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RESEARCH ARTICLE

Inventory Management in Supply Chains with Consideration of Transportation and Green Technology Cost Under Progressive Carbon Taxation

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Abstract

Reducing carbon emissions is an important issue in the global supply chain. Governments have formulated different carbon policies to achieve carbon neutrality or emission reduction, in particular, the carbon tax as a policy provides greater certainty about the potential cost to emitters. The Taiwan government is expected to implement the carbon tax policy in 2024 and does not rule out the inclusion of a progressive mechanism which is more effective than a single carbon tax in curbing high carbon emissions Recent studies have also confirmed that a high level and complete carbon tax could encourage companies to invest in green technologies, which can reduce emissions while reducing internalization costs. In addition, scholars have proposed that the transportation process has a significant impact on carbon emissions. Therefore, in this paper, we combine with the EOQ model of the integrated supply chain under the progressive carbon tax, transportation cost, and green technology investment, the proposed model can help decision makers determine the optimal order quantity and green technology investment costs to minimize total costs and carbon emissions. It is also for the government to the trade-off between the carbon tax system and economic activities. Finally, numerical results are discussed to provide managerial insights.

Keywords: Progressive carbon tax, Invest in green technology, EOQ model

1. Introduction

Governments and businesses are striving to address global warming and climate change by reducing carbon emissions. For example, organizations such as the United Nations and the European Union and several national governments have implemented regulations to control carbon emissions, including carbon taxes, carbon fees, cap-and-trade policies, carbon offsets, and carbon credits.

During the twenty-first session of the Conference of the Parties in Paris, 195 countries agreed to the Paris Climate Agreement as a replacement for the Kyoto Protocol. This agreement requires countries to submit a climate pledge, known as a nationally determined contribution, and commit to reducing carbon emissions. Every 5 years, governments must update their plans for slowing climate change and limiting the global temperature rise to below 1.5 °C to avoid worst-case climate scenarios [1]. At the twenty-sixth session of the Conference of the Parties in Scotland, the parties set a goal of achieving global net-zero emissions by 2050 and established a mechanism for implementing a global carbon market system. However, the United Nations Environment Programme has warned that the current

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reductions in carbon emissions are insufficient and that if present trends continue, the average temperature will rise by 2.7 °C by the end of this century (2100), engendering catastrophic consequences [2].

According to Renewable Energy 100, companies account for half of the world's energy consumption. Therefore, companies are expected to implement green strategies for environmental responsibility, such as implementing green supply chains and reducing their carbon footprints, in response to regulatory mechanisms and customer expectations [3]. Recently, Apple committed to a substantial reduction in emissions by announcing that all of its supply chains must be carbon neutral by 2030. Similarly, other major companies such as Amazon, Facebook, Google, Microsoft, Mercedes, and IBM have stated their commitments to reducing emissions by at least 50 % or even to zero by 2030.

The main cause of climate change is greenhouse gases, including CO2, N2O, chlorofluorocarbons (CFCs), and SF6. According to a survey by the Intergovernmental Panel on Climate Change, CO2 has the largest contribution to the greenhouse effect. Fuel combustion is the primary source of CO2 emissions, and the amount of emission is related to the carbon content of the fuel [4]. Carbon pricing strategies have been proposed to reduce emissions, and the three most common pricing strategies are outlined as follows: (I) cap and trade, (II) carbon taxes, and (III) carbon credits. A carbon tax is a mechanism designed to incorporate the cost of environmental damage induced by greenhouse gas emissions into the cost of business for companies. This helps stakeholders consider the cost of carbon emissions when making decisions, which can result in reduced emissions. Imposing a carbon tax increases production costs for carbon-emitting companies. To reduce this tax burden, companies may adopt green technologies for reducing carbon emissions, furthering global climate goals.

Carbon taxes were first applied in northern European countries in the early 1990s. In 2001, the United Kingdom implemented a carbon tax as the Climate Change Levy. Various provinces and municipalities in the United States and Asia, such as Japan and Singapore, have also recently introduced carbon taxes [5]. Taiwan plays a key role in the global supply chain through the production of many commodities. Taiwan has implemented the Climate Change Response Law as part of its intention to levy a carbon tax from 2024; this tax may be progressive. However, implementing methods such as carbon caps or emission trading in Taiwan may be challenging because Taiwan's carbon market would be small and might thus have low liquidity. Additionally, disputes regarding Taiwan's statehood may cause difficulties in the implementation of these measures.

The aim of this study was to develop an economic order quantity (EOQ) model that considers carbon emissions generated at various stages of the production process, such as transportation and warehousing. The model accounts for the effects of a progressive carbon tax policy, transportation costs, and green technology investment to determine the optimal inventory and green technology investment costs, which can help minimize both the total costs and carbon emissions of enterprises.

The rest of this paper is organized as follows. Section 2 presents a review of the relevant literature. Section 3 provides the definitions of the model parameters and assumptions, in addition to presenting the development of the integrated inventory model. Section 4 presents the model solution, the optimal solution, numerical examples, and a sensitivity analysis. Finally, Section 5 provides the conclusion and future research directions.

