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Closed-Loop Supply Chain Models Considering Government Subsidy and Corporate Social Responsibility Investment

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Abstract: In addition to pursuing profits, more and more international enterprises are beginning to pay attention to environmental sustainability and corporate social responsibility (CSR). How to effectively encourage enterprises to undertake more CSR and maintain the sustainable development of society has become an urgent task for managers and researchers. Under this background, this paper considers the recycling of used products for environmental sustainability and takes into account profit donation as a CSR investment. Aiming at the decision-making of single-cycle closed-loop supply chain (CLSC) with a dominant retailer when considering government subsidies and CSR investment, and based on the Stackelberg Game analysis technology, we formulate three distinct donation (CSR investment) models; the centralized system's donation model, the manufacturer's donation model, and the retailer's donation model, and by doing system comparisons and numerical examples to analyze the impact of government subsidy and CSR investment on new product pricing and waste product recovery from the perspectives of government, environment and CLSC system. The results show that government subsidy is not only conducive to expanding market demand and increasing waste recycling rates, but also to improving CSR investment levels. Under the two decentralized decision-making models, regardless of whether the dominant retailer makes CSR investment, she can always get more channel profits than the manufacturer. From the view of environmental, economic, and social perspectives, the manufacturer makes CSR investment a better choice, and at this time the government has the best effect of implementing subsidy. Finally, based on the principle of cost sharing, a CSR cost sharing contract which can realize the coordination of CLSC is designed to solve the channel conflict and optimize the decision-making. Counterintuitively, the dominant retailer can gain more profits when it bears more cost in the CSR cost sharing contract.

Keywords: closed-loop supply chain; corporate social responsibility; government subsidy; Stackelberg game; coordination

1. Introduction

In recent years, with the continuous development of globalization and economy, the iterative speed of product updates is gradually accelerating, and the production of a large number of discarded products makes the problems of environmental pollution and resource shortage increasingly serious. How to properly dispose of discarded products has aroused widespread concern in society [1]. The recycling and remanufacturing of waste products offers an excellent opportunity for social and economic sustainability because it can save 50% of the cost, 60% of the energy, and 70% of the raw materials, and reduce air pollution by 80% [1–3]. This also makes enterprises focus not only on the use of forward supply chain for the procurement, production, and sales of new products, but also

gradually start to focus on the use of reverse supply chain for the recycling and utilization of waste products, that is, to implement closed-loop supply chain (CLSC) management [4]. In reality, Fuji Xerox, Ford, IBM, and other enterprises, through the implementation of CLSC management, actively carry out the recycling and remanufacturing of waste products, while achieving good economic benefits, and achieving a wide social reputation [1,5,6]. Therefore, CLSC management can effectively help companies achieve the balance of the triple bottom line of economic, social, and environmental responsibility, and play an important role for companies in achieving global sustainable development [7].

As is well-known, governments and consumers are focusing more on manufacturers' recycle and disposal of EOL (end of life) products [4], and many regulations and directives, such as WEEE Directive of the European Union (waste electrical and electronic equipment Directive), require manufacturers to assume responsibility for proper recycling and disposal of EOL products, which aim to recover the residual value of products as much as possible, reduce environmental implication of EOL products, and minimize the number of final waste products [8]. However, in many countries, especially emerging developing countries, due to the lack of advanced remanufacturing technology and other reasons, manufacturers generally lack the motivation to participate in the recycling and remanufacturing activities of waste products [9]. In this context, many national and regional governments are concerned about the recycling and remanufacturing of waste products, and have promulgated a series of laws and regulations to support enterprises in participating in the recycling and remanufacturing of waste products [10]. Among them government subsidies, as a form of financial incentive, have been implemented in many countries, including China, Sweden, and Germany [11–13]. For example, the United States, Japan, and Canada have begun allocating subsidies for the recycling of discarded electronics [9,10]. The Chinese government has long offered subsidies to manufacturers to support develop of recycling and remanufacturing activities [14,15]. It is clear that the government subsidy mechanism is an important driving force to support recycling and remanufacturing, however, almost all existing studies considering government subsidies or reward and punishment mechanisms ignore the influence of corporate social responsibility (CSR) behaviors of enterprises on decision-making and coordination of CLSC.

In fact, with continuous development of the global economy, how to effectively achieve coordinated development of the economy, society, and the environment has become an important topic of common concern for governments, enterprises, the media, and consumers. Under this background, to achieve long-term development, companies must change the traditional concept of profit as the sole goal in production and operation, and actively take responsibility for consumers, society, and the environment in the process of product production, sales, and distribution, which means fulfilling the corresponding CSR [16,17]. With the widespread attention of CSR from all walks of life, CSR has become one of the main influential factors in the strategic decision-making process of enterprises [18]. More and more well-known international companies such as Apple, Huawei, and Alibaba have started to release CSR reports regularly [19–21]. Furthermore, recent studies have shown that CSR behavior of enterprises can not only reduce the operational risk of enterprises and increase the value of enterprises, but also effectively promote the purchase behavior of consumers [22,23].

At the same time, from the perspective of supply chain enterprise practice, fulfilling CSR can not only establish a good image for the enterprise, but also effectively improve the company's marketing power and efficiency in the long run [24,25]. For example, Dettol Co. perceived a growth in the sales of Dettol products after the company implemented a CSR-related marketing strategy whereby upon purchase of any of their products a shilling is donated to charity [26]. Therefore, the company's CSR strategy helped its products stand out from other products in the market. Moreover, companies donate part of their profits to social welfare organizations as their own CSR investment, which not only helps improve their own performance, but also contributes to the sustainable development of society [25,26]. In reality, more and more companies have begun to perform CSR through donation activities, which not only enhances the public image and reputation of the company, but also achieves good economic and social benefits [26,27]. For example, Apple implemented a number of large-scale social welfare

activities and fulfilled CSR by actively donating to the society. Procter and Gamble stated that the CSR program has helped 280,000 children gain education in India through cumulative donations over the past eight years. Walmart donated $311.6 million to social and economic development, environmental protection, and hunger issues, fulfilling its CSR and facilitating the good operation of its supply chain [28]. Similarly, companies such as Google, Intel, and Microsoft also implement CSR through similar donation activities [29]. These examples illustrate how companies use donations as a core tool for CSR investment.

Integrating CSR into the classic framework of CLSC and considering its impacts on operations of CLSC are meaningful theoretically, empirically, and practically. Therefore, some scholars have begun to discuss the impact of CSR on the operation of CLSC. By combing the existing relevant literature, it can be found that the existing research can be roughly divided into two categories. The first one is from the perspective of CSR macro behavior, and it believes that enterprises can achieve the goal of improving the interests of stakeholders by setting the goal of maximizing social welfare considering consumer surplus, as discussed by Panda et al. [30], Shu et al. [31], and so on. Another kind of research is from the perspective of micro-investment, and believes that CSR behavior refers to an investment behavior in which an enterprise spends a certain amount of investment to improve the interests of stakeholders and stimulate consumption at the same time (Ni et al. [32], Huseh [17], Modak et al. [26] and so on).

However, the existing research describes CSR from the perspective of micro-investment generally and regards the CSR investment behavior of enterprises as a pure cost investment behavior similar to advertising or sales efforts, ignoring that many companies began to fulfill CSR through profit donation because profit donation can improve their reputation and create a better public image [26]. Secondly, the few existing studies on the impact of corporate donation on the operation of CLSC almost all assume that the channel leader is the manufacturer, and usually only consider that the manufacturer makes the CSR investment. In fact, with the rise of Walmart, Suning, and other retail giants, and the development of chain retail, in some industries, retail enterprises have gradually formed as the core of the supply chain partnership [6,33]. At the same time, in reality, many retail giants such as Walmart and Carrefour attach great importance to the construction of CSR and have achieved significant results. However, few studies have compared and analyzed the impact of CSR investment behavior of different member enterprises on the operation of CLSC. Thirdly, few existing studies have analyzed the impact of government recycling and remanufacturing subsidy mechanisms on enterprises' CSR investment behavior of different enterprises and CLSC performance from the perspective of the environmental, economic, and social. Finally, with the promotion and implementation of the extended producer responsibility system in various countries around the world (for example, the state council of China again published the notice of the general office of the state council on printing and distributing the implementation plan of the extended producer responsibility system in 2017), manufacturers are further required to assume more responsibility for the recovery and remanufacturing of waste products. Therefore, it is of great practical significance to study the influence of government subsidies and different CSR investment modes on the decision-making of CLSC with a dominant retailer under the channel structure when the manufacturer is responsible for recycling.

At the same time, decentralized decision-making will lead to the CLSC to produce double marginal effect, so that the overall performance of CLSC cannot reach the level of centralized decision-making. Recently, a variety of coordination contracts are used to improve the overall performance of CLSC, but there are few coordination contracts designed for the CLSC considering CSR investment and government subsidy.

Based on the above research situation, in this paper, we aim to discuss the following issues by distinguishing existing research:

1. In the CLSC considering government subsidies and CSR investment, when the different CLSC members make donations, what is the impact of the government's policy of recycling and remanufacturing subsidy on the wholesale and retail prices of new products, recovery rate, the CSR investment level, and channel performance?

2. Under the government's subsidy, how does the change of CSR investment (different member enterprises make donations) affect the CLSC pricing decision, CSR investment level, and channel performance? Which is a better decision choice for the subject to donate? Moreover, when consumers' sensitivity to CSR investment level changes, what impact will it have on CLSC decision making and channel performance?
3. How to formulate and implement appropriate contracts to effectively improve the performance of CLSC considering government subsidies and CSR investment?

To shed light on these research questions, this paper discusses a single-cycle CLSC consisting of a manufacturer and a dominant retailer considering government subsidy and CSR investment. Meanwhile, we investigate the impact of profit donation as CSR investment and government subsidy from the profit maximization motive. Based on observations from current practices and the extant literature, we consider three different CLSC decision models: (1) The central planner gets the government subsidy, undertakes the product recovery and profit donation under the centralized system (Model C); (2) the manufacturer gets the government subsidy, undertakes the product recovery and profit donation under the decentralized system (Model M); (3) the manufacturer gets the government subsidy and undertakes the product recovery, the retailer undertakes the profit donation under the decentralized system (Model R). We first characterize the optimal equilibrium solutions for the three models and discuss the effects of government subsidies and corporate profit donations on the optimal equilibrium solutions for the different decision models. Then, we systematically compare and analyze the equilibrium solutions under the three decision models. Finally, we design a CSR cost-sharing contract to effectively resolve channel conflicts between the manufacturer and retailer, thereby improving the efficiency of the CLSC.

