INVENTORY AND LOGISTIC MANAGEMENT IN SUPPLY CHAINS WITH CONSIDERATION OF CARBON EMISSIONS

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Abstract - This study investigates the effects that carbon policies and green technologiesmay have on the integrated inventory of a two-echelon supply chain with consideration of carbon emissions during the processes of product production, transportation, and storage. We consider the three carbon policies: limited total carbon emissions, carbon taxation, and cap and trade, and determine their corresponding optimal production quantity, delivery quantity, and green investment amount with an aim of minimizing the costs, and examine the feasibility of a green technology in reducing carbon emissions for different carbon taxes, trading prices, and cap limits. The results show that firms adopting the carbon tax policy would prefer to invest a relatively efficient green technology. With regard to the sources of carbon emissions, the effects of unit carbon emissions during production and unit distance of transportation are the most dramatic, and the cap limit has greater effects than the carbon emissions reduction factor of the green technology.

Keywords - Carbon Emissions, Carbon Taxation, Carbon Trading, Green Technology, Integrated Vendor-Buyer Inventory.

I. INTRODUCTION

Enhanced levels of environmental awareness mean that the public is now familiar with the ideas of saving energy and reducing carbon emissions(Grafton et al., 2014; Perera et al., 2013). Some countries have thus set regulations to limit carbon emissions and reduce greenhouse gases, which may indirectly impact the energy development and business operations of companies (Gharaie et al., 2013;Toptal et al., 2014). Firms thus have to pay more attention to the reduction of carbon emissions during all stages of product life cycles, from design to retirement(Agrawal &Ulku, 2011;Swami & Shah, 2013), and the effects of environmental issues on their cost structures thus has to be considered when making business decisions.

With supply chain coordination,businesses no longer consider their cost structures, such as inventory, sorely from their own perspectives (suppliers or retailers), but focus instead on the cost structure of the entire supply chain to form an integrated inventory model, which can be utilized to develop appropriate strategies to enhance competitiveadvantages (Chu & Leon, 2008; Ketzenberg& Ferguson, 2006).Environmental awareness enables supply chains to investigate the effects that carbon emissions policies and environmental taxation have on their integrated cost structures. If firms in a supply chain are socially responsible, they have to seek different ways of producing products to reduce the carbon emissions whichmay occur at any time along a supply chain(Benjaafar et al., 2013; Sugino&Arimura, 2011). However, previous research rarely focused on such an integrated inventory problem in which carbon emissions during the processes of production, delivery, and storage are simultaneously considered in a supply chain (Glock, 2012;Jha&Shanker, 2013). Moreover, instead of passively considering limited carbon emissions and penalty cost due to excessive carbon emissions, some firms may actively invest in green technology to reduce such emissions (Lukas & Welling, 2014; Wang et al., 2013). However, the use of green technology would incursubstantialcapital costs. This study considers the investment in green technologies to develop optimal strategies for integrated inventory management with consideration of reducing carbon emissions along supply chain in order to achieve a win-win situation between the economy and environment.

This workdeals with the integrated inventory problem for supply chains with a single supplier and retailer with consideration of carbon emissions during the processes of production, delivery, and storage for the three conditions, limited carbon emissions, carbon tax, and cap and trade, in which the investment in green technologies to reduce carbon emissions in compliance with government regulations is considered to obtain the optimal delivery quantity, number of deliveries, and amount of green investment with the aim of minimizing the total cost.

The remainder of this study is organized as follows: Section 2 describes the research problem and assumptions. Section 3 introduces the process of model construction and investigates the effects that carbon emissions have on the costs. Section 4 presents a comparative analysis. Section 5 then gives the concluding remarks and suggestions for future research.

II. GREEN INVESTMENT AND CARBON EMISSIONS REDUCTION

This study investigates the integrated inventory with consideration of carbon emissions, in which carbon emissions are assumed to be from the processes of production, transportation, and storage.

The assumptions of this study are as follows:

1. This study considers a centralized supply

chain, in which a single supplier offers a single product to a retailer, and the product demand is not affected by seasonal factors.

2. The production rate is constant and greater than the demand rate of the retailer. Product shortages are not considered.
3. The storage and transportation vehicles of both parties do not have capacity constraints, i.e., the storage space is sufficient for excessive production quantity or transportation lot size.
4. Carbon emissions occur in the processes of production, transportation, and storage, and carbon emissions from other processes are not considered.

