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Research Article

Optimal Decisions in the Closed-Loop Supply Chain considering Capacity Constraints and Stochastic Demand under the Cap-and-Trade Regulation

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In the current context of resource scarcity and increased pollution, enterprises need to better allocate capacity and achieve carbon emission reduction. We examine the optimal decision problem for a closed-loop supply chain (CLSC) considering capacity constraints and stochastic demand under a cap-and-trade system. A two-level CLSC comprising a supplier and a manufacturer is established. To make the model more realistic, we treat demand as a random variable, consider the manufacturer's production capacity within a certain upper limit, and allow the manufacturer to make investments to expand capacity to complete production demand. Based on this CLSC, the collection activities of the supplier and manufacturer are considered. Meanwhile, government carbon limits and carbon trading controls on the manufacturer are considered based on carbon reduction by enterprises. Through modeling and analysis, optimal decisions are derived for the amount of capacity investment, level of carbon emission reduction, and collection price variables. The results indicate that supplier collection has a positive effect on the sustainability of the CLSC. Moreover, the government's carbon quota and carbon trading control of manufacturers can effectively reduce the carbon emissions of the CLSC, encourage enterprises to reduce carbon emissions, and improve the sustainability of the CLSC.

1. Introduction

With gradual technological development in recent years, mankind's consumption of nature and resources has intensified, leading to increasingly serious problems of environmental pollution and resource shortages. A primary cause of this chronic natural disaster is the "carbon" element produced during the manufacturing process. As the quality of human beings increases, conscious environmental behavior begins to emerge. A German survey revealed that people are more likely to buy cars with lower carbon emission (CE), even if they are more expensive than conventional cars [1]. Furthermore, many manufacturing companies have begun incorporating collecting and remanufacturing activities, such as Kodak's collection and remanufacturing of disposable camera lenses and Michelin's collection and reuse of the tires it sells to achieve complete resource efficiency. Many countries and companies have also made CE reduction a key strategic decision for development, with the expectation that CE will be as minimal as possible. In some European countries, CE from production processes is controlled by adding carbon footprint labels to the product packaging [2]. As the world's largest developing country, China has made energy conservation, CE reduction, and low-carbon development a long-term development strategy while setting targets for reducing domestic carbon dioxide emissions. Reducing CE has become vital for the future development of various countries and enterprises. A closed-loop supply chain (CLSC) that considers reverse logistics is conducive to achieving low-carbon development for enterprises. By considering CE reduction decisions based on a CLSC, the CE generated in the manufacturing process may be reduced, and the development of remanufacturing activities may be promoted to realize the effective use of resources. This study examines the impact of each decision on CE and CLSC sustainability from the perspective of a CLSC that considers CE reduction.

A CLSC game problem that considers carbon reduction considers the CE of suppliers, manufacturers, retailers, and other CLSC members based on a CLSC. Then, it induces the carbon reduction behavior of the members, adds a carbon reduction cost, and solves and analyzes the optimal decision. We divide this problem into two categories. The first category only considers CE reduction behavior. It sets the level of CE reduction per unit as a constant value, which is only reflected in the demand and cost functions. The second category considers the level of CE reduction as one of the decision variables of CLSC members, and the level of emission reduction affects the costs, benefits, and optimal decisions. In this study, to better promote the CE reduction behavior of the CLSC and thus achieve low-carbon production, the second category of "CLSC game problem considering CE reduction" is used as the benchmark problem, with the CE reduction level as a decision variable and with the corresponding CE reduction cost.

In existing studies of CLSC games that consider carbon reduction, manufacturers' production capacity is often seen as infinite, which is not in line with reality. In practice, there must be a limit to a company's production capacity, for example, the car engine remanufacturer Cummins produces only 3,000 units per year, and the engine plant in China produces only 5,000 modified cars per year. Moreover, carbon is mainly generated during the product manufacturing process [3]. For CLSCs, a product's manufacturing and remanufacturing processes are the main sources of CE; in fact, carbon is often seen as a byproduct of these processes. If capacity is considered infinite, manufacturers will be unable to make reasonable capacity allocations, and the CE from the production process will become difficult to quantify. Consequently, the carbon reduction behavior of the product manufacturing and remanufacturing processes cannot be comprehensively studied. Therefore, it is essential to consider a decision-making environment for capacity constraints.

In recent years, in addition to a large amount of CE that threatens the environment, resource wastage has exerted a negative environmental effect [4]. In current CLSC problems that consider carbon reduction decisions, demand is often considered a linear function of price. In practice, however, demand is often unpredictable, leading to a failure to achieve a perfect equilibrium between supply and demand and, consequently, resource wastage. Uncertainty, a specific and unavoidable feature of CLSCs, increases the complexity of managing CLSCs. Therefore, by considering the capacity constraints, we also consider the stochastic nature of demand in this study. We examine the CLSC game problem based on this innovation by considering carbon reduction decisions.

In the CLSC game problem of carbon reduction decisions under capacity constraints and stochastic demand, the relationship between production and demand becomes complex. In a situation where demand exceeds supply or supply exceeds demand, manufacturers need to determine their optimal output in the face of uncertainty in demand and capacity constraints. When considering manufacturing and remanufacturing activities, decision-makers need to rationalize the capacity of production activities. Capacity investment is an appropriate solution when manufacturers cannot achieve an optimal output under capacity constraints. In 2007, the three largest US automakers responded to demand and competitive pressures by using capacity investments to increase production capabilities, and the right investment decisions earned them higher returns [5].

In addition, sound capacity investment in remanufacturing activities can further reduce CE. For example, in the United States, investment in remanufacturing activities increased by 15%, and the CE decreased by 50% annually from 2009 to 2011 [6]. The appropriate investment in capacity for the manufacturer has a significant impact on the profitability of companies and their competitiveness in the marketplace. Capacity investment affects manufacturers' production and directly impacts the extent to which demand is met, thereby affecting the image and competitiveness of the company. At the same time, capacity investment determines the value of CE from manufacturing activities, which in turn determines the sustainability and environmental benefits of the chain. Therefore, considering the above-mentioned capacity constraints and stochastic demand, this study investigates the impact of capacity investment on the CLSC game problem, considering CE reduction decisions.

Most studies on CLSC games that consider carbon reduction decisions discuss manufacturers, retailers, and third-party collectors, thereby leaving a gap in research on supplier collection. However, companies are becoming more connected to their suppliers. Caterpillars have handed over their collection processes and remanufacturing activities to their key component suppliers [7]. We consider a scenario in which suppliers provide raw materials and components for manufacturers and are more familiar with components than other members of the CLSC. Thus, they can have better quality control over recycled components and a greater capability to ensure the quality of remanufactured products. The quality of recycled parts is one of the most important factors affecting the operation of a CLSC, and low-quality secondary parts can have a negative impact on the remanufactured products produced [8]. In addition, collaboration with suppliers plays a role in reducing CE; for example, Walmart mandates that its suppliers coparticipate in production projects to reduce production emissions. Dell collaborates with its suppliers to reduce CE [9]. Therefore, we add a new supplier collecting approach to the CLSC game problem that considers carbon reduction decisions under the above innovation, and conduct a comparative analysis of different collecting approaches.

A chief concern in the CLSC game problem of CE reduction decisions under the above innovation is how to achieve better CE reduction. Cap-and-trade is a widely applied policy for CE control. For example, in China, Beijing, Shanghai, Hubei, and Shenzhen were permitted to carry out carbon trading pilots as early as 2012 [10]. At the Global Climate Conference, the Chinese government pledged to reduce CE per unit of gross domestic product by more than 40% in 2020 relative to the rate in 2005; such a target has been incorporated into China's Plan [11]. An increasing number of countries are collaborating toward environmental protection to promote global sustainable development and carbon reduction, and they have great flexibility in meeting reduction targets [10]. Upon integrating the cap-and-trade approach and based on a CLSC game problem that considers carbon reduction decisions, countries could control CE more effectively, resulting in greater benefits to environmental protection.

In this study, we examine the optimal decision problem for a CLSC considering capacity constraints and stochastic demand under a cap-and-trade system. A two-level CLSC comprising a supplier and a manufacturer is established. To make the model more realistic, we treat demand as a random variable, consider the manufacturer's capacity to have a certain upper limit, and allow the manufacturer to invest in and expand capacity to meet production demand. In such a CLSC, maximizing sustainability while ensuring that the CLSC is profitable is considered. Therefore, based on this CLSC, we view the supplier and manufacturer as initiators of collecting activities to recycle and use products with a residual value in the CLSC, ultimately reducing resource waste and environmental pollution. Owing to the worldwide control of CE and increasing consumers' environmental awareness, there is an urgent need to reduce the carbon footprint of products. Therefore, CLSC should be considered in the context of the current low-carbon environment. Under a cap-and-trade system, we consider a government-imposed cap on the CE generated by manufacturers during the production process. There is a shortage of carbon allowances, and manufacturers can purchase carbon allowances in the carbon trading market to complete their production. To reduce the cost of this transaction, manufacturers would seek to reduce their CE by making corresponding investments in carbon reduction.

The main contributions of this study are summarized as follows: First, this study adds decision environment constraints to the CLSC game problem, which considers CE reduction decisions by setting an upper limit on manufacturers' production capacity and considering demand as a more realistic stochastic type. Second, for manufacturers to make optimal production decisions and minimize CE, we consider their capacity investment behavior. We propose the amount of capacity investment as a new decision variable to discuss the impact of manufacturers' capacity investment behavior on CLSC benefits and environmental efficiency. Third, with the expectation that manufacturers will be committed to remanufacturing and that the quality of remanufactured products can be controlled, we increase the collecting channels by assigning collecting activities to the supplier because they are more familiar with those components' qualities and compare the differences between different collection models. Fourth, for the first time, cap-and-trade is considered in the context of these innovations, and optimal carbon reduction decisions under controls are discussed to enhance the sustainability of this chain. This study is the first to investigate the optimal capacity investment, carbon reduction, and pricing decisions for a CLSC considering capacity constraints and stochastic demand under the cap-and-trade system.

The remainder of this study is organized as follows. Section 2 presents a review of the relevant literature. Section 3 presents the research problem, relevant parameter settings, and model assumptions and then performs model building and calculations. Section 4 details the numerical experiments and model analysis and compares the models. Section 5 presents conclusions and directions for future research.

2. Literature Review

The literature review is examined through two directions: (1) studies related to supply chain collecting issues and (2) studies related to supply chain carbon emission reduction issues.

2.1. Supply Chain Collection. With the emergence of resource shortage problems, a growing number of studies are focusing on the field of CLSC research. Among them, the reverse collecting process in the CLSC is the most important, and methods to choose the appropriate collecting channels and make appropriate collecting decisions are the focus of managing the CLSC system.

The issue of collecting channels has been studied extensively. Savaskan, Bhattacharya, and Van Wassenhove [12] studied the impact of different collecting channels on pricing decisions in CLSCs and used two-part tariff contracts to mitigate channel conflicts and improve CLSC efficiency. Pal and Sarkar [13] considered a CLSC consisting of a manufacturer, retailer, supplier, and a third-party recycler. In this case, the manufacturer has direct and traditional channels of the retailer. The level of green innovation of the manufacturer and the promotion strategy of the retailer is considered. Ding et al. [14] examined the pricing, purchasing, and collecting decisions of manufacturers and retailers using a CLSC framework consisting of a manufacturer and two competing retailers, in which the retailer performs the collecting. The results show that the higher the wholesale price, the less active the retailer's collecting activity. When the collecting price is higher, the retailer will be more proactive in collecting the product. Wen et al. [15] developed a CLSC game model consisting of manufacturers and retailers to explore members' pricing and collecting decisions based on the consideration that consumers have environmental responsibilities. Feng et al. [16] considered the reverse logistics of perishable items and investigated the optimal control of production and remanufacturing of collecting systems. They also compared the optimal dynamic strategy with the static optimal strategy and found that the former was significantly better.

Some scholars have also studied multichannel collections. Mondal et al. [17] considered a CLSC system with dual sales and collecting channels, in which the manufacturer has two online and offline sales channels and channels. The impact of different channels on decision-making and revenue was analyzed and compared upon combining different sales and collecting channels. Taleizadeh et al. [18] established a CLSC network consisting of a manufacturer, retailer, and third-party collector. The manufacturer has dual sales channels, and collecting activities can be performed by the retailer or third-party collector. A new coordination mechanism was introduced and discussed to reduce channel conflicts and increase the profitability of each supply chain member. Xu [19] developed a CLSC consisting of a manufacturer and retailer. Similarly, the manufacturer has online and offline sales, and collecting activities can be performed by either the manufacturer or retailer. Consumer preferences for sales channels are considered, and the analysis compares the optimal price and the best collecting decision under different models. Wang et al. [20] constructed a CLSC system consisting of manufacturers, remanufacturers, and retailers to study the optimal decision problem of members under three different mixed collecting models.

Many scholars have studied collecting issues in combination with other issues. Wang et al. [21] constructed a closed-loop e-commerce supply chain consisting of a remanufacturer and a web-based collecting platform to study collecting services and quality improvement issues. Wang et al. [20] examined a CLSC consisting of suppliers and third-party collectors, considering the manufacturer's capacity constraints where the two are in competition. The most available pricing and collection decisions of study members were examined. Wang and Shao [22] discussed capacity investment decisions under the manufacturer's capacity constraints and examine the issue of coordination contracts among members.

Among the studies on CLSC collecting channels, manufacturer collection, retailer collection, and third-party collector collection are the most frequently discussed collecting channels. There is scant literature on the structure of CLSC with supplier participation. Based on the existing research results, under the stochastic demand constraint, this study considers the supplier-collecting channel in the CLSC with a capacity constraint to explore the optimal decision in the CLSC.