The remainder of this paper is organized as follows. The next section presents the literature review. In Section 3, we describe the problem in detail, including assumptions and annotations. The modelling of different structures and solution are provided in Section 4. The analytical optimal results for the different CLSC structures are presented in Section 5. In Section 6, the channel coordination considering CSR cost sharing contract is discussed. Section 7 illustrates the numerical simulation. We conclude the paper in Section 8 and point out some possible directions for future research.

2. Literature Review

In this section, the literature closely related to our work can be classified as three main categories: (1) Product recovery management, pricing decision, and coordination contract in CLSC; (2) government subsidy and CLSC operation; (3) CSR and corporate donation in supply chain.

2.1. Product Recovery Management, Pricing Decision, and Coordination Contract in Closed-Loop Supply Chain (CLSC)

At present, many scholars have studied the operation management of CLSC from multiple perspectives. In these studies, pricing decision, recovery management, and coordination mechanism are the main research directions of most scholars. Savaskan et al. [5] earlier studied the impact of different recycling channel structures on CLSC pricing decisions and used two-part tariff contracts to ease channel conflicts and improve the efficiency of CLSC. Wei et al. [34] studied the influence of information asymmetry and channel power structure on the recovery and pricing decision of CLSC. Ke et al. [35] made analysis of competitive pricing and remanufacturing of CLSC under uncertain market demand and the optimal pricing decision of CLSC under fuzzy conditions, respectively. On the premise that there were two sales channels in the CLSC, Zheng et al. [36] used two-part pricing contracts to achieve the coordination of the CLSC under different channel power. Xie et al. [37] discussed the impact of revenue-sharing and cost-sharing contracts on CLSC recovery and pricing. On the premise that there are both defective product recycling and waste product recycling in a CLSC, Zhang et al. [38] used a revenue sharing contract to achieve the coordination of the CLSC. In consideration of the difference between new products and remanufactured products, Ferrer et al. [39] studied the differential pricing decisions of new products

and remanufactured products in the CLSC considering that the product life cycle was two-stage and multi-stage. Zhao et al. [40] studied the impact of patent licensing model and remanufacturing entity differences on service input and pricing decisions of CLSC. Wang et al. [41] analyzed the impact of single recycling channels and competitive recycling channels on CLSC pricing decisions.

The above literature has expanded the research direction of CLSC from multiple levels and enriched the research of CLSC on recovery management, pricing decision, and coordination strategy; it also helped us to better understand the impact of different power structures, recycling channels, and coordination contracts on the operation of CLSC. However, few studies have focused on the impact of government subsidy mechanisms on the operation of the CLSC. In fact, due to the significant economic and social benefits of recycling and remanufacturing of waste products, many governments have introduced financial incentives to promote and encourage enterprises to develop the recycling and remanufacturing of waste products [13,42]. Therefore, under government subsidy mechanisms, to research the operation of CLSC with CSR is in line with social trends and extends the scope of existing research.

2.2. Government Subsidy and CLSC Operation

Waste product recycling management and CLSC operation involve many stakeholders, including governments. Modeling government regulation and its impact on CLSC operation is a rapidly developing research area [15]. At the same time, government subsidy, as a financial incentive, has been widely implemented in many countries, including China, Sweden, Japan, and Germany [10–13]. Recently, some scholars have begun to study the impact of government subsidies on the operation of CLSC. Tan et al. [43] studied the impact of government remanufacturing subsidies on the operation of CLSC, and pointed out that government subsidies can effectively improve the recycling rate of waste products and remanufacturing technology. Wan et al. [9] comparatively analyzed the impact of government's recycling subsidies and remanufacturing subsidies on the recycling and pricing decisions of CLSC. Taking the Chinese auto parts industry as an example, Wang et al. [10] used a system dynamics method to analyze the impact of the government's subsidy on the recycling and remanufacturing of enterprises. Jena et al. [14] studied the impact of government incentives on the efficiency of CLSC recovery and overall profit under the premise of price competition. Chen et al. [44] studied the impact of the government's reward and punishment mechanism on green input and waste product recovery in the green CLSC. Ma et al. [45] studied the impact of government consumption subsidies on the dual-channel CLSC decision from the perspective of consumers, enterprises, and the system as a whole. Liu et al. [46] studied the impact of government incentives and price competition between formal and informal recycling channels on the WEEE recycling market. Guo et al. [47] studied the impact of government subsidies on CLSC recycling and production strategies, and pointed out that the government formulated a reasonable subsidy policy to facilitate the recycling of waste products. He et al. [48] studied the impact of government subsidies on the choice of sales channels and pricing decisions of a dual-channel CLSC.

The above research helps us to understand the impact of government subsidies on the operation of CLSCs. Moreover, it can be found that many governments are using subsidies to encourage relevant companies to participate in the recycling of waste products, mobilize the initiative of recycling and remanufacturing companies, including US, Canadian, German, and Chinese governments [10–13]. However, few studies have explored the impact of government subsidies on the operation of CLSC with CSR. According to the 2019 global top 25 supply chains released by Gartner, nearly all of them scored full marks on CSR, indicating that CSR has become an inevitable trend in the supply chain management. Therefore, a comprehensive study of the effects of government subsidy and CSR on the operation of CLSCs is helpful to expand the existing research scope.

2.3. Corporate Social Responsibility (CSR) and Corporate Donations in Supply Chains

CSR is defined as an enterprise's business activities and their impact on different social groups, including social concern, environmental protection, pollutant emission control, charitable donations,

etc. [49]. Among them, charitable donation is a kind of pro-social behavior and is considered an important part of CSR [3], and fulfilling CSR is also found to impact investment behavior on socially responsible initiatives, thus improving the efficiency and performance of firms [26]. CSR has been a wide concern in academia, and many scholars have studied the impact of CSR on the operation of supply chains from multiple perspectives. CSR is an evolving and dynamic concept, and there is currently no universally accepted and unified definition. Combining the literature, we can find that scholars' definitions and descriptions of CSR can be roughly divided into two categories. One type thinks that the CSR behavior of enterprises is to achieve the purpose of improving stakeholder and social welfare by setting goals that maximize consumer social welfare. For example, Panda et al. [50] studied the impact of manufacturers' CSR behavior on supply chain profit distribution and channel coordination. Modak et al. [51] introduced CSR into a dual-channel supply chain and analyzed the impact of manufacturers' CSR behavior on supply chain decision-making and coordination. Liu et al. [52] introduced CSR to a supply chain with multiple suppliers competing, and studied supply chain coordination issues that consider CSR behavior. Panda et al. [30] earlier introduced CSR to CLSCs, and research indicates that manufacturers' CSR behavior is conducive to improving the recovery rate of waste products and the performance of CLSCs. Shu et al. [31] analyzed the impact of CSR behavior and carbon emission constraint on enterprise carbon emission and waste product recovery in CLSCs. Liu et al. [53] studied the influence of CSR preference on the selection of reverse channel structure, pricing and recovery ratio of CLSCs.

The other type thinks that CSR refers to various investment behaviors in which the enterprise makes certain cost investments to improve the interests of its stakeholders. For example, Ni et al. [32] analyzed the internal relationship between the CSR investment behavior of upstream and downstream companies in the two-stage supply chain, and explored the impact of CSR investment behavior on supply chain performance. Ma et al. [54] studied the CSR coordination problem of the two-stage supply chain under the condition of asymmetric cost information, and proved that the two-part tariff contracts can realize the coordination of the supply chain with symmetric and asymmetric information, respectively. Liu et al. [55] studied the impact of symmetry and asymmetry of CSR cost information on supply chain decision-making and coordination. Wu et al. [56] studied the supply chain coordination problem with CSR investment, and compared and analyzed the impact of quantitative flexible contracts and wholesale price incentive contracts on the profits of member companies. Liu et al. [57] studied the impact of government CSR incentive subsidies on supply chain decisions and CSR investment levels. In terms of charitable donations, Aaya et al. [58] took product donations as an enterprise's CSR investment and analyzed the impact of the government's CSR subsidy on the two-stage supply chain decision-making. Zhu et al. [59] analyzed the impact of government incentive policies on remanufacturing donations from the perspectives of economic, environmental, and social welfare, respectively. Wang et al. [27] analyzed the influence of government CSR subsidies and different donor bodies on decision-making of CLSCs. Modak et al. [26] studied the selection of recovery channel and pricing decision of the CLSC when the dominant manufacturer is responsible for the CSR investment.

The above research has helped us better understand CSR practices and the impact of CSR on the operation of the supply chain. However, they still have the following insufficiencies compared with the practical problems: (1) The existing research generally considers the traditional manufacturer-led supply chain, and rarely involves the retailer-led situation. In fact, with the rapid development of retail giants such as Walmart and Jingdong, in many industries supply chain partnerships with retail companies as the core have been formed. (2) The existing research generally assumes that corporate CSR investment is a cost investment behavior similar to advertising, with less consideration that more and more companies begin to make CSR investment through donation behavior. (3) The existing research also rarely involves the impact of government recycling and remanufacturing subsidies on profit donations of different member companies. The problem of the comparative analysis of profit donation behavior of different member companies has been paid less attention to. (4) Few existing studies have proposed how to effectively coordinate the CLSC considering government subsidy and CSR investment.

To sum up, we borrow from some previous research assumptions, in the context of a single-cycle CLSC, the company's profit donation behavior as a CSR investment, waste recycling and remanufacturing activities carried out by manufacturer as environmentally sustainable. At the same time, the government provides a certain unit subsidy (financial subsidy policies) for each unit of waste product produced by the manufacturer. Therefore, we establish three decision-making models for profit donation by different entities, compare and analyze the impact of different donor entities on the operation of CLSC from the perspectives of economic, environmental, and social performance, and further design the CSR cost sharing contract to improve the efficiency of CLSC. Finally, the main conclusions in this paper and the validity of the coordination contract are analyzed and verified by numerical simulation. The research of this paper provides a theoretical reference for CLSC operation considering government recycling and remanufacturing subsidies and CSR investment.

3. Problem Description and Assumptions

We consider a single-cycle CLSC consists of a manufacturer and a dominant retailer. This assumption is in line with the conventional research on CLSC [31]. The manufacturer and retailer belong to the Stackelberg game under complete symmetry information. In the forward supply chain, the manufacturer is responsible for the production of the new product and the retailer is responsible for the sales of the new product to the end consumer. In the reverse supply chain, the manufacturer is responsible for recycling and remanufacturing waste products. It is assumed that there is no difference between the new product and the remanufactured product [5,34]. For example, Kodak sells cameras made from recycled waste products to consumers in the same market at the same price as cameras made from new materials [6].

At the same time, in order to reduce the environmental impact of waste products and improve manufacturers' enthusiasm for recycling and remanufacturing of waste products, the government will give manufacturers certain recycling and remanufacturing subsidies. Referring to the research of Wang et al. [10], the government subsidies in this paper are government financial subsidy policies. For example, China established the "WEEE Collection and Use of Management Practices Fund" on July 1, 2012. The government uses the funds to give companies a certain amount of subsidies for each amount of WEEE they dismantle [10,13].

