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Multi-objective optimization of sustainable supply chain under carbon policies

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Abstract

As the effects of global climate change increase, both academics and policymakers are assessing the impacts of carbon reduction strategies on industrial systems. Businesses now face the challenge of designing supply chain networks that are both economically efficient and environmentally sustainable. This study examines the impacts of carbon policies on sustainable supply chain networks by developing a multi-objective optimization model. The study analyses how three main carbon policy instruments, namely carbon cap, carbon taxes and carbon cap-and-trade, affect total costs and carbon emissions in a multi-stage supply chain by using mathematical modeling. The Augmented Epsilon Contraint method is used to generate Pareto optimum solutions that result in trade-offs between environmental impact and total cost. These Pareto optimal solutions are ranked using the TOPSIS method, presenting strategic alternatives for decision-makers. The results clearly show that carbon regulatory tools are necessary for designing the supply chain with climate awareness.

Keywords: Carbon policy, European green deal, Multi-objective optimization, Sustainable supply chain.

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1. Introduction

The increasing impacts of global climate change have placed the sustainability-oriented approach in the center of industrial strategy and policymaking. Particularly, the need to decarbonize economic systems has driven organizations to adopt regulatory frameworks that incentivize low carbon emission practices. The primary initiative is the European Union's Green Deal, which encourages carbon neutrality, resource efficiency and circular economy practices across industries [1].

In this context, supply chains face growing pressure to align economic efficiency with environmental responsibility due to their significant contribution to industrial emissions. To design supply chains that align with sustainability goals, environmental policies must be integrated into operational planning and decision-making processes. To effectively assess how the environmental regulations influence supply chain operations, mathematical modeling offers a structured and analytical approach. These tools help evaluate trade-offs between cost and emissions under different carbon policies.

In this study, a multi-stage supply chain model comprising suppliers, distributors, and retailers is proposed, and the effects of carbon policies are examined under several scenarios. Economic and environmental aspects of sustainability are considered by attempting to minimize total costs and total carbon emissions simultaneously. The model was solved using the Augmented Epsilon-Constraint method (AUGMENCON), and the comparative analysis of the impact of various carbon policies on the model's performance was conducted [2, 3].

The three primary carbon emission regulatory tools -carbon cap, carbon tax, and carbon cap and trade systems- have emerged as key policy mechanisms. According to Ellerman and Buchner [4] the carbon cap policy limits the amount of carbon that can be produced in a given time frame and penalizes companies that surpass this limit. Sectoral emission quotas are used to govern this system, which is supported by apps like the European Union Emission Trading System (EU ETS) (European Commission). The carbon tax, on the other hand, seeks to reduce the economic appeal of processes with large carbon emissions by placing a direct cost on the quantity of emissions [5]. In order to establish a predictable cost structure, industrial companies take this strategy into account while making strategic plans. In contrast, the Cap-and-Trade system establishes a cap on overall emissions and provides a flexible mechanism that allow the market to buy and sell emission quotas within these limitations. In this way, it supports economic efficiency as well as environmental goals [6].

As carbon regulations become a central element of the environmental policy, the importance of comprehending its implications for supply chains is becoming more crucial. Multi-objective optimization models that simultaneously address cost efficiency and carbon emissions provide a powerful analytical foundation for examining the influence of carbon policies on industrial systems. These models support evidence-based policy-making by simulating the outcomes of various regulations under uncertain condition and assist in aligning regulatory objectives with practical implementation.

2. Review of Literature

Studies examining how carbon emission reduction policies affect the architecture of sustainable supply chain networks have grown in number in recent years. The integration of carbon cap, carbon tax, and carbon cap-and-trade policies into closed-loop supply chain models, as well as the implications of these policies on social, environmental, and economic sustainability, are the main topics of this field's research.

This study examines the impact of different carbon policies on total cost and total emission caused by the supply chain activities. Review of the literature reveals a gap, as most of the proposed models consider carbon emission prodused primarily from transportation, while emissions caused by material usage and electricity consumption during production were not evaluated together. One of the important contributions of the study to the literature is the integrated modeling of emissions from both production (material and electricity usage) and transportation activities. By comparing the effects of carbon regulations, the proposed multi objective optimization model provides a flexible method that goes beyond traditional cost minimization models.

Multi-objective mathematical models are particularly used to integrate carbon pricing systems into supply chain activities. To examine the impact of implementing a carbon tax on supply chain operating expenses and emissions, Hashmi, et al. [7] created a closed-loop supply chain model. This study directly included carbon pricing into the cost function and performed sensitivity assessments under different carbon tax scenarios.

A single carbon tax, a carbon cap-and-trade, and a mixed carbon policy were the three policy scenarios that Huang, et al. [8] compared. The results showed that, in some circumstances, a mixed carbon strategy can perform better in terms of the economy and the environment. In comparison to the carbon trading policy at the border, the mixed policy offered a more efficient solution, particularly when the carbon quota above a particular threshold.

The impact of carbon control laws on the reverse supply chain was assessed by Alkhayyal and Gupta [9] in three distinct scenarios: cap-and-trade, carbon tax, and carbon cap. This study highlighted the critical role that carbon policies play in reverse logistics operations by analyzing the effects of each policy on the cost function using a mathematical model. According to the authors, stringent carbon emission laws promote cycle behaviors like reuse and recycling.

A sustainable supply chain network design model with uncertainty that considers both social aspects and greenhouse gas emissions was given by Kumar and Kumar [10]. In addition to controlling carbon emissions, this study's model also includes social sustainability variables like the amount of customer complaints and the length of time suppliers receive training. The modeling of uncertainty was done using the chance constrained programming method, and greedy heuristic algorithms were employed to tackle large-scale issues.

A multi-objective optimization model was created by Mirzaee, et al. [11] in order to solve the issue of green supplier selection and order establishment in closed-loop supply chains. Decision factors for the purchase and sale of carbon permits are defined in the model, which also incorporates the carbon cap-and-trade legislation. The model was solved using a strong optimization technique, and solutions were found for various scenarios (realistic, pessimistic, and optimistic). The findings showed that high carbon pricing and low carbon quotas are more successful in cutting emissions.

In closed-loop supply chain models, Xu, et al. [12] compared the effects of market forces and carbon emission policies. The adoption of the carbon tax led to more favorable costs in private closed-loop supply chains, according to the model created using mixed integer linear programming (MILP). Furthermore, supply chain performance was more influenced by consumer demand than by the scale impact.

