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A Bilevel Model for Carbon Pricing in a Green Supply Chain Considering Price and Carbon-Sensitive Demand

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Abstract: In today's industrial landscape, there is a mounting urgency to mitigate the adverse environmental impacts of emissions stemming from supply chain operations. On one front, policymakers impose increasingly stringent emission reduction targets for supply chains, while on another front, consumers express a heightened preference for products and services with reduced carbon footprints. This study addresses the challenge of determining an optimal carbon pricing strategy by integrating the imperatives of a green supply chain with carbon taxation policies. To this end, we introduce a bi-level mixed-integer linear programming model for supply chain network planning, encompassing considerations of carbon taxation policies and the responsiveness of demand to the final product's price and associated carbon emissions. Findings from a case study underscore that an escalation in carbon pricing prompts the supply chain to prioritize emissions reduction through the utilization of environmentally conscious approaches. The results reveal the need for a USD 0.9/kg carbon price to achieve a 10% emission reduction, resulting in an 80% profit decline. Notably, a 10% reduction has profound impacts, which leads to the suggestion of a gradual approach. Furthermore, as carbon prices reach higher levels, the supply chain tends toward curtailing production, thereby fostering an environment conducive to emission abatement. Consequently, policy formulators must judiciously calibrate a fitting carbon pricing mechanism to strike a harmonious equilibrium between emission reduction targets and the financial outlays of the supply chain.

Keywords: carbon-sensitive demand; carbon pricing; green supply chain; emission reduction policies; bi-level programming

Citation: Mesrzade, P.; Dehghanian, F.; Ghiami, Y. A Bilevel Model for Carbon Pricing in a Green Supply Chain Considering Price and Carbon-Sensitive Demand. *Sustainability* **2023**, *15*, 16563. https://doi.org/10.3390/su152416563

Academic Editor: Kalle Kärhä

Received: 15 August 2023
Revised: 29 November 2023
Accepted: 2 December 2023
Published: 5 December 2023

1. Introduction

Climate change and its detrimental effects on the Earth and human life have been continuously increasing, posing a threat to economic integration, security, and the quality of human life [1]. Carbon dioxide gas, recognized as the foremost pollutant among greenhouse gases, significantly contributes to global warming [2]. In 1995, the Intergovernmental Panel on Climate Change (IPCC) stated that the increase in the temperature of the Earth's surface is primarily due to the rising concentration of greenhouse gases in the atmosphere, particularly carbon dioxide [3]. Multiple sources contribute to this issue. The growth in transportation operations due to globalization, coupled with production and storage processes, have highlighted supply chain activities as the main sources of emissions.

This issue has become one of the main challenges for societies, triggering various governmental and international organizations and programs to mitigate carbon emissions. Additionally, as of May 2008, 181 countries accepted the Kyoto Protocol, which was initiated in 1997 and initially signed by 37 members of the European Union (EU) and industrialized nations. The Kyoto Protocol sets out carbon reduction commitments for developed countries and obliges the participating nations to focus on reducing greenhouse gas emissions. Furthermore, in April 2016, 175 countries signed the Paris Agreement, which requires global climate action beyond 2020 and aims at limiting the rise in the global temperature to a maximum of 2 degrees Celsius [4]. As a result of the emerging regulations, the traditional focus of supply chains on efficiency and responsiveness has gradually shifted toward also including the environmental impacts of their operations.

In response to this growing issue, the concept of green supply chain management has been introduced in the academic literature [5,6]. Various methods have been introduced in the literature to address this environmental concern. The carbon pricing policy has been widely employed as the primary tool to reduce emissions. Additionally, measures such as the implementation of subsidy and taxation policies like carbon trading have been introduced by governments. In this pursuit, companies also benefit from technological advancement in production, storage, and transportation [7]. According to global statistics published in 2022, Western European and North American countries have actively contributed to emission reduction through the implementation of carbon taxes. Among these, Sweden has the highest carbon tax rate at USD 55, followed by France at USD 31, and Norway at USD 21. On the other end of the spectrum, Mexico has the lowest carbon tax rate at USD 1.5, followed by Japan at USD 1.8, and Ukraine at USD 0.3 per kilogram of emissions. The data indicate that carbon taxes have resulted in a significant reduction of approximately 25% in carbon emissions [8].

The objective behind implementing a carbon tax control framework is to impose taxes on greenhouse gas emitters proportionate to their emission levels. This policy motivates companies to reduce their emissions by adopting new methods and smart technologies [9].

Considering that a significant portion of carbon emissions comes from the transportation of goods and industrial production and storage methods, numerous companies are actively working to reduce these emissions by re-evaluating their production and storage practices and incorporating eco-friendly technologies. While theoretical projections suggest that integrating green technologies into production and storage could potentially mitigate up to 60% of the impacts of climate change, there is limited empirical evidence regarding the support from both the governmental and private sectors. This is mainly due to the substantial capital investment required and concerns about the financial viability of organizations [10]. Furthermore, certain previous investigations have indicated that achieving the successful integration of green technology may require additional measures and alternative emission reduction strategies to avoid potential adverse effects on organizations' profitability, depending on the various scenarios [11].

Consumer awareness acts as one of the main drivers of such changes. Hence, several regulatory agencies, such as the United States Environmental Protection Agency (EPA), Natural Resources Canada (NRCan), the European Commission (EC), and the Certification Standard Council (CSC), apart from enforcing regulations, have also focused on raising consumer awareness. According to surveys conducted by these agencies, consumers are willing to pay higher prices for low-carbon products [12]. The increase in consumers' awareness has introduced new requirements to businesses, i.e., apart from criteria such as quality and price, customers also assess the products and their supply chain through environmental criteria. This translates into more fierce competition in the marketplace where companies must operate and optimize their operation considering conflicting objectives.

In support of low-carbon consumption, the Chinese Ministry of Environmental Protection has officially launched the Low-Carbon Economy Project. The project connects low-carbon-related products with a carbon logo to raise consumer awareness of such products [9,13]. This change in consumer behavior has led to a re-evaluation of supply chain management [14]. Certain researchers have unveiled a favorable connection between consumer behavior and production approaches. Drawing from this standpoint, they have introduced two customer categories: standard customers, unconcerned with carbon footprint in production, and green customers, who exhibit sensitivity toward carbon emissions during production. Consequently, with consumer behavior progressively molded by environmental consciousness, supply chains confront continuous demands to adapt to this pivotal shift. An argument can be posited that these dual customer categories may shape product demand, ultimately achieving the twin aims of organizational profitability and carbon reduction [15].

This dual concern, wherein demand is directly influenced by both the final price and the associated carbon emissions, creates a multifaceted problem for supply chain management. Simultaneously, governments and organizations are contemplating the implementation of carbon taxes as a means to reduce greenhouse gas emissions.

In this study, our objectives encompass addressing following research questions:

(I) What is the influence of customer demand sensitivity on the operational performance of the supply chain?

(II) Can the government enhance company profitability through optimal carbon pricing, and what methods can be employed to determine this optimal pricing?

To address these questions, we develop a bi-level model using the so-called Stackelberg game, to determine the optimal carbon pricing in the implementation of carbon taxation. The primary objective of this model is to concurrently attain a reduction in carbon emissions while safeguarding organizational profitability. Nurturing a consumer inclination for low-carbon goods, the model integrates demand sensitivity toward both the final product price and carbon emission levels. Subsequent sections of this research encompass a review of recent studies, elucidation of problem formulation in the Section 3, presentation of numerical findings and the solution methodology in the Section 4, and the conclusion of the research in the final section.

2. Literature Review

The global increase in awareness about the disadvantages of greenhouse gas emissions and environmental degradation, along with the establishment of governmental and private regulations to mitigate such emissions, has captured the attention of numerous researchers.