3.1. Model Notations

For the sake of clarity, Table 1 summarizes the notations regarding decision variables and parameters in our models.

Table 1. Notations description.

Notations	Description
w	The unit wholesale price at which the retailer orders new products from the manufacturer
c_m	The manufacturer's unit cost of production a new product, $w > c_m$
c_r	The manufacturer's unit cost of remanufacturing a used product, to ensure that remanufacturingis economically feasible, $c_m > c_r$
A	A unit transfer payment made by a manufacturer to a consumer when recycling waste productsIn order to make recycling and remanufacturing waste products economically feasible, obviously $\Delta_1 = c_m - c_r - A > 0$
τ	Recycling of waste products, $0 \le \tau \le 1$
s	In order to improve manufacturers' enthusiasm for recycling and remanufacturing of waste products, the government gives units subsidy to manufacturers' recycling and remanufacturing, $s > 0$
m	The profit a retailer makes from selling a unit of a new product, $p = m + w$
$c(\tau)$	Cost of recovery effort of the recovery party. Refer to Savaskan et al. [5] etc., assume $c(\tau) = k\tau^2$, where k represents the scale parameter and $k > 0$
$h(d)$	The base cost of a manufacturer or retailer's corporate social responsibility (CSR) investment. Refer to Modak et al. [26], assume $h(d) = gd^2$,where g represents the manufacturer or retailer's scale parameter and $g > 0$
π_X^i	represents the profits obtained by member enterprises X under i decision model. Where $i = \{C, M, R\}$ represents the centralized CSR investment model, the manufacturer's CSR investment model and the retailer's CSR investment model, respectively. And $X = \{m, r, s\}$ represents the manufacturer, retailer, and the whole closed-loop supply chain (CLSC) system, respectively.

3.2. Model Description and Construction

In this paper, the manufacturer participates in the product recovery activity for environmentally sustainable development, since the manufacturer is the main participant of EPR (Extended Producer Responsibility) and is required to assume the responsibility of the product recovery for better environmental performance [27]. It is assumed that both manufacturer and retailer have the consciousness to make CSR investment. In order to better compare and analyze the impact of different CSR investment patterns on decision-making of CLSC, we assumed that manufacturer and retailer have the same cost structure when making CSR investment, and the charitable donation is an important embodiment of CSR. So, we consider that the manufacturer or the retailer makes CSR investment through donating a certain amount of money directly to social organizations for every unit of new product wholesale or sold [26]. Meanwhile, the CSR investment of manufacturer or retailer can bring good reputation and publicity for their products, thus effectively promoting the sales of new products. Referring to the research of Modak et al. [26], the market demand function is

$$q = a - \beta p + \theta d \tag{1}$$

where, a represents the market potential of the new product, $a > 0$, p represents the retail price of the retailer's new product, β represents the price sensitivity of consumers to new products, d represents the amount of direct donation (CSR investment level) by the manufacturer or retailer to a social good organization for each unit of new product wholesale or sale, θ represents the sensitivity coefficient of consumers to CSR invest level, $a > \beta p$ ensures that under any circumstance the demand at the retailer's end is non-negative, $\theta > \beta > 0$, $\theta > \beta$ indicates that consumers are more sensitive to the CSR investment level than the retail price [26].

In order to ensure the optimal recovery rate is bounded within a given range ($0 \le \tau \le 1$), the profit function of each member enterprise is concave, and the related expressions have certain economic feasibility. Consistent with previous research hypotheses (Savaskan et al. [5]; Zheng et al. [33]; Wei et al. [34]), the scaling parameters are assumed to be sufficiently large, that is, $k > \frac{g\beta(a-\beta c_m)(\Delta_1+s)+g\beta^2(\Delta_1+s)^2}{4g\beta-(\theta-\beta)^2}$, $g > \frac{\theta(\theta-\beta)}{2\beta}$.

4. Construction of CLSC Decision-Making Models Considering Different CSR Investment Modes under Government Subsidy

In this section, we propose three different CLSC decision models with government subsidy and CSR investment, namely, the centralized decision model for manufacturer and retailer to jointly conduct CSR investment (Model C), the decentralized model with the manufacturer conducting CSR investment (Model M), and the decentralized model in which the retailer conducts CSR investment (Model R). Model C is a benchmark case which is used to analyze the inefficiency of decentralized decision-making and derive the coordination mechanism of CLSC.

4.1. Centralized Decision Model (Model C)

Under Model C, all members of CLSC as a whole make a decision to maximize the total profits. That is, manufacturer and retailer jointly determine the retail price of new products, recycling rate of waste products, and the level of CSR investment. Meanwhile, in order to reduce the environmental impact caused by improper disposal of waste products, the government gives the CLSC a certain amount of subsidy to promote the recycling and remanufacturing of waste products. Therefore, in line with the studies of Wan [9] and Modak et al. [26], it can be concluded that the overall profit function of CLSC under this model is

$$\pi_s^C(p, d, \tau) = (p - c_m - d)(a - \beta p + \theta d) + (c_m - c_r - A + s)\tau(a - \beta p + \theta d) - gd^2 - k\tau^2 \tag{2}$$

The initial step to solve the model is to check the concavity condition of the profit function in the centralized decision model. The convexity condition can be checked by Hessian matrix H_c, which is calculated as follows:

$$H_c = \begin{pmatrix} \frac{\partial \pi_s^2}{\partial p^2} & \frac{\partial \pi_s^2}{\partial p \partial d} & \frac{\partial \pi_s^2}{\partial p \partial \tau} \\ \frac{\partial \pi_s^2}{\partial d \partial p} & \frac{\partial \pi_s^2}{\partial d^2} & \frac{\partial \pi_s^2}{\partial d \partial \tau} \\ \frac{\partial \pi_s^2}{\partial \tau \partial p} & \frac{\partial \pi_s^2}{\partial \tau \partial d} & \frac{\partial \pi_s^2}{\partial \tau^2} \end{pmatrix} = \begin{pmatrix} -2\beta & \theta+\beta & -\beta(\Delta_1+s) \\ \theta+\beta & -2(\theta+g) & \theta(\Delta_1+s) \\ -\beta(\Delta_1+s) & \theta(\Delta_1+s) & -2k \end{pmatrix} \quad (3)$$

Under the assumption of scale parameter k, g, it is easy to verify that, $\Delta_s^1 = -2\beta < 0$, $\Delta_s^2 = \begin{vmatrix} -2\beta & \theta+\beta \\ \theta+\beta & -2(\theta+g) \end{vmatrix} = 4\beta\big(\theta+g\big) - (\theta+\beta)^2 > 0$ and $\Delta_s^3 = \begin{vmatrix} -2\beta & \theta+\beta & -\beta(\Delta_1+s) \\ \theta+\beta & -2(\theta+g) & \theta(\Delta_1+s) \\ -\beta(\Delta_1+s) & \theta(\Delta_1+s) & -2k \end{vmatrix} = 2(k(\theta-\beta)^2 + g\beta^2(\Delta_1+s)^2 - 4kg\beta) < 0$. So, the Hessian matrix H_c of the profit function for centralized decision model is negative definite matrices, and the profit function $\pi_s^C(p,d,\tau)$ of the centralized channel is a concave function of p, d, τ. According to the first order condition, that is, $\frac{\partial \pi_s^C}{\partial p} = 0$, $\frac{\partial \pi_s^C}{\partial d} = 0$, $\frac{\partial \pi_s^C}{\partial \tau} = 0$, the overall optimal feedback functions of the CLSC system can be obtained as follows:

$$p^C = \frac{a + (\theta+\beta)d + \beta c_m - \beta(\Delta_1+s)\tau}{2\beta} \quad (4)$$

$$d^C = \frac{-a + \beta p + \theta(p - c_m + (\Delta_1+s)\tau)}{2(\theta+g)} \quad (5)$$

$$\tau^C = \frac{(\Delta_1+s)(a-\beta p+\theta d)}{2k} \quad (6)$$

Furthermore, the optimal retail price, CSR investment level, and recovery rate of the CLSC system can be obtained by combining Equations (4)–(6).

$$p^{C*} = \frac{ag(2k-\beta(\Delta_1+s)^2) + 2kg\beta c_m + k(\theta-\beta)(a-\theta c_m)}{g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2} \quad (7)$$

$$d^{C*} = \frac{k(\theta-\beta)(a-\beta c_m)}{g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2} \quad (8)$$

$$\tau^{C*} = \frac{g\beta(a-\beta c_m)(\Delta_1+s)}{g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2} \quad (9)$$

According to formula (1), the optimal market demand for new products under Model C can be calculated as

$$q^{C*} = \frac{2kg\beta(a-\beta c_m)}{g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2} \quad (10)$$

Finally, substituting Equations (7)–(9) into Equation (2), the optimal total profits of CLSC under centralized decision-making can be obtained as

$$\pi_s^{C*} = \frac{kg(a-\beta c_m)^2}{g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2} \quad (11)$$

After simple mathematical arrangement, the relevant equilibrium results under Model C are shown in the second column of Table 2.

Table 2. Equilibrium results under different decision models.

	Model C (*i*=*C*)	**Model M (*i*=*M*)**	**Model R (*i*=*R*)**
w^{i*}	null	$\frac{ag\Delta_4+\Delta_6}{2\Delta_3}$	$\frac{ag\Delta_4+\Delta_9}{\Delta_{10}}$
τ^{i*}	$\frac{g\beta(a-\beta c_m)(\Delta_1+s)}{\Delta_3}$	$\frac{g\beta(a-\beta c_m)(\Delta_1+s)}{2\Delta_3}$	$\frac{g\beta(a-\beta c_m)(\Delta_1+s)}{\Delta_{10}}$
d^{i*}	$\frac{k(\theta-\beta)(a-\beta c_m)}{\Delta_3}$	$\frac{k(\theta-\beta)(a-\beta c_m)}{2\Delta_3}$	$\frac{k(\theta-\beta)(a-\beta c_m)}{\Delta_{10}}$
m^{i*}	null	$\frac{a-\beta c_m}{2\beta}$	$\frac{(a-\beta c_m)\Delta_{11}}{\Delta_{10}}$
p^{i*}	$\frac{ag\Delta_4+\Delta_5}{\Delta_3}$	$\frac{2ag\beta\Delta_7+\Delta_8}{2\beta\Delta_3}$	$\frac{2ag\Delta_7+\Delta_{12}}{\Delta_{10}}$
q^{i*}	$\frac{2kg\beta(a-\beta c_m)}{\Delta_3}$	$\frac{kg\beta(a-\beta c_m)}{\Delta_3}$	$\frac{2kg\beta(a-\beta c_m)}{\Delta_{10}}$
π_m^{i*}	null	$\frac{kg(a-\beta c_m)^2}{4\Delta_3}$	$\frac{kg^2\beta(a-\beta c_m)^2\Delta_2}{\Delta_{10}^2}$
π_r^{i*}	null	$\frac{kg(a-\beta c_m)^2}{2\Delta_3}$	$\frac{kg(a-\beta c_m)^2}{\Delta_{10}}$
π_s^{i*}	$\frac{kg(a-\beta c_m)^2}{\Delta_3}$	$\frac{3kg(a-\beta c_m)^2}{4\Delta_3}$	$\frac{kg(a-\beta c_m)^2\Delta_{13}}{\Delta_{10}^2}$

* represents the equilibrium state of variables or functions.