2. Literature review

This section introduces the relevant literature regarding climate change and the proposed model. First, an overview of global agreements related to climate change is presented, followed by an examination of the development and advantages of carbon taxes and progressive carbon taxes. Corporate investment in green technologies to reduce carbon emissions is also discussed. Finally, mathematical modeling methods for green supply chains are introduced.

2.1. Agreement on climate change

The Kyoto Protocol requires countries to limit anthropogenic greenhouse gas emissions and maintain the greenhouse gas content in the atmosphere at an appropriate level; between 2008 and 2012, industrialized countries were required to reduce their overall emissions by at least 5 % compared with 1990 levels [6]. The Paris Agreement established the Sustainable Development Mechanism (SDM) [7], which resembles the Clean Development Mechanism of the Kyoto Protocol and has dual goals of reducing global greenhouse gas emissions and supporting sustainable development [8]. Parties to the Paris Agreement can collaborate on emission reductions. According to a 2021 report from Global Carbon Budget, global annual CO2 emissions from fossil fuels have been increasing, reaching 9.5 ± 0.5 Gt in 2020 (Fig. 1). The concentration of CO_2 in the atmosphere has also increased from approximately 277 ppm in 1750 to 412.4 ± 0.1 ppm in 2020 (Fig. 2) [9].

2.2. Carbon tax

Numerous countries have already adopted carbon reduction policies such as carbon taxes, cap-and-trade policies, and carbon offsets to reduce carbon emissions. Among these policies, a carbon tax, in which firms are taxed for the CO_2 emissions of each product, is considered a key strategy that is highly recommended by economists and international organizations because it can effectively reduce carbon emissions with a minimal impact on the economy [10].

Implementing carbon taxes can reduce the global costs of achieving emission targets more efficiently than can conventional regulations that rely on command-and-control approaches. In a carbon tax regime, the costs associated with meeting emission targets are predictable; specifically, most corporations must pay the tax if the costs of reducing emissions are higher than anticipated [11]. A carbon tax, also known as a price-based mechanism, is a fixed payment per unit CO_2 emission [12]. A stable carbon tax price would reduce uncertainty and prompt companies to adjust their operations and activities.

Each country that has implemented a carbon tax has levied it differently, and companies operating in these countries must consider the cost of carbon emissions when making production and pricing decisions [13]. A higher carbon tax can encourage manufacturers to adopt low-carbon production processes, and retailers and manufacturers with eco-friendly operations can benefit from the imposition of carbon taxes [13,14].

Although lower emissions are typically linked to higher costs, manufacturers can achieve considerable emission reductions without substantially increasing their operating costs by adjusting ordering decisions. This is because costs tend to be stable around the cost-optimal solution. Therefore, even modest carbon prices or taxes can result in substantial emission reductions [15]. A carbon tax indirectly controls the level of emission reduction through direct control of the price of carbon. The carbon tax policy is cost-effective because emitters only choose to reduce emissions if the cost of doing so is less than the carbon tax; in this aspect, a carbon tax is similar to the cap-and-trade system [16].

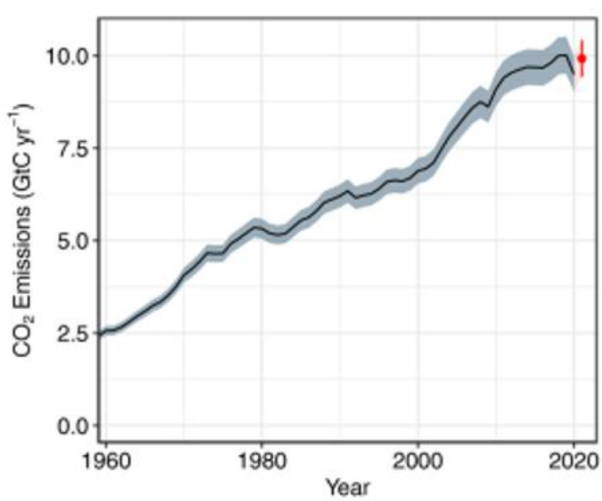

Fig. 1. Annual global fossil-fuel CO2 emissions through 2020 with an uncertainty of ±5 % and a projection for 2021 (Global Carbon Budget 2021).

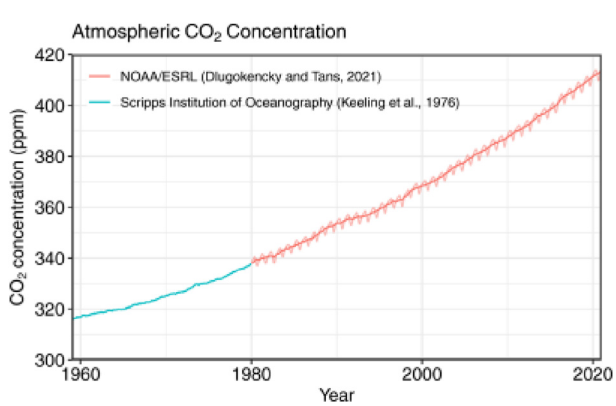

Fig. 2. Average sea-level atmospheric CO2 concentration (ppm; Global Carbon Budget 2021).