A substantial body of literature exists, with a primary focus on aligning supply chain operations and technology with various carbon regulations to promote sustainability and environmental responsibility. Lopez et al. [16] identified that one of the carbon-emitting sectors lies within the transportation domain. Consequently, novel innovations such as electric transportation and pollution-free transportation should be prioritized in supply chains to enhance the environmental performance of the supply chain and lead to a reduction in carbon emissions. Jaggi et al. [17] have presented an effective management model for deteriorating items through investment in inventory-holding technologies with a carbon tax mechanism. In their model, they maximize the total profit of the manufacturer by jointly optimizing the production rate, investment in inventory-holding technology, and selling price. Additionally, this model provides pricing for deteriorating items along with maintenance and renewable energy strategies.

Du et al. [11] investigated the impact of green technology on carbon emissions. Their findings revealed a direct relation between the adoption of green technology and revenue level, indicating that it may not be effective for organizations with revenues below a certain threshold. Díaz et al. [18] conducted an analysis of the impact of carbon capture technology on carbon emission reduction in the United States' refining industry. Their results indicated that carbon capture technology, as a green technology, can effectively reduce carbon emissions.

Sundarakani et al. [19] demonstrated in their research that carbon emissions from a supply chain should be divided into two aspects: the first aspect includes direct sources, such as emissions from production and storage, and the second aspect involves non-fixed sources, such as transportation and procurement emissions. In their model, their objective is to increase the profitability of the supply chain while mitigating the impact and risk of carbon emissions through the implementation of carbon tax policies. Bozorgi et al. [20] conducted a research study at the University of Michigan, focusing on the importance of transportation in environmental pollution. They addressed the impact of transportation on the creation of pollution levels and emphasized its significance in the overall emissions. Homayouni et al. [21] investigated sustainability strategies for carbon regulation mechanisms through the development and utilization of a multi-objective planning model solved by an improved algorithm. They designed a sustainable logistics model and used a novel exploratory optimization approach to support decision-makers in comparing and selecting carbon reduction policies in supply chains with various types of vehicles, demands, and economic uncertainties. Their results showed that the exploratory approach can effectively address demand and economic uncertainties, particularly in large-scale problems. Additionally, government incentives for carbon trading policies in supply chains are effective in reducing pollution by investing in clean technologies and adopting green practices.

In the context of sustainability, where multiple stakeholders with varying and sometimes conflicting interests are involved, it is imperative to employ methodologies that take this diversity into account. Approaches such as game theory and agent-based modelling prove to be particularly valuable in addressing the complex dynamics of such multifaceted interactions. Dong et al. [22] proposed a two-stage green supply chain model with carbon trading regulations to reduce carbon emissions. In this supply chain, the manufacturer will produce low-carbon products due to the implementation of these policies. Furthermore, they utilized game theory to find the stable level of the supply chain.

Tang et al. [23] conducted research in which they proposed a simulation model of the Emission Trading Scheme (ETS) using a multi-agent-based approach to analyze the allocation of carbon allowances in China. The proposed model considered two main agents: the government, responsible for implementing the ETS, and various firms from different sectors, which are subject to ETS goals. Their findings indicated that, overall, the ETS leads to positive effects in terms of reducing carbon emissions and improving the energy structure. If the carbon price exceeds CNY 40, it will adversely affect the economy. Therefore, the existing carbon market allowances should be carefully adjusted to achieve a well-balanced combination of economic growth and effective carbon reduction.

Du [24] investigated a two-stage supply chain. In this supply chain, a low-carbon product is produced by a manufacturer and then sold by a retailer. The optimal price of the product and the amount of carbon emissions are determined using Stackelberg games in this problem. The study also examined the impact of a green supply chain on the product price. The results showed that the production of a low-carbon product leads to an increase in the final product price.

Xiong et al. [25] proposed a significant measure in response to the escalating environmental degradation the intensive development of an integrated energy system. This initiative aims to achieve a low-carbon objective. By utilizing a bi-level optimized low-carbon economic operations model for a regional integrated energy system, this article effectively reduces carbon emissions and minimizes the overall operational costs. At the first level, the optimization objective encompasses economic considerations, including carbon emission costs. This encourages the system to transition its energy preference away from carbon-intensive sources, consequently limiting the carbon emissions of the system. At the second level, a pricing model for electricity and natural gas is employed to calculate the carbon emission costs.

Zhaofu Hong et al. [26] utilized a bi-level modeling approach for carbon emission reduction. In this research, the government sets the regional emission reduction target and allocates emission credits to firms. The companies then plan their production based on their cost constraints. To solve their proposed model, they formulated a Stackelberg game model to analyze the decisions of the government and firms, aiming to maximize the regional social welfare and the profit of each company.

Li et al. [27] proposed a fixed pricing mechanism based on a multi-agent structure to coordinate supply chain operations in a two-tier supply chain composed of multiple manufacturers and multiple retailers. In the first stage, they develop a multi-agent social welfare model for the two-tier supply chain structure. Subsequently, pricing and carbon taxation policies within different dominant rights are discussed to determine optimal transaction prices and carbon taxation policies to maximize social welfare. The research findings indicate that, as the carbon tax rate increases, transaction prices also increase. Moreover, with the rise in the carbon tax rate, social welfare decreases. Therefore, the government should formulate carbon taxes within a reasonable range.

Tao Wu [28] conducted a study on asymmetric dual-channel models of two competing supply chains with different carbon emission technologies. The results showed that the main barrier to carbon emission reduction is the high cost of using clean energy, which reduces the market competitiveness of companies that rely on clean energy. To encourage the use of clean energy technology for carbon reduction, the government should use carbon emission taxes for each product to incentivize traditional supply chains to upgrade their carbon emission technologies and encourage financial institutions to provide preferential loans to supply chains that adopt clean energy practices.

Kang et al. [29] employed the Stackelberg game approach to develop the four combinations of low-carbon strategies in a two-tier supply chain consisting of a retailer and a manufacturer. The results indicate that, during the low-carbon technology development phase, only one player (either the manufacturer or the retailer) needs to adopt a low-carbon behavior. In the advanced low-carbon technology phase, only the retailer needs to implement a low-carbon behavior.

There is a widespread consensus that the demand for numerous products is increasingly influenced by their carbon emissions levels, as previously discussed. The literature has thoroughly examined the willingness of customers to pay higher prices for environmentally conscious products.

Nita et al. [30] presented an inventory model for deteriorating items under a carbon cap and a carbon tax policy for controllable carbon emissions through investment in green technology. Their proposed paper focuses on demand dependent on stocks and carbon-sensitive pricing. A solution is provided to define optimal strategies for cycle time, selling price, green technology investment, and green technology investment, maximizing total profit in each case.

Elhedhli et al. [31] proposed a new modelling approach for designing a supply chain network that incorporates a dominant trend in consumer selection and demand influenced by the carbon footprint. They considered a factory and multiple distribution centers with different technologies, similar to the model proposed by Benjaafar [32], which includes both fixed and variable components for costs and emissions.

Imen Nouira et al. [33] considered the demand for the final product as carbon-sensitive, meaning that, with a reduction in carbon emissions, the demand increases. Their results present several scenarios in a case study. One of the most significant findings is that, when the market includes both regular and environmentally conscious customers, a company that designs its supply chain without considering the sensitivity of green customers to carbon emissions can incur significant losses.

