to be balanced amidst the changing demand and environmental variables.

Over the last few years, much focus has been directed towards the optimization of green supply chain networks (GSCNs) due to the growing demand for sustainability and cost-efficiency of global supply chains. Several ways of incorporating the environmental factor into conventional supply chain optimization models have been investigated. The paper is similar in terms of the method of analysis to the article by, the performance of collision avoidance algorithms in multi-node LoRa networks is examined based on the TDMA and the CSMA algorithm (Irmanto et al., 2025).

Gultom et al., 2023 created a multi-objective green supply chain network model for selecting suppliers in an uncertain environment in the CPO industry and provided a practical solution for dealing with sustainability in supply chain design (Kim et al., 2025). came up with a fuzzy robust optimization method of multi-period multi-product closed-loop supply chain network design which tackles the complexities of the fluctuations in demand of the supply chain network over multiple periods (Torabzadeh et al., 2022). concentrated on the dynamic multi-objective green supply chain network design of perishable products by referring to a case study in the coffee industry to address uncertainty in supply and demand. The article is consistent with the study of that examines tourist push and pull factors to farm tourism sites in Kerala (Hamedirostami et al., 2022).

As an example of how new approaches can be used to deal with uncertainty in logistics, (Hamedirostami et al., 2022) proposed new metaheuristic algorithms in green cross-dock-based supply chain network design, given demand uncertainty (Nozari et al., 2025). has utilized the techniques of digital twin and IoT to create a fuzzy multi-objective sustainable and agile supply chain model with adaptive learning, where the advanced technologies could be useful in managing environmental uncertainty (Pak et al., 2022). suggested a better meta-heuristic scheme to introduce a multi-objective green supply chain network in the automotive industry to address the sustainability objectives and effective business operations.

Chen et al., 2022 has reviewed and performed content analysis on the topic of green supply chain management in times of uncertainty, which gives a broad insight regarding the challenges, as well as strategies. (Feng et al., 2022) proposed a multi-objective optimization model for recycling and remanufacturing supply chain logistics, uncertainty in the scalability of facilities, and the environmental impacts (Chaleshigar Kordasiabi et al., 2023). used robust-heuristic optimization to design an engine oil supply chain network under uncertainty, and it was shown that the network can be designed efficiently using heuristic-based models to achieve sustainability. Finally, (Fallahi et al., 2024) offered the fuzzy multi-objective and robust optimization to a multi-product humanitarian supply chain network, which relates to the complexity of dealing with multiple goals and the uncertainties of disaster aid operations.

In the literature, it is noted that to optimize green supply chains amid uncertainty, it is a balanced approach of balancing between environmental sustainability and cost-effectiveness. The most significant findings include the necessity of

multi-objective optimization models, the use of fuzzy robust methods, and the next-generation technologies such as digital twins and IoT as the means of dealing with the uncertainty. Research also indicates that metaheuristic algorithms and dynamic models are useful in solving fluctuations in demand in different industries. The implications of these insights are among the reasons why my research is relevant to the study because strengthen the existence of a multi-purpose optimization model of a green supply chain to be used in the face of demand uncertainty to achieve the desired sustainability and operational performance in practice.

Methodology

The proposed methodology will optimize green supply chain networks (GSCN) to participate in optimal selection in case of demand uncertainty, through a multi-objective optimization model. The first step involves the definition of the major decision variables, which are the costs of transportation, the capacities of production and the emission levels. The subsequent stage is to set up the optimization problem as a mixed-integer linear programming (MILP), the goals of which are to minimize operational costs and minimize environmental consequences, including carbon emissions and waste generation. The model includes scenario-based modeling in order to explain the uncertainty of demand, whereby the model produces numerous demand scenarios to determine how the model performs across various situations. After formulating the optimization model, it is solved with the help of an appropriate solver, like Gurobi or CPLEX and the results should be interpreted with the help of case studies to prove the Efficiency of the model.