2.3. Progressive carbon tax

Scholars have proposed a novel carbon tax system, namely, a progressive carbon tax, to address the inequality associated with the conventional carbon tax system. In contrast to the conventional carbon tax system, the progressive carbon tax system entails an increase in the price of carbon if total carbon emissions exceed a threshold. This system could achieve more equitable and effective carbon pricing policies [17]. Specifically, a higher rate is imposed on products with higher carbon content levels, and all carbon content levels have corresponding progressive rates. According to Zhang, a high carbon tax and the gap value in the progressive carbon tax system can substantially affect manufacturer production and abatement decisions, lowering carbon emissions; a low carbon tax has smaller effects [18]. Although enforcing carbon emission regulations can dampen economic activity and result in lost profits in supply chains, it is effective in reducing carbon emissions. The imposition of a progressive carbon tax may prompt manufacturers to explore green technologies, such as sustainable design and manufacturing technologies, to reduce the carbon emissions attributable to their products. To investigate this tax, this study selected the progressive carbon tax system as the carbon regulation policy in the proposed model.

2.4. Green-tech innovation

Firms have mainly attempted to reduce emissions through technological innovation, such as by replacing energy-inefficient equipment and facilities, redesigning products and packaging, and deploying or using low-pollution energy sources. Promoting investments in energy-saving technologies (green technologies) is a key method for reducing carbon emissions. Li proposed an alternative pollution tax policy in which an instantaneous Pigouvian tax is imposed on total externalities, providing an incentive for manufacturing firms to invest in more environmentally friendly production technologies [19]. By using green technology, firms can reduce the amount of carbon tax paid while minimizing changes in product quality. Groot conducted a survey of Dutch companies and observed that the majority of companies were willing to comply with more stringent environmental regulations [20]. Furthermore, investing in green technologies to save energy has become a common practice in business operations. The main motivation for green investments is typically the economic potential for cost savings.

Industry is a major contributor to greenhouse gas emissions. Datta proposed that industry emissions could be reduced by efficiently using advanced technologies; green investments can offer dual benefits of both reducing emissions and partially offsetting carbon taxes, thus boosting profitability [21]. Yang also stated that if a government imposes a low carbon tax, manufacturers or retailers would prioritize the development of carbon reduction technologies; moreover, consumers prefer low-carbon products [22].

2.5. Model case

Van der Zwaan studied a macroeconomic model of climate change that includes the effects of endogenous technological innovation on optimal CO2 abatement strategies and carbon tax levels [23]. The study concluded that accelerating the development of carbon-free energy technologies is the most effective option for reducing emissions. Battini, Persona, and Sgarbossa proposed an EOQ model that describes the effects of transportation on the environment; the model incorporates factors such as internal and external transportation costs, supplier locations, and the characteristics of different freight vehicles [24]. Tao developed a mathematical model of carbon taxes and cap-and-trade policies that considers consumer desires for low-carbon products [25]. Furthermore, Tsao used fuzzy optimization to produce an EOQ model of the ecological benefits of carbon trading and credits; the model calculates carbon emissions from the quantity, location, and production capacity of production centers and distribution centers [26]. Chen and Elomri proposed that businesses could adjust their operations to effectively reduce carbon emissions without considerably increasing costs [27]. They used an EOQ model to identify methods of reducing emissions by modifying numbers of orders, and they discussed the factors that affect emission reductions and cost increases. El developed a method of measuring and evaluating environmental quality factors in terms of cost and presented a two-level supply chain model that incorporates green aspects to optimize profits while reducing environmental costs [28]. The study reported that investing in improving environmental performance can result in cost savings. Chelly et al. proposed a multicriteria analysis method for assessing the effectiveness of progressive carbon taxes in terms of reducing carbon emissions and maximizing supply chain profits [29]. Sepehri et al. proposed a sustainable production inventory model for optimizing carbon emissions given the high costs of production and item deterioration; they focused on poor-quality deteriorating items and examined how conservation methods and green technologies can affect total profits [30].

3. Model

The proposed model is based on the inventory management model developed by Huang and Lin; their model optimizes logistics and green investments for various carbon emission policies [31]. We modified their carbon tax formula by adopting a progressive carbon tax model, which is more equitable, flexible, and effective for reducing carbon emissions.

3.1. Variables notation

The notations used in this paper:

3.2. Assumptions

1. In this study only single product is considered, and the supply chain system consists of a single vender and a single buyer.
2. The demand rate (D) of the buyer and the production rate (P) of the vendor are known and constant, with $P > D$.
3. Shortage are not allowed.
4. The government adopts a progressive carbon tax mechanism for manufacturer. The emission tax function is now a piecewise-defined function of its total emission.
5. The stages and tax rates of the progressive mechanism have not been set, and can be changed with government policies.
6. The government subsidies are not considered.
7. Carbon emission comes from manufacturing products, transporting products, and holding inventory, and other processes are not considered.
8. The green technology investments cannot fully offset carbon emissions.

3.3. EOQ model

The inventory level of the vendor and buyer is showed as Fig. 3. The vendor manufactures the product in the quantity of mQ, and buyer would get the product in m lots with having a quantity of Q in each delivery. For each manufacturing cycle time as mQ/D, and the delivery cycle time is Q/D.