4.2. The Decision Model for Manufacturer's CSR Investment (Model M)

Under Model M, the manufacturer is not only responsible for the production of new products and the recycling and remanufacturing of waste products, but also makes certain CSR investment. In order to improve manufacturers' enthusiasm for recycling and remanufacturing of waste products, government departments give manufacturers a certain subsidy. The retailer is only responsible for selling the new product to the consumer, similar to Section 4.1, the profit functions of manufacturer and retailer can be expressed as

$$\pi_m^M(w,d,\tau) = (w-c_m-d)(a-\beta(w+m)+\theta d)+(c_m-c_r-A+s)\tau(a-\beta(w+m)+\theta d)-gd^2-k\tau^2 \quad (12)$$

$$\pi_r^M(m) = m(a-\beta(w+m)+\theta d) \quad (13)$$

According to the game sequence of CLSC dominated by retailer, the reverse recursion method is used to solve the problem.

$$\text{The Hessian matrix of } \pi_m^M \text{ is } H_m = \begin{pmatrix} \frac{\partial\pi_m^2}{\partial w^2} & \frac{\partial\pi_m^2}{\partial w\partial d} & \frac{\partial\pi_m^2}{\partial w\partial\tau} \\ \frac{\partial\pi_m^2}{\partial d\partial w} & \frac{\partial\pi_m^2}{\partial d^2} & \frac{\partial\pi_m^2}{\partial d\partial\tau} \\ \frac{\partial\pi_m^2}{\partial\tau\partial w} & \frac{\partial\pi_m^2}{\partial\tau\partial d} & \frac{\partial\pi_m^2}{\partial\tau^2} \end{pmatrix} = \begin{pmatrix} -2\beta & \theta+\beta & -\beta(\Delta_1+s) \\ \theta+\beta & -2(\theta+g) & \theta(\Delta_1+s) \\ -\beta(\Delta_1+s) & \theta(\Delta_1+s) & -2k \end{pmatrix},$$

it is easy to verify that $\Delta_m^1 = -2\beta < 0$, $\Delta_m^2 = 4\beta\big(\theta+g\big)-(\theta+\beta)^2 > 0$, $\Delta_m^3 = 2(k(\theta-\beta)^2+g\beta^2(\Delta_1+s)^2-4kg\beta) < 0$. So, the Hessian matrix H_m of profit function for Model M is negative definite matrices, and $\pi_m^M(w,d,\tau)$ is a strictly concave function of w,d,τ. According to the first order condition, that is, $\frac{\partial\pi_m^M}{\partial w} = 0$, $\frac{\partial\pi_m^M}{\partial d} = 0$ and $\frac{\partial\pi_m^M}{\partial\tau} = 0$, the best feedback functions of new product's wholesale price, CSR investment level, and waste product recovery are obtained as

$$w^M = \frac{g(a-\beta m)(2k-\beta(\Delta_1+s)^2)+2kg\beta c_m+k(\theta-\beta)(a-\beta m-\theta c_m)}{g\beta(4k-\beta(\Delta_1+s)^2)-k(\theta-\beta)^2} \quad (14)$$

$$d^M = \frac{k(\theta-\beta)(a-\beta m-\beta c_m)}{g\beta(4k-\beta(\Delta_1+s)^2)-k(\theta-\beta)^2} \quad (15)$$

$$\tau^M = \frac{g\beta(a-\beta m-\beta c_m)(\Delta_1+s)}{g\beta(4k-\beta(\Delta_1+s)^2)-k(\theta-\beta)^2} \quad (16)$$

Substituting Equations (14)–(16) into Equation (13), we can easily get $\frac{\partial \pi_r^2}{\partial m^2} = \frac{-4kg\beta^2}{4kg\beta - g\beta^2(\Delta_1+s)^2 - k(\theta-\beta)^2} < 0$, so $\pi_r^M(m)$ is strictly concave in. According to the first-order condition, the optimal unit profit of the retailer can be obtained as

$$m^{M*} = \frac{(a-\beta c_m)}{2\beta} \tag{17}$$

Substituting Equation (17) into Equations (14)–(16), the optimal wholesale price of new products, CSR investment level, and recycling rate of waste products can be obtained as

$$w^{M*} = \frac{ag(2k-\beta(\Delta_1+s)^2) + g\beta c_m(6k-\beta(\Delta_1+s)^2) + k(\theta-\beta)(a-(2\theta-\beta)c_m)}{2(g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2)} \tag{18}$$

$$d^{M*} = \frac{k(\theta-\beta)(a-\beta c_m)}{2(g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2)} \tag{19}$$

$$\tau^{M*} = \frac{g\beta(a-\beta c_m)(\Delta_1+s)}{2(g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2)} \tag{20}$$

According to $p = w + m$ and Equation (1), the optimal retail price and market demand of new product can be obtained as

$$p^{M*} = \frac{2ag\beta(3k-\beta(\Delta_1+s)^2) + 2kg\beta^2 c_m + k(\theta-\beta)(2a\beta-\theta(a+\beta c_m))}{2\beta(g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2)} \tag{21}$$

$$q^{M*} = \frac{kg\beta(a-\beta c_m)}{g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2} \tag{22}$$

Furthermore, by substituting Equations (18)–(21) into Equations (12)–(13), the profits of manufacturer, retailer, and whole CLSC system can be obtained as

$$\pi_m^{M*} = \frac{kg(a-\beta c_m)^2}{4(g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2)} \tag{23}$$

$$\pi_r^{M*} = \frac{kg(a-\beta c_m)^2}{2(g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2)} \tag{24}$$

$$\pi_s^{M*} = \frac{3kg(a-\beta c_m)^2}{4(g\beta(4k-\beta(\Delta_1+s)^2) - k(\theta-\beta)^2)} \tag{25}$$

After simple mathematical arrangement, the relevant equilibrium results under Model M are shown in the third column of Table 2.

4.3. The Decision Model for Retailers' CSR Investment (Model R)

Under Model R, the manufacturer is responsible for new product production, recycling and remanufacturing of waste products, while the retailer is responsible for new product sales and CSR investment. Government departments give the manufacturer a certain subsidy. At this point, similar to Sections 4.1 and 4.2, the profit functions of manufacturer and retailer can be expressed as

$$\pi_m^R(w,\tau) = (w-c_m)(a-\beta(w+m)+\theta d) + (c_m-c_r-A+s)\tau(a-\beta(w+m)+\theta d) - k\tau^2 \tag{26}$$

$$\pi_r^R(m,d) = (m-d)(a-\beta(w+m)+\theta d) - gd^2 \tag{27}$$

Similar to the processing in Section 4.2, the reverse recursion method is adopted to obtain the relevant equilibrium results under Model R, as shown in the fourth column of Table 2.

Where, $c_m - c_r - A = \Delta_1$, $4k - \beta(\Delta_1 + s)^2 = \Delta_2$, $g\beta\Delta_2 - k(\theta - \beta)^2 = \Delta_3$, $2k - \beta(\Delta_1 + s)^2 = \Delta_4$, $2kg\beta c_m + k(\theta - \beta)(a - \theta c_m) = \Delta_5$, $g\beta c_m(6k - \beta(\Delta_1 + s)^2) + k(\theta - \beta)(a - (2\theta - \beta)c_m) = \Delta_6$, $3k - \beta(\Delta_1 + s)^2 = \Delta_7$, $2kg\beta^2 c_m + k(\theta - \beta)(2a\beta - \theta(a + \beta c_m)) = \Delta_8$, $g\beta c_m(6k - \beta(\Delta_1 + s)^2) - kc_m(\theta - \beta)^2 = \Delta_9$, $2g\beta\Delta_2 - k(\theta - \beta)^2 = \Delta_{10}$, $g\Delta_2 + k(\theta - \beta) = \Delta_{11}$, $kc_m(2g\beta - (\theta - \beta)^2) + k(\theta - \beta)(a - \beta c_m) = \Delta_{12}$, $3g\beta\Delta_2 - k(\theta - \beta)^2 = \Delta_{13}$. Under the assumption of scale parameter $k, g, \Delta_1, \Delta_2, \cdots, \Delta_{13} > 0$.

5. Equilibrium Result Analysis

In this section, we first analyze the impact of government recycling and remanufacturing subsidies on equivalent variables and profits of CLSCs. Secondly, we analyze the influence of consumer sensitivity to CSR investment on CLSC decision-making and performance. Finally, we compare and analyze the equilibrium variables under different decision models.

Property 1. $\frac{\partial w^{R*}}{\partial s} < \frac{\partial w^{M*}}{\partial s} < 0$, $\frac{\partial \tau^{M*}}{\partial s} > \frac{\partial \tau^{R*}}{\partial s} > 0$.

Proof. See Appendix A.

Property 1 shows that in the CLSC considering government subsidy and CSR investment, whether the manufacturer or the retailer makes CSR investment, with the increase of governments' recycling and remanufacturing subsidy, the manufacturer will not only increase the recycling rate of waste products, but also reduce the wholesale price of new products. In fact, with the increase of government subsidies, regardless of whether the manufacturer has invested in CSR or not, it will try to improve the recycling rate of waste products in order to obtain higher marginal benefits brought by recycling and remanufacturing of waste products. The increase of waste product rate can further reduce the average cost of new products for the manufacturer, so the manufacturer will also reduce the wholesale price of new products to encourage retailers to lower retail prices, aiming to stimulate consumption and further improve the market demand and the recovery rate of waste products, finally achieving the purpose of gaining more income.