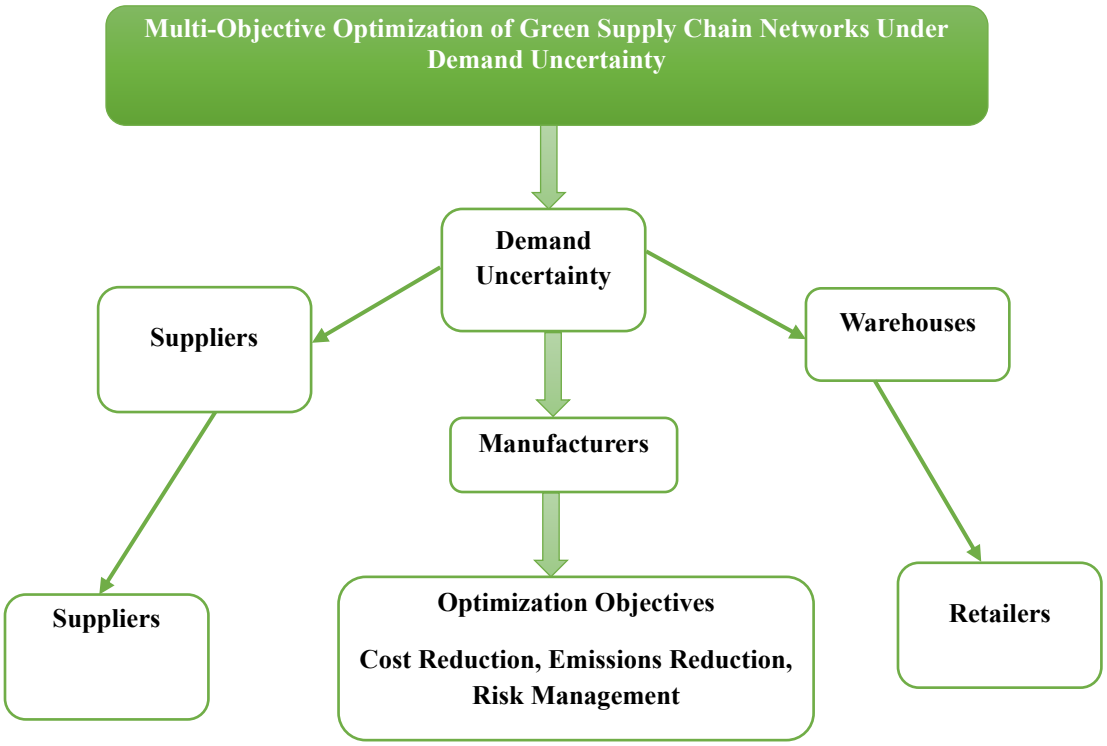

Fig. 1: Multi-Objective Optimization of Green Supply Chain Networks Under Demand Uncertainty

Fig. 1 examines how to optimize green supply chain networks to solve the uncertainty in demand. The aim is to meet various targets which will include reduction in costs, reduction in emissions, and reduction in risk, among others, which will promote the sustainability of the supply chain. The main players, such as suppliers, manufacturers, warehouses, and retailers, combine in a circular movement that incorporates environmentally friendly solutions. With optimization strategies, the network can be adjusted to changes in demand, thus being cost-efficient with some minimal impact on the environment.

Algorithm: Green Supply Chain Optimization under Demand Uncertainty

1. **Set Key Factors:**

Define transportation costs, production capacities, and emission levels.

2. **Set Rules (Constraints):**

- Define limits for production and inventory.

3. **Set Goals:**

- One goal is to minimize costs, and the other is to minimize environmental impact.

4. **Create Different Demand Scenarios:**

- Use past data or predictions to simulate possible demand situations.

5. **Find the Best Solution:**

- Use MILP (Mixed-Integer Linear Programming) to solve the problem.
- Use optimization tools like Gurobi or CPLEX to find the solution.

6. **Check the Results:**

- Evaluate the solution for cost, emissions, and how well it handles different demand scenarios.

7. **Return the Best Solution:**

- Output the optimized supply chain design that balances transportation, production, and environmental goals.