Shaofu Du et al. [34] proposed a multi-product optimization model for regular and low-carbon goods, taking into account consumers' environmental awareness. They identified virtual thresholds for carbon production, where low-carbon production beyond these thresholds becomes profitable. Additionally, they aimed to find the optimal carbon price that influences the final product price and, in turn, affects demand. When the carbon price is high, the demand increases initially due to its sensitivity, but after a certain point, it decreases due to the impact on the final product price. Consequently, the use of carbon insurance policies for low-carbon products results in reduced emission costs and ultimately lowers the product prices. As a result, the demand for these products has shown an upward trend.

Bilir et al. [35] pursued an optimal location-allocation by utilizing a three-level supply chain design and considering price-sensitive and carbon-emission-sensitive demand. Their objective was to minimize the distance between the distribution center and the customers to reduce pollution levels.

Yunlong Liu [36] conducted a research study examining the decisions of manufacturers and retailers under a decentralized decision-making system and a centralized decision-making system, considering the impact of carbon pricing and consumer environmental awareness. Their model includes three characteristics of a low-carbon supply chain: consumer environmental awareness, which compels the producer to reduce emissions; emission reduction, leading to increased demand and higher profits for retailers; and greenhouse gas emissions from transportation being a significant part of the product life cycle. Their findings resulted in various scenarios of centralized and decentralized decision-making, but the most crucial revelation was that, when carbon pricing and consumer awareness constraints exist within specific time frames, a centralized decision-making approach outperforms a decentralized one.

Jiang et al. [37], in their study, derived a consumer carbon-sensitive utility function based on consumers' purchasing intentions and established a two-tier supply chain model consisting of a manufacturer and a contractor under government subsidies. Consequently, they analyzed the impact of government subsidies, customer composition ratio, and carbon sensitivity on the optimal decision-making of the manufacturer. The results indicate that, as government subsidies increase from USD 0 to USD 20 per kilogram of emissions for contractors' pollution reduction costs, there is a corresponding rise in the ratio of carbon-sensitive consumers and consumers' carbon sensitivity. This leads to an increase in market demand, thereby improving manufacturers' profits. This framework can serve as a decision-making reference for organizational product pricing, emission reduction, and government subsidies.

The existing models in the literature typically address particular facets of reducing carbon footprints, covering various aspects such as the selection of production technologies, supplier choices, transportation methods, and more. In the majority of cases, researchers tend to concentrate on the selection of technologies within a production system and often neglect the comprehensive planning of an integrated supply chain. Furthermore, most of the supply chain design models discussed in our literature review tend to overlook the connection between demand and carbon emissions and pricing is ignored. At the same time, the predominant theme in the literature concerning the modification of supply chain operations and technologies in response to carbon regulations is the recognition that substantial investments may be required to effectively reduce environmental pollutants. Consequently, it is imperative to consider supplementary factors and policies that empower organizations to confidently implement their strategies aimed at carbon emission mitigation. The relevant research is summarized and compared in Table 1.

Table 1. Overview of the related published research.

Paper	Model			Carbon Regulation		Demand			Optimal Carbon Price
	Single Level	Bi-Level	Tri-Level	Carbon Tax	Carbon Trading	Deterministic	Carbon-Sensitive	Price-Sensitive	
Lopez [16]	√					√			
Jaggi [17]	√			√		√			
Du [11]	√						√		
Díaz [18]	√					√			
Sundarakani [19]	√			√		√			
Bozorgi [20]	√					√			
Homayouni [21]	√			√	√		√		
Dong [22]		√			√	√			
Tang [23]	√				√	√			
Du [24]	√			√				√	
Xiong [25]		√				√			√

Table 1. *Cont.*

Paper	Model			Carbon Regulation		Demand			Optimal Carbon Price
	Single Level	Bi-Level	Tri-Level	Carbon Tax	Carbon Trading	Deterministic	Carbon-Sensitive	Price-Sensitive	
Zhaofu [26]		√			√	√			
Li [27]		√		√		√			√
Tao Wu [28]		√		√		√			
Kang [29]		√				√			
Nita [30]	√			√			√		
Elhedhli [31]	√						√		
Imen Nouira [33]	√						√		
Shaofu Du [34]	√			√				√	
Bilir [35]			√				√	√	
Yunlong [36]	√						√		
Jiang [37]		√					√		
This paper		√		√			√	√	√

In this research, we examine a three-tier supply chain planning scenario under the influence of carbon tax regulations. The demand in this context is influenced by both carbon considerations and pricing. Recognizing that carbon taxes can introduce additional costs to the supply chain, we construct a bi-level programming model. Here, the government, acting as the leader, strives to determine the minimum carbon tax necessary to meet its carbon reduction targets while minimizing adverse effects on the supply chain's profitability. Meanwhile, the supply chain, functioning as a follower, adjusts its operational planning and product pricing by considering carbon tax and the environmental awareness of its customer base. To the best of our knowledge, this represents the initial endeavor to comprehensively integrate all these facets within the green supply chain planning.

3. Model Formulation

3.1. Model Description

In this study, we develop a bi-level carbon pricing model to implement carbon taxation. At the first level, the leader, who has a higher position and therefore sets the rules, aims at finding the best carbon pricing strategy to minimize emission production. The follower, at the second level, focuses on maximizing the supply chain's profitability with respect to the carbon price set by the leader. This cycle continues until the model's constraints on the leader's policy are met. These constraints control the overall carbon emissions throughout the supply chain according to the policies set by the government.

The players at the second level of this game are the supply chain's decision-makers. We consider a three-echelon supply chain consisting of manufacturers, warehouses, and customers, with a finite planning horizon. A specific product is manufactured at plant $i \in \{1,2, \ldots, n\}$. These plants are heterogenous in terms of capacity and the production technology used. The product is then sent to warehouse $j \in \{1,2,\ldots,n\}$. The transportation operation between these echelons is performed using vehicle type $v \in \{1,2,\ldots,n\}$. We assume that the fleet of vehicles is heterogenous, i.e., they are different in terms of capacity, emission, and transportation cost. Customers consider two different criteria to make a purchase: price and carbon emission produced per unit of the product, i.e., the demand is price-emission-sensitive. In case customer $k \in \{1,2,\ldots,n\}$ places an order for the item and it is available at the warehouses, the item will be delivered to the customer's location using vehicle type v. When the item is not available, the supply chain backlogs all the demand received. Although shortages are allowed, the supply chain aims at fulfilling the backlogged demand by the end of the planning horizon.

3.2. Notation

To formulate the problem, we use the notation that we have summarized in the Abbreviations part. Abbreviations part lists all the sets used in this study, and present the parameters and decision variables respectively.

3.3. Mathematical Model

In this problem, the follower's aim is maximizing its profit. The revenue is generated from the items sold at the retail level:

$$Z_1 = \sum_q pr_q g_q \sum_j \sum_k \sum_v \sum_t X_{jkvt} \quad (1)$$

The binary variable g_q gets a value of 1 if the price of pr_q $(q \in Q)$ is chosen as the final sales price, or 0 otherwise. To linearise this revenue function, we replace the term $g_q \sum_j \sum_k \sum_v \sum_t X_{jkvt}$ with a new variable g'_q which transforms the revenue function to $Z_1 = \sum_q pr_q g'_q$. To further implement this linearization to the model, we introduce the following constraints [38]:

$$\begin{cases} M(g_q - 1) + \sum_j \sum_k \sum_v \sum_t X_{jkvt} \le g'_q \le \sum_j \sum_k \sum_v \sum_t X_{jkvt} \\ g'_q \le M g_q \end{cases} ;\ \forall q \quad (2)$$

In the above set of constraints, M represents a very large positive value.