In their study on the conversion of Istanbul's metrobus fleet to electric vehicles, Gungor and Satoglu [13] proposed a multi-objective model that included a carbon tax and other incentive scenarios. The cost of buying an electric bus, the cost of batteries and charging infrastructure, and carbon emissions were all included in the model. The model was solved using the AUGMECON2 (imrpved Augmented ε-constraint method) method [3] and the cost-emission balance was examined under various policy conditions.

Fareeduddin, et al. [14] introduced a mixed integer optimization model for logistics operations in a closed-loop supply chain network based on carbon regulation laws. The models developed under three distinct carbon policies (carbon cap, carbon tax, and carbon cap-and-trade) were assessed in terms of the cost-emission balance.

A multi-objective nonlinear model that examines how carbon policies affect online platforms and seeks to optimize producer profitability while minimizing overall carbon emissions and environmental harm was put forth by Yu, et al. [15]. According to the study, a carbon price reduces carbon emissions and increases social welfare. According to this research, a carbon tax may be a useful instrument for advancing social and environmental sustainability.

Govindan, et al. [16] created a multi-objective model that was integrated with carbon tax policy and concentrated on designing closed-loop supply chain networks in accordance with the objectives of the circular economy. The model uses scenario-based analysis to manage uncertainties and a carbon price to reduce carbon emissions from production, transportation, and disposal activities.

Through the use of various modeling methodologies and scenarios, all of these research examined how carbon regulation regulations affected the design of sustainable supply chain networks, allowing for the simultaneous optimization of environmental and economic objectives. The effects of cap-and-trade and carbon tax policies have been the main focus of the literature, but some research has indicated that mixed models, in which these two policies are implemented simultaneously, may yield better outcomes [8, 15]. Nonetheless, it is noted that the aspect of social sustainability has not yet received enough attention. Particularly, there is a great deal of room for future research given the model's incorporation of human aspects, labor education levels, and supply chain consumer behavior. Furthermore, a more thorough examination of the ways in which the Intergovernmental Panel on Climate Change (IPCC) [17] emission factors, which are used to calculate carbon emissions, varies depending on the industry and region is required.

3. Methodology

In order to create a sustainable supply chain network, this study offers a multi-objective optimization technique that seeks to reduce expenses and carbon emissions at the same time. Four steps make up the modeling process: first, the fundamental model is created, and then, depending on scenarios, three distinct carbon policies—the carbon cap, carbon tax, and carbon trading—are incorporated into the model. Lastly, all models are solved using the Epsilon constraint approach, and the outcomes are acquired using GAMS software.

3.1. Model 1: Fundamental Model of Multi-Objective Optimization

A simple two-objective optimization model called Model 1 was created for a multi-stage supply chain network that includes distributors, retailers, and suppliers. The two primary goal functions of this model are (i) minimizing overall system costs and (ii) minimizing carbon emissions caused by manufacturing and transportation. Figure 1 depicts the model's supply chain network.

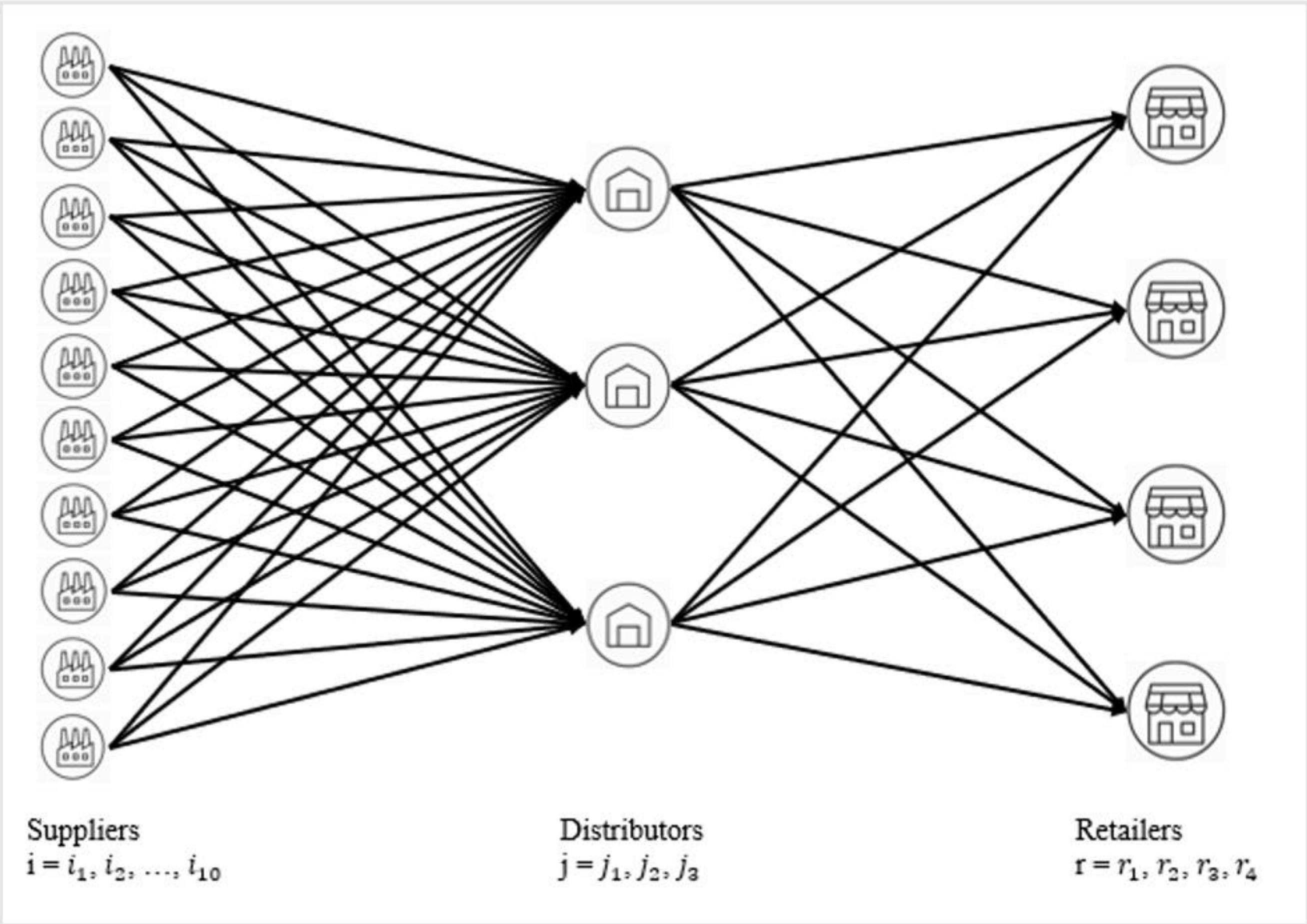

Figure 1.
Network Diagram of the Supply Chain.