Based on the above notations and assumptions, the total expected costs for the vendor is given by

$$SC_v = \text{production setup cost} + \text{holding cost} + \text{transportation cost} = \frac{D}{mQ}S_v + \frac{Q}{2}\left(1 + m\left(1 - \frac{D}{P}\right)\right)h_v + \frac{D}{Q}Td \quad (1)$$

The buyer's costs is given by

$$SC_b = \text{ording cost} + \text{holding cost} = \frac{D}{Q}S_b + \frac{Q}{2}h_b \quad (2)$$

The supply chain costs with green technologies cost G, we combine (1), (2) as follows:

$$SC = \frac{D}{mQ}S_v + \frac{D}{Q}Td + \frac{Q}{2}\left(1 + m\left(1 - \frac{D}{P}\right)\right)h_v + \frac{D}{Q}S_b + \frac{Q}{2}h_b + G \quad (3)$$

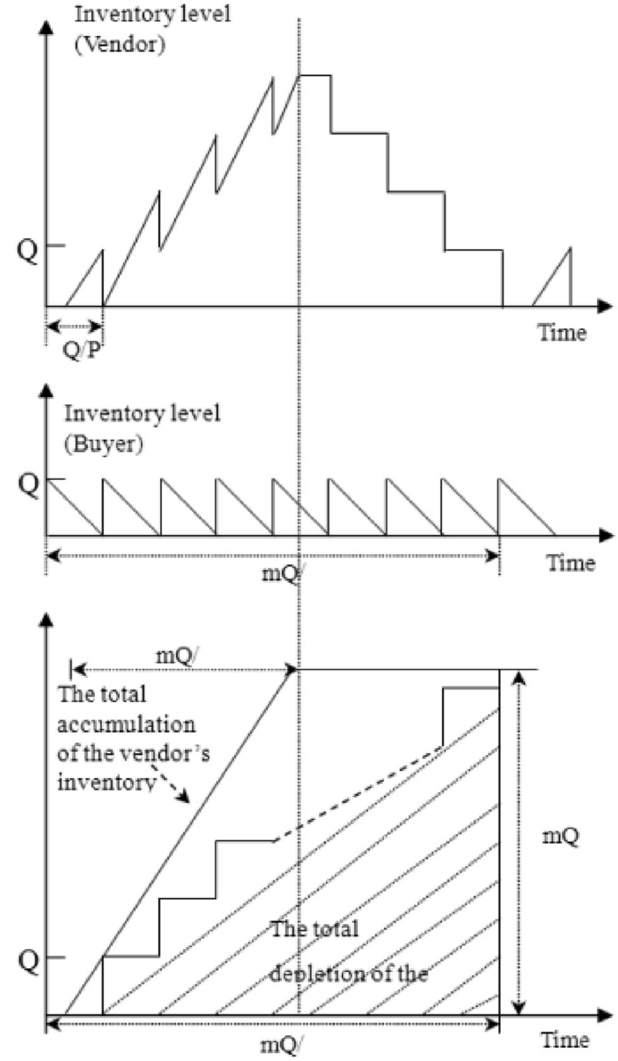

Fig. 3. Vendor and buyer inventory levels.

3.4. Carbon emissions in supply chain

Carbon emissions are generated by supply chain activities, such as vendors' production practices, transportation, and vendors and buyers' warehousing. The emissions generated by these activities can be calculated as follows:

The carbon emissions generated by production processes can be derived by summing emissions generated by vendors' production infrastructure Es and emissions per unit product Ep, and formula is given by

$$\frac{D}{mQ}\text{Es} + D\text{Ep} \quad (4)$$

The distance of transportation is an important factor. The carbon emissions from transporting products is Et per unit distance, and formula is given by

$$\frac{D}{Q}\text{Et}d \quad (5)$$

The carbon emissions from vendor and buyer's holding inventory are E_h, and formula is given by

$$\frac{Q}{2}\left(2+m\left(1-\frac{D}{P}\right)\right)E_h \quad (6)$$

We discuss the green technology investment G, results in an αG reduction of carbon emissions, and βG^2 as the offsetting carbon reduction factor [32,33]. The formula for green technology carbon reduction is given by

$$\alpha G-\beta G^2 \quad (7)$$

Finally, we combine formula (4), (5), (6), and (7). The Carbon emissions is formulated as follows:

$$E=\frac{D}{mQ}\mathrm{Es}+DE_P+\frac{D}{Q}\mathrm{Et}d+\frac{Q}{2}\left(2+m\left(1-\frac{D}{P}\right)\right)E_h-\alpha G+\beta G^2 \quad (8)$$

which is rewrote as

$$E=DE_P+\frac{D}{mQ}(E_s+mE_td)+\frac{Q}{2}\left(2+m\left(1-\frac{D}{P}\right)\right)E_h-\alpha G+\beta G^2 \quad (9)$$

3.5. Progressive carbon tax

In a progressive tax system, all taxable objects are divided into several brackets, with higher brackets having higher tax rates. A progressive tax may be a fully progressive tax or an excess progressive tax. For a fully progressive tax, the total value of each taxable object is taxed at the highest applicable rate; however, this method can result in substantial increases in taxation when the value of an object slightly exceeds the limit of a bracket. In an excess progressive tax, each taxable object is first taxed at the lowest rate until the amount exceeds the limit of the bracket; the remaining amount is taxed at the next higher rate. This process continues until the total amount has been taxed. In such a tax, an increase in the value of the taxed object is never larger than the increase in the tax. Excess progressive taxes are commonly used worldwide, and this method was also adopted in this study.