The cost function of the supply chain consists of fixed cost at the manufacturing sites, variable production cost, transportation cost between echelons, fixed cost at the warehouses, inventory-holding cost, shortage cost, and carbon emission cost. The cost function is formulated as follows:

$$\begin{aligned} Z_2 = &\sum_i \sum_t FC_{it} Y_{it} + \sum_i \sum_t PC_{it} I_{it} + \sum_i \sum_j \sum_v \sum_t TC_{ijvt} X'_{ijvt} + \sum_j \sum_t FC'_{jt} Y'_{jt} + \sum_j \sum_t HC_{jt} I'_{jt} + \\ &\sum_j \sum_k \sum_v \sum_t TC'_{jkvt} X_{jkvt} + \sum_k \sum_t SH_{kt} S_{kt} + \pi \sum_t TE_t \end{aligned} \quad (3)$$

In this problem, carbon emission is produced in three different operations: production, warehousing, and transportation. The following term quantifies the amount of emission produced in period t:

$$TE_t = \sum_i I_{it} e^1_{it} + \sum_j I'_{jt} e^2_{jt} + \sum_i \sum_j \sum_v X'_{ijvt} e^3_{ijvt} + \sum_j \sum_k \sum_v X_{jkvt} e^4_{jkvt};\ \forall t \quad (4)$$

The demand function is dependent on both the selling price and the amount of carbon emissions produced in operations. In order to model the demand of customer k at time period t, we use the following function [24]

$$D_{kt} = \theta_{kt}\left(1 - \sum_q \rho_q g_q\right) + \delta_t (E0_t - E_t);\ \forall k, t \quad (5)$$

As the function shows, any increase in the price may negatively impact the demand. Moreover, exceeding the predefined threshold for the emission may result in a decrease in the demand. We use the following constraint to guarantee that the model chooses one specific price:

$$\sum_q g_q = 1 \quad (6)$$

The amount of carbon emissions produced per unit of product in period t is calculated by dividing the total carbon emissions in the entire supply chain for that period by the quantity of products sent to customers. It is important to note that emissions in one period are not solely associated with the items sent to customers during that same period. They also arise from production, warehousing, and transportation operations related to items stored in the supply chain. Therefore, while the model may sometimes overestimate or underestimate emissions in one period, it tends to correct itself in subsequent periods.

$$E_t = \frac{TE_t}{\sum_j \sum_k \sum_v X_{jkv}};\ \forall t \tag{7}$$

To linearize the above equation, we first assume that the number of items sent to customers falls in the following range.

$$1 \leq \sum_j \sum_k \sum_v X_{jkv} \leq n \tag{8}$$

We divide this range into $n-1$ intervals and define the binary variables η_l where $l \in \{1, 2, \ldots, n-1\}$. This variable is defined in such a way that if $\sum_j \sum_k \sum_v X_{jkv}$ falls within the lth interval, then η_l takes the value of 1, and 0 otherwise. This will add the following constraints to the model:

$$l\eta_l \leq \sum_j \sum_k \sum_v X_{jkv} \leq l + 1 + M(1-\eta_l);\ l \in \{1, 2, \ldots, n-1\} \tag{9}$$

$$\sum_{l=1}^{n-1} \eta_l = 1 \tag{10}$$

Given the intervals defined above, the value of E_t will fall into one of the following intervals, which will determine the upper bound for E_t:

$$E_t \leq \frac{TE_t}{l} + M(1-\eta_l);\ l \in \{1, 2, \ldots, n-1\} \tag{11}$$

It is evident that, as the defined intervals become narrower and closer in values, the upper bound for E_t will be more precise.

In the following, we present the rest of the constraints of the problem at hand:

$$0 \leq E_t \leq E0_t;\ \forall t \tag{12}$$

$$I_{it} \leq R_{it}\ ;\ \forall i, t \tag{13}$$

$$I_{it} \times c_{it} \leq \alpha_{it}\ ;\ \forall i, t \tag{14}$$

$$I'_{jt} \leq \alpha'_{jt}\ ;\ \forall j, t \tag{15}$$

$$X'_{ijvt} \leq \beta_{ijvt}\ ;\ \forall i, j, v, t \tag{16}$$

$$X_{jkvt} \leq \beta'_{jkvt}\ ;\ \forall j, k, v, t \tag{17}$$

$$I'_{jt} - I'_{j(t-1)} = \sum_i \sum_v X'_{ijvt} - \sum_k \sum_v X_{jkvt}\ ;\ \forall j, t \tag{18}$$

$$\sum_j \sum_v X_{jkvt} = D_{kt} - S_{kt} + S_{k(t-1)}\ ;\ \forall k, t \tag{19}$$

$$\sum_i \sum_t I_{it} = \sum_k \sum_t D_{kt} + \sum_j \lambda'_j - \sum_j \lambda_j \tag{20}$$

$$S_{kt} \leq S_{kt}^{max}\ ;\ \forall k, t \tag{21}$$

$$I'_{j0} = \lambda_j\ ;\ \forall j \tag{22}$$

$$I'_{jT} = \lambda'_j\ ;\ \forall j \tag{23}$$

$$0 \leq I_{it} \leq Y_{it} \times M\ ;\ \forall i, t \tag{24}$$

$$0 \leq X'_{ijvt} \leq Y_{it} \times M\ ;\ \forall i, j, v, t \tag{25}$$

$$0 \leq X'_{ijvt} \leq Y'_{jt} \times M\ ;\ \forall i, j, v, t \tag{26}$$

$$0 \leq X_{jkvt} \leq Y'_{jt} \times M \; ; \; \forall j,k,v,t \tag{27}$$

$$I'_{jt} \geq 0 \; ; \; \forall j,t \tag{28}$$

$$S_{kt} \geq 0; \forall j,t \tag{29}$$

Constraints (12) impose the allowed threshold for emission produced per unit of item in each period. In manufacturing plants, the production is bounded by the amount of raw material. Moreover, the production facilities are limited to a certain capacity specified in terms of hours. Constraints (13) and (14) guarantee these limitations, respectively. Constraints (15) warrant the capacity constraints at the warehouses. Constraints (16) and (17) ensure that the capacity of the transportation service is respected. To guarantee the inventory balance at the warehouses, we use the constraints (18). In a similar way, constraints (19) impose inventory balance on the customers. Constraints (20) ensure that the overall demand during the planning horizon will be eventually met. Constraints (21) guarantee service levels agreed with the customers. Constraints (22) and (23) state that the inventory levels at the beginning and the end of the planning horizon must be equal to certain values, respectively. Lastly, constraints (24)–(29) ensure non-negativity conditions of the decision variables.

At the second level of this leader–follower model, the leader (policy maker/government) aims at finding the minimum possible value for the carbon price π in a way that guarantees a certain amount of reduction in the total emission of the supply chain. To this end, the leader first determines the desired amount of emission reduction throughout the whole supply chain, denoted by ϕ. The leader model is formulated as follows:

$$Leader: \; \min \pi \tag{30}$$

$$\sum_t TE_t \leq \phi \times \left(\sum_t TE_t \right)_{\pi=0} \tag{31}$$

4. Case Study

This case study addresses the supply chain of a specific item in Australia, with planning activities spanning a 12-period horizon. The supply chain structure involves two separate production facilities located in different Australian cities, each equipped with dedicated production capacities and specific technologies. One facility employs older technology, resulting in higher carbon emissions, while the other utilizes modern technology, leading to reduced emissions.

The produced item is transported to three warehouses in different Australian cities, using three distinct transportation modes: road, rail, and sea. Each transportation mode exhibits varying emission levels and capacities. Similar to the production centers, the warehouse design incorporates both conventional and green technologies. Finally, the product is delivered to the customers. This case study investigates the dynamics of this supply chain, considering several production and transportation methods alongside their environmental implications.