The notation used in this study are as follows:

D	The demand rate for the retailer
P	The production rate for the supplier
Q	The transportation lot size
A_V	The production setup cost for the supplier
A_B	The order processing cost for the retailer
h_V	The storage cost for the supplier
h_B	The storage cost for the retailer
n	The number of shipments
F	The unit transportation cost
d	The delivery distance
E_h	The carbon emissions for storage
E_T	The carbon emissions for transportation
E_P	The carbon emissions for production
E_S	The carbon emissions for production setup
G	The green investment amount
α	The carbon emissions reduction factor
β	The offsettingreduction factor
U	The upper limit of carbon emissions
C_1	The carbon tax of unit carbon emission
C_2	The carbon trading price
X	The carbon emissions allowance

III. THE INTEGRATED INVENTORY MODEL WITH CARBON EMISSIONS

Fig. 1shows the inventory levels of the supplier and retailer, respectively. The supplier continuously produces products after delivering products to the retailer until the predetermined production quantity has been reached.

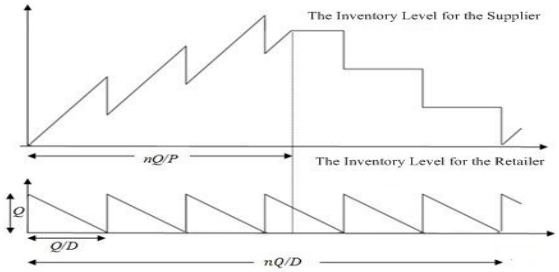


Fig.1. The inventory levels for the supplier and retailer

3.1. The Basic Model without Carbon Emissions

The supplier's costs consist of the costs of production setup, transportation, and inventory holding.Fig. 2shows the accumulated inventory of the supplier.

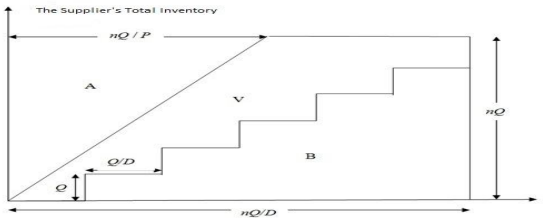


Fig.2. The supplier's accumulated inventory

Therefore, the sum of the total costs for the supplier and retailer, i.e., the supply chain, is given by

$$TC_0(n,Q) = \frac{D(A_V + nA_B)}{nQ} + \frac{D}{Q}Fd + \frac{Q}{2}\left(\left(1+n\left(1-\frac{D}{P}\right)\right)h_V + h_B\right). \quad (1)$$

Lemma 1: The total cost of the basic integrated inventory model, $TC_0(n,Q)$, is convex with a minimum value, and the optimal transportation lot size is given by

$$Q_0^*(n) = \sqrt{\frac{2D\left(n(Fd+A_B)+A_V\right)}{n\left(h_B + h_V\left(1+n\left(1-\frac{D}{P}\right)\right)\right)}}, \quad (2)$$

and the optimal number of shipments is a positive integer, which satisfies the following inequality

$$n_0^*(n_0^*-1) \le \frac{A_V(h_B+h_V)}{\left(1-\frac{D}{P}\right)(A_B+Fd)h_V} \le n_0^*(n_0^*+1). \quad (3)$$

3.2. Carbon Emissions Policies and Investments in Green Technology

Delivery distance and transportation lot size would have significant impacts on carbon emissions during the transportation process. Carbon emissions may also occur from storing undelivered or unsold products due to product characteristics or other factors. When the amount of carbon emissions in the supply chain exceeds the limited amount of the regulations, instead of incurring the penalty cost, we consider that a green technology can be invested in to reduce the emissions, and the carbon reduction function for the green technology is given by $R(G) = \alpha G - \beta G^2$,where α denotes the carbon reduction efficiency factor and β denotes the offsetting carbon reduction factor (Toptal et al., 2014). This indicates that as the supply chain invests the green cost, G, in the green technology, αG of carbon emissions reduction can be obtained. However, since the use of the green technology may also cause energy consumption, βG^2 denotes such additional carbon emissions. Note that α and β can be obtained by fitting the historical data of carbon emissions reduction and the amount of green investment.