Transportation from supplier to distributor, transportation from distributor to retailer, manufacturing cost, and supplier opening cost make up the first objective function in the model, which seeks to reduce the overall cost. The second goal function seeks to reduce the quantity of CO_2 (kg) released as a result of production (material and electricity consumed) and transportation.

3.2. Sets

i: suppliers, $i = 1,2,..,I$
j: distributors, $j = 1,2,..,J$
r: retailers, $r = 1,2,\ldots,R$
t: trucks, $t = 1,2,\ldots,T$
p: product type, $p = 1,2,\ldots,P$

3.3. Parameters

d^1_{ij}: Distance between supplier I to distributor J
d^2_{jr}: Distance between distributor J and retailer R
c^1_{ij}: Transportation cost from supplier I to distributor J
c^2_{jr}: Transportation cost from distributor J to retailer R
E_f: emission factor
ck: fuel cost per km
M: a big number M
dem^2_{rp}: Demand of retailer R for product P
dem^1_{jp}: Demand of distributor J for product P
e^1_{ij}: Produced CO2 emission (kg) by transportation from supplier I to distributor J
e^2_{jr}: Produced CO2 emission (kg) by transportation from distributor J to retailer R
ep^1_{ip}: Produced CO2 emission (kg) by electricity used in production for product P at supplier I
ep^2_{p}: Produced CO2 emission (kg) by material used in production for product P at supplier I
ci: Facility openning cost for supplier I tedarikçisinin açılma maliyeti
pfacility: Maximum supplier quantity to open

capacity: Supplier capacity
pc_{ip}: Unit production cost for product I at supplier I

3.4. Variables
x^1_{ijpt}: Quantity of product P transported from supplier I to distributor J by truck T
x^2_{jrpt}: Quantity of product P transported from distributor J to retailer R by truck T
x^3_{ip}: Production quantity of product P at supplier I
y^1_{ijpt}: Transportation decision from supplier I to distributor J by truck T {0,1}
y^2_{jrpt}: Transportation decision from distributr J to retailer R by truck T {0,1}
y^3_i: Openning decision of supplier I {0,1}
Objective functions

$$\text{Min Z1} = \sum_I \sum_J \sum_P \sum_T c^1_{ij} * x^1_{ijpt} + \sum_J \sum_K \sum_T c^2_{jr} * x^2_{jrpt} + \sum_I \sum_P pc_{ip} * x^3_{ip} + \sum_I y^3_i * ci \quad (1)$$

$$\text{Min Z2} = \sum_I \sum_J \sum_P \sum_T e^1_{ij} * y^1_{ijpt} + \sum_I \sum_J \sum_P \sum_T e^2_{jr} * y^2_{jrpt} + \sum_I \sum_P ep^1_{ip} * x^3_{ip} + \sum_K \sum_I ep^2_p * x^3_{ip} \quad (2)$$

Subject to

$$\sum_J \sum_T x^1_{ijpt} \le x^3_{ip} \quad \forall i, p \quad (3)$$

$$\sum_R \sum_T x^2_{jrpt} \le \sum_I \sum_T x^1_{ijpt} - dem^1_{jp} \quad \forall j, p \quad (4)$$

$$\sum_J \sum_T x^2_{jrpt} \ge dem^2_{rp} \quad \forall r, p \quad (5)$$

$$x_{ip} \le capacity \quad \forall i, p \quad (6)$$

$$\sum_I y^3_i = pfacility \quad (7)$$

$$\sum_I \sum_T y^1_{ijpt} \ge 1 \quad \forall j, p \quad (8)$$

$$\sum_J \sum_T y^2_{jrpt} \ge 1 \quad \forall r, p \quad (9)$$

$$y^3_i \ge y^1_{ijpt} \quad \forall i, j, p, t \quad (10)$$

$$x^1_{ijpt} \le y^1_{ijpt} * M \quad \forall i, j, p, t \quad (11)$$

$$x^2_{jrpt} \le y^2_{jrpt} * M \quad \forall j, r, p, t \quad (12)$$

$$y^1_{ijpt}, y^2_{jrpt}, y^3_i \in \{0,1\} \quad \forall k, i, t \quad (13)$$

$$x^1_{ijpt}, x^2_{jrpt}, x^3_{ip} \ge 0 \quad \forall k, i, t \quad (14)$$

The constraints of the model can be grouped under seven main headings: (1) balance for supply and demand, (2) capacity of production, (3) facility opening limitation, (4) assignment decisions, (5) material flow, (6) feasibility restrictions and (7) positivity conditions. Decision varibales include the amount of transported products, the production volume, the route for the trucks, and the facility openning decision. The third constraint ensures that the product quantity transported from the supplier to the distributor doesn't exceed the product quantity that is produced. The quantity of goods that are transported from the distributor to the retailer cannot be more that amount of goods remain after satisfying its own demand, according to constraint 4. Constraint 5 ensures that the demand of each retailer is covered by the quantity of products transported from distributor to retailer. The sixth constraint number 6 limits the production capacity of each supplier to the facility's capacity. The number of suppliers to be opened are limited to a maximum value by Constraint 7. Constraint 8 ensures that each distributor's demand for each product will be met by at least one supplier , while constraint 9 guarantees that each retailer's demand for each product will be provided by at least one distributor. Constraint 10 limits the model to selecting routes from only the opened suppliers. Constraints 11 and 12 make sure that the products are only transported if the route is chosen. Production quantities and the transported product quantities are defined as positive variables by constraint 13 and the binary varibales are defined by constraint 14.

A Mixed Integer Linear Programming model with two objective functions is presented in this paper. The Intergovernmental Panel on Climate Change (IPCC) [17] guide's formula and the emission factors of the fuel type used for transformation are utilized to compute total carbon emissions. 74,100 kg/TL(Turkish Lira) is the emission factor applicable to trucks that run on diesel fuel. The model assumptions are defined as follows:

- Uniform distribution determines the distances between sites and facility demands.
- Each supplier's capacity is established at 1000 goods.
- The cars are identical and use an average of 25 liters of diesel fuel per 100 kilometers.

- No more than five of the ten possible suppliers will be chosen to open.
- The selling and buying price of carbon is 10,5 TL/kg CO2 and 17,5 TL/kg CO2 [14].