2.2. CE Reduction in Supply Chains. CLSCs considering CE reduction can be broadly divided into two types: one is combined with manufacturers' CE reduction instruments, and the other is combined with government actions. Zhang et al. [10] discussed CE reduction in CLSCs without collecting links, analyzed the impact of input CE reduction on the benefits to CLSC members, and found that a single-channel CLSC structure is more conducive to CE reduction when consumers have environmental preferences. Dong et al. [23] discussed CE reduction in a dual-channel CLSC and examined the impact of compensation contracts and consumers' low-carbon preferences, concluding that CLSCs should aim to improve consumers' low-carbon preferences to increase their benefits. Yu et al. [24] examined the low-carbon advertising investment of manufacturers and retailers in the context of CE reduction by comparing the relationship between the level of profit, demand, and advertising investment across a CLSC under three-game models. Yang and Xu [2] investigated how carbon abatement costs and remanufacturing ratios affect participants' decisions in a CLSC network (CLSCN) under dynamic conditions by developing a differential game model. They concluded that greater investment in carbon abatement technologies leads to better reductions in CE and increased CLSC benefits. Wu et al. [25] discussed the impact of decision-makers equity concerns on the benefits of each decision-maker and the members of the CLSC that considers carbon abatement.

Government actions include subsidies, taxes, and carbon cap-and-trade on CE. Wu et al. [26] examined carbon abatement decisions in the presence of government subsidies, green preferences among consumers, and coordination contracts. The results showed that manufacturers' efforts to reduce CE affect demand for the product, and fixed government subsidies do not affect member benefits. Zhang et al. [10] examined the impact of government interventions on carbon reduction decisions and social welfare and concluded that government interventions effectively control total CE and improve social welfare but have some impact on member benefits. Zhang et al. [10] investigated the impact of government incentives and disincentives related to CE and collection rates on CLSC members' decisions and investigated asymmetric information about such incentives and disincentives for the first time. Li et al. [27] discussed the impact of a carbon tax on CLSCs using chaos analysis and other methods by introducing a tax on CE in a two-oligarch game model of a multichannel CLSC. Wang et al. [28] studied government subsidies and cost-sharing contracts under pressure from environmentally conscious manufacturers and corporate social responsibility. Wang et al. [29] constructed a closed-loop e-commerce supply chain and discussed the impact of government subsidies on decision-making.

Some studies have investigated the carbon cap-and-trade regulations in CLSCs. Wang et al. [30] examined the production decision under capital constraints and CE permit repurchase strategy (CEPRS) and analyzed the impact of CEPRS on the decision and benefits. Zhang et al. [31] studied the impact of cap-and-trade regulations on a three-tier CLSCN consisting of suppliers, manufacturers, and carbon trading centers. It then used variational inequalities to derive optimality conditions. Yang et al. [32] examined the impact of cap-and-trade regulations on CLSCs consisting of manufacturers, retailers, and third-party collectors and investigated the CE and benefits of membership under different collecting channels. The results revealed that collecting remanufactured products can increase carbon reduction and improve the low-carbon sustainability of CLSCs. Under a CLSC structure consisting of manufacturers, retailers, and third-party collectors, Jauhari et al. [33] investigated the impact of carbon cap-and-trade policies and investments in green technologies on members' decision-making. The findings indicated that CLSC benefits are maximized under centralized decision making. Yan et al. [34] examined the optimal collecting strategy in a CLSC consisting of a manufacturer, retailer, and third-party collector, considering carbon cap-and-trade policies. Xu et al. [35] examined how CLSCs with hybrid and dedicated structures were affected by several carbon policies.

Other studies have analyzed carbon cap-and-trade control policies compared to other CE policies. Yang et al. [36] examined how CLSC participants' optimal decisions are affected when they do not follow a cap-and-trade policy and offered recommendations on the management of imported products and CE regulation. Hu et al. [37] discussed two additional government subsidies in a CLSC considering cap-and-trade regulations, namely, policy bias and direct subsidy and concluded that there is little difference in the impact of the two types of government subsidies on the CLSC. Alegoz et al. [38] analyzed and compared three different carbon policies, and found the optimal decision for each member of the CLSC under the three emission policies. Mohammed et al. [39] compared and analyzed the various carbon regulation mechanisms implemented for carbon emissions in CLSCs and proposed a model that improves the overall benefits and emissions of CLSCs. Samuel et al. [40] examined the impact of CE policies and carbon cap-and-trade controls, on CLSCN. The results indicated that CE policies and carbon cap-and-trade controls have a greater impact on CLSCs than carbon cap-and-trade policies.

Relationships between members are also a direction for related research. Wang et al. [41]examined a low-carbon supply chain consisting of a retailer and a manufacturer and discussed the manufacturer's investment in carbon reduction technologies. Mondal and Giri [42] examined competition and cooperation in a CLSC consisting of a manufacturer and two competing retailers under carbon trading control and concluded that carbon cap-and-trade policies have some positive benefits for each member of the CLSC. Similarly, Gan et al. [43] examined the coordination and cooperation between CLSC members. The impact of profit-sharing contracts between manufacturers and retailers on pricing strategies was also investigated in the context of carbon cap-and-trade policies. This study reported a positive relationship between the benefits of CLSC members and carbon caps. Similarly, Wang et al. [44] discussed carbon emission reduction in the context of a CLSC structure and studied the coordination contracts between members.

In recent studies related to CE reduction in CLSCs, scholars have discussed CE reduction decisions combined with coordination problems, government subsidies, government reward and punishment mechanisms, carbon taxes, and advertising investments. In this study, the optimal decision problem of the CLSC is discussed by combining CE reduction, carbon quotas, and carbon trading in an innovative supply chain structure and constraint environment.

3. Problem Description and Assumptions

In this study, we examine the optimal decision for a CLSC considering capacity constraints and stochastic demand under a cap-and-trade system. A two-level CLSC, comprising one supplier and one manufacturer is established. To make the problem more realistic, we treat demand as a random variable, consider the manufacturer's capacity to have a certain upper limit, and allow the manufacturer to invest in and expand capacity to meet production demand. In such a CLSC, maximizing sustainability while ensuring that the CLSC is profitable is considered. Based on this CLSC, we view the supplier and manufacturer as initiators of collecting activities to recycle and reuse products with a residual value in the CLSC, ultimately reducing resource waste and environmental pollution. Thus, CLSC should be considered in the context of the current low-carbon environment. Under a cap-and-trade system, we consider a government-imposed cap on the emissions generated by manufacturers in manufacturing and remanufacturing. There is a shortage of carbon allowances, and manufacturers can purchase carbon allowances in the carbon market to complete their production. To reduce the cost of this transaction, manufacturers would seek to reduce their CE by making corresponding investments in carbon reduction.

In this section, we consider a CLSC comprising one manufacturer and one supplier. In the forward CLSC, the manufacturer uses new raw materials and recycled materials for manufacturing and remanufacturing and has a certain upper capacity limit that requires capacity investment. In the reverse CLSC, two collecting models are considered: (1) the supplier collecting model, where the collecting activity is handed over to a supplier who is more familiar with the component, and then the manufacturer obtains the remanufactured raw material from the supplier; and (2) the manufacturer collecting model, where the manufacturer remanufactures the product directly from the consumer. To improve the sustainability of the CLSC, we set the models to consider a carbon cap-and-trade system and investment in carbon reduction. The CLSC structures of the six models are shown in Figure 1.

We summarize the parameters and decision variables used in the models in Table 1, which represent the profits of player i in model j as Π_i^j, where $j = \mathrm{M}$, ME, MC, S, SE, and SC, representing the following models: manufacturer collecting model without carbon reduction decision, manufacturer collecting model with carbon reduction, manufacturer collecting model with carbon trading controls and carbon reduction, retailer collecting model without carbon reduction decision, retailer collecting model with carbon reduction, and retailer collecting model with carbon trading controls and carbon reduction, respectively. $i = \mathrm{S}$, M, C, which denotes the supplier, manufacturer, and CLSC, respectively.

3.1. Notations. Table 1 provides all the relevant symbols and parameters that used.

3.2. Assumptions. To facilitate subsequent research and analysis, we make the following assumptions.

Assumption 1. The manufacturer's production capacity has an upper limit ϕ and cannot produce without limits.

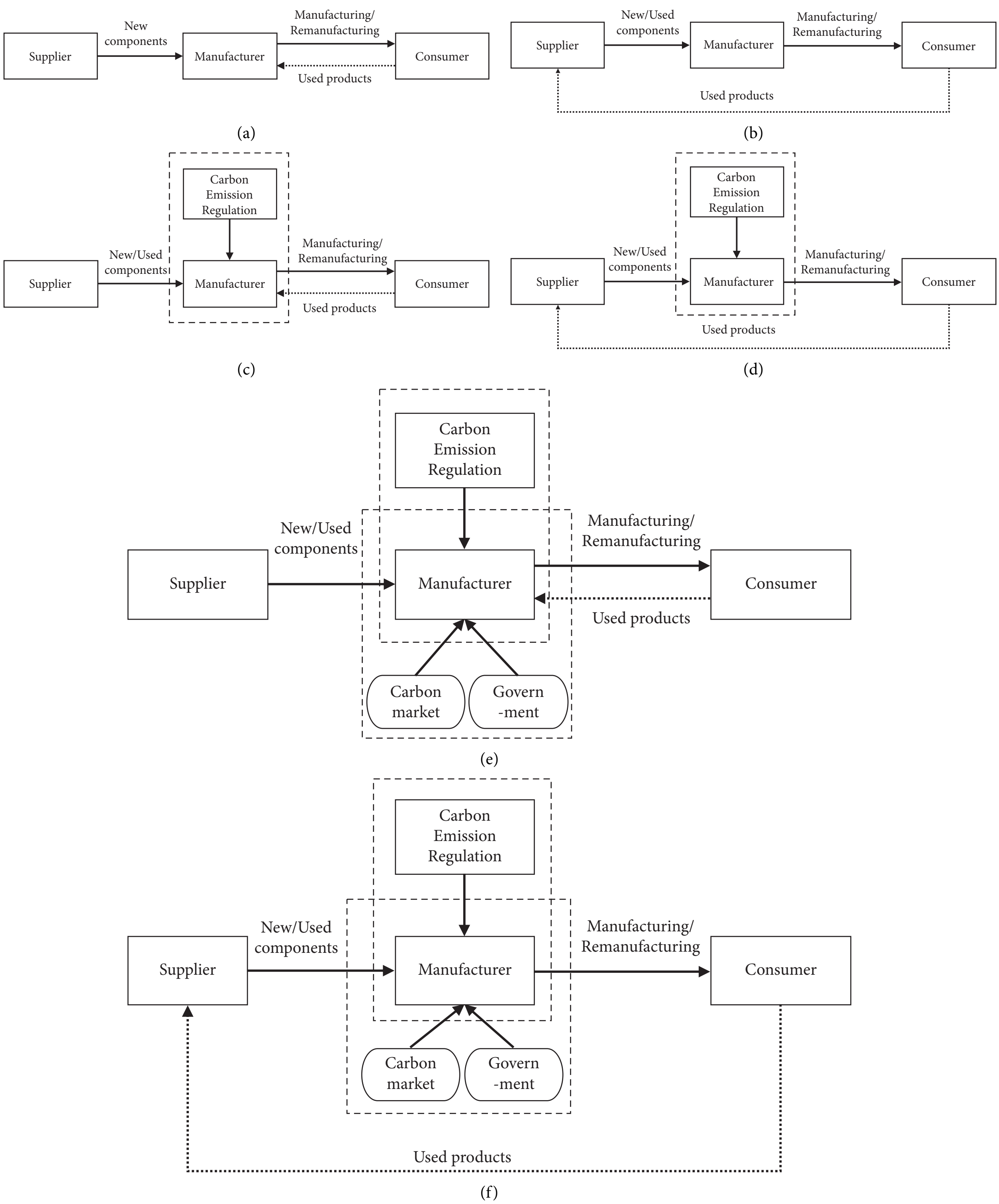


Figure 1: The CLSC structures. (a) Model M. (b) Model S. (c) Model ME. (d) Model SE. (e) Model MC. (f) Model SC.

Manufacturers can make appropriate capacity investments, and their capacity investment costs can be viewed as a primary function of the amount of capacity investment, denoted by rk. This method has been widely used in literature. The invested capacity kk is fully utilized based on the capacity investment and the manufacturer's final output $Q = \phi + k$.

Assumption 2. The quantity of recycled products is positively related to the collecting price offered by the collector; that is, the quantity recycled can be expressed as $q = a + bp_0$ [45, 46].

When the collector does not offer a collecting price, some green-conscious consumers will be willing to offer their products for collection; thus, a can indicate consumers' environmental awareness. The price offered by the collector

Table 1: Notations.

	Model parameters
α	Total market volume
D	Market demand for products
D_0	Linear part of product market demand
ε	Random parts of product market demand
β	Sensitivity factor of market demand to product price
θ	Sensitivity factor of market demand to the level of carbon reduction
ϕ	Upper limit of manufacturer's production activity capacity
c_m	Production and manufacturing costs per unit of product
c_t	Carbon trading price per unit of product on the carbon trading market
c_s	Production costs per unit of product components
s	Residual value of unsold products
b	Sensitivity factor of product recovery volume to recovery price
λ	Carbon reduction cost factor
r	Capacity investment cost factor
p_1	Supply price per unit of parts
p_2	Selling price per unit of product
e_0	Carbon emissions per unit of product produced
Ω	Government-given carbon quotas for manufacturers
	Decision variables
e	Emission reduction levels per unit of product
p_0	Recovery price per unit of product in the market
k	Volume of manufacturers' investment in production activities
	Derived variables
q	Product recovery volume
Q	Total product output
Π_S	Total supplier profit
Π_M	Total manufacturer profit
Π_C	Total CLSC profit
	Indexes
$*$	Represents the optimal solution in each case

serves as an incentive for consumers to recycle. Hence, the higher the price, the more collection occurs.

Assumption 3. The cost of a manufacturer's investment in CE reduction is a quadratic function of the level of carbon reduction, which can be expressed as $1/2\lambda e^2$.

Assumption 4. There is no difference in the market between the two kinds of products. Manufacturers price them the same, and market preferences are the same.

In a CLSC that considers collecting activities, there are usually two ways of dealing with the collected products. One is to refurbish and repair the collected products directly and bring them back to the market as second-hand products. Consumers can distinguish between new and second-hand products in this market, resulting in differences in the two product types and pricing levels. The second is to dismantle the collected product into components, inspect them for quality, and reuse those that meet the criteria for use in manufacturing a new product. There is no difference in form and function between the remanufactured product and the new product; hence, the consumer does not recognize any differences between these product types.