In considering the carbon emissions from the processes of production, transportation, and storage

as well as the investment in the green technology, the total inventory cost and amount of carbon emissions are given by

$$TC(n,Q,G) = \frac{D(A_V + nA_B)}{nQ} + \frac{D}{Q}Fd + \frac{Q}{2}\left(\left(1 + n\left(1 - \frac{D}{P}\right)\right)h_V + h_B\right) + G \quad (4)$$

and

$$E(n,Q,G) = DE_P + \frac{D}{nQ}(E_S + nE_T d) + \frac{Q}{2}\left(2 + n\left(1 - \frac{D}{P}\right)\right)E_h - \alpha G + \beta G^2 \quad (5)$$

respectively.

3.2.1. Carbon Taxation

In the scenario of carbon taxation, the carbon tax is C_1 for unit carbon emissions, which would increase linearly along with the amount of carbon emissions. Both the supplier and retailer can invest in green technologies to reduce carbon emissions, and thus reduce the cost of paying the carbon tax. The costs of the integrated inventory model consist of the supplier's production setup cost, the retailer's order processing cost, product transportation cost, the supplier's and retailer's inventory holding costs, the total cost of paying the carbon tax, and the expenditure of the green investment. Therefore, total cost for carbon taxation is given by

$$TC_1(n,Q,G) = \frac{D(A_V + nA_B + C_1E_s)}{nQ} + \frac{D}{Q}d\left(C_1E_T + F\right) + \frac{Q}{2}\left(\left(1 + n\left(1 - \frac{D}{P}\right)\right)h_V + h_B + \left(2 + n\left(1 - \frac{D}{P}\right)\right)C_1E_h\right) + C_1DE_P - C_1(\alpha G - \beta G^2) + G \quad (6)$$

Lemma 2: The total cost of the integrated inventory model, $TC_1(n,Q,G)$, for the scenario of carbon taxation is convex with a minimum value, and the optimal transportation lot size is given by

$$Q_1^*(n) = \sqrt{\frac{2D\left(n\left(d(F + C_1E_T) + A_B\right) + A_V + C_1E_S\right)}{n\left(C_1\left(2 + n\left(1 - \frac{D}{P}\right)\right)E_h + h_B + h_V\left(1 + n\left(1 - \frac{D}{P}\right)\right)\right)}}, \quad (7)$$

the optimal number of shipments is a positiveinteger, which satisfies the following inequality

$$n_1^*(n_1^* - 1) \le \frac{(A_V + C_1E_S)(2C_1E_h + h_B + h_V)}{\left(1 - \frac{D}{P}\right)\left(A_B + d\left(F + C_1E_T\right)\right)(C_1E_h + h_V)} \le n_1^*(n_1^* + 1), \quad (8)$$

and the optimal green investment is given by

$$G_1^* = \frac{\alpha C_1 - 1}{2\beta C_1}. \quad (9)$$

We further investigate the effects that the carbon emissions reduction effectiveness and carbon tax price have on the total inventory cost and amount of carbon emissions, and compare the differences before and after the green investment. The effectiveness of the investment in the carbon emissions reduction in the supply chain is discussed in Proposition 1.

Proposition 1:For the scenario of carbon taxation,the investment in the green technologycan cut down the total cost by $\frac{(\alpha C_1 - 1)^2}{4C_1\beta}$, and reduce the amount of carbon emissions by $\frac{\alpha^2 C_1^2 - 1}{4C_1^2\beta}$.

From Proposition 1, for a fixed carbon emissions reduction factor, α , and offsetting carbon reduction factor, β , i.e., green technologies with the same effectiveness, when the carbon tax price, C_1 , increases, whether to invest in green technologies or not would have a significant effect on carbon emissions reduction, which indicates that investing in carbon emissions reduction would be more beneficial than paying the carbon tax. As a result, the investment in the green technology to reduce carbon emissions is feasible for the scenario of carbon taxation.

3.2.2. Cap and Trade

The cap and trade policy regulates the total amount of carbon emissions from the supplier and retailer. If carbon emissions do not exceed the upper limit, U, the surplus X can be sold at C_2 per unit to offset the expected costs. In contrast, if carbon emissions exceed U, the firm has to purchase allowances from others or invest in green cost to comply with the regulations of limited carbon emissions. Suppose that the surplus is valid only at the current period regardless of selling or purchasing, and the carbon trading price, C_2 , is the average price in the market. We also assume that the carbon emissions allowances are sufficient in the market for purchasing. In considering the scenario of the cap and trade,the total cost consists of the supplier's production cost, retailer's order processing cost, product transportation cost, both parties' inventory holding cost, carbon trading cost, and the amount of investment in green technologies. The total integrated cost under the scenario of cap and trade is given by

$$TC_2(n,Q,G) = \frac{D(A_V + nA_B + C_2E_s)}{nQ} + \frac{D}{Q}d\left(F + C_2E_T\right) + \frac{Q}{2}\left(\left(1 + n\left(1 - \frac{D}{P}\right)\right)h_V + h_B + \left(2 + n\left(1 - \frac{D}{P}\right)\right)C_2E_h\right) - C_2U + C_2DE_P - C_2(\alpha G - \beta G^2) + G \quad (10)$$