4.1. Estimation of Parameters

Given the absence of specific parameters within the demand function, a process of estimation based on available data and problem conditions has been implemented. To estimate the pricing parameter for the final product, the model was initially solved, disregarding the sensitivity of demand to carbon emissions, with a focus on determining the profit break-even point. According to the results, the calculated break-even price stands at 208. Consequently, three approved prices, namely 280, 290, and 300, were derived to ensure that 35–45% of the net profit for the supply chain is maintained. Opting for the first price results in a 10% customer drop-off rate, while this rate is 30% and 50% for the price of 290 and 300, respectively.

In order to estimate the parameter for the carbon emission threshold, the model was initially solved without taking into account the sensitivity of demand to carbon emissions. This was performed for three specified prices. Subsequently, the maximum value of emissions per product was calculated for each price level, and this value, 130 kg per product, was considered as the parameter value for $E0_t$.

δ_t is set to 10 to represent the sensitivity of customers to the emission level compared to the carbon threshold. The parameter φ is assigned a value of 0.9, signifying the leader's intention to reduce the overall carbon emissions by 10%.

4.2. Determining the Linearization Intervals for the Carbon Emission

The model was initially solved using GAMS v.25.1.2 software. with a carbon price (π) set to zero in both the linear and nonlinear cases. This was achieved using two different solvers, Bonmin and CPLEX. The choice of setting π = 0 was made because, in this scenario, with no carbon tax penalties, the demand reaches its maximum value.

To estimate the value of the variable $\sum_j \sum_k \sum_v \sum_t X_{jkvt}$, a parameter was defined, with upper and lower bounds set at 1740 and 1400, respectively. Consequently, a range of [1000, 2000] was considered, and the length of the selected intervals was initially set at 100 units. Subsequently, it was reduced to 50 units in the next step and finally to 25 units.

Table 2 presents the results derived from solving the model with varying interval lengths. Notably, a trend emerges as the interval length decreases, wherein both costs and carbon emissions increase, resulting in a reduction in supply chain profitability. This rise is attributed to the demand function's continual drive to maximize its value in the absence of carbon tax. Since the carbon tax remains at zero, emission costs are not imposed on the system, leading to an upward trajectory in emissions across different intervals.

It is worth observing that demand remains constant in all three cases and reaches its maximum value. This steady demand component stems from the constant difference, denoted as $E0_t - E_t$, which induces alterations in inventory holding and transportation costs between the warehouse and the customer. Consequently, as interval lengths diminish, cost values increase.

In the nonlinear solution, the software was able to find only one feasible solution, selecting the second price, USD 290, as the optimal price. Even in this case, without a carbon tax, demand did not reach its peak level, and the escalation in costs and carbon emissions was more pronounced in the transition from the nonlinear model to the linear model. This suggests that the linearization results can be trusted, as the term $\delta_t(E0_t - E_t)$ ensures that demand remains at its maximum level without losing customers due to a higher product price. As a result, the model also determined a higher product price to maximize profitability.

4.3. Solving the Model and Determining the Price of Carbon

As observed from the results in Table 3, after solving the model, it is evident that, in the scenario wherein there is no tax on carbon, the total carbon emissions in the supply chain amount to 2,093,969 kg. To comply with the constraints set by the leader, which requires a minimum 10% reduction in total emissions in the chain, the minimum carbon price that should be imposed on the chain would be USD 0.9/kg of carbon emissions. This would lead to a reduction of 1,791,058 kg in the total emissions, and a decrease of 80% in the supply chain profit. It is obvious that strictly enforcing a 10% reduction in carbon emissions would severely impact this supply chain. In such cases, it would be better if the policy-maker took a more lenient approach and considered a transition period during which the supply chain could invest in new technologies. As shown in Figure 1, with the increase in the carbon price from 0 to 1 USD/kg, the total emissions in the supply chain exhibit a decreasing trend. This downward trend in emissions is more pronounced at higher carbon prices.

Table 2. Comparison of linear and non-linear models.

Interval Length	Model		Profit (USD)	Total Emissions (tons)	Increase in Emission Compared to the Previous Row (%)	Demand	Price (USD)	Cost (USD)	Increment in Costs Relative to the Previous Row (%)	Solving Time (minutes)
	Non-Linear	Linear								
-	✓		1,226,400	1680	0	13,830	290	2,804,600	0	17
100		✓	2,181,993	2036	21	17,560	300	3,686,006	31	12
50		✓	2,170,536	2075	1	17,560	300	3,697,464	0.3	18
25		✓	2,162,298	2093	0.8	17,560	300	3,705,702	0.2	21

Table 3. The results of optimization in different carbon prices.

Carbon Price (USD per kg)	Carbon Emission Components (kg)			Total Emissions (kg)	Carbon Emission Reduction (%)	Cost Components (USD)				Cost (USD)	Revenue (USD)	Profit (USD)
	Production	Warehouse	Transportation			Production	Warehouse	Transportation	Emissions			
0	923,422	15,000	1,155,546	2,093,969	0	2,837,662	510,620	355,949	0	3,705,701	5,688,000	2,162,298
0.1	923,422	18,877	1,151,403	2,093,704	0.01	2,837,662	51,454	354,809	209,370	3,915,767	5,688,000	1,952,232
0.2	923,370	18,668	1,148,087	2,090,126	0.18	2,837,770	512,681	353,905	418,025	412,571	5,688,000	1,744,218
0.3	923,422	15,080	1,110,826	2,049,329	2.1	2,837,959	511,209	341,469	614,798	4,306,907	5,688,000	1,561,092
0.4	923,422	11,715	1,098,991	2,034,129	2.9	2,838,113	509,533	337,695	813,651	4,500,464	5,688,000	1,367,535
0.5	923,317	6139	1,095,639	2,025,096	3.3	2,838,200	506,894	336,705	1,012,548	4,695,679	5,688,000	1,172,320
06	922,267	2961	1,092,021	2,017,250	3.7	2,835,187	505,529	335,497	1,210,350	4,887,614	5,862,000	974,385
0.7	920,692	842	1,088,440	2,009,974	4	2,831,812	504,439	334,321	1,406,982	5,078,184	5,853,000	774,815
0.8	894,600	6528	1,032,172	1,933,301	7.7	2,715,900	507,546	315,997	1,546,640	5,086,085	5,670,000	583,914
0.9	856,800	3073	931,185	1,791,058	14	2,574,900	505,525	284,586	1,611,952	4,976,964	5,400,000	423,035
1	819,000	8040	894,000	1,721,040	17.8	2,523,900	507,940	273,283	1,721,040	5,026,163	5,250,000	223,836

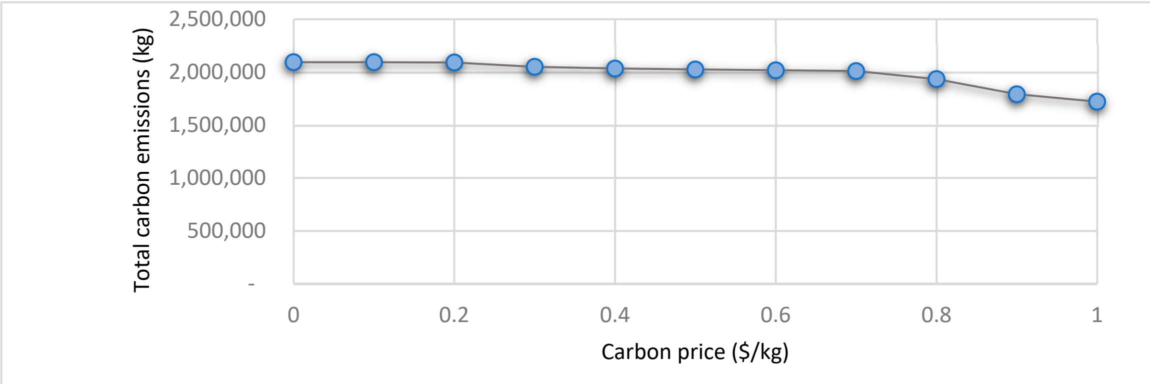

Figure 1. Changes in carbon emissions in the entire chain at different carbon prices.