In contrast to single goal functions like cost minimization or carbon emissions, which are commonly included in the literature, this work offers a flexible framework that evaluates environmental and economic sustainability combined. By combining distribution-related emissions, production-related emissions, electricity and material costs, and overall transportation expenses, it offers a new approach. The research by Fareeduddin, et al. [14] is used as a reference to examine the implications of different implementations of Carbon Cap, Carbon Tax, and Carbon Cap-and-Trade policies on costs and carbon emission levels.

3.5. Model 2: Implementation of the Carbon Cap Policy

In Model 2, carbon cap policy was implemented, and an upper limit was added to the model to restrict the total carbon emissions. According to the carbon cap policy, organizations are directed to maintain production processes while not exceeding this carbon emission quota. The main purpose of the model is to minimize both costs and carbon emissions under the defined carbon limits.

To implement the Carbon Cap policy, some modifications were made to the constraints and parameters to observe the impacts on the supply chain network design model. A new constraint was added to the established model with a parameter carbon cap (ccap) and the changes in the optimal solution were examined.

Objective functions:

$$Min\ Z1 = \sum_{I}\sum_{J}\sum_{P}\sum_{T} c_{ij}^{1} * x_{ijpt}^{1} + \sum_{J}\sum_{K}\sum_{T} c_{jr}^{2} * x_{jrpt}^{2} + \sum_{I}\sum_{P} pc_{ip} * x_{ip}^{3} + \sum_{I} \mathrm{y}_{\mathrm{i}}^{3} * ci \quad (1)$$

$$Min\ Z2 = \sum_{I}\sum_{J}\sum_{P}\sum_{T} e_{ij}^{1} * y_{ijpt}^{1} + \sum_{I}\sum_{J}\sum_{P}\sum_{T} e_{jr}^{2} * y_{jrpt}^{2} + \sum_{I}\sum_{P} ep_{ip}^{1} * x_{ip}^{3} + \sum_{K}\sum_{I} ep_{p}^{2} * x_{ip}^{3} \quad (2)$$

Subject to: Constraints (3) through (14) and

$$\sum_{I}\sum_{J}\sum_{P}\sum_{T} e_{ij}^{1} * y_{ijpt}^{1} + \sum_{I}\sum_{J}\sum_{P}\sum_{T} e_{jr}^{2} * y_{jrpt}^{2} + \sum_{I}\sum_{P} ep_{ip}^{1} * x_{ip}^{3} + \sum_{K}\sum_{I} ep_{p}^{2} * x_{ip}^{3} \leq ccap \quad (15)$$

An analysis was perfomed for different carbon cap values in Model 2. As a result of the scenario analysis based on different carbon cap values, it was observed that the first change in the total cost and total emission amount was at 16.000 kg CO_2. Table 1 displays the findings of total cost and total emissions.

Table 1.
Carbon Limit Scenario Analysis Results.

Carbon Cap (kg CO_2)	Total Cost (TL)	Total Emission (kg CO_2)
19.000	1.176.262,271	16.370,730
18.500	1.176.262,271	16.370,730
18.000	1.176.262,271	16.370,730
17.500	1.176.262,271	16.370,730
17.000	1.176.262,271	16.370,730
16.500	1.176.262,271	16.370,730
16.000	1.338.619,335	15.999,171

Compared to Model 1, a carbon cap constraint is added that includes the limitation of the total carbon emissions. By narrowing the solution space, more environmentally friendly but less economic solutions are obtained.

3.6. Model 3: Implementation of the Carbon Tax Policy

In Model 3, the Carbon Tax Policy is integrated into the model. A fixed carbon tax rate is defined for each unit of carbon and added to the total cost function. The aim of this model is to minimize both operational costs and carbon-related tax burdens.

Objective functions:

$$\mathrm{Min\ Z3} = \sum_{I}\sum_{J}\sum_{P}\sum_{T} c_{ij}^{1} * x_{ijpt}^{1} + \sum_{J}\sum_{K}\sum_{T} c_{jr}^{2} * x_{jrpt}^{2} + \sum_{I}\sum_{P} pc_{ip} * x_{ip}^{3} + \sum_{I} \mathrm{y}_{\mathrm{i}}^{3} * ci + ctax * \left(\sum_{I}\sum_{J}\sum_{P}\sum_{T} e_{ij}^{1} * y_{ijpt}^{1} + \sum_{I}\sum_{J}\sum_{P}\sum_{T} e_{jr}^{2} * y_{jrpt}^{2} + \sum_{I}\sum_{P} ep_{ip}^{1} * x_{ip}^{3} + \sum_{K}\sum_{I} ep_{p}^{2} * x_{ip}^{3}\right) \quad (16)$$

$$\text{M}in\ Z2 = \sum_I \sum_J \sum_P \sum_T e_{ij}^1 * y_{ijpt}^1 + \sum_I \sum_J \sum_P \sum_T e_{jr}^2 * y_{jrpt}^2 + \sum_I \sum_P ep_{ip}^1 * x_{ip}^3 + \sum_K \sum_I ep_p^2 * x_{ip}^3 \quad (2)$$

Subject to: Constraint (3)-(14)

In this revised model, a carbon cost term is added to the cost function and cost minimization is achieved by combining the Z1 and Z2 objective functions into a single function. The carbon tax parameter used in the model is taken as 21 TL per kg (1 kg CO_2=\$0.6, \$1=35TL). This approach makes high carbon emissions solutions less attractive due to increased costs and encourages decision makers towards low-emission strategies.

3.7. Model 4: Implementation of Carbon Cap-and-Trade Policies

In Model 4, Carbon Cap-and-Trade policy was implemented which allows companies to buy and sell emission permits. This policy is based on a structure that each company is limited to a carbon quota, but an established market mechanism gives permission to companies to sell the excess carbon quotas or purchase the inadequate quota on the market.

The first objective function was modified by adding the revenue to be obtained from selling the excess quota and the cost to be incurred by purchasing additonal quata and equation 17 was obtained. Additionally, to determine the carbon emission amount resulting from transportation and production exceed or below the defined carbon limit, constraint number 18 is added to the fundamental model.