Lemma 3: The total cost of the integrated inventory model, $TC_2(n,Q,G)$, for the scenario of cap and trade is convex with a minimum value, and the optimal transportation lot size is given by

$$Q_2^*(n) = \sqrt{\frac{2D\left(n\left(d(F + C_2E_T) + A_B\right) + A_V + C_2E_S\right)}{n\left(C_2\left(2 + n(1 - \frac{D}{P})\right)E_h + h_B + h_V\left(1 + n(1 - \frac{D}{P})\right)\right)}}, \quad (11)$$

the optimal number of shipments is a positiveinteger that satisfies the following inequality

$$n_2^*(n_2^* - 1) \le \frac{(A_V + C_2E_S)(2C_2E_h + h_B + h_V)}{\left(1 - \frac{D}{P}\right)\left(A_B + d\left(F + C_2E_T\right)\right)(C_2E_h + h_V)} \le n_2^*(n_2^* + 1), \quad (12)$$

and the optimal green investment is given by

$$G_2^* = \frac{\alpha C_2 - 1}{2\beta C_2}. \quad (13)$$

We further investigate the effects of that the carbon emissions reduction effectiveness and average trading price have on the total inventory cost and amount of carbon emissions, and compare the differences before and after the green investment in carbon emissions reduction. The effects of the investment in the carbon emissions reduction in the supply chain arediscussed in Proposition 2.

Proposition2: For the scenario of cap and trade, the investment in the green technology can cut down the total cost by $\frac{(\alpha C_2 - 1)^2}{4C_2\beta}$, and reduce the amount of carbon emissions by $\frac{\alpha^2 C_2^2 - 1}{4C_2^2\beta}$.

From Proposition 2, for a fixed carbon reduction factor of green technologies, α, and the offsetting carbon emissions reduction factor, β, when the carbon market trading price, C_2, increases, the total cost and carbon emissions would be more significantly affected. For a greater U, the investment in carbon emissions reduction could result in more trading subsidies. From the firm's perspective, the investment in carbon emissions reduction can not only comply with the government regulations but also gain trading subsidies. Moreover, the subsidy offset increases as the trading price increases. Even for a smaller U, the investment in carbon emissions reduction can decrease the purchasing allowances. As a result, the investment in carbon emissions reduction is a beneficial strategy for the scenario of the cap and trade policy.

Moreover, the upper limit of carbon emissions, U, would have significant impacts on the carbon emissions amount and cost. When the firm invests in green technologies to reduce carbon emissions, if its amount of carbon emissions exceeds the upper limit, the firm does not have any allowance to sell and gain carbon trading offset, and $X \le 0$. The firm thus has to purchase allowances from the carbon trading market. When the trading price of allowances is relatively high, selling unused allowances may offset more cost. The maximum carbon emissions reduction effectiveness is $\alpha^2/4\beta$. Firms with high productivity and carbon emissions, which invest a large amount in reducing such emissions, may sometimes not be able to have sufficient allowances to offset the carbon cost, and thus see negative effects from investing in green technology.

Proposition 3: For the scenario of cap and trade, there should be an upper bound U* for the limit of carbon emissions.

From Proposition 3, if the government sets a higher limit of carbon emissions, the firm may gain more carbon subsidies from trading with other firms, and thus the total cost may be less than zero, i.e., $TC_2(n,Q,G) < 0$. However, in practice, selling carbon emission surplus to completely offset the cost or even earn profit should not be possible. Therefore, the government has to determine the limit of carbon emissions within a reasonable range.