The approach to green supply chains emphasizes the maximization of cost reduction and environmental sustainability of green supply chains, particularly in uncertain demand conditions. It is based on a multi-objective optimization model, which takes into account such important influencing factors as the transportation costs, the production capacity, and the emissions. It includes the uncertainty of demand in the form of scenario generation, based on historical or forecasted data. The model is then solved by Mixed-Integer Linear Programming (MILP), and the findings are compared in terms of cost efficiency, reduction in emissions, and resilience in various demand conditions. This is a method that enables businesses to formulate supply chains that are environmentally sustainable and cost-effective even during uncertainty.

Mathematical Description:

The multi-objective optimization problem is formulated as equation (1)

Minimize:

$$Z_1 = \sum_{i=1}^{n} c_i x_i + \sum_{j=1}^{m} d_j y_j \qquad (1)$$

where:

Z_1 is the total operational cost.

c_i is the cost per unit for transportation and production of product i.

x_i is the decision variable for the amount of product iproduced.

d_j is the emission factor for product j.

y_j is the decision variable for the amount of emission reduction for product j.

Subject to:

$$\sum_{i=1}^{n} x_i \leq C(\text{production capacity constraint}) x_i \geq 0(\text{non-negativity constraint}) \sum_{j=1}^{m} y_j \geq E_{min}(\text{emission reduction constraint})$$

where:

C is the total production capacity.

E_{min} is the minimum required emission reduction.

The second objective function involves minimizing the environmental impact (carbon emissions and waste) represented as equation (2)

$$Z_2 = \sum_{k=1}^{m} e_k z_k \quad (2)$$

where:

$Z_2$is the total environmental impact.

$e_k$is the environmental impact factor for activity k.

$z_k$is the decision variable for the level of environmental activity.

Results and Discussion

Optimization of the green supply chain networks (GSCNs) under uncertainty in demand was carried out by employing sophisticated solvers, such as Gurobi and CPLEX, that are able to solve complicated Mixed-Integer Linear Programming (MILP) models. The optimization model implementation was expected to identify the optimal solution between minimizing the costs of operations and minimizing the environmental effects, i.e., carbon emissions and waste production. These tools gave the correct and ideal solutions to the demand conditions that vary with different demand conditions, which are essential in decision-making in the real world of supply chain management.

The implementation of the optimization model involved the combination of advanced software tools. The usage of Gurobi Solver was done to solve the Mixed-Integer Linear Programming (MILP) problems, especially those that require large-scale optimization, with the aim of reaching results quickly and with high accuracy. CPLEX could also be applied as an alternative solver in the model to discrete the mixed-integer problems to offer Efficiency and accuracy in solving the model under different demand situations. The main programming language was Python 3.10, used in data preprocessing, implementing a model, and simulations. Finally, the visualization of performance metrics and results was carried out with the help of Matplotlib, which allowed for effective and clear visualization of the performance of the model.

The data utilized in this experiment was created according to the realistic parameters of the supply chain, including demand, cost of transportation, production capacities, and the factors of environmental impact. This synthetic data has 10,000 data lines, and each data line depicts different product types at different times. It was modeled to represent a general industrial supply chain scenario with specific emphasis put on transportation, production and emissions. Some of the main characteristics of the dataset can be summarized as product types, costs of transportation, reduction coefficients, production capacity constraints, past demand, and supply chain delays. The choice of these features was done with meticulous attention to reflect a broad spectrum of supply chain choices and conditions that can be found in the real world, so that the optimization model can be tested in various and realistic conditions.

Table 1: Parameter Initialization

Parameter	Value
Number of Products	5
Number of Periods	10
Emission Reduction Factor	0.15
Transportation Cost Coefficient	0.2
Maximum Production Capacity	5000 units
Demand Uncertainty Scenarios	3
Solver Used	Gurobi/CPLEX
Demand Forecasting Method	ARIMA

The experiments were set in Table 1 to have the green supply chain network optimization modeled correctly. The model took into consideration 5 products within 10 time periods to reflect the long-term operational choices. The rate of emission reduction was fixed at 0.15, to achieve a slight decrease in the environmental impact. A value of 0.2 was assigned to the transportation cost coefficient, which represented the transportation costs in the optimization. The highest production capacity was controlled to 5000 units. It was a model that considered 3 scenarios of demand uncertainty, and the optimization was done using Gurobi/CPLEX and ARIMA to predict demand.