In our model, carbon emissions are divided into several brackets, and an upper limit (in tons) is set for each bracket $(E_1, E_2, E_3, \cdots E_i)$; each bracket has a corresponding tax rate (t_1, t_2, t_3, $\cdots t_n$; Fig. 4). Here, $f_n(E)$ is the relationship between the carbon emissions E and the total owed carbon tax $T_t(E)$ (Fig. 5) [34].

$$T_t(E)=\begin{cases} f_1(E)=t_1E, \\ (E_0\le E<E_1) \\ f_2(E)=t_1E_1+t_2(E-E_1), \\ (E_1\le E<E_2) \\ f_3(E)=t_1E_1+t_2(E_2-E_1)+t_3(E-E_2), \\ (E_1\le E<E_2) \\ \vdots \\ f_n(E)=t_1E_1+t_2(E_2-E_1)+\cdots t_n(E-E_{n-1}), \\ (E_{n-1}\le E<E_n) \end{cases} \quad (10)$$

The summation formula is as follows:

$$T_t(E)=\sum_{i=1}^{n-1}t_i(E_i-E_{i-1})+t_n(E-E_{n-1}) \quad (11)$$

The total cost is combined with (3) and (11) as follows:

$$Total\ cost\ (TC)=Supply\ chain\ cost(SC)+Total\ carbon\ tax(Tt)$$

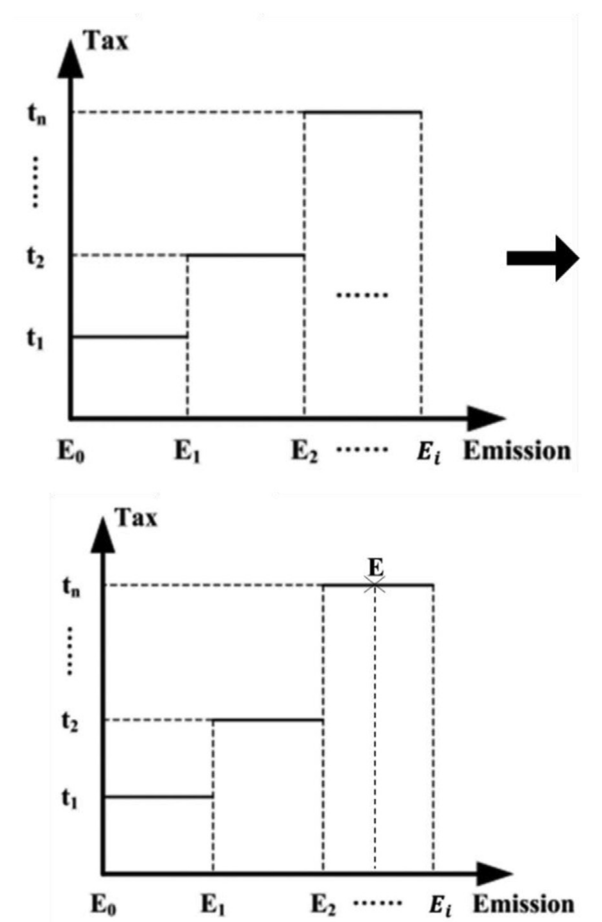

Fig. 4. Carbon emission brackets.

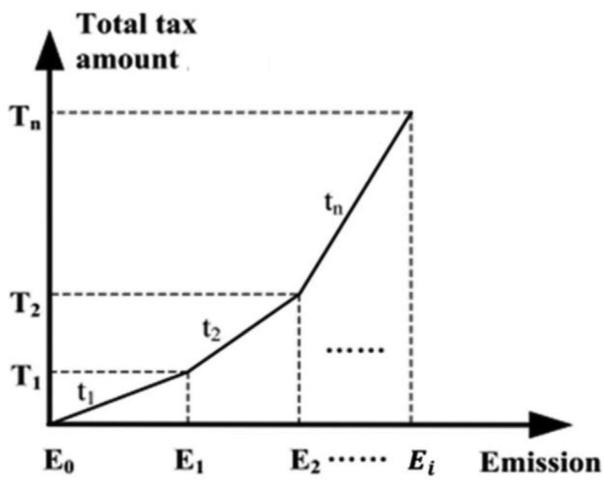

Fig. 5. Relationship between carbon emissions and the total carbon tax.

$$TC=\frac{D}{mQ}S_v+\frac{D}{Q}Td+\frac{Q}{2}\left(1+m\left(1-\frac{D}{P}\right)\right)h_v+\frac{D}{Q}S_b+\frac{Q}{2}h_b+G+\sum_{i=1}^{n-1}t_i(E_i-E_{i-1})+t_n(E-E_{n-1}) \tag{12}$$