3.2.3. Limited Carbon Emissions

In considering the scenario of limited carbon emissions, the supplier and retailer have to adjust their business operations to comply with the limited carbon emissions U. In case of excessive carbon emissions, both parties can invest in green technologies to reduce these. The total cost consists of the supplier's production cost, retailer's order processing cost, product transportation cost, both parties' inventory holding cost, and amount of investment in green technologies. The programming model for the scenario of limited carbon emissions is given by

Minimize

$$TC_3(n,Q,G) = \frac{D(A_V + nA_B)}{nQ} + \frac{D}{Q}Fd + \frac{Q}{2}\left(\left(1 + n\left(1 - \frac{D}{P}\right)\right)h_V + h_B\right) + G \quad (14)$$

Subject to

$$DE_P + \frac{D}{nQ}(E_S + nE_S d) + \frac{Q}{2}\left(2 + n\left(1 - \frac{D}{P}\right)\right)E_h - \alpha G + \beta G^2 = U. \quad (15)$$

We use the Lagrange multiplier method to derive the minimum value of the total cost and the corresponding optimal transportation lot size, number of shipments, and investment amount as the decision variables.

Lemma 4: In considering the scenario of the limited carbon emissions,the total cost of the integrated inventory model, $TC_3(n,Q,G,\lambda)$,has a minimum, and the optimal transportation lot size is given by

$$Q_3^*(n,\lambda) = \sqrt{\frac{2D\left(n(A_B + Fd) + A_V + \lambda(dnE_T + E_S)\right)}{n\left(h_V\left(1 + n\left(1 - \frac{D}{P}\right)\right) + h_B + \lambda\left(2 + n\left(1 - \frac{D}{P}\right)\right)E_h\right)}}, \quad (16)$$

the optimal number of shipments is a positiveinteger that satisfies following inequality

$$n_3^*(n_3^* - 1) \le \frac{(A_V + \lambda E_S)(h_B + 2e_h\lambda + h_V)}{(1 - \frac{D}{P})(\lambda E_h + h_V)(A_B + d(F + \lambda E_T))} \le n_3^*(n_3^* + 1), \quad (17)$$

and the optimal green investment is given by

$$G(\lambda) = \frac{\alpha\lambda - 1}{2\beta\lambda}. \quad (18)$$

IV. COMPARATIVE ANALYSIS

This study presents a numerical example to investigate the effects that the different carbon emissions policies have on the total inventory cost in the supply chain and the feasibility of investing in green technologies.The parameter settings aresummarized in Table 1.

Table 1: Parameter Settings

Parameter	Value	Parameter	Value
D	500	E_T	5
P	1,000	E_P	2
A_V	\$1,200	E_S	10
A_B	\$300	α	4
h_V	\$300	β	0.01
h_B	\$350	C_1	\$0.6
F	\$10	C_2	\$0.9
d	10	U_2	617.289
E_h	4	U_3	1200

Firms confront different carbon emissions regulations in different areas, and the effects that different regulations have on the cost structures thus need to be considered. In particular, investment in green technology to reduce carbon emissions may reduce the total cost. This study compares the feasibility of investing in green technology to reduce carbon emissions for the three scenarios of the carbon taxation, cap and trade, and limited carbon emissions in terms of different α and β .Fig. 3 shows the iso-curves for separating different decision zones in terms of carbon emissions reduction factor, α , and the offsetting carbon emissions factor, β .

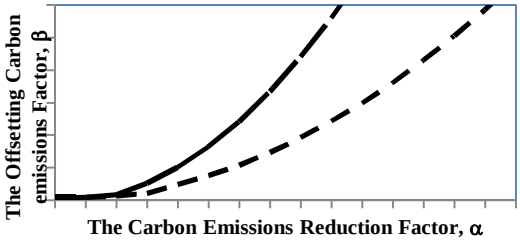


Fig.3. Zones for different carbon emissions policies

Ascan be seen in Fig. 3, managers can choose an appropriate carbon emissions policy based on the realization of the two carbon emissions reduction factors of the green technology.

Proposition4: (1) For a larger carbon emissions reduction factor,operating under the limited carbon emissions policy would be more profitable. (2) For a larger offsetting carbon emissions reduction factor, operating under the carbon tax policy would be more profitable. (3) For moderate α and β , operating under the cap and trade policy would be more profitable.