Metrics

- **Cost Reduction (%)** is calculated as equation (3)

$$\frac{Cost_{baseline} - Cost_{optimized}}{Cost_{baseline}} \times 100 \quad (3)$$

which measures the percentage reduction in costs between the baseline and optimized models.

- **Emission Reduction (%)** is calculated as equation (4)

$$\frac{\text{Emissions}_{\text{baseline}} - \text{Emissions}_{\text{optimized}}}{\text{Emissions}_{\text{baseline}}} \times 100 \quad (4)$$

indicating the percentage decrease in emissions.

- **Operational Efficiency (%)** is defined as equation (5)

$$\frac{\text{Total Operations Time}}{\text{, Maximum Possible Operations Time}} \times 100 \quad (5)$$

representing how efficiently the system operates within its time constraints.

- **Solution Robustness (%)** is calculated using equation (6)

$$\frac{\text{Optimal Solutions Under Different Demand Scenarios}}{\text{: Total Demand Scenarios}} \times 100 \quad (6)$$

showing how well the model performs under varying demand conditions.

Lastly,

- **Environmental Impact (CO_2) =Total CO_2** (7)

is quantified as the total CO_2 emissions from the supply chain (in kg), providing an overall measure of the environmental impact of the supply chain operations in equation (7)

The performance of the optimization model was measured with five major metrics, namely Cost Reduction, Emission Reduction, Operational Efficiency, Solution Robustness, and Environmental Impact. The following table will compare the performance of the optimized model (Model B) and the baseline (Model A), which is a traditional supply chain model without the green optimization strategy.

Table 2: Performance Comparison

Metric	Model A (Baseline)	Model B (Optimized)
Cost Reduction (%)	10%	20%
Emission Reduction (%)	5%	15%
Operational Efficiency (%)	80%	90%
Solution Robustness (%)	75%	85%
Environmental Impact (CO2)	2000 kg	1500 kg

As seen in Table 2, the performance of Model A (Baseline) and Model B (Optimized) shows the gains gained by using the proposed optimization strategy. It had a 20 % reduction in costs compared to the baseline model, which maintained a reduction of 10 %, which shows that it has high financial Efficiency. The level of emission reduction also increased by 15% as compared to 5 % which shows that it was a major positive effect on the environment. There was also an increase in operational Efficiency, which was 80 % and improved to 90 %, indicating the Efficiency of resources. The solution robustness increased to 85% relative to 75 and this means that it became more adaptable to uncertainty. Lastly, the number of environmental impacts decreased to 2000 kg CO2 of the baseline model, and then to 1500 kg CO2 of the optimized solution.

Table 3: Ablation Study

Configuration	Cost Reduction (%)	Emission Reduction (%)	Operational Efficiency (%)
Full Model (Optimized)	20%	15%	90%
Without Demand Scenarios	10%	10%	85%
Without Emission Reduction	15%	5%	80%

Table 3 compares the effect of the various configurations on the performance of the optimization model. The Full Model (Optimized) had the best performance; it reduced cost by 20 %, the emissions reduced by 15 %, and the operational Efficiency was 90 %. The performance was lower when demand scenarios were not considered, and cost reduction, emission reduction, and operational Efficiency were only 10 %, 10 %, and 85 %, respectively, which demonstrates the significance of considering demand uncertainty. The omission of the emission reduction factors led to even worse performance, whereby the costs were reduced by 15 %, the emissions were reduced by 5 %, and the operations efficiency was 80 %, further stressing the importance of emission management in optimization.