Assumption 5. The linear partial function of product demand is expressed as $D_0 = \alpha - \beta p_2 + \theta e$.

Where D_0 is the linear part of product demand, α is the total market volume for such a product, p_2 is the selling price of the product, β is the sensitivity coefficient of the product market demand to the selling price, e is the manufacturer's level of CE reduction, and θ is the sensitivity coefficient of demand to the level of carbon emission reduction. As environmental problems become increasingly serious, consumers' preferences for green products have become evident, and products with higher green levels tend to be favored by consumers. Meanwhile, product price remains an important factor influencing product demand, and an increase in product pricing will have a negative impact on consumers' willingness to purchase products. We consider solely the linear effect of the CE reduction level and pricing on product demand, with α, β, θ being positive constants.

Assumption 6. The total market demand for a product, D, can be regarded as consisting of a linear demand, D_0, and a stochastic demand, ε, that is, $D = D_0 + \varepsilon = \alpha - \beta p_2 + \theta e + \varepsilon$.

In practice, many factors influence demand for a product, which leads to a certain stochastic nature of demand. Many scholars have considered the stochastic part of the demand to make it more approximate to the actual situation. There are usually two ways to consider demand uncertainty: in multiplicative or in additive forms. In this study, we refer to the additive form in which a random variable ε is added to the linear demand within the range $[A, B]$. We consider this random variable ε to have a variance of σ, expectation of μ, and cumulative distribution function of $F(\cdot)$. The probability density function is $F(\cdot)$.

Assumption 7. When supply exceeds demand, the unsold product still has surplus value; the surplus value per unit of product is s, and the total surplus value is $s[\phi + k - E(Q, D)]$, where $E(Q, D)$ is the actual sales volume.

4. Models and Analysis

We present two different types of mathematical models to compare the two collecting approaches: manufacturer-collecting and supplier-collecting models. Based on these models, the effects of the two carbon reduction instruments on decision making, carbon reduction decisions, and CE control and trading are investigated. Thus, six different scenarios are discussed as follows: a manufacturer collecting no carbon decisions, a manufacturer collecting with carbon reduction, a manufacturer collecting with carbon trading control and carbon reduction, a retailer collecting no carbon decisions, a retailer collecting with carbon reduction, and a retailer collecting with carbon trading control and carbon reduction. These models are used to develop manufacturers' optimal collection, production, investment, and carbon reduction decisions under different scenarios.

This model focuses on CE reduction and capacity investment decisions by combining the unit price of parts supply p_1 and the unit price of product sales p_2. The result is considered to be the optimal value that has been decided upon. In the manufacturer's collecting model, the manufacturer must decide on the optimal collecting price p_0, the optimal level of CE reduction e, and the optimal level of capacity investment k. In the supplier-collecting model, the supplier must decide on the optimal collecting price p_0 while the manufacturer must decide on the optimal level of CE reduction e and the optimal level of capacity investment k.

In this study's model, the stochastic nature of demand is considered. Thus, the demand function can be seen as a linear part and a stochastic part, that is, the total market demand function is $D = \alpha - \beta p_2 + \theta e + \varepsilon$. To facilitate the derivation of the relevant law in the model calculation, we treat the random variable of demand as a random variable subject to a uniform distribution $U(0, m)$ of random variables (where $m > 0$).

The actual sales volume function for the product is therefore given by

$$\left.\begin{aligned} E(Q,D) &= E[\min(Q,D)] = \begin{cases} k+\phi & (\varepsilon \geq k+\phi-D_0) \\ D_0+\varepsilon & (\varepsilon \leq k+\phi-D_0) \end{cases} \\ &= \int_0^{k+\phi-D_0} (D_0+\varepsilon) f(\varepsilon)d\varepsilon + \int_{k+\phi-D_0}^{m} (k+\phi) f(\varepsilon)d\varepsilon \\ &= k+\phi - \frac{(k+\phi-D_0)^2}{2m} \end{aligned}\right\}. \quad (1)$$

4.1. Models without Carbon Emission

4.1.1. The Manufacturer Collecting Scenario (Model M).

We consider a scenario in which the manufacturer's CE reduction decisions and the government's carbon trading controls are not considered. The manufacturer and supplier carry out collecting, manufacturing, and remanufacturing activities without consideration of carbon emissions and make the best decisions accordingly. In this scenario, the manufacturer performs collecting and manufacturing activities independently, and the supplier supplies the manufacturer with the parts needed for production.

The profit functions for the manufacturer and supplier are as follows:

$$\begin{aligned} \Pi_M^M &= p_2 E^M(Q,D) + s\left[\phi + k^M - E^M(Q,D)\right] \\ &\quad - p_0^M q^M - c_m\left(\phi + k^M\right) - rk^M, \\ &\quad - p_1\left(\phi + \left(k^M - q^M\right)\right), \\ \Pi_S^M &= (p_1 - c_s)\left(\phi + \left(k^M - q^M\right)\right), \end{aligned} \quad (2)$$

where $E^M(Q,D) = k^M + \phi - (k^M + \phi - D_0)^2/2m$ £ $q^M = a + bp_0^M$ £ $D_0 = \alpha - \beta p_2$.

The first term in the manufacturer's profit function $p_2 E^M(Q,D)$ represents the profit earned through the sale of the product, the second term $s[\phi + k^M - E^M(Q,D)]$ represents the total residual value of unsold product when capacity exceeds demand, the third term $p_0^M q^M$ represents the cost of recovery, the fourth term $c_m(\phi + k^M)$ represents the cost of manufacturing the product, the fifth term rk^M is the cost of investment in capacity, and the sixth $p_1(\phi + k^M - q^M)$ is the purchase cost of parts purchased from supplier. The supplier profit function comprises the profit from the sale of parts and the cost of acquiring the parts.

Total CLSC profit is $\Pi_C^M = \Pi_S^M + \Pi_M^M$.

Proposition 1. *The following optimal solutions regarding the amount of investment and recovery price are derived from the manufacturer recovery model without CE.*

$$\begin{aligned} k^{M^*} &= \frac{-c_m m - mp_1 + mp_2 - mr + p_2\alpha - s\alpha - p_2^2\beta + p_2 s\beta}{(p_2 - s)} - \phi, \\ p_0^{M*} &= \frac{(-a + bp_1)}{2b}. \end{aligned} \quad (3)$$

The proof of Proposition 1 is presented in Appendix A.

Based on the above equation, the actual sales and recovery at this point can be derived as follows:

$$\begin{aligned} E^{M*}(Q,D) &= \frac{1}{2}\left\{2\alpha + \frac{m(p_2 - p_1 - r)(p_1 + p_2 + r - 2s)}{(p_2 - s)^2} + \frac{p_2^2(\beta - 1)\beta}{m}, -\frac{2mc_m(p_1 + r - s)}{(p_2 - s)^2} - \frac{mc_m^2}{(p_2 - s)^2} - 2\beta p_2\right\}, \\ p_0^{M*} &= \frac{(-a + bp_1)}{2b}, \end{aligned} \quad (4)$$

where superscript M indicates the solution under the manufacturer's collecting model that does not consider CE and superscript $*$ indicates the optimal solution. This uniform identifier is also used in subsequent sections.

Returning the above equilibrium solution back to the manufacturer and supplier profit function and simplifying it yields the following:

$$\Pi_M^M = \frac{a^2}{4b} + \frac{bp_1^2}{4} + \frac{c_m^2 m + m(p_1 - p_2 + r)^2 + 2c_m[m(p_1 - p_2 + r) - (p_2 - s)(\alpha - \beta p_2)]}{4(p_2 - s)},$$
$$+ \frac{(p_2 - s)[ap_1 - 2(p_1 - p_2 + r)(\alpha - \beta p_2) + 2r\phi]}{4(p_2 - s)}, \quad (5)$$
$$\Pi_S^M = \frac{(p_1 - c_s)[2m(p_2 - p_1 - r - c_m) + (p_2 - s)(2\alpha - a - bp_1 - 2\beta p_2)]}{2(p_2 - s)}.$$

The following corollary can be drawn from the above optimal solution.

Corollary 1

(1) $\partial p_0^{M*}/\partial a < 0, \partial \Pi_S^{M*}/\partial a < 0$
(2) $\partial p_0^{M*}/\partial b > 0, \partial \Pi_S^{M*}/\partial b < 0$
(3) $\partial k^{M^*}/\partial m > 0, \partial \Pi_M^{M^*}/\partial m > 0$
(4) $\partial k^{M^*}/\partial r < 0, \partial k^{M^*}/\partial \beta < 0.$

The proof of Corollary 1 is presented in Appendix B.

Corollary 1 gives the effects of consumers' green awareness, collecting the price sensitivity coefficient, the upper limit of demand change, capacity investment cost coefficient, and product price sensitivity coefficient on each decision variable and members' returns. (1) An increase in consumers' green awareness leads to a decrease in collection prices and supplier returns. When consumers' green awareness increases, manufacturers can recover products from consumers at lower collection prices. Thus, collecting remanufacturing activities become more active, and manufacturers are more willing to use collected products for remanufacturing. This condition results in fewer orders for new parts from suppliers and longer lead times and affects supplier earnings. (2) When consumers become more sensitive to collecting prices, manufacturers as collectors will increase the collecting price, and suppliers' earnings will fall. When the price is more sensitive, it needs to be raised appropriately for recycling. The manufacturer will choose to produce fewer products, resulting in fewer orders for new parts from suppliers, longer lead times, and lower returns to the suppliers. (3) When the upper limit of demand is raised, manufacturers' capacity investment and profit increase. As demand increases, manufacturers invest in capacity and increase their production schedules to meet demand, resulting in higher sales profit. (4) The manufacturer's capacity investment decreases as investment cost and product price sensitivity factors increase. The higher the cost, the more constrained the manufacturer's capacity investment, whereas an overly price-sensitive market causes the manufacturer to reduce production efforts and thus reduce investment.

4.1.2. The Supplier Collecting Scenario (Model S). We consider a scenario in which the manufacturer's CE reduction decisions and the government's carbon trading controls are not considered. The manufacturer and supplier conduct collecting, manufacturing, and remanufacturing activities without considering CE and making the best decisions accordingly. In this model, the supplier collects the activities and supplies the parts needed for production. The profit functions for the manufacturer and the supplier are as follows:

The profit functions for the manufacturer and supplier are as follows:

$$\Pi_M^S = p_2 E^S(Q,D) + s[\phi + k^S - E^S(Q,D)]$$
$$- c_m(\phi + k^S) - rk^S - p_1(\phi + k^S), \quad (6)$$
$$\Pi_S^S = p_1(\phi + k^S) - p_0^S q^S - c_s(\phi + k^S - q^S),$$

where $E^S(Q,D) = k^S + \phi - (k^S + \phi - D_0)^2/2m$, $q^S = a + bp_0^S$, and $D_0 = \alpha - \beta p_2$.

The first term in the supplier profit function $p_1(\phi + k^S)$ represents the profit received from the sale of parts to the manufacturer, the second term $p_0^S q^S$ represents the cost of the recycled product, and the third term $c_s(\phi + k^S - q^S)$ represents the cost of supplying new parts. The meanings of the other terms remain unchanged.

The total CLSC profit is $\Pi_C^S = \Pi_S^S + \Pi_M^S$.

Proposition 2. *The following optimal solutions were derived from the supplier recovery model without carbon emissions:*

$$k^{S*} = \frac{-c_m m - mp_1 + mp_2 - mr + p_2\alpha - s\alpha - p_2^2\beta + p_2 s\beta}{(p_2 - s)}$$
$$- \phi,$$
$$p_0^{S*} = \frac{(-a + bc_s)}{2b}. \quad (7)$$

Returning to the above equation, the actual sales and recoveries at this point can be derived as follows:

$$E^{S*}(Q,D)=\frac{m(p_2-p_1-r)(p_1+p_2+r-2s)+2(p_2-s)^2(\alpha-\beta p_2)-mc_m^2}{2(p_2-s)^2},-\frac{mc_m(p1+r-s)}{(p_2-s)^2},$$
$$q^{S*}=\frac{a+bc_s}{2}, \tag{8}$$

where superscript S indicates the solution under this supplier recovery model without carbon emissions and superscript $*$ indicates the optimal solution. This uniform identifier is also used in the subsequent sections herein.

Bringing the above equilibrium solution back to the manufacturer and supplier profit function and simplifying it yields the following:

$$\Pi_M^S=\frac{(p_2-p_1-c_m-r)[m(p_2-p_1-r-c_m)+2(p_2-s)(\alpha-\beta p_2)]}{2(p_2-s)}+r\phi,$$
$$\Pi_S^S=\frac{a^2}{4b}+\frac{bc_s^2}{4}+\frac{c_m m(c_s-p_1)-p_1[m(p_1-p_2+r)+(p_2-s)(-\alpha+\beta p_2)]}{p_2-s},+\frac{c_s[2m(p_1-p_2+r)+(p_2-s)(a-2\alpha+2\beta p_2)]}{2(p_2-s)}. \tag{9}$$

Next, Corollary 2can be drawn from the above optimal solution.

Corollary 2

(1) $\partial p_0^{S^*}/\partial a<0, \partial\Pi_S^{S^*}/\partial a<0$
(2) $\partial p_0^{S^*}/\partial b>0, \partial\Pi_S^{S^*}/\partial b<0$
(3) $\partial k^{S^*}/\partial m>0, \partial\Pi_S^{S^*}/\partial m>0$
(4) $\partial k^{S^*}/\partial r<0, \partial k^{S^*}/\partial\beta<0$

Corollary 2 presents the effects of consumer green awareness, collecting the price sensitivity coefficient, the upper limit of demand change, capacity investment cost coefficient, and product price sensitivity coefficient on each decision variable and members' returns. Similar conclusions can be drawn from Model M. It can be seen that (1) an increase in consumers' green awareness leads to a decrease in the collection price and the supplier's revenue. (2) When the consumer's sensitivity coefficient to the collecting price increases, the manufacturer, as the collector, raises the collecting price when the supplier's revenue decreases. (3) When the upper limit of demand increases, the amount of manufacturer capacity investment and supplier revenue increases. (4) The amount of manufacturer capacity investment decreases with increased investment cost and product price sensitivity coefficients.