The aforementioned analysis indicates thatfor a high carbon emissions reduction factor, the inventory cost under the limited carbon emissions policy would be less than that under either the carbon tax policy or the cap and trade policy. However, for a highoffsetting carbon emissions reduction factor, the inventory costs under the limited carbon emissions and cap and trade policies would graduallyconverge, and operating under the cap and trade policy would be beneficial. In considering the low carbon emissions reduction effectiveness, for a relatively highoffsetting carbon emissions factor, operating under the carbon tax policy would be beneficial. However, as the carbon emissions reduction effectiveness increases, the inventory costs under the carbon tax and cap and trade policies would gradually converge and, as a result, operating under the carbon tax policy would be beneficial. In summary, when a green technology is effective, the firm should choose to operate under the limited carbon emissions policy; when a green technology is ineffective, the firm should choose to operate under the carbon tax policy; when a green technology is moderately effective, the firm should choose to operate under the cap and trade policy.

Moreover, comparative analyses among the three policies in terms of their corresponding important parameters are performed. A comparison between the carbon tax and cap and trade policies is made first.

Proposition 5: There exist a threshold U_2^*, if$U_2<U_2$*, operating under the cap and trade policy would be more profitable than under the carbon tax policy.

Proposition 6: When the carbon tax, C_1, is equal to the carbon trading price, C_2, for the same effective green technology, operating under the cap and trade policy would be more profitable than under the carbon tax policy. The difference in the total inventory costs is C_2U_2, butthere is no difference in the total amount of carbon emissions.

Proposition 5 indicates that managers can choose to operate under certaina carbon emissions policy based on the government determined U_2 for the cap and trade policy. It is obvious that operating under the cap and trade policy is not always better than under the carbon tax policy for a small U_2 . Proposition 6 indicates that if the carbon taxis equal to the carbon trading price, the firm would choose to operate under the cap and trade policy involving incentives rather than under the carbon tax policy involving penalties. Moreover, for a greater limit of carbon emissions for the cap and trade policy, firms would be more willing to operate under the cap and trade policy. However, their willingness to reduce carbon emissions would decrease. As a result, the regulation of carbon taxation involving a penalty would be more feasible to achieve the predetermined government goal of lower carbon emissions. The determination of regulations for an appropriate carbon emissions policy balances economic growth and environmental preservation, which is a government important issue.

A comparison between the carbon tax and limited carbon emissions policies is also made, and the important key for these are the carbon tax, C_1, and the limit of carbon emissions, U_3, respectively. Fig. 4 shows the zones for operating under the two policies.

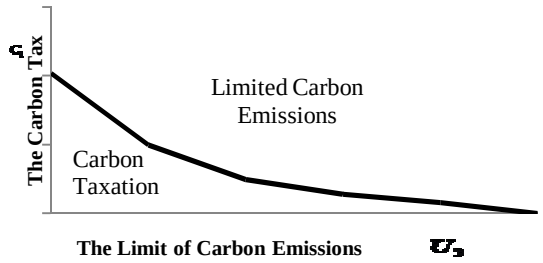


Fig.4. Cost advantage zones in terms of C_1 and U_3

Finally,suppose that the carbon trading price, C_2, remains unchanged, we compare the advantages and disadvantages with consideration of the variations in the limit of carbon emissions for the scenarios of cap and trade and limited carbon emissions.Fig. 5 shows the zones for operating under the two policies.

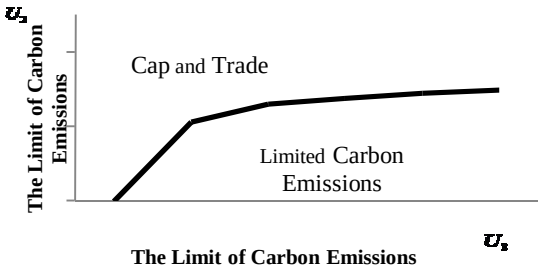


Fig.5. cost advantage zones in terms of U_2 and U_3

CONCLUSION

This study proposes an integrated inventory model for a supply chain, in which carbon emissions from the processes of production, transportation, and storage are considered to investigate the effects that carbon emissions have on the cost structure, and then determines the optimal number of shipments, transportation lot size, and amount of investment in green technologies for the three scenarios of the carbon taxation, limited carbon emissions, and cap and trade. In summary, this study investigates the feasibility of investing in green technologies to obtain an integrated strategy with consideration of environmental and economic benefits, and thus offers insights for managers to benefit both supply chains and the environment under different carbon emissions policies. Moreover, the results from discussing the three scenarios also have practical implications for governmentsworking to determine appropriate regulations in this context.

Future research may be extended to an integrated inventory model with multiple retailers, since suppliers may offer products to many retailers.Firms often consider their own benefits first, and remain passive with regard to complying with environmental regulations. Future research could thus consider subsidies to encourage firms to reduce their carbon emissions.

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