To minimize TC (Q, G), set

$$\frac{\partial TC(Q,G)}{Q}=\frac{\partial TC(Q,G)}{G}=0$$

Set

$$\frac{\partial TC}{Q}=\frac{\partial SC}{Q}+\frac{\partial Tt}{Q}=0$$

as follows:

$$\frac{\partial TC}{Q}=-\frac{D}{Q^2}\left(\frac{1}{m}S_v+Td+S_b\right)+\frac{1}{2}\left(\left(1+m\left(1-\frac{D}{P}\right)\right)h_v+h_b\right)-\frac{D}{Q^2}\left(\frac{1}{m}E_s+E_td\right)t_n+\frac{1}{2}t_n\left(2+m\left(1-\frac{D}{P}\right)\right)E_h=0 \tag{13}$$

Set $\frac{\partial TC}{G}=\frac{\partial SC}{G}+\frac{\partial Tt}{G}=0$,
as follows:

$$\frac{\partial TC}{G}=1+t_n(-\alpha+2\beta G)=0 \tag{14}$$

Under the EOQ model with progressive carbon tax, the optimal TC (*Q*, *G*) is convex and has a minimum value. The optimal order quantity and green technology cost are:

$$Q^*=\sqrt{\frac{2D\left(\frac{1}{m}(S_v+E_st_n)+d(T+E_tt_n)+S_b\right)}{h_v\left(1+m\left(1-\frac{D}{P}\right)\right)+t_n\left(2+m\left(1-\frac{D}{P}\right)\right)E_h}} \tag{15}$$

and

$$G^*=\frac{-1+t_n\alpha}{2t_n\beta}\ \text{which is satisfied with}\ \ t_n\alpha>1 \tag{16}$$

4. Results

This section presents the implementation of the proposed model and provides numerical examples. The section also presents a sensitivity analysis conducted using parameters selected for subgroups. Finally, a concise explanation of the results is provided.

4.1. Numerical example

Tables 1 and 2 presents the model parameters. A numerical example involving a fixed data set is also

Table 1. The notations.

Notations	Interpretation
Basic model	
D	The buyer's demand rate
P	The vendor's production rate
Q	The order quantity
m	The transport lots
S_v	The vendor's production setup cost
S_b	The buyer's order cost
H_v	The vendor's storage cost
H_b	The buyer's storage cost
T	The unit transportation cost
d	The delivery distance
Carbon emissions	
E_h	The carbon emissions from storing
E_t	The carbon emissions from delivering
E_p	The carbon emissions from producing
E_s	The carbon emissions from production setup
α	The efficiency factor of carbon emissions reduction
β	The offset factor of carbon emissions reduction
G	The invest cost in green technology

Table 2. Numerical example.

Parameters	Value
Basic model	
D	4200
P	5200
m	2
S_v	1250
S_b	110
H_v	60
H_b	70
T	12
d	250
Carbon emissions	
E_h	8
E_t	10
E_p	4
E_s	20
α	12
β	0.01

Table 3. Types of progressive carbon tax.

Type	Tax rate		Upper limit	
2-level	t_1	0.08	E_1	5000
	t_2	0.1		
3-level	t_1	0.08	E_1	5000
	t_2	0.1	E_2	25000
	t_3	0.14		
4-level	t_1	0.06	E_1	5000
	t_2	0.1	E_2	25000
	t_3	0.14	E_3	40000
	t_4	0.2		

provided as follows to demonstrate the proposed model. The optimal results are derived for this data set.

According to assumption, the government will implement progressive carbon tax policy, but the stages and the tax rates is still unknown. Then in Table 3, we assume that the tax rates are 2-level, 3-level, and 4-level, 3 types of progressive tax, and calculate the total costs for each type with parameters in Table 2.

Our objective is to identify the optimal order quantity and green investment strategies for an integrated supply chain under various tax levels. Under the two-level progressive carbon tax, the optimal order quantity is 464.80 units, the green investment cost is $100, the minimum total cost is $73 606.5, and the total carbon emission is 42 814.29 tons. Under the three-level carbon progressive tax, the optimal order quantity is 469.46 units, the green investment cost is $242.86, the minimum total cost is $74 286.85, and the total carbon emission is 41 409 tons. Finally, under the four-level progressive carbon tax, the optimal order quantity is 476.29 units, the green investment cost is $350, the minimum total cost is $74 340.65, and the total carbon emission is 40 501.79 tons. These results are listed in Table 4.

Table 4. Optimal solutions for integrated supply chains with various carbon tax schemes.

Type	Q^*	G^*	SC^*	E^*	Tt^*	TC^*
2-level	464.80	100	69425.07	42814.29	4181.43	73606.5
3-level	469.46	242.86	69589.59	41409	4697.26	74286.85
4-level	476.29	350	69740.29	40501.79	4600.36	74340.65

4.2. Sensitivity analysis

We present a sensitivity analysis conducted to examine the effect of changing various parameters on the total costs and carbon emissions. We can assume that the baseline values of the parameters are the same as those listed in Table 3 and that the progressive carbon tax has four levels (Table 4). The effects of changing the parameters by −20 %, −10 %, +10 %, and +20 % on total costs, carbon emissions, and green investment costs are determined. Finally, we provide some managerial insights on the basis of the analysis results.