4.2. Models with Carbon Emission

4.2.1. The Manufacturer Collecting Scenario (Model ME). In a situation where the manufacturer's carbon reduction decision is considered, the manufacturer and supplier carry out collecting, manufacturing, and remanufacturing activities in different collecting modes and then make the best decisions accordingly. Here, the manufacturer performs collecting and manufacturing activities independently, and the supplier supplies the manufacturer with the parts needed for production.

The profit functions for the manufacturer and supplier are as follows:

$$\begin{aligned}\Pi_M^{ME}&=p_2E^{ME}(Q,D)-p_0^{ME}q^{ME}-c_m\left(\phi+k^{ME}\right)\\&\quad-rk^{ME}-p_1\left(\phi+k^{ME}-q^{ME}\right),\\&\quad+s\left[\phi+k^{ME}-E^{ME}(Q,D)\right]-\frac{\lambda}{2}e^{ME^2},\\ \Pi_S^{ME}&=(p_1-c_s)\left(\phi+k^{ME}-q^{ME}\right),\end{aligned} \tag{10}$$

where $E^{ME}(Q,D)=k^{ME}+\phi-(k^{ME}+\phi-D_0)^2/2m$, $q^{ME}=a+bp_0^{ME}$, and $D_0=\alpha-\beta p_2+\theta e^{ME}$.

The last term in the manufacturer's benefit function $\lambda/2e^2$ represents the costs incurred by the manufacturer in undertaking carbon reduction activities. The definitions of the other terms remain unchanged.

The total CLSC profit is $\Pi_C^{ME}=\Pi_S^{ME}+\Pi_M^{ME}$.

Proposition 3. *The following equilibrium solutions were derived by backward induction in a model in which the manufacturer recycles and its carbon reduction activities are considered.*

$$
\begin{aligned}
k^{ME^*} &= \frac{-c_m m - m p_1 + m p_2 - m r + p_2\alpha - s\alpha - p_2^2\beta + p_2 s\beta + e^{ME} p_2\theta - e^{ME} s\theta}{p_2 - s}, -\phi,\\
p_0^{ME^*} &= \frac{-a + b p_1}{2b},\\
e^{ME^*} &= \frac{(p_2 - c_m - p_1 - r)\theta}{\lambda}.
\end{aligned}
\tag{11}
$$

On the basis of the above equation, the amount of capacity investment, actual sales, and recoveries at this point can be derived as follows:

$$
\begin{aligned}
k^{ME^*} &= \frac{m(p_2 - p_1 - r) - c_m m + (p_2 - s)(\alpha - \beta p_2)}{(p_2 - s)} + \frac{(p_2 - c_m - p_1 - r)\theta^2}{\lambda} - \phi,\\
E^{ME^*}(Q, D) &= \frac{2c_m m(2p_2 - p_1 - r - s) + m(p_1 - p_2 + r)(3p_2 - p_1 - r - 2s) - c_m^2 m}{2(p_2 - s)^2},\\
&\quad + \frac{m(p_1 - p_2 + r)(3p_2 - p_1 - r - 2s)}{2(p_2 - s)^2} - \frac{(c_m + p_1 - p_2 + r)\theta^2}{\lambda},\\
q^{ME^*} &= \frac{(a + b p_1)}{2},
\end{aligned}
\tag{12}
$$

where superscript ME denotes the solution under this manufacturer collecting model that considers the manufacturer's carbon reduction decision and superscript $*$ denotes the optimal solution. This uniform identifier is also used in the subsequent sections.

Bringing the above equilibrium solution back to the manufacturer and supplier profit function and simplifying it yields the following:

$$
\begin{aligned}
\Pi_M^{ME} &= \frac{a^2}{4b} + \frac{b p_1^2}{4} + \frac{2r(p_2 - s)\lambda\phi}{2(p_2 - s)\lambda}\\
&\quad + \frac{-2p_1(p_2 - r)(p_2 - s)\theta^2 + p_1^2\left[(p_2 - s)\theta^2 - 3m\lambda\right] + c_m^2\left[(p_2 - s)\theta^2 + m\lambda\right]}{2(p_2 - s)\lambda}\\
&\quad + \frac{p_1[6m(p_2 - r) + a(p_2 - s) + 2(p_2 - s)(-\alpha + \beta p_2)]\lambda}{2(p_2 - s)\lambda}\\
&\quad + \frac{+(p_2 - r)\left[(p_2 - r)(p_2 - s)\theta^2 + 3m(-p_2 + r)\lambda - 2(p_2 - s)(-\alpha + \beta p_2)\lambda\right]}{2(p_2 - s)\lambda}\\
&\quad + \frac{2c_m\left[(p_1 - p_2 + r)(p_2 - s)\theta^2 + m(p_1 - p_2 + r)\lambda + (p_2 - s)(-\alpha + \beta p_2)\lambda\right]}{2(p_2 - s)\lambda},\\
\Pi_S^{ME} &= -\frac{1}{2}p_1(a - b p_1) + \alpha p_1 - \beta p_1 p_2 + \frac{m p_1(p_1 - p_2 + r - c_m)}{p_2 - s} - \frac{p_1(c_m + p_1 - p_2 + r)\theta^2}{\lambda}.
\end{aligned}
\tag{13}
$$

Next, the following corollary can be drawn from the above optimal solution:

Corollary 3

(1) $\partial p_0^{ME^*}/\partial a < 0, \partial\Pi_S^{ME^*}/\partial a < 0, \partial\Pi_M^{ME^*}/\partial a > 0$

(2) $\partial p_0^{ME^*}/\partial b > 0, \partial\Pi_S^{ME^*}/\partial b < 0, \partial\Pi_M^{ME^*}/\partial b < 0$

(3) $\partial e^{ME^*}/\partial\theta > 0, \partial k^{ME^*}/\partial\theta > 0, \partial\Pi_S^{ME^*}/\partial\theta > 0, \partial\Pi_M^{ME^*}/\partial\theta > 0$

(4) $\partial k^{ME^*}/\partial\lambda < 0$, $\partial e^{ME^*}/\partial\lambda < 0$

The proof of Corollary 3 is presented in Appendix C.

Corollary 3 provides the effects of consumers' green awareness, price sensitivity coefficients, carbon emission sensitivity coefficients, and carbon reduction investment of cost coefficients on each decision variable and members' benefits. (1) An increase in consumers' green awareness leads to a decrease in the price of collecting and returning products to suppliers, whereas the return to manufacturers increases. When consumer awareness increases, manufacturers can recycle products from consumers at a lower price, thus making collecting activities more active and profitable. Manufacturers are more willing to remanufacture recycled products at this time. This condition results in fewer orders for new parts from suppliers and longer lead times and affects supplier earnings. (2) When consumers become more sensitive to the collecting price, manufacturers, as collectors, increase the collecting price, and the supplier's and manufacturer's earnings fall. In the case of high price sensitivity, the price must be raised appropriately for recycling. Price-sensitive consumers will make collecting activities difficult, resulting in lower returns for the manufacturer. The manufacturer chooses to produce fewer products, resulting in fewer orders for new parts from the supplier, longer lead times, and lower returns to the supplier. (3) When the carbon sensitivity factor increases, the level of carbon reduction, the amount of capacity investment by the manufacturer, manufacturer's profit, and supplier's profit increase. Given an increased carbon sensitivity factor, the higher the level of CE reduction by the manufacturer, the greater the market demand, leading to a higher production volume of products requiring greater capacity investment and a significant increase in the profitability of CLSC members. (4) The amount of capacity investment and level of CE reduction by the manufacturer decreased with an increase in the carbon reduction cost factor. The higher the cost, the lower the level of carbon reduction that manufacturers choose and the lower the market demand for carbon-emission-sensitive products. This scenario results in lower production volumes and capacity investments.

4.2.2. *The Supplier Collecting Scenario (Model SE).*

When the manufacturer's carbon reduction decision is considered, the manufacturer and supplier carry out collecting, manufacturing, and remanufacturing in different collecting modes and then make the best decisions accordingly. In this scenario, the manufacturer completes production activities, and the supplier completes the collecting activities and supplies the manufacturer with the parts needed for production.

The profit functions for the chain members are as follows:

$$\begin{aligned}\Pi_M^{SE} &= p_2E^{SE}(Q,D) + s\left[\phi + k^{SE} - E^{SE}(Q,D)\right] - c_m\left(\phi + k^{SE}\right) - rk^{SE} - p_1\left(\phi + k^{SE}\right) - \frac{\lambda}{2}e^{SE^2},\\ \Pi_S^{SE} &= p_1\left(\phi + k^{SE}\right) - p_0^{SE}q^{SE} - c_s\left(\phi + k^{SE} - q^{SE}\right),\end{aligned} \tag{14}$$

where $E^{SE}(Q,D) = k^{SE} + \phi - (k^{SE} + \phi - D_0)^2/2m$, $q^{SE} = a + bp_0^{SE}$, $D_0 = \alpha - \beta p_2 + \theta e^{SE}$.

The last term in the manufacturer's benefit function $\lambda/2e^2$ represents the costs incurred by the manufacturer in undertaking carbon reduction activities. The definitions of the other terms remain unchanged.

The total CLSC profit is $\Pi_C^{SE} = \Pi_S^{SE} + \Pi_M^{SE}$.

Proposition 4. *The following equilibrium solutions were derived by backward induction in a model in which the supplier recycles and the manufacturer's carbon reduction activities are considered.*

$$\begin{aligned}k^{SE^*} &= \frac{-c_m m - mp_1 + mp_2 - mr + p_2\alpha - s\alpha - p_2^2\beta + p_2 s\beta + e^{SE}p_2\theta - e^{SE}s\theta}{p_2 - s} - \phi,\\ p_0^{SE^*} &= \frac{-a + bc_s}{2b},\\ e^{SE^*} &= \frac{(p_2 - c_m - p_1 - r)\theta}{\lambda}.\end{aligned} \tag{15}$$

On the basis of the above equation, the amount of capacity investment, actual sales, and recoveries at this point can be derived as follows:

$$
\begin{aligned}
k^{SE^*} &= \frac{m[(p_2 - p_1 - r - c_m) + (p_2 - s)(\alpha - \beta p_2)]}{(p_2 - s)} \\
&\quad + \frac{(p_2 - c_m - p_1 - r)\theta^2}{\lambda} - \phi, \\
E^{SE^*}(Q, D) &= \frac{2c_m m(2p_2 - p_1 - r - s) + m(p_1 - p_2 + r)(3p_2 - p_1 - r - 2s)}{2(p_2 - s)^2} \\
&\quad + \frac{2(p_2 - s)^2(\alpha - \beta p_2) - c_m^2 m}{2(p_2 - s)^2} - \frac{(c_m + p_1 - p_2 + r)\theta^2}{\lambda}, \\
q^{SE^*} &= \frac{(a + bc_s)}{2},
\end{aligned} \tag{16}
$$

where superscript SE indicates the solution under the supplier recovery model considering carbon emissions and superscript $*$ indicates the optimal solution. This uniform identifier is also used in the subsequent sections.

Bringing the above equilibrium solution back to the manufacturer and supplier profit function and simplifying it yields the following:

$$
\begin{aligned}
\Pi_M^{SE} &= \frac{c_m^2\left[(p_2 - s)\theta^2 + m\lambda\right] + 2cmp1 - p2 + rp2 - sE2}{2(p_2 - s)\lambda}, \\
&\quad + \frac{c_m[m(p_1 - p_2 + r)\lambda + (p_2 - s)(-\alpha + \beta p_2)\lambda]}{(p_2 - s)\lambda}, + \frac{(p_2 - s)(p_1 - p_2 + r)^2\theta^2 + m\lambda(p_1 - p_2 + r)^2}{2(p_2 - s)\lambda}, \\
&\quad + \frac{2(p_2 - s)(p_1 - p_2 + r)(-\alpha + \beta p_2)\lambda + 2r(p_2 - s)\lambda\phi}{2(p_2 - s)\lambda}, \\
\Pi_S^{SE} &= \frac{a^2}{4b} + \frac{bc_s^2}{4} + \frac{(c_s - p_1)(c_m + p_1 - p_2 + r)\theta^2}{\lambda}, \\
&\quad + \frac{mc_m(c_s - p_1) - p_1[m(p_1 - p_2 + r) + (p_2 - s)(-\alpha + \beta p_2)]}{(p_2 - s)}, + \frac{c_s[2m(p_1 - p_2 + r) + (p_2 - s)(a - 2\alpha + 2\beta p_2)]}{2(p_2 - s)}.
\end{aligned} \tag{17}
$$

Next, the following corollary can be drawn from the above optimal solution:

Corollary 4

(1) $\partial p_0^{SE^*}/\partial a < 0, \partial \Pi_S^{SE^*}/\partial a > 0$
(2) $\partial p_0^{SE^*}/\partial b > 0, \partial \Pi_S^{SE^*}/\partial b < 0$
(3) $\partial e^{SE^*}/\partial \theta > 0, \partial k^{SE^*}/\partial \theta > 0, \partial \Pi_S^{SE}{}^*/\partial \theta > 0, \partial \Pi_M^{SE}{}^*/\partial \theta > 0$
(4) $\partial k^{SE^*}/\partial \lambda < 0, \partial e^{SE^*}/\partial \lambda < 0$

Corollary 4 provides the effects of consumers' green awareness, collection price sensitivity, carbon emission sensitivity, and carbon abatement investment costs on the decision variables and member benefits. Similar conclusions can be drawn to the ME model. It can be obtained that (1) .An increase in consumers' green awareness leads to a decrease in the collecting price and an increase in the supplier's revenue. (2) When consumers become more sensitive to collecting prices, manufacturers, as collectors, will increase collecting prices, and at this time, all the supplier's gains will decrease. (3) When the carbon sensitivity coefficient increases, the level of carbon reduction, amount of capacity investment by the manufacturer, manufacturer's revenue, and supplier's revenue increase. (4) The amount of capacity investment by the manufacturer and the level of carbon reduction decreased as the cost of carbon reduction increased.

4.3. Models with CE Reduction and Cap-and-Trade Regulation

4.3.1. The Manufacturer Collecting Scenario (Model MC). In a scenario that considers the manufacturer's CE reduction decisions and the government's carbon trading controls, the manufacturer and supplier undertake collecting, manufacturing, and remanufacturing activities with consideration of carbon emissions and make the best decisions accordingly. Here, the manufacturer completes the manufacturing, remanufacturing, and collecting activities, and the supplier supplies the manufacturer with the parts needed for production.