Furthermore, with the increase of government subsidies for recycling and remanufacturing, when the retailer makes CSR investment, the wholesale price of new products decreases greatly, and when the manufacturer makes CSR investment, the recycling rate of waste products increases greatly. This is because the government subsidy can also improve the CSR investment level of CLSC (Property 2 indicates that the increase of government subsidy can prompt manufacturer or retailer to increase the CSR investment level), so with the increase of government subsidy for recycling and remanufacturing, the manufacturer's CSR investment cost will increase with its own CSR investment level. Therefore, in order to make up the cost of increasing CSR investment, the manufacturer will reduce the extent of wholesale price reduction to improve the unit marginal profit. Meanwhile, the manufacturer will make more efforts to improve the recycling rate of waste products to win more subsidies from the government and further reduce the production cost of new products, so as to ensure the increase of its own profits. Therefore, with the increase of the government's subsidy, compared with the retailer's CSR investment, the wholesale price reduction of new products is relatively smaller while the recovery rate of waste products is relatively larger under the manufacturer's CSR investment.

Property 2. $\frac{\partial p^{M*}}{\partial s} < \frac{\partial p^{R*}}{\partial s} < 0$, $\frac{\partial q^{M*}}{\partial s} > \frac{\partial q^{R*}}{\partial s} > 0$, $\frac{\partial d^{M*}}{\partial s} > \frac{\partial d^{R*}}{\partial s} > 0$.

Proof. See Appendix A.

Property 2 shows that in the CLSC considering government subsidy and CSR investment, whether manufacturer or retailer makes the CSR investment, with the increase of government subsidy, the retail price of new products will reduce, and the market demand and the level of CSR investment will increase. In fact, with the increase of government subsidy, the manufacturer takes the initiative to lower the wholesale price of new products, and the dominant retailer will lower the retail price of new products to respond to manufacturer and further stimulate consumption. Meanwhile, the profits of manufacturer and retailer are mainly determined by the market demand of new products, and the CSR investment level is the key factor influencing market demand (Wang et al. [1] also pointed out that CSR behavior of enterprises is an important factor influencing consumers' purchasing behavior). Therefore, with the increase of government subsidies, both the manufacturer and retailer will increase CSR investment level in order to bring greater market demand.

Furthermore, compared with the dominant retailer's CSR investment, the retail price of new products decreases more, and the market demand and CSR investment level increase more when the manufacturer makes CSR investment. Actually, as a follower, the manufacturer has relatively weaker bargaining power in the CLSC and is more dependent on market demand. Therefore, with the increase of government subsidies, the manufacturer will be more motivated to increase CSR investment to stimulate consumption and increase market demand so as to ensure the increase of its own profits. At the same time, when the manufacturer makes CSR investment, the retailer as the dominant of CLSC, enjoys more benefits that brought by the CSR investment of manufacturer. Therefore, the retailer will strategically increase the retail price reduction extent at this time to stimulate consumption and increase market demand, so as to encourage the manufacturer to further increase CSR investment level and achieve the purpose of consolidating its own market leadership. Finally, since manufacturers' CSR investment is accompanied by a larger reduction extent in the price of new products and a larger increase extent in CSR investment, the market demand also has larger increase extent at this time.

Wang et al. [27] shows that the implementation of CSR subsidy by the government is conducive to improving the recovery rate and CSR investment level. And our research further shows that government subsidy can also improve the recovery rate and CSR investment level. Meanwhile, we find that the recycling decision in the CLSC is inherently consistent with the CSR investment decision, that is, there is no conflict between the economic benefits brought by recycling and remanufacturing and the social benefits brought by CSR investment. Therefore, the internal relationship between the recycling and the CSR investment decision of the CLSC should be taken into account when the members of the CLSC make decisions, so as to achieve the synchronous increase of economic benefits, environmental benefits, and social benefits. This conclusion also provides some reference for the government department to formulate policies on corporate recovery and CSR implementation.

Property 1 and Property 2 jointly reveal that whether the manufacturer or the retailer makes CSR investment, with the increase of government subsidies, it is not only beneficial to reduce the wholesale price and retail price of new products and stimulate consumption, but also to improve the recycling rate of waste products and CSR investment level of CLSC. Furthermore, the government's policy can achieve the best effect by recycling and remanufacturing subsidy when the manufacturer makes CSR investment.

Property 3. $\frac{\partial \pi_m^{L*}}{\partial s} > 0$, $\frac{\partial \pi_r^{L*}}{\partial s} > 0$, $\frac{\partial \pi_s^{L*}}{\partial s} > 0$. *Where*, $L = \{M, R\}$.

Proof. See Appendix A.

Property 3 shows that in the CLSC considering government subsidy and CSR investment, whether the manufacturer or the retailer makes CSR investment, the overall profits of the manufacturer, retailer, and whole CLSC will increase with the government's subsidy. This is because the increase of government subsidies not only enhances the waste product recycling and remanufacturing, but can also effectively improve the CSR investment level of CLSC, thus greatly stimulating consumption and enhancing market demand, therefore, the CLSC members and the whole system can benefit accordingly.

Wan et al. [9] pointed out that government recycling and remanufacturing subsidy is conducive to increasing the profits of all CLSC members. Meanwhile, we further reveal that in the CLSC with CSR investment by the manufacturer or retailer, the government recycling and remanufacturing subsidy mechanism is not only conducive to improving the recycling rate of waste products and increasing the profits of CLSC members, but also conducive to improving the CSR investment level.

In terms of joint Property 1, 2, and 3, whether the manufacturer or the retailer makes CSR investment, the government subsidy will not only help to reduce the wholesale and retail prices of new products, but also improve the recycling rate of waste products, market demand, and CSR investment level, increasing the profits of CLSC members and the whole system. Therefore, government subsidy is beneficial to consumers, environment, social welfare, and the CLSC members and system as a whole. Moreover, government subsidy policy has the best effect when the manufacturer makes CSR investment.

Property 4. (1) $\frac{\partial w^{L*}}{\partial \theta} > 0$, $\frac{\partial \tau^{L*}}{\partial \theta} > 0$, $\frac{\partial d^{L*}}{\partial \theta} > 0$, $\frac{\partial p^{L*}}{\partial \theta} > 0$, $\frac{\partial q^{L*}}{\partial \theta} > 0$, (2) $\frac{\partial \pi_m^{L*}}{\partial \theta} > 0$, $\frac{\partial \pi_r^{L*}}{\partial \theta} > 0$, $\frac{\partial \pi_s^{L*}}{\partial \theta} > 0$. *Where*, $L = \{M, R\}$.

Proof. See Appendix A.

Property 4 shows that in the CLSC considering government subsidy and CSR investment, whether the manufacturer or the retailer makes CSR investment, as the consumers become more sensitive to CSR investment, the wholesale and retail price, market demand, the recovery rate of used product, and CSR investment level will all increase. Meanwhile, the profits of CLSC members and whole system will also increase. This is because whether the manufacturer or retailer makes CSR investment, it will actively increase their CSR investment levels in order to better attract consumers. Since the cost of CSR investment has increased, the manufacturer or retailer will make up for their losses in CSR investment by increasing wholesale or retail prices. However, the rise in wholesale and retail price will not significantly affect consumers' purchase needs, and consumers are also more willing to pay for companies that actively undertake CSR (in fact, without considering government subsidy mechanisms, Panda et al. [30] also show that consumers are willing to pay higher prices for products with CSR attributes). At the same time, the increase in market demand for new products and the recovery rate of used products will also increase the profits of CLSC members and whole system.

Property 4 reveals that the CSR investment behavior of manufacturer or retailer increases their own costs, and consumers need to share a certain amount of corporate CSR investment costs, which reduces the effectiveness of consumers in purchasing products to a certain extent. On the whole, the CSR investment behavior of the enterprise has brought higher market demand and the recovery rate of waste products. Therefore, the CSR investment is extremely beneficial to CLSC members, social benefits, and environmental protection.

Proposition 1. In the CLSC considering government subsidy and CSR investment, when the manufacturer or retailer makes CSR investment under decentralized decision-making, the wholesale price satisfies $w^{M*} > w^{R*}$.

Proof. See Appendix A.

Proposition 1 shows that in the CLSC considering government subsidy and CSR investment, compared with manufacturer makes CSR investment, it is more conducive to reducing the wholesale price of new product when the dominant retailer makes CSR investment. In fact, as the follower of CLSC, the manufacturer already makes less profit than the dominant retailer (Proposition 3 also shows that the dominant retailer always makes more profit than the manufacturer). Therefore, when the manufacturer makes CSR investment, she will relatively increase the wholesale price in order to make up for its own CSR investment cost. On the other hand, the increase in demand caused by the CSR

investment in the end will be stronger than the decrease in demand caused by the wholesale price, so it is more advantageous for the manufacturer to set a higher wholesale price at this time.

Proposition 1 reveals that when the manufacturer makes CSR investment, it will increase the wholesale prices compared to the retailer makes CSR investment. At this time, the manufacturer's CSR investment will have two effects on the demand terminal. On one side, the increase in market demand brought by CSR investment; on the other hand, the decrease in market demand caused by the increase in wholesale prices. And by the analysis of equilibrium solution, it can be found that the effect of increasing CSR investment on demand is stronger than the effect of decreasing demand caused by rising wholesale prices. Therefore, in a retail-oriented CLSC when the manufacturers make CSR investment, it can appropriately increase the wholesale prices to add their own profits.

Proposition 2. *In the CLSC considering government subsidy and CSR investment, the decision variables in three different models satisfy* $\tau^{C*} > \tau^{M*} > \tau^{R*}$, $d^{C*} > d^{M*} > d^{R*}$, $p^{R*} > p^{M*} > p^{C*}$. *Consequently, we have* $q^{C*} > q^{M*} > q^{R*}$.

Proof. See Appendix A.

Proposition 2 shows that in a CLSC considering government subsidy and CSR investment, compared with decentralized decision-making, the retail price of new products is the lowest under centralized decision-making and the recycling rate of waste products, CSR investment level, and market demand are the highest. Under decentralized decision-making, compared with the retailer's CSR investment, when the manufacturer makes CSR investment, the retail price of new product is lower, the recycling rate of waste products, CSR investment level, and market demand are higher.

In fact, under centralized decision-making, the manufacturer and retailer make decisions as a whole, which effectively eliminates the "double marginal" effect in the CLSC. Therefore, each equilibrium result under centralized decision-making is better than that of decentralized decision-making. Under decentralized decision-making, compared with the dominant retailer, the manufacturer has weaker bargaining power in the CLSC and is more dependent on market demand, so the manufacturer will provide higher CSR investment levels when she makes CSR investments and aims to stimulate consumption more effectively; finally, it can obtain higher profits (Proposition 3 also shows that the profit of manufacturer is greater when the manufacturer makes CSR investment). At the same time, the manufacturer will be more motivated to recycle more used products to reduce production costs and ultimately increase profits. At this time, the retailer as the leader of CLSC fully enjoys the benefits brought by the manufacturer's CSR investment, so in order to maintain its dominant position, it will provide a relatively low retail price to stimulate consumption and make up for the manufacturer's CSR investment costs, while achieving the purpose of motivating manufacturer to further increase the CSR investment level.