Objective functions:

$$Min\ Z4 = \sum_I \sum_J \sum_P \sum_T c_{ij}^1 * x_{ijpt}^1 + \sum_J \sum_K \sum_T c_{jr}^2 * x_{jrpt}^2 + \sum_I \sum_P pc_{ip} * x_{ip}^3 + \sum_I y_i^3 * ci - pplus * eplus + pminus * eminus \quad (17)$$

$$Min\ Z2 = \sum_I \sum_J \sum_P \sum_T e_{ij}^1 * y_{ijpt}^1 + \sum_I \sum_J \sum_P \sum_T e_{jr}^2 * y_{jrpt}^2 + \sum_I \sum_P ep_{ip}^1 * x_{ip}^3 + \sum_K \sum_I ep_p^2 * x_{ip}^3 \quad (2)$$

Subject to: Constraints (3)-(14) and

$$\sum_I \sum_J \sum_P \sum_T e_{ij}^1 * y_{ijpt}^1 + \sum_I \sum_J \sum_P \sum_T e_{jr}^2 * y_{jrpt}^2 + \sum_I \sum_P ep_{ip}^1 * x_{ip}^3 + \sum_K \sum_I ep_p^2 * x_{ip}^3 = ccap + eminus - eplus \quad (18)$$

The purchased (eminus) and sold (eplus) amounts of carbon permits are added to the model as decision variables. Purchasing and selling prices are defined as parameters and these economic tools are used in the model to balance the costs and carbon emissions.

3.8. Solution Approach

The Augmented Epsilon Constraint approach, also known as the Augmented ε-constraint approach, is widely used in the literature to solve multi-objective problems. This method's basic idea is that one objective function is optimized while the others are constrained to a threshold value and defined as constraints [2]. All of the multi-objective optimization models proposed in this study are coded and solved using the General Algebraic Modelling System (GAMS) software.

In multi-objective optimization problems the conflict between multiple objectives results in a Pareto optimal solution set [18, 19]. This Pareto optimal solution set consist of non-dominated alternatives where improving a performance of one goal deteriorate the performance of another [20]. In order to determine the best alternative among the Pareto optimal solution set, Multi-Criteria Decision Making (MCDM) methods are frequently used in the literature [21].

In this study, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), which is one of the most frequently used MCDM method, was applied. This method provides a systematic framework for evaluating the performances of different alternatives and selecting the best Pareto optimal solution according to the decision maker's criteria preferences was applied. A similar approach was taken by Jamili, et al. [22] to address a course scheduling problem. They developed a multi-objective optimization problem and solved using Augmented Epsilon constraint in GAMS software. TOPSIS was used to select the best alternative among the Pareto optimal solutions. In a recent study, Taghipour Anari, et al. [23] also developed a multi-objective model and applied Augmented constraint approach in order to retrieve Pareto optimal solution set. They used TOPSIS to rank the alternative solutions to establish the best solution that fits the decision makers' preferences.

Each model's total cost values, total emission levels, production quantities, transportation routes, and the location of the facility that should be opened were all determined. Based on these results, a comparative study of how carbon regulations affect sustainable supply chains was carried out.

4. Results and Discussion

The created multi-objective optimization model is tested in this work under four distinct scenarios, and the effects of each carbon policy on the cost and carbon emissions of the supply chain are thoroughly examined. The Pareto optimal solution framework was used to analyze the model after it was solved using the GAMS 47.4.1 program.

The results show that the recommended carbon policy for reaching sustainability targets has a considerable impact on system costs and environmental consequences. These findings can provide beneficial insights for decision-makers in selecting the best policy for low carbon emission supply chain design.

4.1. Optimization Outcomes

This study aims to examine the impacts of carbon regulation policies on a multi-echelon supply chain network by using mathematical modeling, with an emphasis on sustainability. In this context, four different scenarios - No policy implementation (Model 1), Carbon Cap (Model 2), Carbon Tax (Model 3), and Carbon Cap-and-Trade (Model 4) policies were implemented to assess the cost and carbon emission outcomes.

Model 1 is the main model solved without any carbon policies. The solution of this model results in a total cost of 1,176,262.271 TL, while the total carbon emission was found to be 16.370,730 kg CO_2. Suppliers selected to be opened are locations 1-3-8. The model has a balanced solution between emission and costs. The model's solution strikes a compromise between costs and emissions. Figure 2 shows the visual representation of the suppliers that should be opened, supplier, distributor and truck assignments, and quantities transported through the supply chain network obtained by solving the proposed model. The trucks assigned for transportation are defined as T1-T5 where the product types are shown as P1-P3.

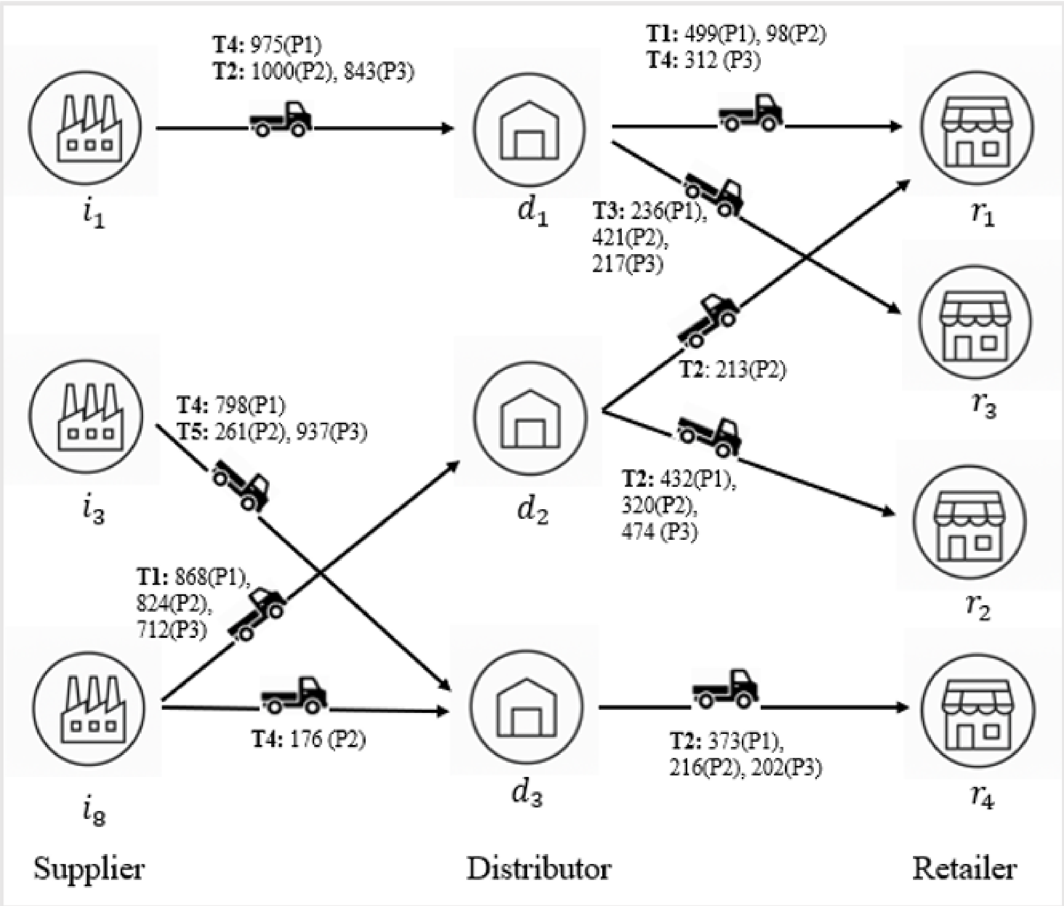

Figure 2.
Main Model Results.
Note: *T: Trucks, P: Products.