The profit functions for the chain members are as follows:

$$\begin{aligned}\Pi_M^{MC} &= p_2 E^{MC}(Q,D) - p_0^{MC} q^{MC} - c_m\left(\phi + k^{MC}\right) - rk^{MC} - p_1\left(\phi + k^{MC} - q^{MC}\right)\\ &\quad + s\left[\phi + k^{MC} - E^{MC}(Q,D)\right] - \frac{\lambda}{2} e^{MC\,2} - \left(e_0 - e^{MC} - \Omega\right)\left(\phi + k^{MC}\right),\\ \Pi_S^{MC} &= (p_1 - c_s)\left(\phi + k^{MC} - q^{MC}\right),\end{aligned} \tag{18}$$

where $E^{MC}(Q,D) = k^{MC} + \phi - (k^{MC} + \phi - D_0)^2/2m$, $q^{MC} = a + bp_0^{MC}$, and $D_0 = \alpha - \beta p_2 + \theta e^{MC}$.

The last term in the manufacturer's benefit function $(e_0 - e^{MC} - \Omega)(\phi + k^{MC})$ represents the costs incurred by the manufacturer in undertaking carbon trading activities under the carbon cap. The definitions of the other terms remain unchanged.

The total CLSC profit is $\Pi_C^{MC} = \Pi_S^{MC} + \Pi_M^{MC}$.

Proposition 5. *The following equilibrium solutions were derived by backward induction in a model in which the manufacturer recycles and CE reduction and cap-and-trade regulations are considered.*

$$\begin{aligned}k^{MC^*} &= \frac{-c_m m - mp_1 + mp_2 - mr + p_2\alpha - s\alpha - p_2^2\beta + p_2 s\beta}{p_2 - s} + \frac{e^{MC} p_2\theta - e^{MC} s\theta + c_t m\left(e^{MC} - e_0 + \Omega\right)}{p_2 - s} - \phi,\\ p_0^{MC^*} &= \frac{(-a + bp_1)}{2b},\\ e^{MC^*} &= \frac{c_m(p_2 - s)\theta + (p_1 - p_2 + r)(p_2 - s)\theta + c_t^2 m(e_0 - \Omega)}{ct^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda} + \frac{c_m c_t m + c_t m(p_1 - p_2 + r) - ct(p2 - s)[\alpha - \beta p2 + \theta(-e_0 + \Omega)]}{ct^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda}.\end{aligned} \tag{19}$$

On the basis of the above equation, we can derive the amount of capacity investment, actual sales volume, and recovery volume. The actual sales volume is more complex and is not listed in detail. The capacity investment and recovery volume are as follows:

$$\begin{aligned}k^{MC^*} &= \frac{c_t\left[-p_2^2\beta\theta + m\lambda(e_0 - \Omega) - s\theta(\alpha + \theta e_0 - \theta\Omega)\right]}{c_t^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda},\\ &\quad + \frac{\theta c_t p_2(\alpha + s\beta + \theta e_0 - \theta\Omega) + (c_m + p_1 - p_2 + r)(p_2 - s)\theta^2}{c_t^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda},\\ &\quad + \frac{[mc_m + m(p_1 - p_2 + r) + (p_2 - s)(-\alpha + \beta p_2)]\lambda}{c_t^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda} - \phi,\\ q^{MC^*} &= \frac{(a + bc_s)}{2},\end{aligned} \tag{20}$$

where the superscript *MC* indicates the solution under this manufacturer recovery model considering carbon emissions and carbon trading, and the superscript $*$ indicates the optimal solution. This uniform identifier is also used in the subsequent sections.

The above equilibrium solution is brought back to the manufacturer's and supplier's profit function and simplified to obtain their optimal profit. The solution is particularly complex and is not listed in detail.

Next, the following corollary can be drawn from the above optimal solution:

Corollary 5

(1) $\partial p_0^{MC^*}/\partial a < 0, \partial\Pi_S^{MC^*}/\partial a < 0, \partial\Pi_M^{MC^*}/\partial a > 0$

(2) $\partial p_0^{MC^*}/\partial b > 0, \partial\Pi_S^{MC^*}/\partial b < 0, \partial\Pi_M^{MC^*}/\partial b < 0$

The proof of Corollary 5 is presented in Appendix D.

Corollary 5 gives the effects of consumers' green awareness and collects price sensitivity coefficients for each decision variable and member gains. (1) Increasing in consumers' green awareness leads to a decrease in collecting prices and supplier returns, whereas manufacturer returns are enhanced. When consumers' green awareness increases, manufacturers as collectors can recover products from consumers at a lower the collecting price; thus, collecting and remanufacturing activities become more active and profitable. Manufacturers are more willing to remanufacture recycled products at this time, resulting in fewer orders for new parts from suppliers, longer lead times, and impacted supplier earnings. (2) When consumers become more sensitive to the collecting price, the manufacturer as a collector increases the price of collection, at which point the supplier's profit decreases. Given the high price sensitivity, the price needs to be appropriately raised for recycling. Price-sensitive consumers make collecting activities difficult, resulting in lower returns for the manufacturers. Manufacturers may choose to produce fewer products at this time, resulting in fewer orders for new parts from suppliers, longer lead times, and lower returns.

4.3.2. The Supplier Collecting Scenario (Model SC). In a scenario that considers the manufacturer's carbon reduction decisions and the government's carbon trading controls, the manufacturer and supplier undertake collecting, manufacturing, and remanufacturing activities with consideration of carbon emissions and make the best decisions accordingly. In this case, the manufacturer completes the manufacturing and remanufacturing activities, and the supplier carries out the collection activities and supplies the manufacturer with the parts needed for production.

The profit functions for the chain members are as follows:

$$\begin{aligned}\Pi_M^{SC} &= p_2 E^{SC}(Q,D) - c_m\left(\phi + k^{SC}\right) - rk^{SC} - p_1\left(\phi + k^{SC}\right) + s\left[\phi + k^{SC} - E^{SC}(Q,D)\right] - \frac{\lambda}{2} e^{SC^2} - \left(e_0 - e^{SC} - \Omega\right)\left(\phi + k^{SC}\right),\\ \Pi_S^{SC} &= p_1\left(\phi + k^{SC}\right) - p_0^{SC} q^{SC} - c_s\left(\phi + k^{SC} - q^{SC}\right),\end{aligned} \tag{21}$$

where $E^{SC}(Q,D) = k^{SC} + \phi - (k^{SC} + \phi - D_0)^2/2m$, $q^{SC} = a + bp_0^{SC}$, and $D_0 = \alpha - \beta p_2 + \theta e^{SC}$.

The last term in the manufacturer's benefit function $(e_0 - e^{SC} - \Omega)(\phi + k^{SC})$ represents the costs incurred by the manufacturer in undertaking carbon trading activities under the carbon cap. The definitions of the other terms remain unchanged.

The total CLSC profit is $\Pi_C^{SC} = \Pi_S^{SC} + \Pi_M^{SC}$.

Proposition 6. *The following equilibrium solutions were derived by backward induction in a model in which the supplier recycles and carbon emission reduction and cap-and-trade regulations are considered.*

$$\begin{aligned}k^{SC^*} &= \frac{-c_m m - m p_1 + m p_2 - m r + p_2\alpha - s\alpha - p_2^2\beta + p_2 s\beta}{p_2 - s} + \frac{e^{SC} p_2\theta - e^{SC} s\theta + c_t m\left(e^{SC} - e_0 + \Omega\right)}{p_2 - s} - \phi,\\ p_0^{SC^*} &= \frac{-a + bc_s}{2b},\\ e^{SC^*} &= \frac{c_m(p_2 - s)\theta + (p_1 - p_2 + r)(p_2 - s)\theta - ct(p2 - s)(\alpha - \beta p2 + \theta(-e_0 + \Omega))}{ct^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda},\\ &+ \frac{c_m c_t m + c_t m(p_1 - p_2 + r) + c_m(p_2 - s)\theta + c_t^2 m(e_0 - \Omega)}{ct^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda}.s\end{aligned} \tag{22}$$

On the basis of the above equation, we can derive the amount of capacity investment, actual sales volume, and recovery volume. The actual sales volume is more complex and is not listed in detail. The capacity investment and recovery volume are as follows:

$$k^{SC^*} = \frac{c_t\left[-p_2^2\beta\theta + m\lambda(e_0 - \Omega) - s\theta(\alpha + \theta e_0 - \theta\Omega)\right]}{c_t^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda},$$

$$+\frac{\theta c_t p_2(\alpha + s\beta + \theta e_0 - \theta\Omega) + (c_m + p_1 - p_2 + r)(p_2 - s)\theta^2}{c_t^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda}, + \frac{\lambda[mc_m + m(p_1 - p_2 + r) + (p_2 - s)(-\alpha + \beta p_2)]}{c_t^2 m + 2c_t(p_2 - s)\theta + (-p_2 + s)\lambda} - \phi,$$

$$q^{SC^*} = \frac{(a + bc_s)}{2}, \tag{23}$$

where the superscript *SC* indicates the solution under this manufacturer recovery model that considers carbon emissions and carbon trading and the superscript $*$ indicates the optimal solution. This uniform identifier is also used in the subsequent sections.

The above equilibrium solution is brought back to the manufacturer's and supplier's profit function and simplified to obtain their optimal profit. The related equation is more complex and is not presented in detail.

Next, the following corollary can be drawn from the above optimal solution.

Corollary 6

(1) $\partial p_0^{SC^*}/\partial a < 0, \partial \Pi_S^{SC^*}/\partial a > 0$

(2) $\partial p_0^{SC^*}/\partial b > 0, \partial \Pi_S^{SC^*}/\partial b < 0$

Corollary 6 provides the effects of consumers' green awareness and the collection of price sensitivity coefficients for each decision variable and members' returns. The same as model MC, it leads to similar conclusions. It can be seen that (1) an increase in consumers' green awareness leads to a decrease in collecting prices and an increase in suppliers' revenue. (2) When consumers are more sensitive to the collection price, suppliers as collectors increase the collection price, and the supplier's revenue decreases.

5. Numerical Analysis

This section combines the parameter values given in some references, conducts numerical experiments on several important parameters, and analyzes them accordingly to derive a richer management opinion. With reference to previous parameter settings, we explore the impact of parameters such as the price sensitivity coefficient, CE reduction sensitivity coefficient, and CE reduction cost coefficient on the amount of capacity investment, level of CE reduction, and profit of each member of the CLSC as a whole. Combining these assumptions and relevant circumstances, we derive the parameter settings in Table 2 after appropriate adjustments.

5.1. Impact of Price Sensitivity Factor. To obtain more obvious conclusions, we set the product price sensitivity coefficients β, with the relevant parameter settings in the references, to $[0.2, 0.3]$ and hold the other parameter values constant. We can derive the impact of the degree of price sensitivity on the amount of capacity investment, supplier returns, manufacturer returns, and overall CLSC returns (Figure 2).

Figure 2(a) shows the effect of market sensitivity to price on the amount of capacity investment by manufacturers. Under the two different recovery models, the amount of capacity investment decreases with increasing price sensitivity in all three models, with the lowest amount of capacity investment occurring in the scenario in which carbon emission reduction and carbon trading are not considered. There is a clear relationship between the magnitude of capacity investment in the three models, with $k^M < k^{ME} < k^{MC}$, $k^S < k^{SE} < k^{SC}$.

Figure 2(b) illustrates the impact of market price sensitivity on supplier earnings. Across the six models, supplier profitability decreases as market price sensitivity increases. A comparison of supplier returns under different scenarios shows that the supplier returns under the supplier collection model are all higher than those under the manufacturer collection model and that the model without CE reduction is lower than the model with CE reduction and the model with CE reduction and CE trading. That is, $\Pi_S^M < \Pi_S^{ME} < \Pi_S^{MC} < \Pi_S^S < \Pi_S^{SE} < \Pi_S^{SC}$.

Figure 2(c) illustrates the effect of market price sensitivity on manufacturers' returns. Across the six models, manufacturers' profits decrease as market price sensitivity increases. Comparing the manufacturers' returns under the different scenarios, we observe that the manufacturers' returns under the supplier recovery model with carbon reduction and carbon trading are the highest. Moreover, the manufacturers' returns under the manufacturer recovery model with carbon reduction and carbon trading are not significantly different from those under the supplier recovery model without carbon reduction and carbon trading and are the lower among the six models. That is, $\Pi_M^{MC} < \Pi_M^S < \Pi_M^{SE} < \Pi_M^M < \Pi_M^{ME} < \Pi_M^{SC}$.

Figure 2(d) illustrates the impact of market price sensitivity on overall CLSC returns. Across the six models, the overall CLSC profit decreases as market price sensitivity increases. A comparison of the CLSC profits in the different scenarios shows that the CLSC profit in the supplier recovery model is higher than that in the manufacturer recovery model, that is, $\Pi_C^{MC} < \Pi_C^M < \Pi_C^{ME} < \Pi_C^S < \Pi_C^{SE} < \Pi_C^{SC}$.

We can draw several conclusions by combining the analyzes in the above diagram. First, the profits of all CLSC participants, including the entire CLSC, are affected when the market becomes more sensitive to product prices. To

Table 2: The value of the parameters.