Figure 6 presents the results of the sensitivity analysis for carbon emissions at each stage of the supply chain. The results indicate that carbon emissions generated from transportation E_t have the most significant effect on total costs. Carbon emissions generated from production processes E_P have the second most significant effect on total costs. Carbon emissions generated from storage

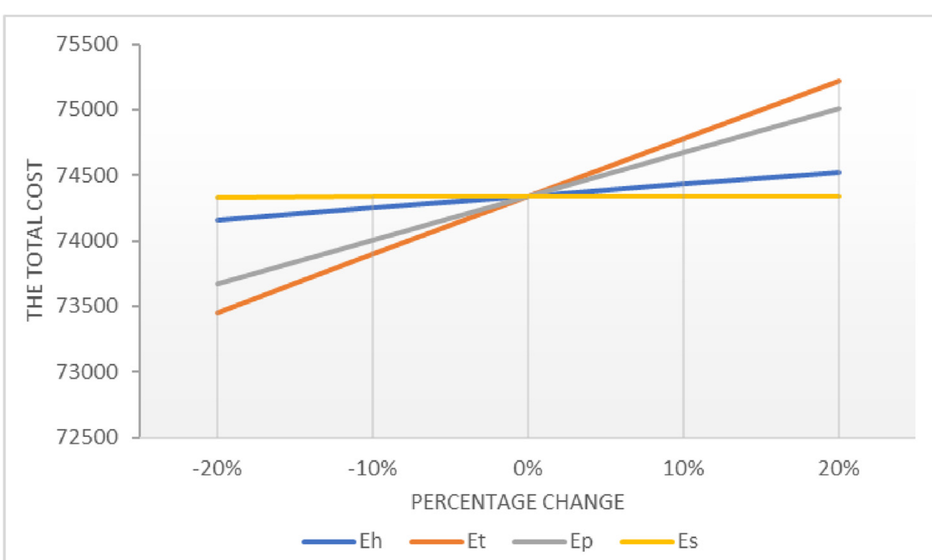

Fig. 6. Sensitivity analysis for E_h, E_t, E_P and E_s.

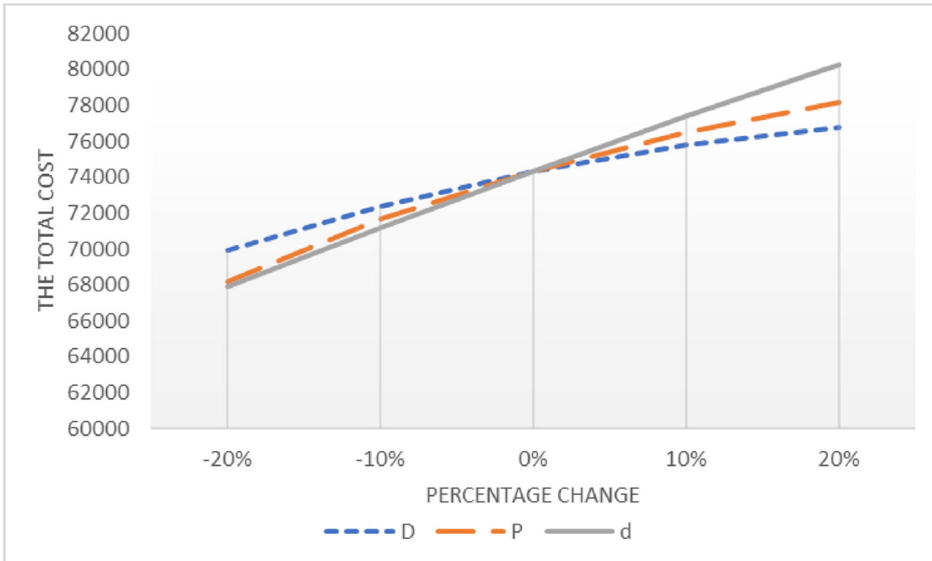

Fig. 7. Sensitivity analysis for D, P and d.

infrastructure E_s and production infrastructure E_h have smaller effects on total costs. These findings suggest that companies seeking to minimize the total cost of carbon emissions should focus on transportation and production processes. Figure 7 presents the results of the sensitivity analysis for the effects of a buyer's demand D, vendor's production P, and transportation distance d on the overall cost performance of the supply chain. The results indicate that changes in P and d have the largest effects on total costs.

Figures 8 and 9 present the effects of changing the values of α, β, and t_n (the highest progressive tax rate) on carbon emissions and green investment costs. Increasing either α or t_n substantially reduces carbon emissions. However, the effect of changing β is relatively small. Moreover, increasing α or t_n increases the cost of investment in green technologies, whereas increasing β reduces costs. These findings indicate that governments can promote companies' investment in green technologies to reduce carbon emissions by setting progressive tax rates and brackets.