Model 2 is performed under the carbon cap policy and the carbon quota was set at 16.000 kg CO_2. As a result of this constraint, the model decreased carbon emissions to 15.999,171 kg CO_2, whereas the total cost increased to 1,338,619.335 TL. This scenario demonstrates that carbon cap policy provides a significant reduction in emissions although results in increased costs. The outputs of the model can be seen in Figure 3.

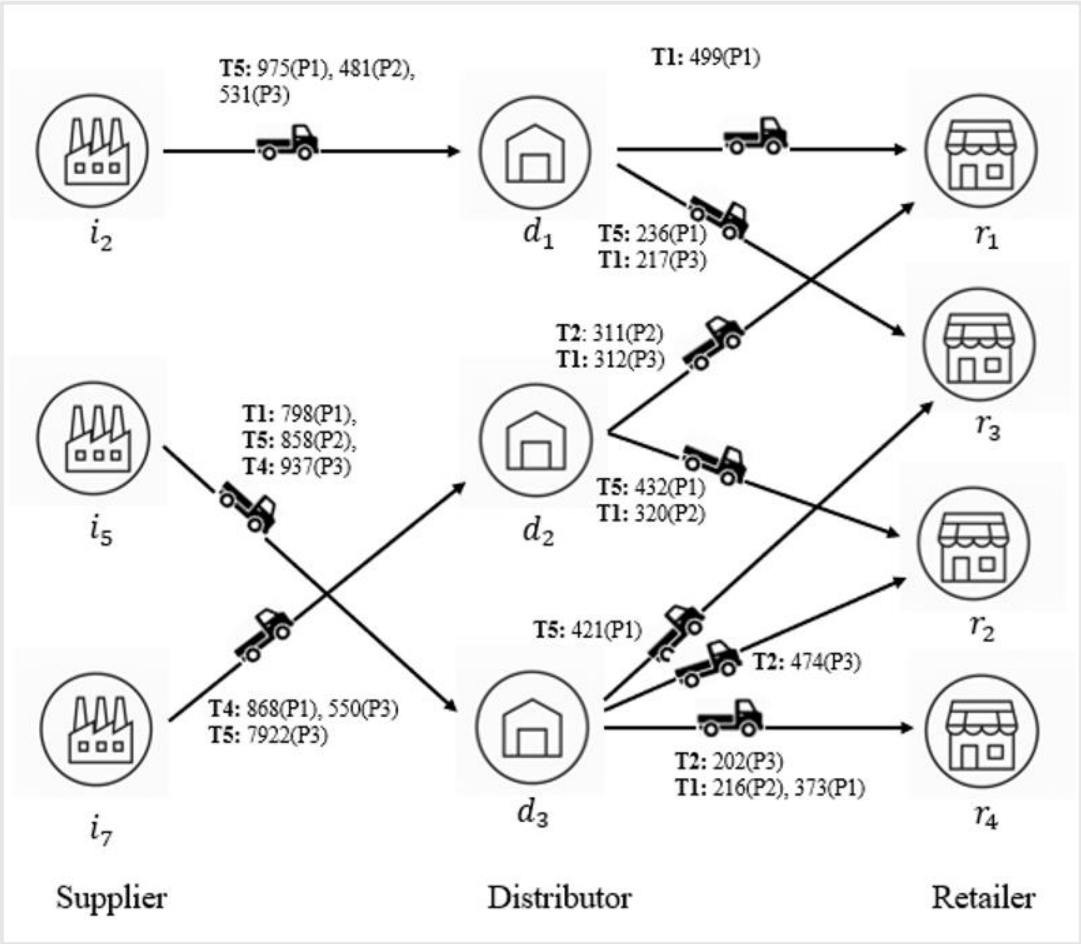

Figure 3.
Model 2 Results (Carbon Cap Policy).

The Carbon Tax Policy was implemented in Model 3, and the objective function of the total cost was modified by adding the price of each unit of carbon emissions. The results indicated a greater reduction in the total emissions, however this reduction resulted in an economic burden. The significant trade-off between economic and environmental preformance was observed by eximining the Pareto optimal solutions. Among the Pareto optimal solution set; Solution 2 (SOL2) was chosen by utilizing TOPSIS methos, a Multi-Criterie Decision Method (MCDM). The results obtained by solving Model 3 are as in Figure 4.