α	ϕ	$\mathbf{c}_m$	$\mathbf{c}_t$	$\mathbf{c}_s$	$\mathbf{a}$	$\mathbf{b}$	$\mathbf{p}_1$	$\mathbf{p}_2$	$\mathbf{e}_0$	Ω
80	60	2	0.8	2	1	0.5	8	15	1	0.3

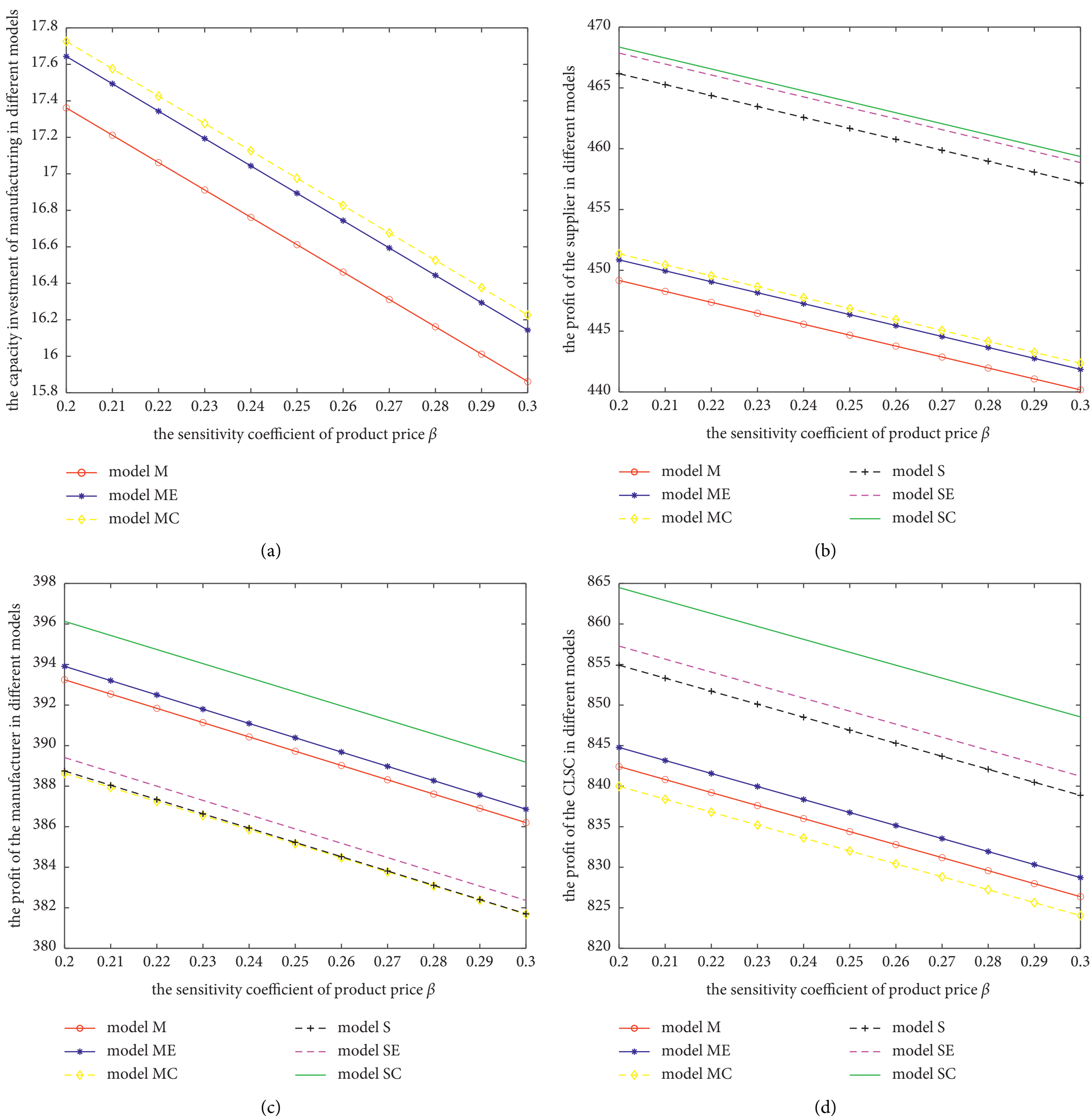


Figure 2: The sensitivity coefficient of product price β. (a) The capacity investment manufacturing in different models. (b) The profit of the supplier in different models. (c) The profit of the manufacturer in different models. (d) The profit of the CLSC in different models.

reduce consumers' concerns about product prices, product manufacturers need to improve the quality of their products and increase the marginal benefit of their products to consumers; that is, they must improve the value for money of their products. Second, the supplier-collecting model benefits the CLSC and is not a weak option for collecting activities. At the same time, reasonable consideration of carbon reduction can bring higher profits to CLSC members and CLSCs.

5.2. Impact of Carbon Reduction Sensitivity Factors. To enrich the conclusions, we set the carbon reduction level sensitivity factor θ in combination with the relevant parameters in the references. The range is $[0.1, 1]$, and the other parameter values are held constant. We can derive the impact of the sensitivity of demand to the level of CE reduction on the amount of capacity investment, level of CE reduction, and supplier, manufacturer, and overall CLSC profits (Figure 3).

Figure 3(a) shows that the trends of capacity investment with the sensitivity factor of carbon emission reduction are similar in both recovery models, with capacity investment increasing with the sensitivity of demand to the level of CE reduction. When the sensitivity of demand to the level of CE reduction is minimal, the amount of capacity investment in the model considering CE reduction is larger than that in the model considering carbon trading. Meanwhile, as the sensitivity of demand to the level of CE reduction increases, the amount of capacity investment in the model considering CE reduction and carbon trading increases.

Figure 3(b) shows that the trends of CE reduction levels with the CE reduction sensitivity factor are similar in both collecting models, with carbon reduction levels increasing as the sensitivity of demand to carbon reduction levels increases. In the model that considers CE reduction and trading, the level of CE reduction is always the highest.

Figure 3(c) shows that the variations in supplier profit with the sensitivity coefficient of CE reduction are similar in both collecting models, with supplier profit increasing as the sensitivity of demand to the level of CE reduction increases. When the sensitivity of demand to CE reduction is low, there is little impact on suppliers' profit when carbon trading is considered. When the sensitivity to CE reduction increases to a certain level, suppliers' profits tend to be higher in the model that considers carbon trading.

Figure 3(d) shows that the trends of manufacturer returns with the carbon reduction sensitivity factor are similar for both collecting models, with manufacturer returns increasing as the sensitivity of demand to the level of carbon reduction increases. In the model without carbon trading, manufacturers' returns are less affected by sensitivity to CE reduction and are higher in the manufacturer collecting model. In the model with carbon trading, manufacturers' returns are higher in the supplier-collecting model.

Figure 3(e) shows that the variations in total CLSC profit with the sensitivity factor of carbon emission reduction are similar in both collecting models and increase with the sensitivity of demand to the level of CE reduction. In the model without carbon trading, the total CLSC profit is less affected by the sensitivity to CE reduction and is higher in the supplier-collecting model. In the model with carbon trading, the total CLSC profit is more affected by the sensitivity to CE reduction and is higher in the supplier-collecting model.

Overall, consumers' growing sensitivity to carbon reduction will have a positive effect on various members of CLSCs and CLSCs as a whole. As consumers become more green-conscious and the carbon footprint of products becomes a consideration in their purchases, the sustainability of CLSCs is expected to improve. Moreover, the consideration of carbon reduction and carbon trading will increase the benefits for each member of the CLSCs, thus increasing the concern for carbon and the sustainability of CLSCs.

5.3. Impact of Carbon Reduction Cost Factors. We set the carbon abatement cost factor with the relevant parameters in the references λ to $[4, 10]$ and held the parameter values constant to obtain clear conclusions. We can derive the impact of carbon abatement costs on capacity investment, the level of carbon abatement, and the supplier, manufacturer, and overall CLSC profits (Figure 4).

Figure 4(a) shows a similar trend in capacity investment with carbon abatement costs for both recovery models. The amount of capacity investment decreases as the cost of carbon abatement increases. The amount of capacity investment is greater in the model that considers carbon trading than in the one that considers only carbon abatement.

Figure 4(b) shows a similar trend in CE reduction with the cost of carbon reduction for both recovery models, with the level of CE reduction decreasing as the cost of carbon reduction increases. The level of CE reduction in the model that considers carbon trading is greater than in the model that considers only carbon reduction.

Figure 4(c) shows that carbon abatement costs have a similar impact on supplier returns in all four models, with higher carbon abatement costs resulting in lower supplier returns. The supplier recovery scenario results in higher returns to suppliers in the model that considers carbon trading.

Figure 4(d) shows that the trends of manufacturers' returns with carbon abatement costs are similar for both collection models, with manufacturers' returns decreasing as the cost of carbon abatement increases. In the model without carbon trading, manufacturers' returns are less affected by the carbon abatement cost and are higher in the manufacturer-collecting model. In the model with carbon trading, manufacturer returns are higher in the supplier-collecting model.

Figure 4(e) shows that the trends of total CLSC profit with carbon abatement cost are similar in both collecting models and decrease with an increase in carbon abatement cost. In the model without carbon trading, the total CLSC profit is less affected by the cost of carbon abatement, and is higher in the supplier-collecting model. In the model with carbon trading, the total CLSC profit is affected more by the carbon abatement cost and is higher in the supplier-collecting model.

According to the analysis, the higher the cost of CE reduction, the lower the corresponding capacity investment and CE reduction level of manufacturers and CLSC members. Here, the overall profit declines. When the cost of CE reduction is too high, the CE of the production process will not be effectively reduced and will exert a negative effect on manufacturing activities. This condition leads to a reduction in the profitability of CLSC members and a reduction in the sustainability of CLSCs. When CE reduction costs are too high, the constraint on carbon

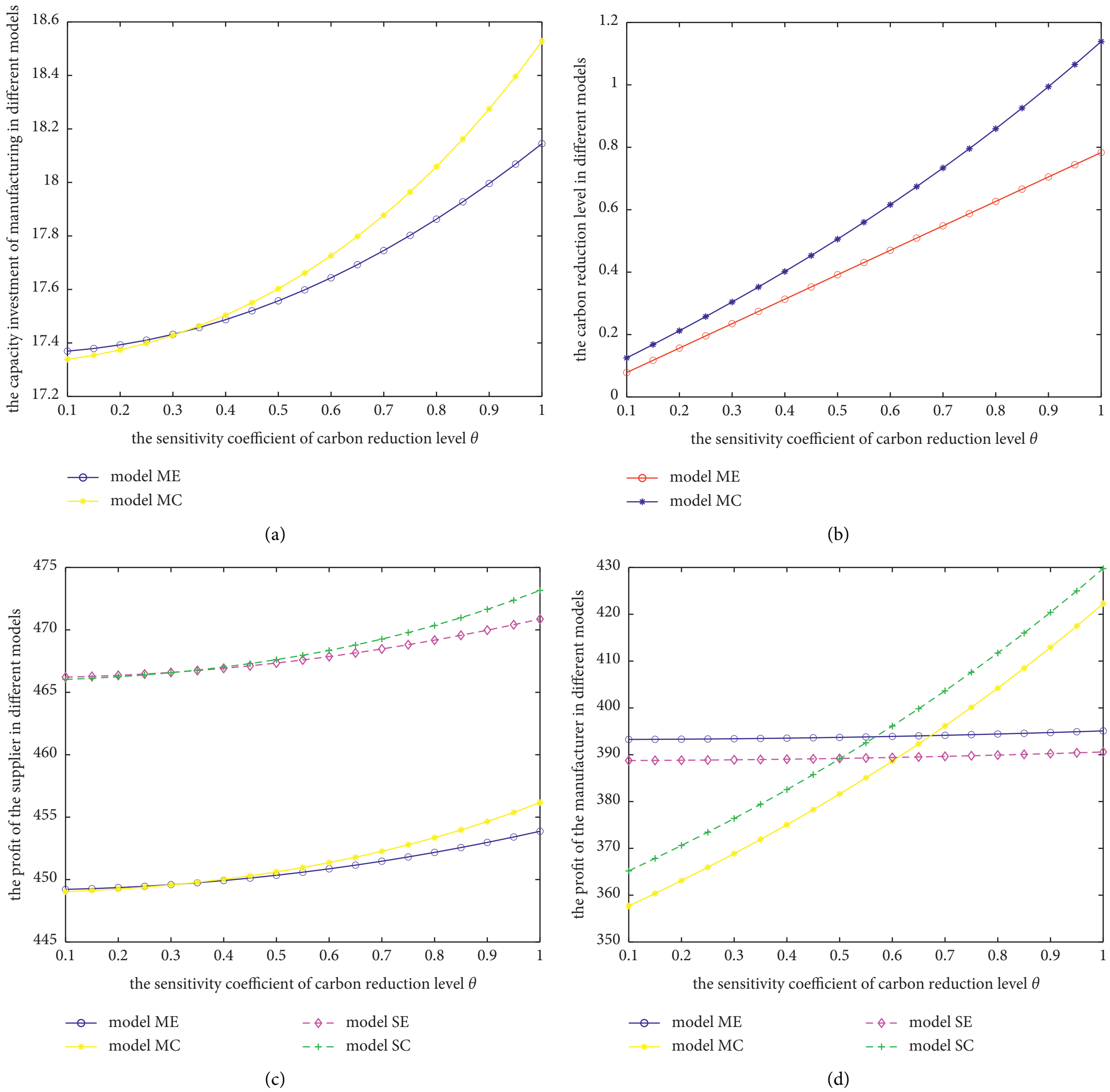
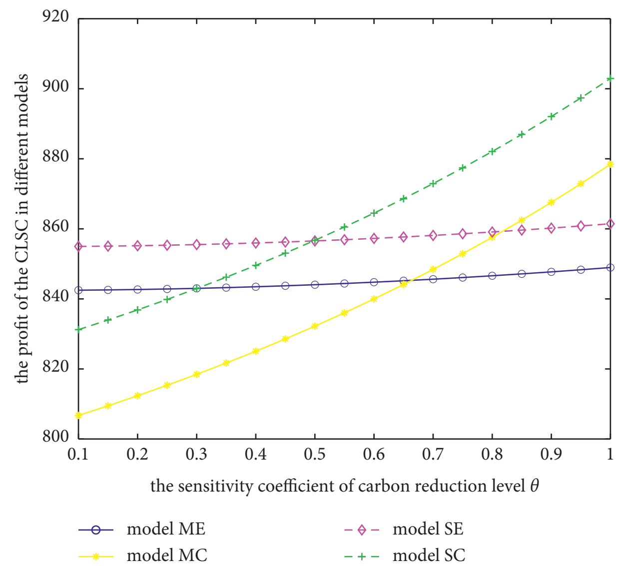
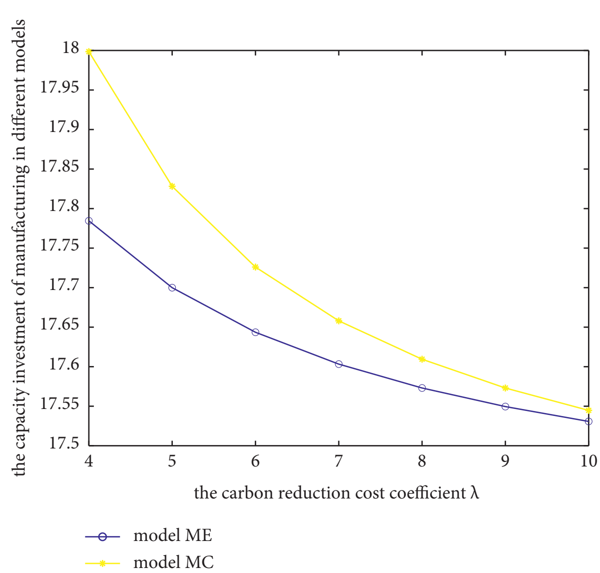


Figure 3: Continued.