Proposition 2 reveals that the retailer's CSR investment will increase its own cost, which will affect the retailer's pricing strategy for new products. This aspect shows that the CSR investment will bring direct costs to enterprises, but in the long run, it can bring more profits and stable development to enterprises. On the other hand, consumers need to share a certain amount of cost for the company's CSR investment, but reduce the environmental pollution caused by waste products, so as to increase the company's profits, and it will bring about larger society welfare.

Modak et al. [26] pointed out that in the CLSC with a dominant manufacturer, the CSR investment behavior of the dominant manufacturer was conducive to improving the recovery rate of waste product and market demand of new product. We further show that in the retail-led CLSC, the CSR investment of the dominant retailer and manufacturer both are conducive to improving the recovery rate of waste product, CSR investment level, and market demand of new product. Moreover, the manufacturer's CSR investment is significantly better than retailer's CSR investment.

Comparing Proposition 1 and Proposition 2, in a CLSC considering government subsidy and CSR investment, when the manufacturer or retailer makes a CSR investment, the changes in wholesale

price and retail price of new product are not completely consistent. Specifically, the wholesale price is lower when the retailer makes CSR investment, while the retail price is lower when the manufacturer makes CSR investment. This shows that enterprises will have a certain cost increase due to the CSR investment, so the manufacturer will correspondingly increase the wholesale price when it makes CSR investment, and the retailer will correspondingly increase the retail price when it makes CSR investment. On the other hand, it also shows that in the CLSC, the CSR investment behavior of the enterprises indirectly affects the pricing decision, and that the CSR investment of different entities has different impacts on the pricing decision.

Proposition 3. *In the CLSC considering government subsidy and CSR investment, the profits of CLSC members in three different models satisfy* $\pi_m^{M*} > \pi_m^{R*}$, $\pi_r^{M*} > \pi_r^{R*}$, $\pi_r^{M*} > \pi_m^{M*}$, $\pi_r^{R*} > \pi_m^{R*}$. *Consequently, we have* $\pi_s^{C*} > \pi_s^{M*} > \pi_s^{R*}$.

Proof. See Appendix A.

Proposition 3 shows that in a CLSC considering government subsidy and CSR investment, under decentralized decision-making, compared with the retailer making CSR investment, the profit of the manufacturer, retailer, and whole CLSC system are all greater when the manufacturer makes CSR investment, but the total profits of the CLSC system is still lower than that of centralized decision-making. Regardless of whether the retailer makes the CSR investment, the retailer as the leader of CLSC always obtains more profit than the manufacturer. This is because when the manufacturer makes CSR investment, the waste product recovery rate and the demand for new product are relatively large, so the manufacturer, retailer, and CLSC system all make greater profits when the manufacturer makes CSR investment.

From the perspective of CSR conscientiousness, Panda et al. [30] pointed out that in the CLSC dominated by a manufacturer, the profit of manufacturer will decline due to its CSR behavior. However, from the perspective of CSR investment, we show that in a retail-led CLSC, the CSR investment behavior of manufacturer is more conducive to improving the performance of all CLSC members. This conclusion also provides some reference for the membership in the CLSC to implement CSR in a certain way.

To sum up, in a CLSC considering government subsidy and CSR investment, whether from the perspective of consumers, society, and the environment, or improving the profits of CLSC members, centralized decision-making is better than decentralization. Under decentralized decision-making, compared with the dominant retailer making CSR investment, when the manufacturer makes CSR investment it is more conducive to lowering retail prices, increasing market demand and CSR investment levels. On the other hand, it is more conducive to mitigating the double marginal effects of CLSC, improving the members and overall performance of CLSC, and promoting the long-term stable development of CLSC. At this time, the implementation of government recycling and remanufacturing subsidy mechanisms is more effective when the manufacturer makes CSR investment. Therefore, the government departments can guide the dominant retailer to jointly formulate reasonable pricing strategies to encourage the manufacturer to increase CSR investment level, which is extremely beneficial to consumer, social benefits, environmental protection, the CLSC members, and whole system.

6. Channel Coordination

Through the analysis in the previous section of this paper, it is found that under decentralized decision making, regardless of the CSR investment of manufacturer or retailer, the profits of the entire CLSC system can be improved to a certain extent, and compared with the retailer's CSR investment, when the manufacturers makes CSR investment it is more conducive to increasing the total profits of the CLSC, but it still cannot reach the optimal level under centralized decision-making. Therefore, it is

necessary to design a reasonable contract to coordinate the CLSC when the manufacturer makes CSR investment, so as to reach the optimal level under centralized decision-making.

In this section, we will design a CSR cost sharing contract (w^{MS}, t) to achieve the coordination of CLSC when the manufacturer makes CSR investment. The specific steps are: Primarily, the dominant retailer cannot only enjoy the benefits brought by the manufacturer's investment, and should take the initiative to bear a certain CSR investment cost for the manufacturer ($(1-t)gd^2$, $t \in (0, 1)$) and reduce the retail price to the centralized decision-making level, and to encourage the manufacturer to increase the level of CSR investment and waste product recovery rate to reach the level of centralized decision-making. At the same time, the manufacturer re-offers a new wholesale price w^{MS} to respond to retailers' aggressive price decreases. Therefore, under this CSR cost sharing contract, the profit functions of manufacturer and retailer can be expressed as (use "MS" to represent the coordination model when manufacturer makes CSR investment under government's subsidy)

$$\pi_m^{MS}(w, d, \tau) = (w - c_m - d)(a - \beta(w + m) + \theta d) + (\Delta_1 + s)\tau(a - \beta(w + m) + \theta d) - k\tau^2 - tgd^2 \quad (28)$$

$$\pi_r^{MS}(m) = m(a - \beta(w + m) + \theta d) - (1 - t)gd^2 \quad (29)$$

Proposition 4. *When the CSR cost sharing contract parameters satisfy* $w^{MS*} = \frac{ag\Delta_{22} + \Delta_{23}}{\Delta_3}$, $t \in [t^*, t^{**}]$, *the CSR cost sharing contract can fully realize the coordination of CLSC, where* $p^{MS*} = p^{C*}$, $d^{MS*} = d^{C*}$, $\tau^{MS*} = \tau^{C*}$, $q^{MS*} = q^{C*}$, $\pi_s^{MS*} = \pi_s^{C*}$. *Further, the profits of the manufacturer and the retailer under the contract can be obtained as* $\pi_m^{MS*} = \frac{kg(a-\beta c_m)^2(g\beta(2t-1)\Delta_2 - kt(\theta-\beta)^2)}{{\Delta_3}^2}$, $\pi_r^{MS*} = \frac{kg(a-\beta c_m)^2(1-t)\Delta_{10}}{{\Delta_3}^2}$. *Where,* $t^* = \frac{5g\beta\Delta_2 - k(\theta-\beta)^2}{4\Delta_{10}}$, $t^{**} = \frac{3g\beta\Delta_2 - k(\theta-\beta)^2}{2\Delta_{10}}$. *Let,* $2k(2t-1) - \beta t(\Delta_1 + s)^2 = \Delta_{22}$, $g\beta c_m(2k(3-2t) - \beta(1-t)(\Delta_1 + s)^2) + k(\theta - \beta)(a - \theta c_m) = \Delta_{23}$. *Under the assumption of scale parameters* $k, g, \Delta_{22}, \Delta_{23} > 0$.

Proof. See Appendix A.

Proposition 4 shows that the CSR cost sharing contract can effectively achieve the coordination of the CLSC. The retail price of new products, CSR investment level, waste product recovery rate, and market demand under the contract are the same as the optimal decision under centralized decision, and the total profits of the CLSC system has reached the level under centralized decision. At the same time, under this CSR cost sharing contract, there is a range for the retailer's share of the CSR cost of the manufacturer, and the specific commitment ratio can be negotiated between the manufacturer and the retailer. Contrary to intuition, when the retailer bears a high proportion of CSR costs (when it is small), the dominant retailer can use the leadership position to obtain all the incremental profits brought by coordination, and the manufacturer can only obtain retained profits under decentralized decision-making, but at this time the recovery rate of waste products and CSR investment levels have been improved, which is beneficial to consumers, the environment, and the CLSC system.

Furthermore, in the current economic environment, CSR investments by companies are not only related to their own interests, but also to the overall performance of other members and entire CLSCs. Therefore, as the leader of CLSC, the retailer takes the initiative to bear certain CSR investment costs for the manufacturer, which is not only conducive to better fulfillment of CSR in CLSC, but also to their own development and can bring more social and environmental benefits. For example, HP (Hewlett-Packard) has taken the initiative to bear certain CSR investment costs for its manufacturers, which not only increased the CSR investment level, but also improved the supply chain performance [60].

7. Numerical Analysis

Consistent with previous research, this section analyzes and verifies the main conclusions of this paper through heuristic numerical simulation. First, the impact of government subsidies on CLSC optimal decision is analyzed. Secondly, the impact of consumer sensitivity about CSR investment level

on optimal decision-making of CLSC is further analyzed. Finally, the validity of the contract designed in this paper is verified by the numerical simulation.

Comprehensively considering the hypothetical conditions of the models, and combining the relevant literature, such as Wan [9], Modak et al. [26], and so on, we set the experimental parameters as follows: $a = 110, \beta = 1, c_m = 60, c_r = 30, A = 10, k = 800, g = 90$. When analyzing the impact of government subsidy on CLSC optimal decisions, we assume $\theta = 4$. When analyzing the impact of consumer sensitivity to CSR investment on optimal decisions in the CLSC, we assume $s = 5$. When verifying the validity of the CSR cost sharing contract, we assume $s = 5$ and $\theta = 4$.

7.1. The Impact of Government Subsidy on CLSC Optimal Decisions

The impact of government subsidy on optimal decision-making in CLSC Model M and Model R is shown in Table 3 and Figures 1 and 2.

Table 3. Decision variables of each model under different government subsidy quotas.

s	1	3	5	7	9
w^{M*}	71.14	70.66	70.11	69.46	68.69
w^{R*}	70.68	70.20	69.63	68.98	68.20
τ^{M*}	0.20	0.22	0.25	0.28	0.32
τ^{R*}	0.19	0.21	0.24	0.27	0.31
d^{M*}	0.28	0.29	0.30	0.31	0.33
d^{R*}	0.27	0.28	0.29	0.30	0.32
p^{M*}	96.14	95.66	95.11	94.46	93.69
p^{R*}	96.37	95.91	95.38	94.75	94.01
q^{M*}	14.99	15.50	16.10	16.80	17.63
q^{R*}	14.74	15.23	15.81	16.49	17.29

* represents the equilibrium state of variables or functions.