The emissions produced through storing operations are significantly lower when compared to the emissions from production and transportation, as shown in Figure 2. Transportation operations contribute the largest share of the total emission in the supply chain. As the carbon price increases, a decreasing trend in emissions from transportation operations is observed. This suggests that, as the carbon price rises, the supply chain prefers transportation methods with lower pollution levels. Consequently, the supply chain adjusts its transportation practices to reduce carbon emissions in response to the carbon pricing mechanism.

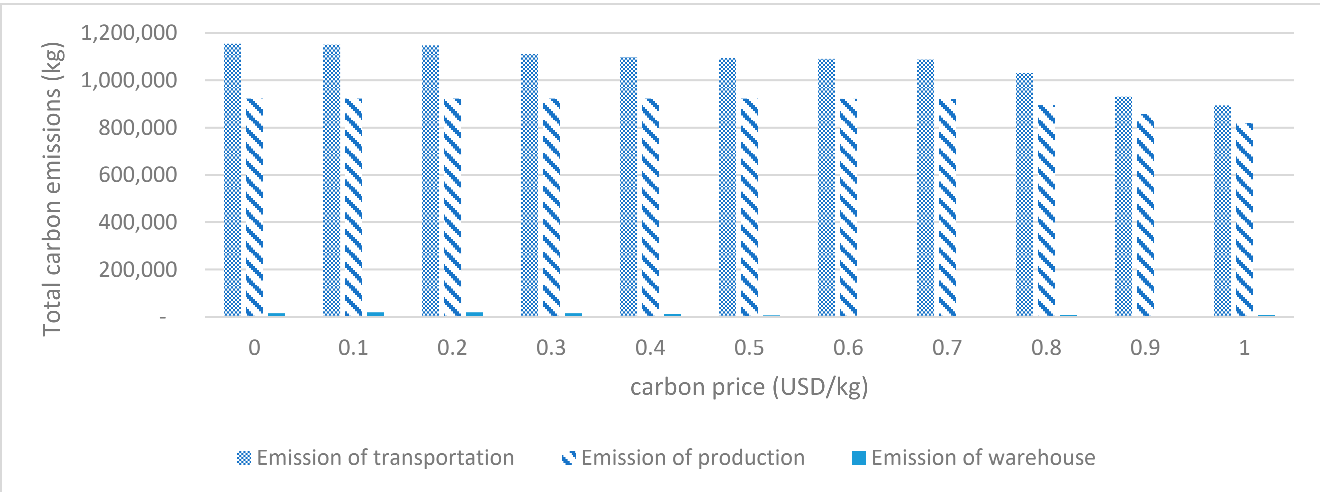

Figure 2. Breakdown of carbon emission components at various carbon prices.

Additionally, the decreasing trend in emissions from production initially exhibits a slower decline. This is because, in the beginning, the supply chain prioritizes using greener production capacities to reduce carbon tax payments. However, as the carbon price exceeds USD 0.7/kg and continues to rise, the supply chain may opt to significantly decrease overall production to achieve lower total emissions. However, this reduction in total production can result in an increase in emission per unit of the final product. Consequently, the elevated emission per unit could prompt a decline in total customer demand, influenced by the sensitivity of customers to carbon emissions, as reflected in the demand function.

These findings illustrate the impact of carbon pricing on emission reduction strategies within the supply chain. They highlight that a higher carbon price encourages the adoption of cleaner transportation methods and more sustainable production practices, contributing to an overall reduction in carbon emissions within the supply chain.

Figure 3 depicts how profit, revenue, and costs change as carbon prices increase. As observed, with the increase in carbon price, costs exhibit an upward trend due to the imposition of carbon taxes. This upward trend continues until the carbon price reaches USD 0.9/kg. However, beyond this point, costs start to decline due to the reduced production levels. The revenue chart also shows a steady trend at the beginning, up to a carbon price of USD 0.7/kg, due to constant demand. However, as the carbon price exceeds USD 0.7/kg, the revenue trend starts to decline due to the reduction in production levels. As seen in the charts, the increasing costs and decreasing revenue result in a larger decrease in the profit. This is a direct impact of carbon pricing on the supply chain's financial dynamics, leading to lower profits due to the combination of higher costs and reduced revenue.

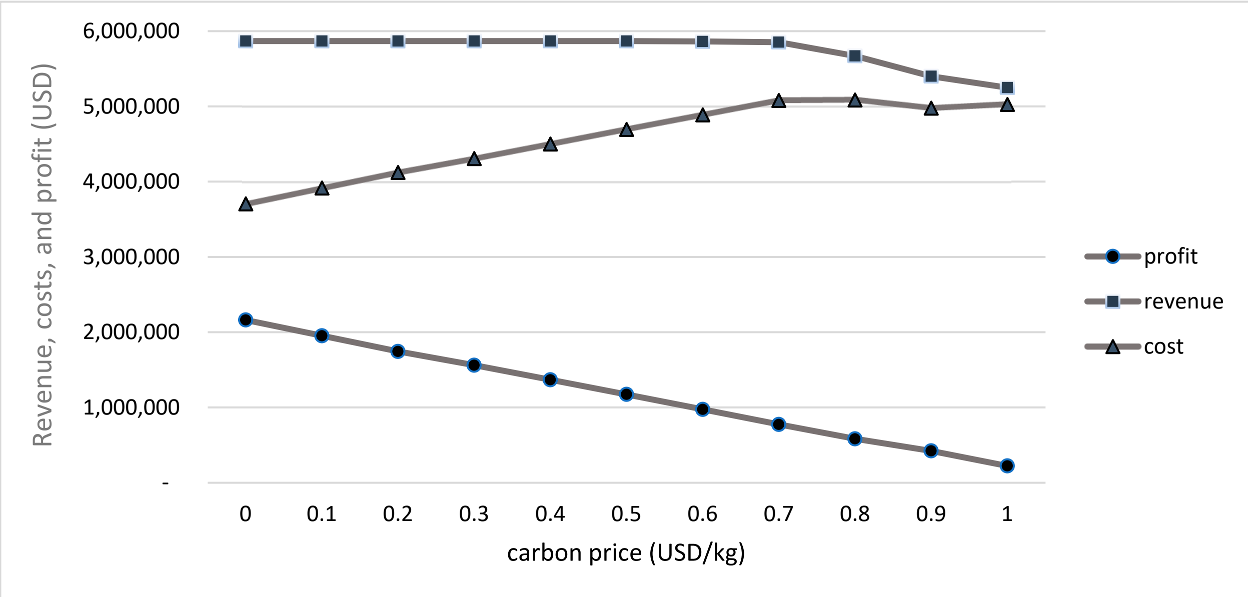

Figure 3. The trend of profit, revenue, and cost function changes in different carbon prices.

From Figure 4, it is evident that, with the increase in carbon price, the carbon deficit cost remains almost constant and negligible, making it less noticeable. The costs related to maintenance and transportation also display a relatively uniform behavior. At a carbon price of USD 1/kg, the transportation costs decrease due to the reduced volume of products sent to customers. However, the changes in carbon emission costs are rather evident, showing an ascending trend until the carbon price reaches USD 0.9/kg, after which they decline due to the reduction in production levels. Production costs represent the largest share in the chain's expenses, and it is evident that, up to a carbon price of USD 0.7/kg, there are no significant changes. In some instances, there is even a slight increase due to the utilization of green production capacities. However, for carbon prices higher than USD 0.7/kg, the supply chain faces challenges in reducing carbon emissions and is forced to decrease production levels, leading to a noticeable decline in production costs.