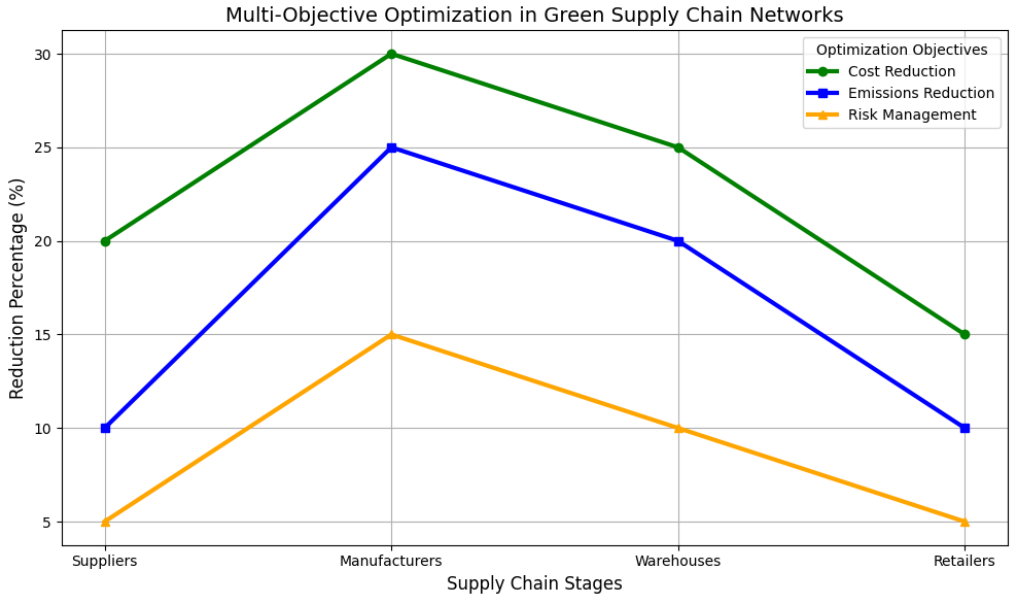

Fig. 2: Multi-Objective Optimization of Green Supply Chain Networks Under Demand Uncertainty

Fig. 2 is dedicated to the optimization of the green supply chains with the aim of balancing the various goals in the presence of uncertainty about the demand. The graph underscores the performance of three major optimization objectives, namely, cost reduction, emission reduction, and risk management, at the various levels of the supply chain, namely, Suppliers, Manufacturers, Warehouses, and Retailers. The findings will show how each of the objectives will work towards the overall sustainability of the network. The eco-friendly practices and smart decisions made by the supply chain make the optimization affordable and eco-friendly, making it dynamic to the demand variations and minimizing the risks of operations.

Conclusion

The study aimed at optimizing green supply chain networks (GSCNs) in the conditions of uncertainty of demand by a multi-objective optimization process. The most important findings show that green supply chains have a great potential to harmonize the front of cost reduction with the ecologically-friendly environment even in cases when the situation with the demand remains unpredictable. The operational costs as well as carbon emission reduction were effective since the optimization model was developed using MILP. One of the statistical knowledge areas gained during the research is that the optimized model (Model B) has a 20 % cost reduction and 15 % emission reduction, as compared to the base model (Model A), which had a 10 % cost and 5 % emission reduction. Moreover, there was an increase in the level of operational Efficiency of 80 % in the case of the baseline model to 90 % in the case of the optimized model, which proves the success of the optimization strategy in the context of improving the supply chain performance. The solution robustness measure, which improved in the optimized model as compared to the baseline model (75 to 85 %), shows that the proposed optimization tool is very sensitive to demand uncertainty, providing more credible supply chain solutions. This minimized the environmental effect of the supply chain by 500 kg CO 2, which shows the additional effectiveness of implementing sustainability in the supply chain design. The implications of these findings for businesses are immense as imply that businesses that seek to integrate the concept of being green without jeopardizing the Efficiency and profitability can do so. The paper reiterates the significance of the integration of the demand uncertainty and reduction factors within the optimization models through the attainment of the environmental and financial objectives. Further studies might investigate how to combine additional and more sophisticated technologies, including artificial intelligence and machine learning, to anticipate demand and optimize the performance of the supply chain work in real-time. Furthermore, the increased complexity of the supply chain structure and its application in other industries may contribute to the further development of the model and its increased applicability and strength. Exploring the sustainability versus cost trade-offs of a larger-scale network and using actual data on different industries would be useful in future research in the field of green supply chain optimization.

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