Table 3 shows that whether the manufacturer or retailer makes CSR investment, with the increase of government recycling and remanufacturing subsidies, the wholesale and retail prices of new products will decline, while the recovery rate of waste products, the level of CSR investment, and market demand will increase. At the same time, when the government subsidy is fixed, compared with retailer CSR investment, it will have lower retail prices for new products when the manufacturer makes CSR investment, and the recycling rate of waste product, CSR investment level, and market demand will be higher. It is more beneficial to consumers and environmental protection.

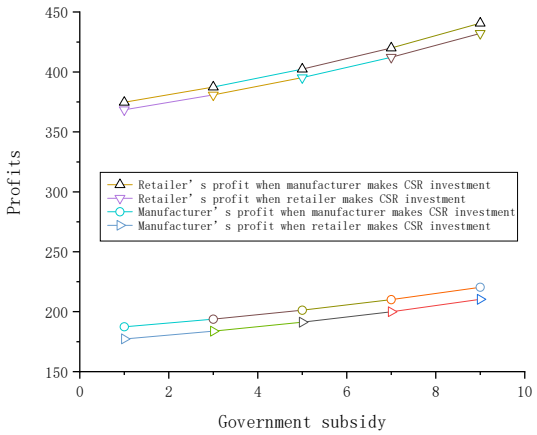

Figure 1. Profits of closed-loop supply chain (CLSC) members under different government subsidy.

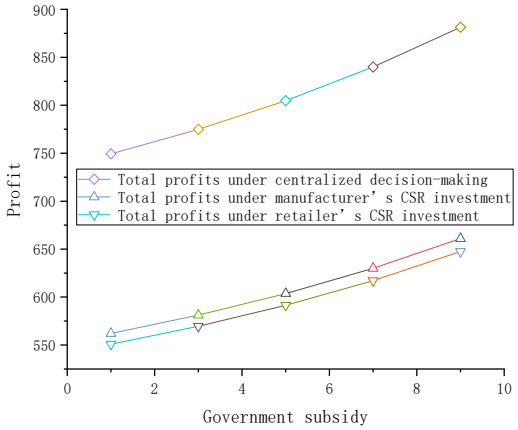

Figure 2. Total profits of the CLSC system under different government subsidy.

Figures 1 and 2 show that with the increase of government subsidy, whether the manufacturer or retailer makes CSR investment, the profits of CLSC members and whole system are increasing. Furthermore, under centralized decision-making, the total profits of CLSC system is always the largest, and under decentralized decision-making, compared with the retailer's CSR investment, the overall profits of CLSC members and whole system are greater when the manufacturer makes CSR investment. It also shows that manufacturers' CSR investment is more beneficial to its own and CLSC system. At the same time, the dominant retailer always gets more profit than the manufacturer, which further validates the relevant properties and conclusions of this paper.

7.2. The Impact of Consumer Sensitivity about CSR Investment Level on Optimal Decisions

The impact of consumer sensitivity about CSR investment level on CLSC Model M and Model R optimal decision is shown in Table 4 and Figures 3 and 4.

Table 4. Decision variables of each model under different levels of CSR invest sensitivity.

θ	2	4	6	8	10
w^{M*}	69.60	70.11	71.02	72.53	75.08
w^{R*}	69.48	69.63	69.95	70.46	71.23
τ^{M*}	0.24	0.25	0.27	0.30	0.35
τ^{R*}	0.23	0.24	0.26	0.27	0.29
d^{M*}	0.10	0.30	0.54	0.84	1.27
d^{R*}	0.09	0.29	0.51	0.75	1.04
p^{M*}	94.60	95.11	96.02	97.53	100.09
p^{R*}	94.63	95.38	96.73	98.84	101.94
q^{M*}	15.59	16.10	17.20	19.18	22.66
q^{R*}	15.56	15.81	16.33	17.17	18.43

* represents the equilibrium state of variables or functions.

Table 4 shows that whether the manufacturer or retailer makes CSR investment, as the consumers become more sensitive to the CSR investment level, the wholesale and retail price of new product, market demand, CSR investment level, and waste product recovery rate will increase. It can also be seen that, as long as the CSR investment of the enterprise meets the psychological expectations of consumers, then consumers are willing to pay for CSR investment even if the retail price has risen. Further, when the retailer makes the CSR investment, the wholesale price is always lower. When the manufacturer makes a CSR investment, the retail price is always lower, and the market demand, waste product recovery rate, and CSR investment level are always higher. So, it is more beneficial to consumers and the environment.

Figures 3 and 4 show that whether the manufacturer or retailer makes CSR investment, as the consumers become more sensitive to the CSR investment level, the profits of CLSC members and whole system are also increasing. At the same time, under centralized decision-making, the total profits of the CLSC system are always the largest. And under decentralized decision-making, compared with the retailer's CSR investment, the total profits of CLSC members and whole system are greater when the manufacturer makes CSR investment.

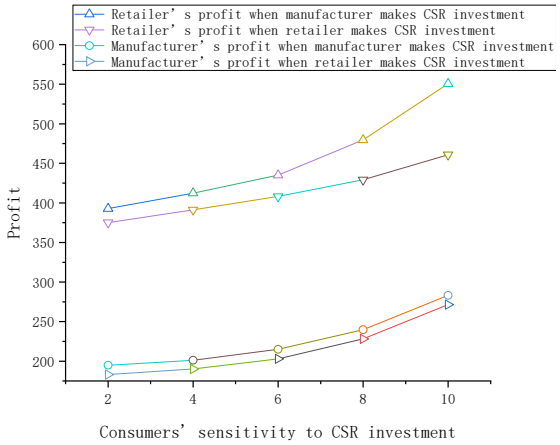

Figure 3. Profits of CLSC members under different corporate social responsibility (CSR) investment sensitivity level.

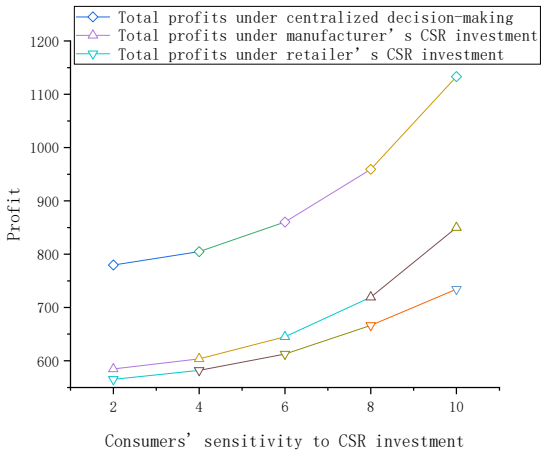

Figure 4. Total profits under different CSR investment sensitivity level.

7.3. The Effectiveness of Contract Coordination

According to the relevant parameter settings in this section, the CSR cost sharing ratio is $t \in (0.63, 0.75)$, so we take a smaller value $t = 0.65$ and a larger value $t = 0.72$, to test the validity of the CSR cost sharing contract designed in this paper. The equilibrium results of decentralized, centralized decision-making, and contract coordination are shown in Table 5.

As seen in Table 5, compared with decentralized decision making, under the CSR cost sharing contract established in this paper, the retail price of new product has decreased, while the market demand for new product, the optimal recovery rate of waste product, and the average level of CSR investment are improved. At the same time, the profits of CLSC members have also been improved, and the total profits of CLSC system have reached the level under centralized decision-making. Therefore, the CSR cost sharing contract can perfectly coordinate the CLSC system and realize the "win-win" purpose. Further, counterintuitively, when the retailer bears a high percentage of CSR cost ($t = 0.65$), the retailer can make relatively more profit. This is because when the retailer bears more CSR cost, the

manufacturer provides the retailer with lower wholesale price, which increases the retailer's profit margin for selling new product, so the retailer can get more coordination profit.

Table 5. Equilibrium decision variables of CLSC under different decision models.

Decision model	w^*	τ^*	d^*	p^*	q^*	π_m^*	π_r^*	π_s^*
Model M	70.11	0.25	0.30	95.11	16.10	201.21	402.41	603.62
Model MS ($t = 0.65$)	62.09	0.50	0.60	80.22	32.19	231.25	573.58	804.83
Model MS ($t = 0.72$)	65.71	0.50	0.60	80.22	32.19	345.96	458.87	804.83
Model C	\	0.50	0.60	80.22	32.19	\	\	804.83

* represents the equilibrium state of variables or functions.

8. Conclusions, Limitations, and Future Direction

8.1. Conclusion

In order to better realize long-term sustainable development, more and more enterprises have begun to take into account the balance of economic profits, environment, and social benefits in production and operation, and many companies have begun to bear their CSR through profit donations, thereby effectively increasing their goodwill. At the same time, with the development of the retail industry, a business mode in which retailers are the core companies in the supply chain has been formed in many industries. In this context, we build CLSC models consisting of a manufacturer and a dominant retailer, and assume both of them could undertake CSR through profit donations. Under the premise that the manufacturer is responsible for the recycling and remanufacturing of waste products, three different CSR investment decision models are constructed, namely the joint CSR investment model under centralized decision-making, the manufacturer's CSR investment model, and the retailer's CSR investment model. The impact of government subsidy and CSR investment on CLSC is analyzed. The efficiency of CLSC system under different decision models is further compared, and the CSR cost-sharing contract is designed to realize the coordination of CLSC.

Based on the results of this study, a number of findings and conclusions are presented as follows. (1) Regardless of the decision-making models, government subsidies will not only help lower the wholesale and retail prices of new products, expand the market demand for new products, and increase the recovery rate of used products, but also improve the CSR investment level and performance of CLSC members. (2) Under the government subsidy mechanism, no matter from the perspective of reducing the retail price of products, increasing the recovery rate of used products, or increasing the CSR investment level and total profits of CLSC system, the centralized decision model is always the best, and the manufacturer's CSR investment behavior is always optimal under the decentralized decision-making. (3) Whether or not the retailer makes CSR investment, the dominant retailer always gets more channel profits than the manufacturer. (4) Compared with the retailer's CSR investment, government subsidy policy can achieve the best effect when the manufacturer makes CSR investment. (5) The CSR cost sharing contract can effectively realize the coordination of CLSC system when the manufacturer makes CSR investment, and the retailer's profit will be greater when it bears more CSR investment costs.