The analysis shows that, initially, the production levels in the regular and green factories remain constant as the carbon price increases and the supply chain tries to reduce carbon emissions through other emission reduction measures, as seen in Figure 5. When the carbon price surpasses USD 0.3/kg, the green production curve shows an increasing trend until the price reaches a value of USD 0.5/kg, indicating that the supply chain utilizes green technology in the production to contribute to the overall carbon reduction in the chain. From this point onwards, the production levels in both regular and green factories start to decrease since the model is aiming at minimizing the costs that also include the carbon emission costs.

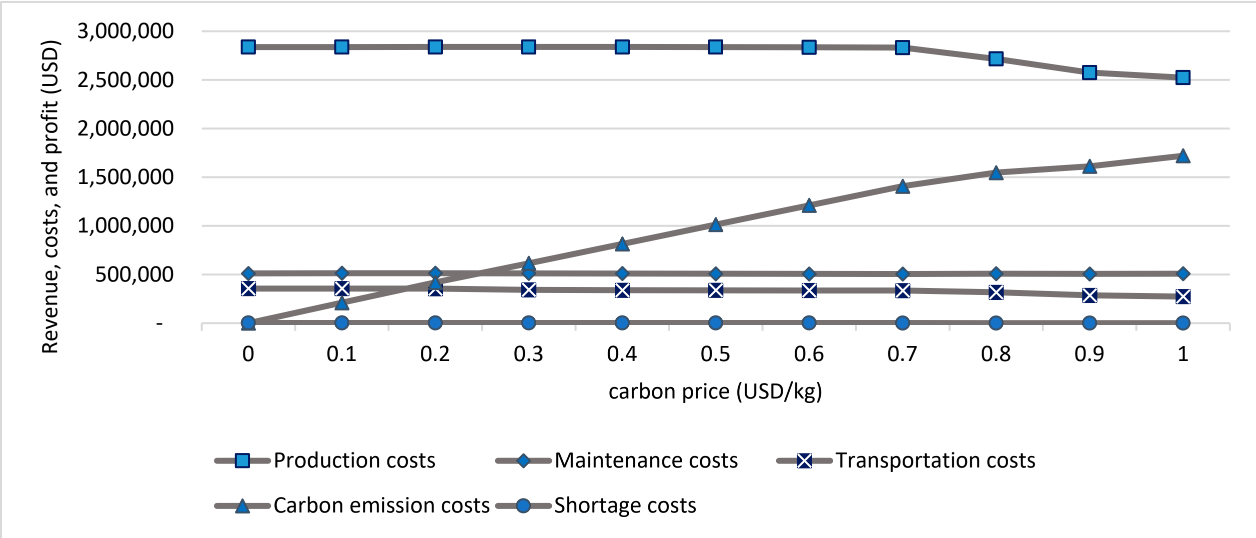

Figure 4. The trend of changes in the cost components in different carbon prices.

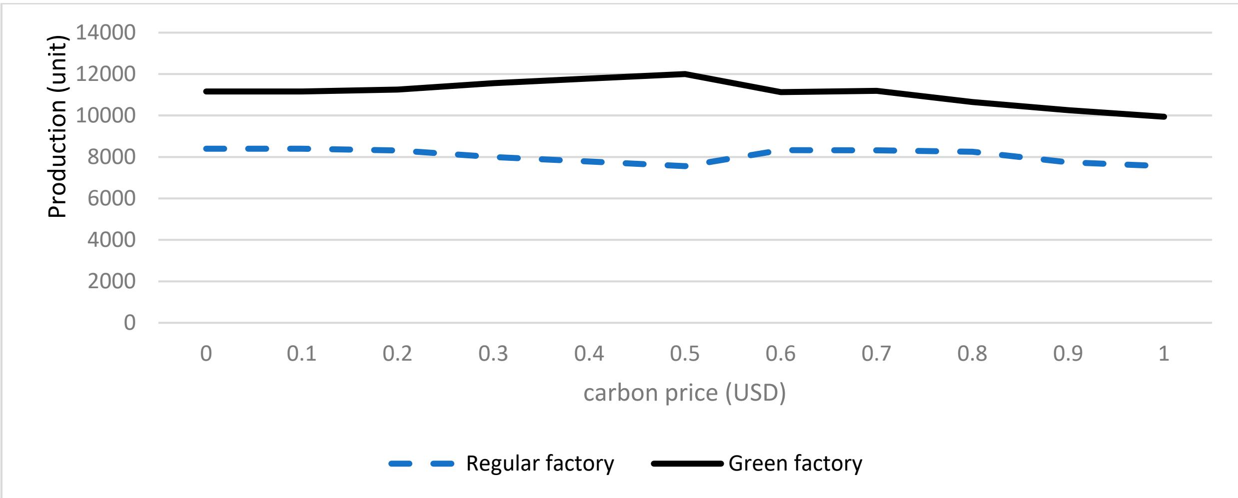

Figure 5. Production quantities in regular and green factories.

Based on the information provided, it can be observed from Figure 6 that, when the carbon price is USD 0.9/kg and the target for carbon emission reduction is 10%, the demand level increases as the sensitivity coefficient of customers to carbon emissions increases from 10 to 16. This implies that environmentally conscious customers will be more inclined to support and purchase low-carbon products. However, when the sensitivity coefficient to emissions decreases from 10 to 2, the demand takes a decreasing pattern. This suggests that customers may be less concerned about environmental issues, leading to a decline in the demand for low-carbon products.

Figure 7 illustrates how the total carbon emission produced in the supply chain changes when the sensitivity coefficient varies. An increase in this coefficient leads to an increase in demand, and subsequently, higher demand results in higher carbon emissions. Having said that, imposing carbon taxes and simultaneously creating customer awareness to emissions does not reduce the emissions since it does not significantly affect profitability and may even lead to increased carbon emissions. Hence, it is not effective to apply both policies simultaneously.

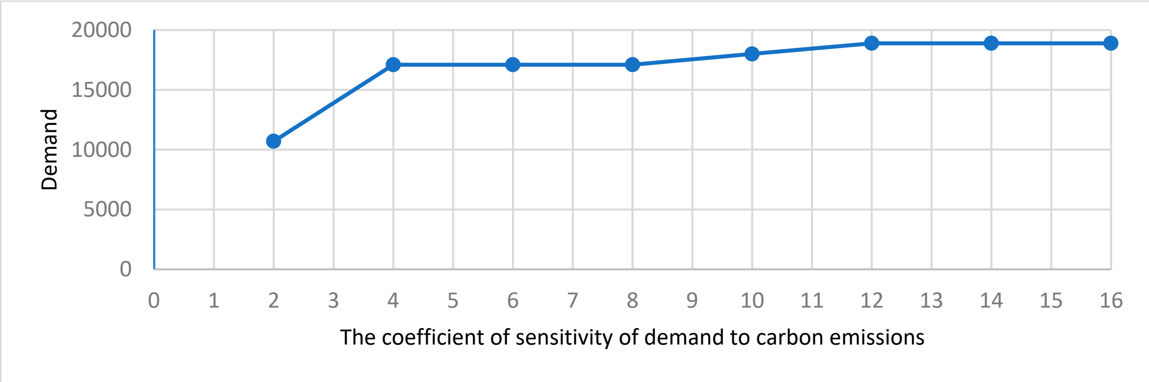

Figure 6. Trend of the demand function with changes in the sensitivity coefficient of customers.