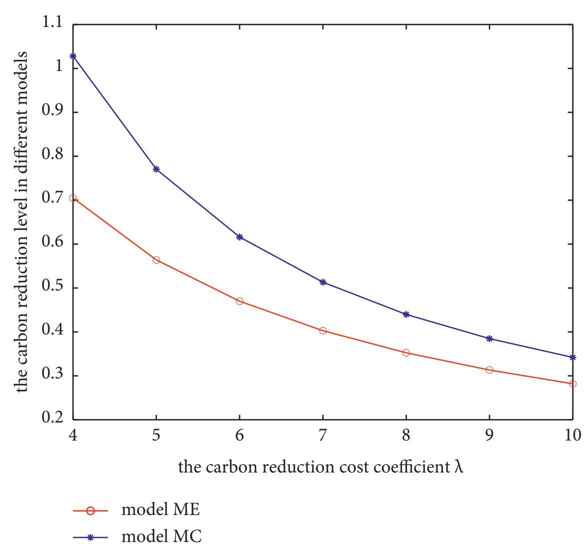


(e)

Figure 3: The sensitivity coefficient of carbon reduction level θ. (a) The capacity investment of manufacturing in different models. (b) The carbon reduction level in different models. (c) The profit of the supplier in different models. (d) The profit of the manufacturer in different models. (e) The profit of the CLSC in different models.

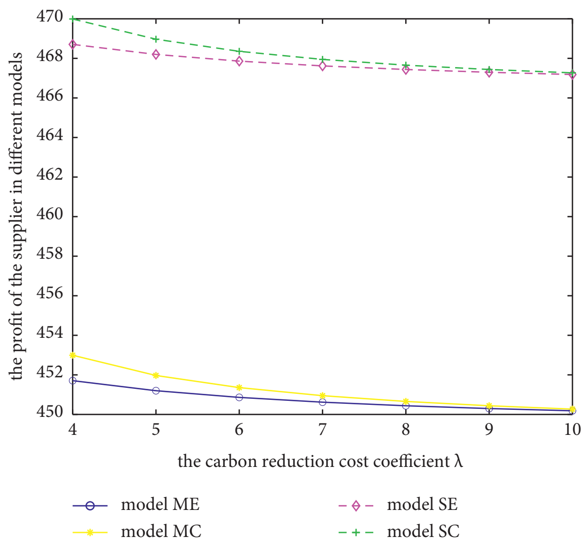


(a)

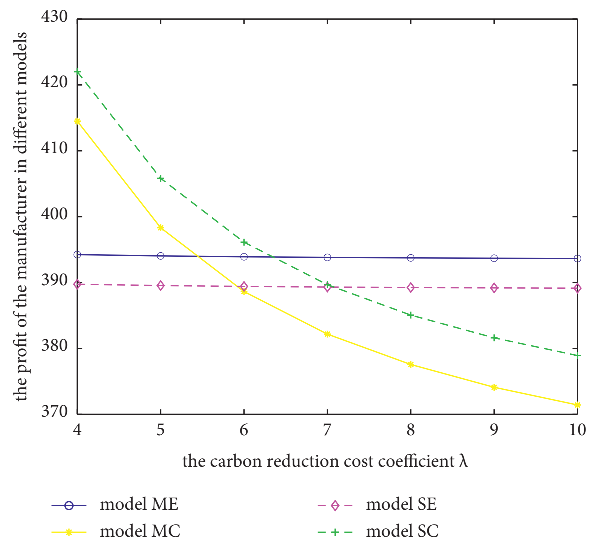


(b)

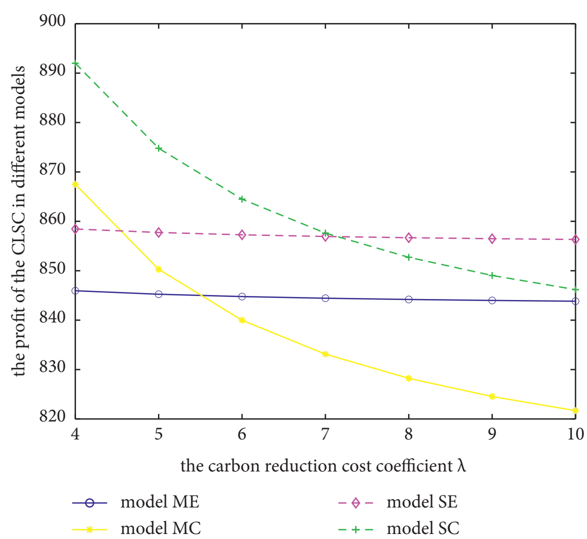
Figure 4: Continued.



(c)



(d)



(e)

Figure 4: The carbon reduction cost coefficient λ. (a) The capacity investment of manufacturing in different models. (b) The carbon reduction level in different models. (c) The profit of the supplier in different models. (d) The profit of the manufacturer in different models. (e) The profit of the CLSC in different models.

limits can play a significant role. Therefore, it is important to study how to reduce the cost of CE reduction and incentivize companies to reduce CE.

5.4. Impact of Capacity Investment Cost Factors. To reach more obvious conclusions, we set the range of capacity investment cost coefficients r, in conjunction with the relevant parameter settings in the references, to $[0.1, 1]$ and hold the other parameter values constant. We can derive the impact of the capacity investment cost on the amount of investment, supplier returns, manufacturer returns, and overall CLSC returns (Figure 5).

Figure 5(a) shows the impact of investment costs on the amount of capacity investment made by manufacturers. Under the two different recovery models, the capacity investment decreases with increasing capacity investment costs in all three models, with the lowest amount of capacity investment occurring when carbon reduction and trading are not considered. There is a clear relationship between the magnitude of capacity investment in the three models, with $k^M < k^{ME} < k^{MC}$, $k^S < k^{SE} < k^{SC}$.

Figure 5(b) illustrates the impact of capacity investment costs on supplier profitability. In all six models, suppliers' profits decreased as capacity investment costs increased. Comparing the supplier returns under different scenarios shows that the supplier recovery model's supplier returns are all higher than those in the manufacturer recovery model. The supplier returns in the model without CE reduction are lower than those considering CE reduction and the model

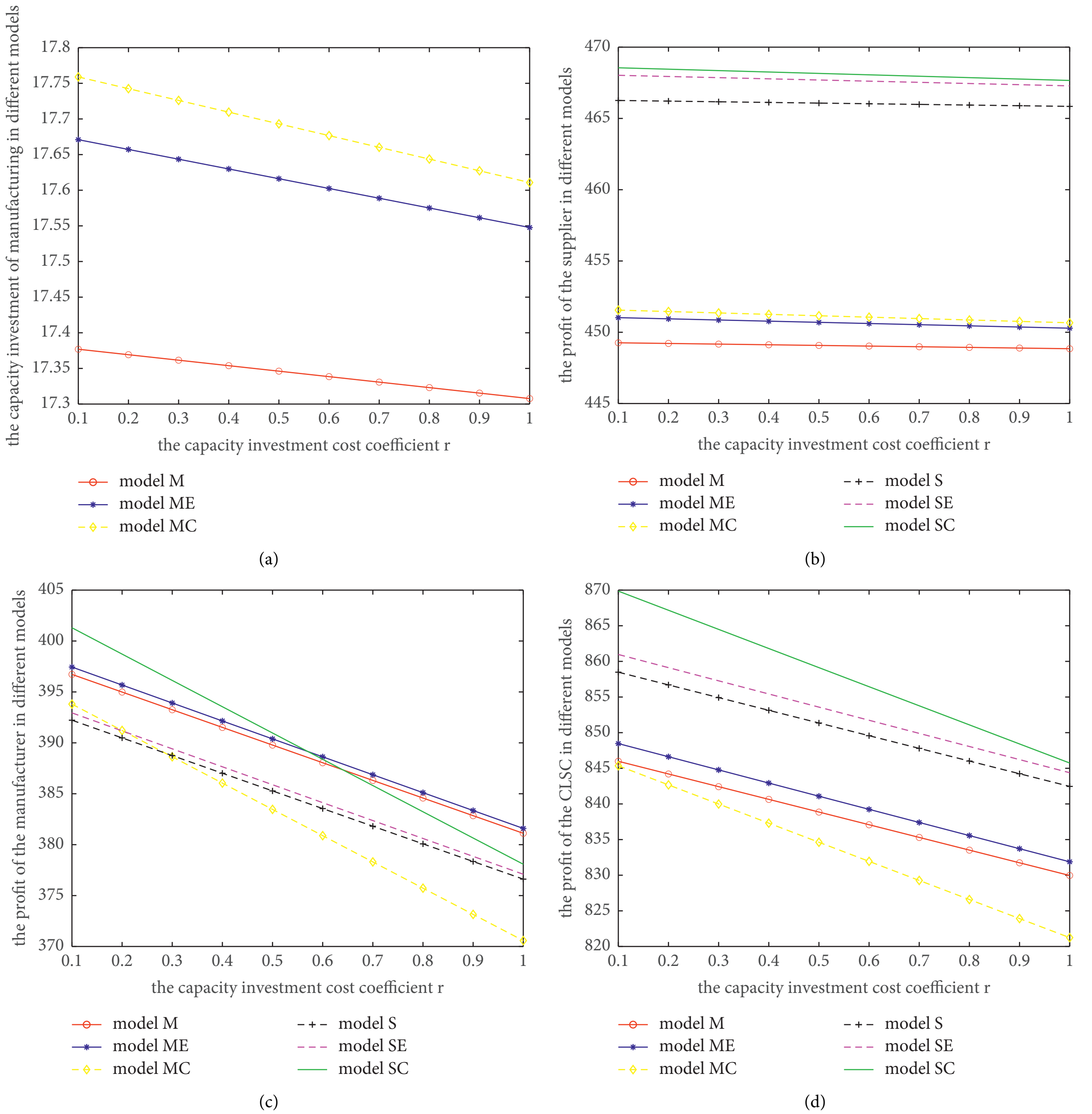


Figure 5: The capacity investment cost coefficient r. (a) The capacity investment of manufacturing in different models. (b) The profit of the supplier in different models. (c) The profit of the manufacturer in different models. (d) The profit of the CLSC in different models.

considering emission reduction and carbon trading. That is, $\Pi_S^M < \Pi_S^{ME} < \Pi_S^{MC} < \Pi_S^S < \Pi_S^{SE} < \Pi_S^{SC}$.

Figure 5(c) illustrates the impact of capacity investment costs on manufacturers' returns. Manufacturers' profits decrease as the capacity investment cost increases in all six models. Comparing manufacturers' returns in the different scenarios reveals that when the capacity investment cost is low, manufacturers' returns are the highest in the scenario where carbon trading is considered under the supplier recovery model. When the capacity investment cost is too high, manufacturers' returns are highest in the model where carbon reduction is considered under the manufacturer recovery model.

Figure 5(d) illustrates the impact of capacity investment costs on overall CLSC returns. Across the six models, the overall CLSC returns decrease as market price sensitivity increases. A comparison of the CLSC returns in the different scenarios shows that the CLSC returns in the supplier recovery model are higher than those in the manufacturer recovery model, that is, $\Pi_C^{MC} < \Pi_C^M < \Pi_C^{ME} < \Pi_C^S < \Pi_C^{SE} < \Pi_C^{SC}$.

Overall, reducing the cost of capacity investment is an effective way to increase CLSC's profit. A greater capacity

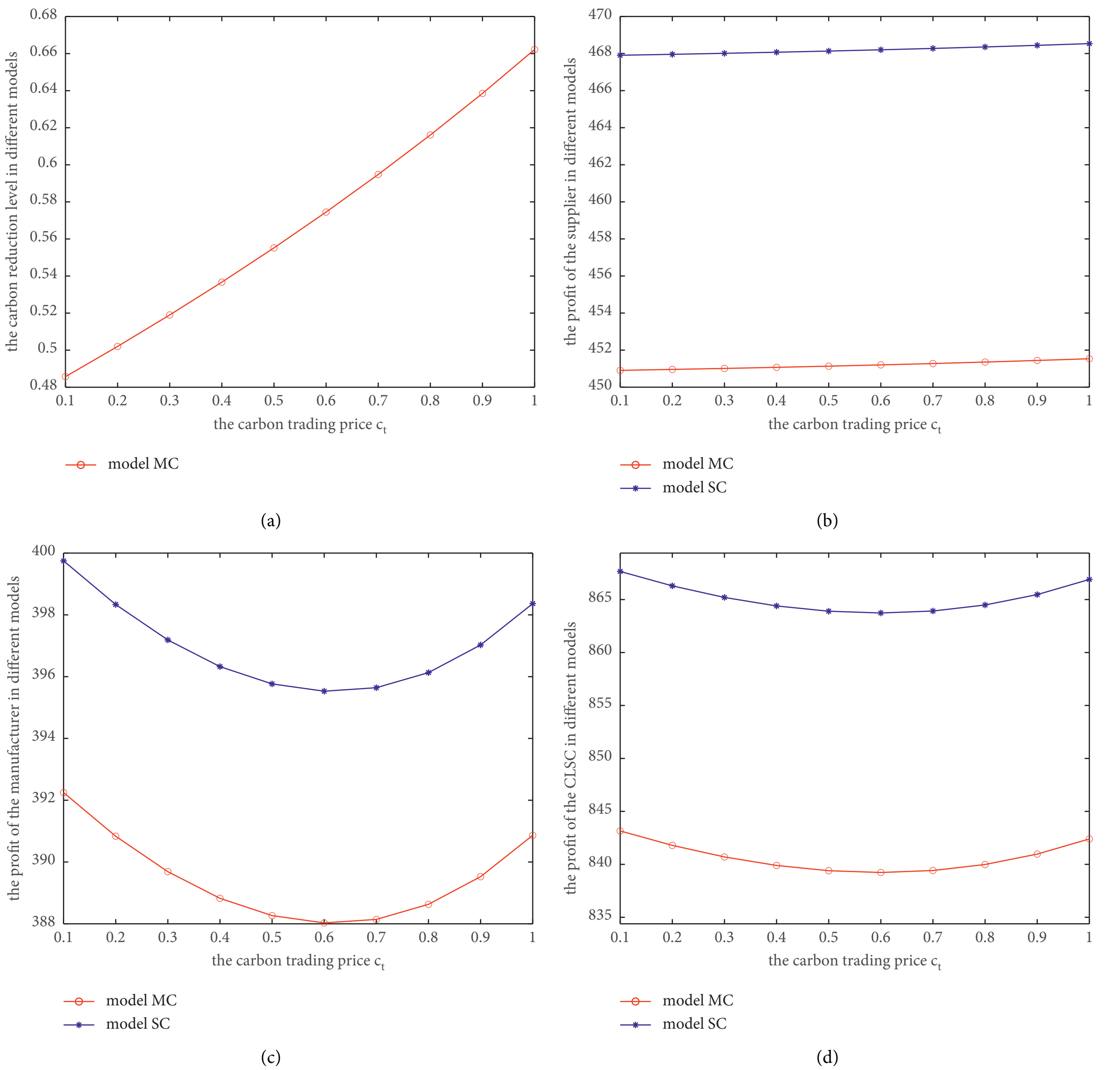


Figure 6: The carbon trading price c_t. (a) The capacity investment of manufacturing in different models. (b) The profit of the supplier in different models. (c) The profit of the manufacturer in different models. (d) The profit of the CLSC in different models.

can better meet market demand and bring positive benefits to CLSCs.