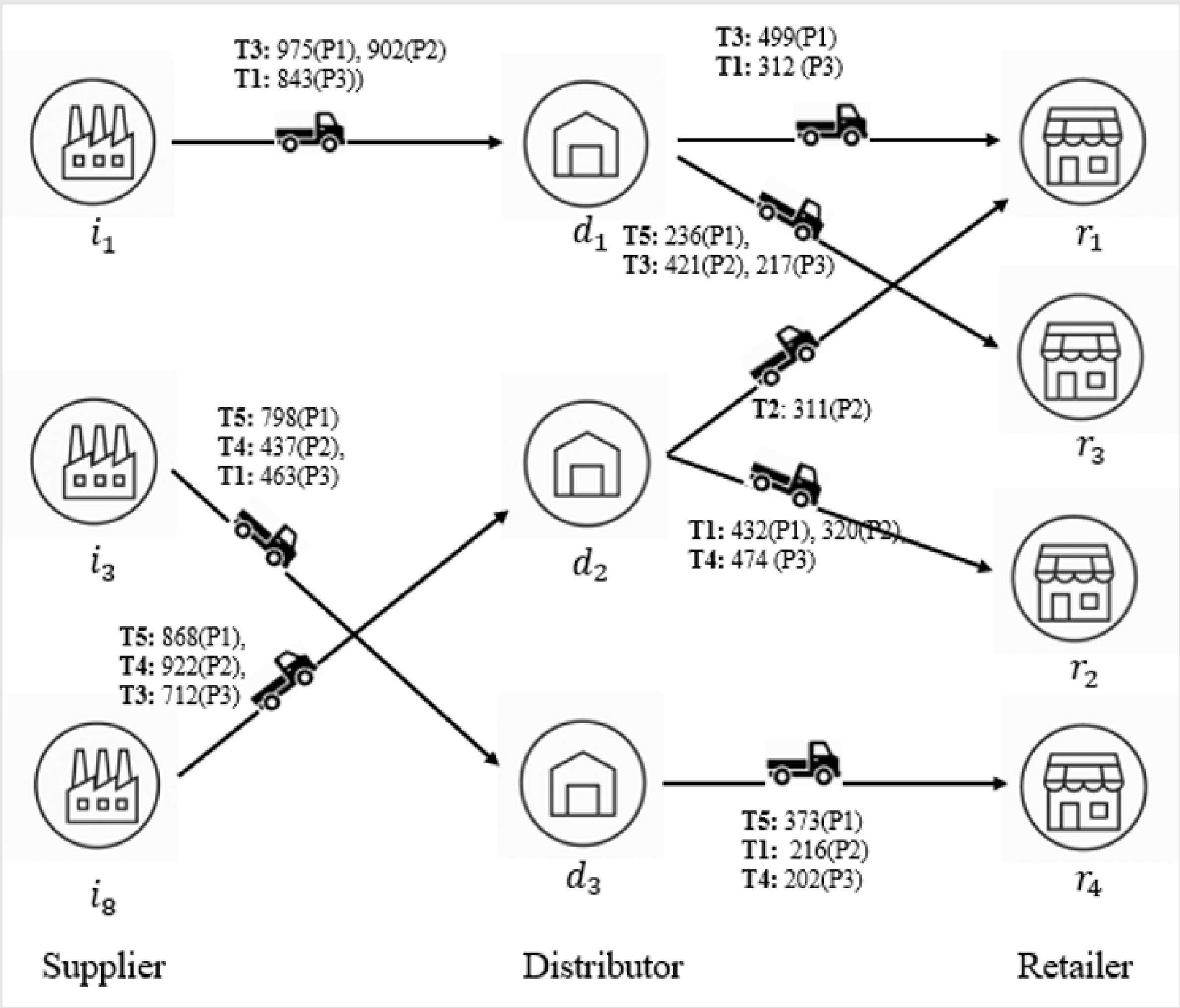

Figure 4.
Model 3 Results (Carbon Tax Policy).

The Carbon Cap-and-Trade policy is simulated in Model 4. Businesses who fall short of their emission quota can sell the remaining quota, while those that surpass it can purchase more quota from the market. The balance between total cost and total emission levels has been identified as the model's solution. Both the overall emission value and the total cost of this model have dropped to 16.345,329 kg CO_2 and 1.182.819,705 TL, respectively. According to the results received by solving Model 4, the facilities to be opened and the transportation quantities are shown in Figure 5.

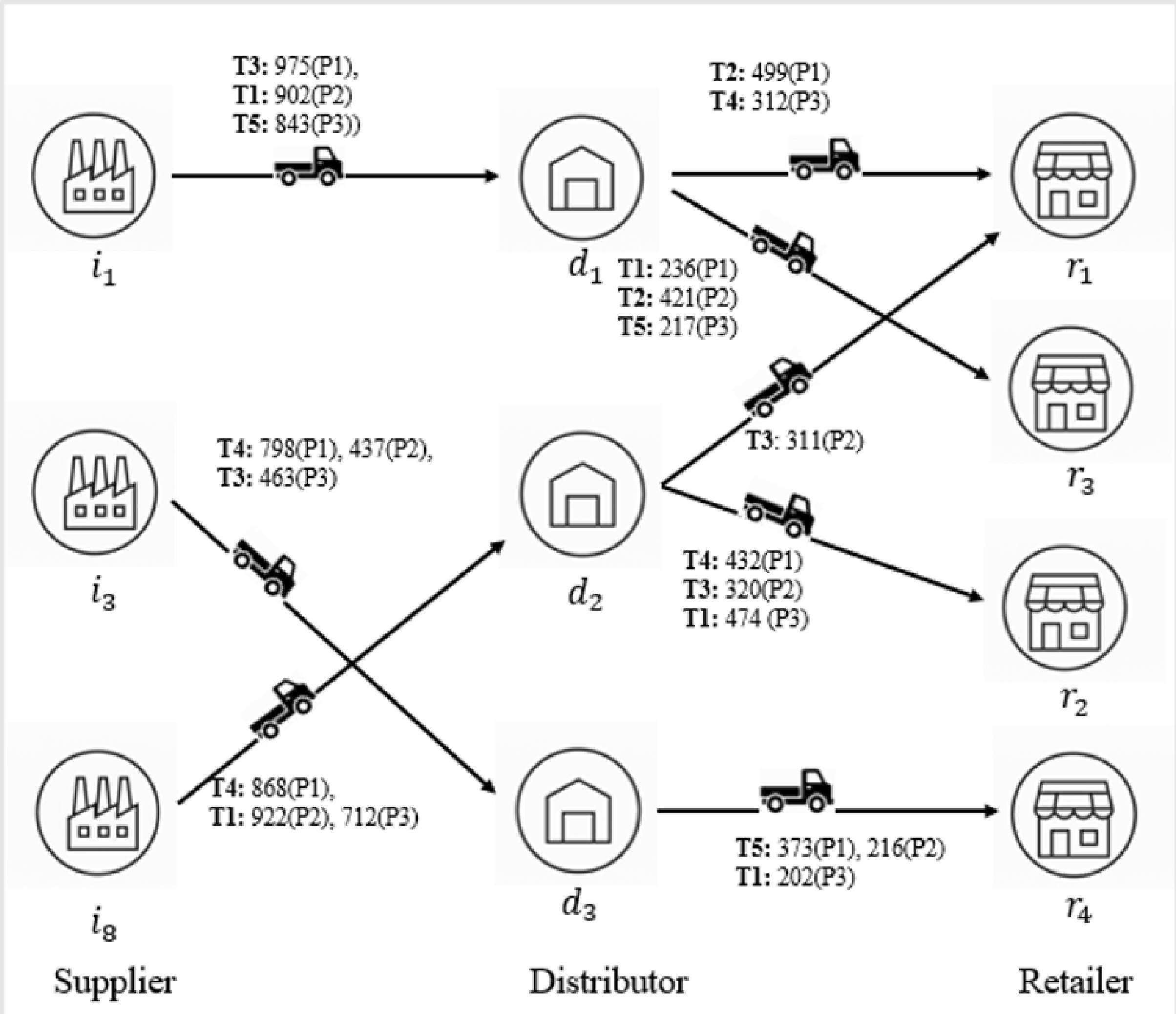

Figure 5.
Model 4 Results (Carbon Cap and Trade Policy).