8.2. Applicability and Management Implications

This paper provides some recommendations for the operation of retail-led CLSCs considering government subsidy and CSR investment, and it might provide valuable suggestions for government to formulate relevant policies on waste product recycling and corporate CSR implementation, and help companies better fulfill CSR. Firstly, the government's formulation of a reasonable subsidy policy for the recycling and remanufacturing of waste products will not only help improve the recycling rate of

waste products and reduce environmental pollution, but also increase the corporate CSR investment level and social welfare. Secondly, the member companies should make clear that recycling decisions within the CLSC are inherently consistent with CSR investment decisions; that is, simultaneously increasing the economic benefits of recycling and remanufacturing and the social benefits of CSR investment are not in conflict. The member companies should comprehensively consider the inherent relationship between the recovery rate decision and the CSR investment decision, so as to achieve a simultaneous increase in economic and social benefits. Finally, although a manufacturer's commitment to CSR in a retail-led CLSC is more conducive to increasing the profits of CLSC and social welfare, when the dominant retailer bears a certain CSR investment cost for manufacturer, it will be more beneficial for the overall long-term development.

8.3. Limitations and Future Direction

Although we have discussed the pricing and coordination of CLSC considering government subsidy and CSR investment, there are still some shortcomings. Firstly, we assume that the CLSC consists of one manufacturer and one retailer and do not consider the impact of competition behavior among retailers or manufacturers on CLSC, which will be an interesting problem in future research. Secondly, this paper focuses on the analysis of the impact of government subsidy on CSR investment, but some countries implement punishment or reward and punishment mechanisms. Therefore, in the next step, we can consider the impact of government reward and punishment mechanism and CSR investment on CLSC decision-making. Thirdly, although this paper studies the decision models of CLSC considering government subsidy and CSR investment by using Stackelberg game method, it lacks further analysis on the stability of the models. Therefore, the next research can analyze the stability of CLSC model considering government subsidy and CSR investment. Finally, we only consider single-cycle CLSC decision models. In the future, we can consider the decision-making of multi-cycle CLSC under government's subsidy and CSR investment.

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

Appendix A

Proof of Property 1. According to the relevant equilibrium results in Table 2, it is easy to obtain

$$\frac{\partial w^{M*}}{\partial s} = \frac{-kg\beta(a-\beta c_m)(\Delta_1+s)\Delta_{14}}{{\Delta_3}^2} < 0,$$

$$\frac{\partial w^{R*}}{\partial s} = \frac{-2kg\beta(a-\beta c_m)(\Delta_1+s)\Delta_{15}}{{\Delta_{10}}^2} < 0,$$

$$\frac{\partial \tau^{M*}}{\partial s} = \frac{g\beta(a-\beta c_m)(k\Delta_{15}+g\beta^2(\Delta_1+s)^2)}{2{\Delta_3}^2} > 0,$$

$$\frac{\partial \tau^{R*}}{\partial s} = \frac{g\beta(a-\beta c_m)(k\Delta_{16}+2g\beta^2(\Delta_1+s)^2)}{{\Delta_{10}}^2} > 0,$$

$$\left|\frac{\partial w^{R*}}{\partial s}\right| - \left|\frac{\partial w^{M*}}{\partial s}\right| = \frac{kg\beta(a-\beta c_m)(\theta-\beta)(\Delta_1+s)(\theta\Delta_{17}+2\beta\Delta_{18})}{{\Delta_3}^2{\Delta_{10}}^2} > 0,$$

$$\frac{\partial \tau^{M*}}{\partial s} - \frac{\partial \tau^{R*}}{\partial s} = \frac{kg\beta(a-\beta c_m)(\theta-\beta)^2\Delta_{19}}{2{\Delta_3}^2{\Delta_{10}}^2} > 0,$$

Where, let $2g\beta-\theta(\theta-\beta) = \Delta_{14}$, $4g\beta-(\theta-\beta)^2 = \Delta_{15}$, $8g\beta-(\theta-\beta)^2 = \Delta_{16}$, $k^2(\theta-\beta)^2(6g\beta-(\theta-\beta)^2)-2g^2\beta^3(\Delta_1+s)^2\Delta_2 = \Delta_{17}$, $kg\beta(4g\beta\Delta_2-3k(\theta-\beta)^2)+\Delta_3^2 = \Delta_{18}$, $(k\Delta_{16}+4g\beta^2(\Delta_1+s)^2)\Delta_3+2g^2\beta^3(\Delta_1+s)^2\Delta_2 = \Delta_{19}$. Under the assumption of scale parameters $k, g, \Delta_{14}, \Delta_{16}, \cdots, \Delta_{19} > 0$. □

Proof of Property 2. Since the process of proving Property 2 are similar to that of Property 1, it is omitted here. □

Proof of Property 3. When $L = M$, according to the relevant equilibrium results in Table 2, it is easy to obtain

$$\frac{\partial \pi_m^{M*}}{\partial s} = \frac{kg^2\beta^2(a-\beta c_m)^2(\Delta_1+s)}{2{\Delta_3}^2} > 0,$$

$$\frac{\partial \pi_r^{M*}}{\partial s} = \frac{kg^2\beta^2(a-\beta c_m)^2(\Delta_1+s)}{{\Delta_3}^2} > 0,$$

$$\frac{\partial \pi_s^{M*}}{\partial s} = \frac{3kg^2\beta^2(a-\beta c_m)^2(\Delta_1+s)}{2{\Delta_3}^2} > 0,$$

When $L = R$, the method and process of proof are similar to this, which is omitted here. □

Proof of Property 4. When $L = M$, according to the relevant equilibrium results in Table 2, it is easy to obtain

$$\frac{\partial w^{M*}}{\partial \theta} = \frac{k(a-\beta c_m)(\Delta_{10}+4k(\theta-\beta)\Delta_{20})}{4{\Delta_3}^2} > 0,$$

$$\frac{\partial \tau^{M*}}{\partial \theta} = \frac{kg\beta(\theta-\beta)(a-\beta c_m)(\Delta_1+s)}{{\Delta_3}^2} > 0,$$

$$\frac{\partial d^{M*}}{\partial \theta} = \frac{k(a-\beta c_m)(g\beta\Delta_2+k(\theta-\beta)^2)}{2{\Delta_3}^2} > 0,$$

$$\frac{\partial p^{M*}}{\partial \theta} = \frac{k(a-\beta c_m)(\Delta_3+2(\theta-\beta)\Delta_{20})}{2{\Delta_3}^2} > 0,$$

$$\frac{\partial q^{M*}}{\partial \theta} = \frac{2k^2g\beta(\theta-\beta)(a-\beta c_m)}{{\Delta_3}^2} > 0,$$

where, let $g\Delta_4+k(\theta-\beta) = \Delta_{20}$. Under the assumption of scale parameter $k, g, \Delta_{20} > 0$. Since the process of proof in Property 1 $L = R$ and Property 2 are similar to the above proof, it is omitted here and completed. □

Proof of Proposition 1. According to the relevant equilibrium results in Table 2, it is easy to obtain

$$w^{M*} - w^{R*} = \frac{k(\theta-\beta)(a-\beta c_m)\Delta_{21}}{2\Delta_3\Delta_{10}} > 0,$$

where, let $g\beta(6k-\beta(\Delta_1+s)^2)-k(\theta-\beta)^2+g\theta\Delta_4 = \Delta_{21}$. Under the assumption of scale parameter $k, g, \Delta_{21} > 0$. □

Proof of Proposition 2. Taking Proposition 1 as an example, according to the relevant equilibrium results in Table 2, it is easy to obtain

$$\tau^{C*}-\tau^{M*} = \frac{g\beta(a-\beta c_m)(\Delta_1+s)}{2\Delta_3} > 0,$$

$$\tau^{M*}-\tau^{R*} = \frac{kg\beta(a-\beta c_m)(\theta-\beta)^2(\Delta_1+s)}{2\Delta_3\Delta_{10}} > 0,$$

Since the method and process of proving Propositions 2–4 are similar to Proposition 1, it is omitted here and completed. □

Proof of Proposition 3. Taking Proposition 1 as an example, according to the relevant equilibrium results in Table 2, it is easy to obtain

$$\pi_m^{M*}-\pi_m^{R*} = \frac{k^3g(a-\beta c_m)^2(\theta-\beta)^4}{4\Delta_3{\Delta_{10}}^2} > 0,$$

Since the method and process of proving Propositions 2–5 are similar to Proposition 1, it is omitted here and completed. □

Proof of Proposition 4. Similar to the solution process in Section 4.2, the inverse recurrence method is used to solve the problem. According to the first order condition of the manufacturer, let $\frac{\partial\pi_m^{MS}}{\partial w} = 0$, $\frac{\partial\pi_m^{MS}}{\partial d} = 0$, $\frac{\partial\pi_m^{MS}}{\partial\tau} = 0$, can be obtained

$$w^{MS} = \frac{gt(a-\beta m)(2k-\beta(\Delta_1+s)^2)+2kg\beta tm+k(\theta-\beta)(a-\beta m-\theta c_m)}{4kg\beta t-g\beta^2t(\Delta_1+s)^2-k(\theta-\beta)^2},$$

$$d^{MS} = \frac{k(\theta-\beta)(a-\beta m-\beta c_m)}{4kg\beta t-g\beta^2t(\Delta_1+s)^2-k(\theta-\beta)^2},$$

$$\tau^{MS} = \frac{g\beta t(a-\beta m-\beta c_m)(\Delta_1+s)}{4kg\beta t-g\beta^2t(\Delta_1+s)^2-k(\theta-\beta)^2},$$

If the total profits of CLSC system under the contract is to reach the level of the total profits under the centralized decision-making, it needs to satisfy $p^{MS*} = w^{MS*}+m^{MS*} = p^{C*}$, $d^{MS*} = d^{C*}$, $\tau^{MS*} = \tau^{C*}$, so can get the re-established wholesale price w^{MS*} under the coordination contract.

Further, according to the coordinated optimal wholesale and retail prices, the optimal recovery rate and the CSR investment level, the optimal profits of manufacturer and retailer under the coordination are, respectively

$$\pi_m^{MS*} = \frac{kg(a-\beta c_m)^2(g\beta(2t-1)\Delta_2-kt(\theta-\beta)^2)}{{\Delta_3}^2},$$

$$\pi_r^{MS*} = \frac{kg(a-\beta c_m)^2(1-t)\Delta_{10}}{{\Delta_3}^2},$$

At the same time, the condition that manufacturer and retailer are willing to participate in the CSR cost sharing contract is that both parties can obtain at least retained profits under decentralized decision-making. So the manufacturer should at least receive no less than profits under decentralized decision-making, let $\pi_m^{MS*} \geq \pi_m^{M*}$, the lower bound for the optimal CSR cost sharing ratio

is $t^* = \frac{5g\beta\Delta_2 - k(\theta-\beta)^2}{4\Delta_{10}}$; and the retailer should at least receive no less than profits under decentralized decision-making, let $\pi_r^{MS*} \geq \pi_r^{M*}$, the upper bound to obtain the optimal CSR cost sharing ratio is $t^{**} = \frac{3g\beta\Delta_2 - k(\theta-\beta)^2}{2\Delta_{10}}$. □

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