5.5. Impact of Carbon Trading Price Factors. To obtain strong conclusions, we set the carbon trading price factor c_t, in combination with the relevant parameters set in the references, to $[0.1, 1]$ and hold the other parameter values constant. We can derive the impact of carbon trading price on the level of CE reduction and the supplier, manufacturer, and overall CLSC profits (Figure 6).

Figure 6(a) shows similar trends in CE reduction with the carbon trading price for both collection models, with the level of carbon reduction decreasing as the trading price increases. When the price of trading increases, the manufacturer's decision to increase the emission reduction level is inevitable to reduce the costs associated with CE.

Figure 6(b) demonstrates that the impact of the carbon trading price on suppliers' returns in both models is not significant, with a small increase in suppliers' returns when trading prices increase. The supplier-collecting scenario results in higher returns for suppliers.

Figure 6(c) shows that the trends of manufacturers' returns with carbon trading prices are similar for both collecting models, with manufacturers' returns decreasing and increasing as the trading price increases. Manufacturers' returns are higher in the supplier-collecting model.

Figure 6(d) shows that the trend in total CLSC profit with the trading price is similar to the trend in manufacturers' profit for both collecting models. It decreases and increases as the trading price increases, again with a higher total CLSC profit for the supplier-collecting model.

Through this analysis, we can conclude that the higher the price of carbon, the higher the level of emission reduction of the manufacturer. The manufacturer and the overall CLSC profits appear to decline and then increase, and the supplier profit is not significantly affected. When the price of carbon is high, manufacturers choose to increase their emission reduction levels to reduce the costs associated with emissions, thereby increasing the returns of CLSC members and improving their sustainability. Therefore, reasonable carbon limit control promotes carbon trading by companies, thus increasing the level of CE reduction in the manufacturing process and promoting the sustainability of CLSCs.

5.6. Comparison. In this section, we draw conclusions regarding different models by comparing them. We analyzed the relationship between the benefits to members under different collection approaches and considered different carbon reduction models.

We derive the optimal equilibrium solution for each member of each model using backward induction, compare the solutions under different models in the table, and draw the following inferences between certain equilibrium solutions:

Corollary 7

(1) $p_{0M} = p_{0ME} = p_{0\,MC} > p_{0\,S} = p_{0\,SE} = p_{0\,SC}$
(2) $T_{M\,M} > T_{M\,S}$
(3) $T_{S\,S} < T_{S\,SE} < T_{S\,SC}$

Corollary 7 (1) shows that the collecting price is lower in the supplier-collecting model and equal in the three-carbon abatement models. As manufacturers mainly carry out carbon abatement behavior, it does significantly impact the collection price. Therefore, the collection price is not related to carbon abatement under our assumptions. In contrast, a lower collecting price under the supplier-collecting model results in lower collecting costs and, thus, higher collecting volumes; hence, it is more beneficial to the sustainability of CLSCs.

Corollary 7 (2) suggests that the manufacturer-collecting model is more beneficial to manufacturers than the supplier-collecting model when carbon reduction behavior is not considered. The benefits are greater when the remanufacturer is the collector.

Corollary 7 (3) suggests that the benefits to suppliers are greatest in models where they are collectors and where carbon reduction and carbon trading are considered and are lowest in models where carbon reduction is not considered. Therefore, carbon reduction improves the sustainability of the CLSC and increases the benefits to the collector.

6. Conclusion

This study examines the optimal decision of a CLSC considering capacity constraints and stochastic demand under the cap-and-trade system. We establish a two-level supply chain comprising one supplier and one manufacturer. To make the model more realistic, we treat demand as a random variable, consider that the manufacturer's production capacity has a certain upper limit, and allow the manufacturer to make investments in capacity to expand the capacity to complete production demand. Meanwhile, based on this supply chain, the recycling activities of suppliers and manufacturers are considered, and the current low-carbon environment is added to consider the CE reduction of manufacturers and the government's carbon trading control. The following conclusions were drawn through a series of analyzes. [6,47–49]

(1) When the market becomes more sensitive to product prices, the profits of all CLSC participants and the entire CLSC are affected. To reduce consumer concerns about product prices, product manufacturers need to improve the quality of products and increase the marginal benefits of their products to consumers, which means that firms must improve the cost-effectiveness of their products. Manufacturing companies can increase the versatility of their production lines when they initially set them up, or they can find lower rental prices for their production lines and use line rentals instead of purchases.

(2) In contrast to previous findings that supplier collection can bring greater benefits to CLSC compared to manufacturer collection, supplier collection is not a weak option for collection activities. Companies can establish closer ties with suppliers and delegate the task of collecting products. Thus, the supplier's profit, product quality, profitability, and sustainability of the entire CLSC are effectively enhanced. Encourage companies to undertake collection and remanufacturing activities for higher returns; meanwhile, closer ties can be established with suppliers when products are first introduced to the market. The task of collecting can be delegated to suppliers.

(3) In the current real-world environment, as the green awareness of consumers improves, consumers, become more sensitive to carbon reduction in products, which will have a positive impact on individual members of CLSCs and the entire CLSCs. When consumers become more green-conscious, the carbon footprint of products becomes a consideration when they make purchases, encouraging companies to invest in CE reduction and strive to reduce CE in their production processes, thereby improving the sustainability of CLSCs.

(4) Under the government's CE control, the benefits of each member of the CLSC and the entire CLSCs will be enhanced, thus improving the carbon concerns of enterprises and the sustainability of CLSCs. As carbon pollution becomes progressively more severe, limiting CE from corporate production activities is important. In the early stage of promoting low-

carbon production, appropriate carbon trading can make the carbon emission reduction of enterprises more flexible and feasible. Encourage enterprises to invest more in CE reduction and strive to reduce CE in the production process to enhance the market reputation and thus increase revenue. Meanwhile, combining enterprises' carbon emission reduction investment with the government's carbon cap-and-trade policy can better achieve carbon emission reduction.

Improvements can be made in subsequent studies in various areas. First, the form of stochastic demand can be modeled by considering more complex and realistic stochastic distributions to obtain a more realistic mathematical model. Second, the inclusion of coordination and cooperation between CLSC members is an important developmental direction of current research on CLSCs. In addition to carbon trading controls, the sustainability of CLSCs could be considered in conjunction with additional carbon policies, such as carbon taxes, and continues to be a focus of research.

Appendix

A. Proof of Proposition 1 in Model M

In order to find the optimal solution for each decision variable in model M, the concavity of the manufacturer's profit function is first checked. The Hessian matrix of the manufacturer's profit function is as follows:

$$\begin{aligned}
H_M^M\left(k^M, p_0^M\right) &= \begin{bmatrix} \dfrac{\partial^2 \Pi_M^M}{\partial k^{M2}} & \dfrac{\partial^2 \Pi_M^M}{\partial p_0^M \partial k^M} \\[2ex] \dfrac{\partial^2 \Pi_M^M}{\partial k^M \partial p_0^M} & \dfrac{\partial^2 \Pi_M^M}{\partial p_0^{M2}} \end{bmatrix} \\
&= \begin{bmatrix} \dfrac{(-p_2 + s)}{m} & 0 \\[2ex] 0 & -2b \end{bmatrix}, \\
\left|H_{1x1}\right| &= \frac{\partial^2 \Pi_M^M}{\partial k^{M2}} \\
&= \frac{(-p_2 + s)}{m} \langle 0, \\
\left|H_{2x2}\right| &= \frac{\partial^2 \Pi_M^M}{\partial k^{M2}} \frac{\partial^2 \Pi_M^M}{\partial p_0^{M2}} - \frac{\partial^2 \Pi_M^M}{\partial k^M \partial p_0^M} \frac{\partial^2 \Pi_M^M}{\partial p_0^M \partial k^M} \\
&= \frac{(-p_2 + s)}{m} (-2b) \rangle 0.
\end{aligned} \tag{A.1}$$

The above results guarantee the concavity of the Hessian matrix of the manufacturer's profit function and therefore the optimal solution exists.

The proofs of Proposition 2-6 are similar.

B. Proof of Corollary 1 in Model M

$$\begin{aligned}
\frac{\partial p_0^{M*}}{\partial a} &= -\frac{1}{2b}\langle 0,\\
\frac{\partial \Pi_S^{M*}}{\partial a} &= \frac{(c_s-p_1)}{2}\langle 0,\\
\frac{\partial p_0^{M*}}{\partial b} &= \frac{p_1}{2b}-\frac{(-a+bp_1)}{2b^2}\\
&= \frac{a}{2b^2}\rangle 0,\\
\frac{\partial \Pi_S^{M*}}{\partial b} &= \frac{1}{2}(c_s-p_1)p_1\langle 0,\\
\frac{\partial k^{M^*}}{\partial m} &= \frac{-c_m-p_1+p_2-r}{(p_2-s)}\rangle 0,\\
\frac{\partial \Pi_M^{M^*}}{\partial m} &= \frac{c_m^2m^2+2c_mm^2(p_1-p_2+r)+m^2(p_1-p_2+r)^2+(p_2-s)^2(-p_2\beta+\beta p_2)^2}{2m^2(p_2-s)}\\
&= \frac{(c_m+p_1-p_2+r)^2}{2(p_2-s)}\rangle 0,\\
\frac{\partial p_0^{M*}}{\partial a} &= -\frac{1}{2b}\langle 0,\\
\frac{\partial \Pi_S^{M*}}{\partial a} &= \frac{(c_s-p_1)}{2}\langle 0,
\end{aligned} \tag{B.1}$$

The proof of Corollary 2 is similar.

C. Proof of Corollary 3 in Model ME

$$\begin{aligned}
\frac{\partial p_0^{S*}}{\partial a} &= -\frac{1}{2b}\langle 0,\\
\frac{\partial \Pi_S^{S*}}{\partial a} &= -\frac{p_1}{2}\langle 0,\\
\frac{\partial \Pi_M^{S^*}}{\partial a} &= \frac{p_1}{2}-\frac{(-a+bp_1)}{4b}+\frac{a+1/2(-a+bp_1)}{2b}=\frac{a+bp_1}{2b}\rangle 0,\\
\frac{\partial p_0^{S*}}{\partial b} &= \frac{p_1}{2b}-\frac{(-a+bp_1)}{2b^2}=\frac{a}{2b^2}\rangle 0,\\
\frac{\partial \Pi_S^{S*}}{\partial b} &= -\frac{p_1^2}{2}\langle 0,\\
\frac{\partial \Pi_M^{S^*}}{\partial b} &= \frac{p_1^2}{2}-\frac{p_1(-a+bp_1)}{4b}-\frac{p_1[a+(1/2)(-a+bp_1)]}{2b},\\
+\frac{(-a+bp_1)[a+(1/2)(-a+bp_1)]}{2b^2} &= \frac{1}{4}\left(-\frac{a^2}{b^2}+p_1^2\right)\langle 0,\\
\frac{\partial p_0^{M*}}{\partial a} &= -\frac{1}{2b}\langle 0,\\
\frac{\partial \Pi_S^{M*}}{\partial a} &= \frac{(c_s-p_1)}{2}\langle 0.
\end{aligned} \tag{C.1}$$

The proof of Corollary 4 is similar.

D. Proof of Corollary 5 in Model MC

$$\begin{aligned}
&\frac{\partial p_0^{MC*}}{\partial a} = -\frac{1}{2b} \langle 0,\\
&\frac{\partial \Pi_S^{MC*}}{\partial a} = -\frac{p_1}{2} \langle 0,\\
&\frac{\partial \Pi_M^{MC*}}{\partial a} = \frac{(a + bp_1)}{2b} \rangle 0,\\
&\frac{\partial p_0^{MC*}}{\partial b} = \frac{p_1}{2b} - \frac{(-a + bp_1)}{2b^2} = \frac{a}{2b^2} \rangle 0,\\
&\frac{\partial \Pi_S^{MC*}}{\partial b} = -\frac{p_1^2}{2} \langle 0,\\
&\frac{\partial \Pi_M^{MC*}}{\partial b} = \frac{1}{4}\left(-\frac{a^2}{b^2} + p_1^2\right) \langle 0.
\end{aligned} \tag{D.1}$$

The proofs of Corollary 6 are similar.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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