Table 2 provides a summary of the specifics of the solutions for the suggested models, and this part compares the outcomes of the models.

Table 2.
Optimum solutions for the models.

Carbon Policy	Cost (TL)	Emission (kg CO_2)	Suppliers
Model 1: Main Model	1.176.262,271	16.370,730	1-3-8
Model 2: Carbon Cap	1.338.619,335	15.999,171	3-5-7
Model 3: Carbon Tax	1.573.280,449	16.168,063	2-5-8
Model 4: Carbon Cap-and-Trade	1.182.819,705	16.345,329	1-3-8

The model generates more ecologically beneficial solutions when the carbon limit value is lowered, but system costs go up as a result. For instance, it was found that lowering the carbon quota to 16.000 kg resulted in a cost increase of about 14%. This instance demonstrates that achieving low carbon emission targets may come at a significant financial cost. Similarly, it was shown that the overall cost rose linearly even while raising the carbon tax rate results in a systematic decrease in carbon emissions. The direct and predictable cost-impact structure of carbon tax regimes is confirmed by this analysis.

4.2. Literature-Based Comparative Analysis

Overall, the results of this investigation are consistent with other studies in the literature. According to Hashmi, et al. [7] carbon taxes are a useful strategy for cutting emissions, but they also raise supply chain costs. They found that the carbon tax scenario had the highest cost but the lowest carbon emissions.

Another discussion frequently emphasized in literature is modeling uncertainty in mathematical models. Govindan, et al. [16] developed scenario-based models to show the impact of evaluating price and demand uncertainties with carbon policies on system dynamics. They created a multi-objective model that was combined with a carbon tax policy, with an emphasis on designing closed-loop supply chain networks in accordance with the objectives of the circular economy.

Huang et al.'s analysis from 2024 showed that a hybrid strategy produced more balanced solutions for the economy and environment. Furthermore, the findings demonstrated that, in contrast to carbon tax and carbon cap systems, carbon cap-and-trade policy may prove to be a successful strategy for a large number of companies.

Kumar and Kumar [10] emphasized the multifaceted impacts of carbon emissions and offered a model that also included social sustainability issues. The economic effects of carbon regulations were examined indirectly, despite the fact that the social sustainability components were not explicitly stated.

4.3. Comprehensive Assessment

The findings of the study show that supply chain designs are significantly impacted by carbon policies, and decision-makers must consider the costs of selecting tactics that align with environmental objectives. A carbon tax program reduces emissions more dramatically than a carbon cap strategy, which offers a more balanced approach. Cap-and-trade systems, on the other hand, are more adaptable to various situations and can be more readily implemented in specific situations.

The European Commission's direct comparative assessment of carbon policies using mathematical models and the use of these systems with workable solution techniques constitute this study's addition to the literature. In this sense, it will support academic research and decision support systems.

5. Conclusion and Suggestions

This study investigates the impacts of carbon regulation policies on a multi-stage sustainable supply chain network by using mathematical modeling. In this context, four different scenarios - No carbon policy implementation (Model 1), Carbon Cap (Model 2), Carbon Tax (Model 3), and Carbon Cap-and-Trade (Model 4) were used to assess the cost and carbon emission levels. The trade-off relationships are established within the Pareto optimal solution framework.

The study's conclusions unequivocally show that supply chain network design structures are directly impacted by the integration of carbon policies in terms of both economic and environmental performance. Without any restrictions, Model 1 had the lowest cost and a comparatively high emission level. This result demonstrates that, despite their economic advantages, traditional methods fall short in terms of environmental sustainability.

By keeping emissions below the legal threshold of 16.000 kg CO_2, Model 2, which included a carbon cap policy, had an environmentally beneficial result; nevertheless, it came at a higher cost. The outcomes show the cost-benefit trade-off under stringent carbon restrictions.

Model 3's incorporation of the carbon price reduced emissions but at the expense of a 30% cost increase. These results showed that while carbon taxes help achieve environmental goals, they also have an increasing cost effect.

Model 4 demonstrated the flexibility of the cap-and-trade policy and provided a more balanced solution between total cost and total emissions. Market conditions were used to achieve system balance, while carbon limits were pereserved. Consequently, companies were allowed to select their own carbon regulations strategy according to the state of the market. Businesses are free to choose the carbon management plans based on their own benefit because the cap-and-trade systems' market flexibility offers more adaptation options than set carbon limits or taxes.

The study's conclusions provides immediately practical implications for decision makers. Instead of concentrating on just one kind of carbon emission-reduction policy, it is recommended to create a hybrid strategy. Businesses can choose their own carbon regulating tactics since cap-and-trade systems offer more opportunities and market flexibility than fixed carbon caps or carbon taxes.

Medium-sized industrial businesses' policymakers ought to take into account how highly applicable carbon limitation rules are. These policies regulate avoiding exceeding a carbon threshold while supporting environmental goals without placing a significant financial burden on individuals. Furthermore, in major corporations with substantial capital and investment capability, cost-oriented policies like carbon taxes might have a greater impact.

As transportaion-realetd emissions become a major focus on environmental policy, carbon management is critical for the logistics operations and supply chain management. Implementing carbon reduction strategies- such as optimized route planning, energy efficient technologies, and transportation modal shift to cleaner options- can significantly improve both economical and environmental performance.

This study adopts a deterministic modeling approach; however it is suggested that future research should address uncertainty in demands, carbon pricing, and operational costs by using methods such as scenario analysis, stochastic modeling, or robust optimization to imrove the real world relevance and resilience. Morover, in addition to considering the envionmental and economic goals, incorporating social sustainability aspect would enable a more holistic approach aligned with the three pillars of sustainability.

Finally, the proposed model offers a structured framework for creating low-cost and low-emission logistics strategies. Future research could enhance its applicability by integrating AI driven systems, such as real time route optimization, demand forecasting or carbon tracking systems to increase responsiveness and accuracy. Incorporating sectoral emission limits or region-spesific carbon quotas could also facilitate more focused, location-sensitive supply chain decisions and promote policy alignment.

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