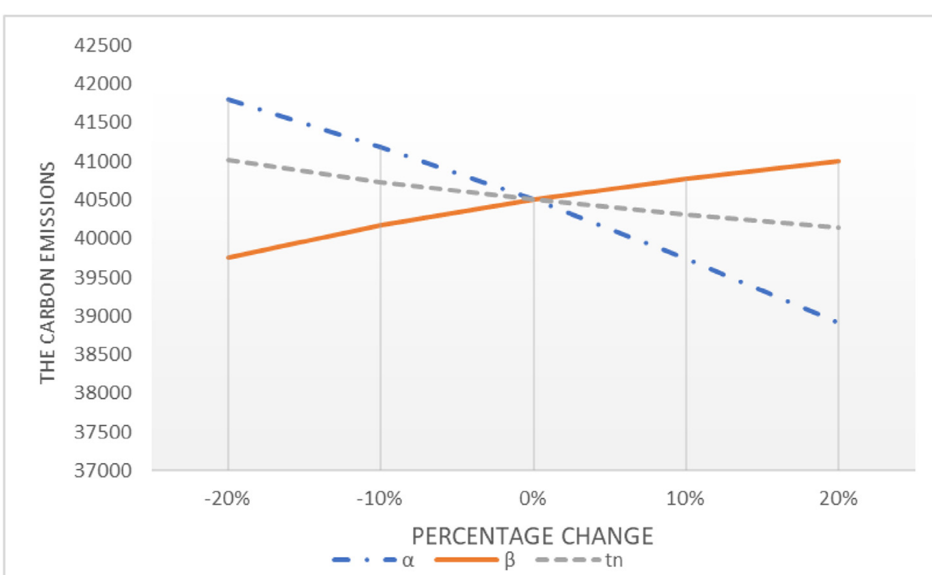

Fig. 8. Sensitivity analysis of α, β, t_n for carbon emissions.

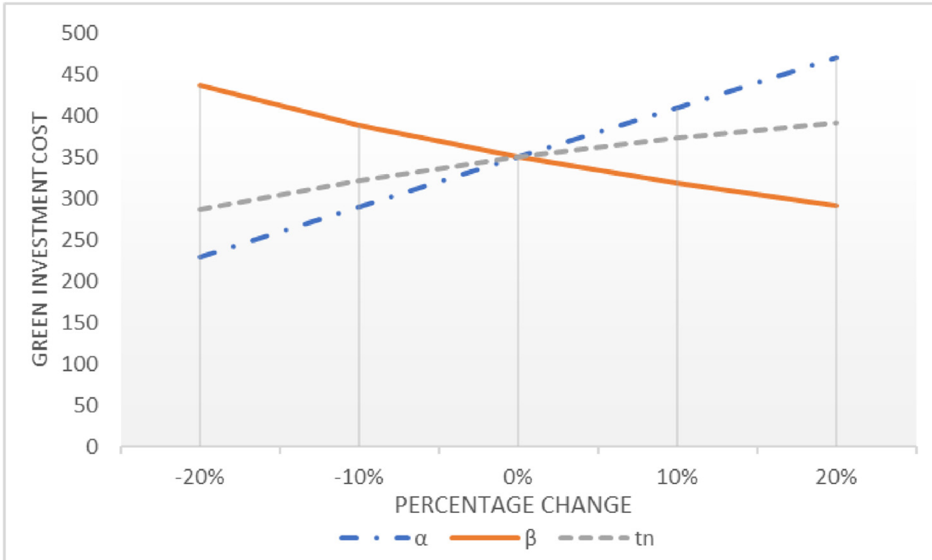

Fig. 9. Sensitivity analysis of α, β and t_n for the green-tech investment costs.

5. Conclusion

The increase in CO2 in the atmosphere due to fossil-fuel combustion, vehicle and factory emissions, coal-powered energy production, and animal farming has led to the greenhouse effect and a rise in global temperature. Therefore, reducing carbon emissions has become a crucial challenge for supply chain management. To address this challenge, companies must implement effective measures to improve their carbon footprints. In this paper, we present an integrated model, a modified version of a model in the literature, that considers the effects of transport costs and investments in green technologies on emissions. The model incorporates a progressive carbon tax system, a fair and flexible carbon policy.

The numerical results demonstrate that transport distance and carbon emissions at each stage of the supply chain considerably affect total costs. Moreover, the highest progressive tax rate affects company investment in green technologies. Companies could use the model to identify optimal order quantities to adjust carbon emissions at each supply chain process; moreover, they could invest in green technology to increase their carbon reduction factor, further reducing carbon emissions. The findings of this study can serve as a valuable reference for government policy planning. Governments should carefully plan the upper limit of carbon emissions and progressive tax rates for each stage by considering the responses of companies in terms of production and investment decisions, which are primarily influenced by marginal utility calculations.

The limitations of this study are that the full complexity of the market and implementation of carbon tax policies cannot be captured and that the numerical simulation may differ from real-world scenarios. Future research could be conducted in several directions. First, the inventory model could be extended to consider multiple buyers and vendors. Second, inflation could be included or the parameter values could be obtained from datasets. Such a model could better reflect real-world situations, especially in cases of war or port congestion. Finally, a model could consider a separate taxation scheme for each supply chain process instead of a consolidated taxation scheme for the entire supply chain. Such a scheme might be better aligned with real-world operations, and modeling findings could enable companies to more effectively plan production and investment strategies.

Conflict of interest

No conflict of interest to declare.

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