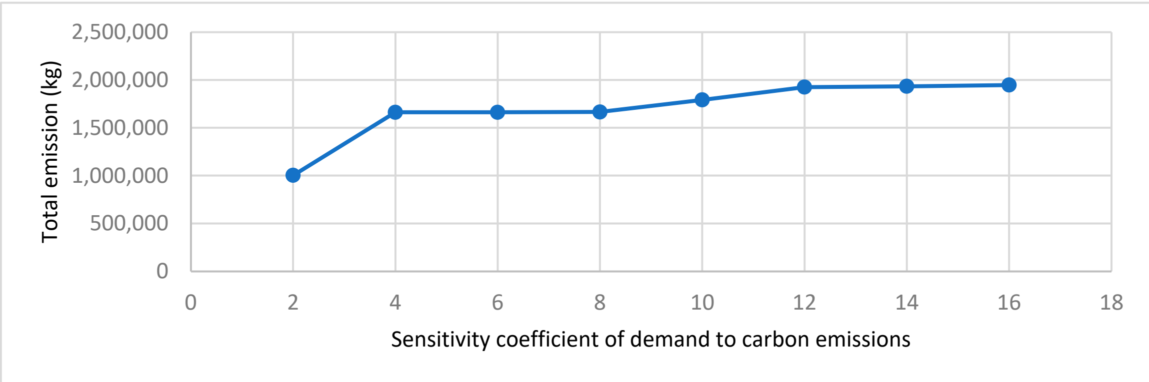

Figure 7. Total carbon emission when sensitivity coefficient changes.

5. Conclusions

The rapid economic developments have increasingly raised environmental concerns in the marketplace and pushed governments and policy-makers to take actions to reduce the consequences on the environment. Many countries face the challenging task of reducing air pollution and carbon emissions while pursuing economic growth. To effectively control carbon emissions, governments have adopted various policies, one of which is the carbon taxation policy. This policy involves the direct pricing of carbon dioxide emissions produced by companies, encouraging them to reduce their emissions. Moreover, the emergence of environmental awareness among customers indicates a change in demand behavior. These changes necessitate a reconsideration of supply chain management and decision-making processes, leaving no option but to adapt to the evolving demands.

In this study, a bi-level leader–follower model is employed to plan a green supply chain. The leader's policy aims to propose the minimum carbon price to be applied to the follower's model, enforcing the implementation of the carbon taxation policy, and reducing carbon emissions to a predetermined level. On the other hand, the follower's model continuously seeks to increase the chain's profitability while considering the effects of consumers' sensitivity to emissions and the final product's price. The sensitivity coefficient of customers to emissions is determined by comparing the total chain emissions to the emissions per unit of the final product delivered to customers. The linearity of this expression in the problem model is also crucial.

The results from the numerical example demonstrate that, with an increase in carbon prices, the chain's emissions decrease for two reasons: initially, the chain utilizes its green technological capacities to reduce emissions, and subsequently, with further increases in carbon prices, it tends to reduce production. Thus, the leader must implement policies to determine emission reduction rates throughout the chain, taking into account the organizations' profitability, to avoid imposing economic challenges and tensions on them.

While our research presents valuable insights, several limitations warrant consideration. The generalizability of our findings may be constrained by the specificity of the case study, and caution is advised when extending results to diverse industries. The assumed linear dependence of the demand function on price and carbon emissions may oversimplify real-world consumer behavior, suggesting avenues for future exploration into more nuanced demand models. Relying on a singular case study may limit the broader applicability of our proposed model, and additional cases across various industries could enhance its robustness. While these limitations exist, they offer opportunities for future research to refine and extend the insights provided by our study.

Indeed, the current study focuses on a single-product supply chain, but future research can explore multi-product supply chains as well. Additionally, other carbon reduction schemes, such as carbon trading and buying/selling carbon permits, can be incorporated into optimization models to generate managerial insights. The demand function is dependent on factors such as the final product's price and the sensitivity to carbon emissions. In future studies, other influencing factors, such as consumers' sensitivity to the quality of the final product, can also be included in the model. This will allow for a more comprehensive analysis of the supply chain and better insights into the behavior of the market and customers in response to carbon-related policies.

Author Contributions: Conceptualization, P.M., F.D. and Y.G.; Methodology, P.M. and F.D.; Software, P.M.; Validation, F.D.; Writing—original draft, P.M.; Writing—review & editing, F.D. and Y.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Notation	Description
I	Set of production sites
J	Set of warehouses for the final product
K	Set of customers
V	Set of transportation modes
T	Set of time periods
L	Set of defined intervals for linearizing the carbon emission equations
Q	Set of final product price levels
PC_{it}	Unit production cost at site i in period t
FC_{it}	Fixed production cost at site i in period t
FC'_{jt}	Fixed cost of opening warehouse j in period t
HC_{jt}	Unit holding cost at warehouse j in period t
TC_{ijvt}	Unit transportation cost from site i to warehouse j using vehicle v in period t
TC'_{jkvt}	Unit transportation cost of the final product from warehouse j to customer k using vehicle v in period t
SH_{kt}	Unit shortage cost of the final product for customer k in period t
α_{it}	Production capacity of site i in period t
α'_{jt}	Capacity of warehouse j in period t
c_{it}	Unit production time at site i in period t
λ_j	Initial inventory at warehouse j at the beginning of the planning horizon
λ'_j	Ending inventory at warehouse j at the end of the planning horizon
S_{kt}^{max}	Maximum allowable shortages for customer k in period t
R_{it}	Available raw materials at site i in period t
β_{ijvt}	Transportation capacity from site i to warehouse j using vehicle v in period t

β'_{jkvt}	Transportation capacity between warehouse j and customer k using vehicle v in period t
e^1_{it}	Carbon emissions produced per unit of item during production operations at site i in period t
e^2_{jt}	Carbon emissions generated in storage operations per unit of item in warehouse j in period t
e^3_{ijvt}	Carbon emissions generated per unit of item in transportation from site i to warehouse j by vehicle v in period t
e^4_{jkvt}	Emissions generated per unit of item in transportation operations from warehouse j to customer k by vehicle v in period t
θ_{kt}	Potential demand of customer k in period t
ρ_q	Customers' demand sensitivity to price level q
pr_q	Price associated to level q
δ_t	Demand sensitivity to carbon emissions in period t
$E0_t$	Carbon emissions threshold per unit of product in period t
$\varnothing$	Carbon emission reduction factor in leader model
π	Carbon price
M	A large positive number
Sign	**Description**
X_{jkvt}	The amount of product sent from warehouse j to customer k by transportation method v in period t
X'_{ijvt}	The amount of product sent from site i to warehouse j by transportation method v in period t
D_{kt}	The amount of customer demand k in period t
I_{it}	Production quantity at site i in period t
I'_{jt}	The amount of finished product inventory in warehouse j at the end of period t
S_{kt}	Shortage amount for customer k in period t
TE_t	Total amount of carbon in period t
E_t	The amount of carbon emitted per unit of final product in period t
P	Selling price of the final product
Y_{it}	If site i is used in period t, 1; otherwise; 0
Y'_{jt}	If warehouse j is used in period t, 1; otherwise, 0
g_q	If the price of state q is selected, it is 1; otherwise, it is 0
W_{ijvt}	If the final product is transported from site i to warehouse j by transportation method v in period t, 1; otherwise, 0
W'_{jkvt}	If the final product is transported from warehouse j to customer k by transportation method v in period t, 1; otherwise, 0
g'_q	The linearization variable of the income equation and replaces the X_{jkvt} variable
η_l	The linearization variable of the equation of dividing the total amount of carbon emission by the total number of products sent: if the variable $\sum_j \sum_k \sum_v X_{jkv}$ is in the defined range, the value is 1; otherwise, the value is 0

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