RAIRO-Oper. Res. 59 (2025) 907–937
https://doi.org/10.1051/ro/2025021

RAIRO Operations Research
www.rairo-ro.org

DECISION AND COORDINATION OF SUSTAINABLE SUPPLY CHAIN CONSIDERING CSR IMPLEMENTATION AND CHANNEL LEADERSHIP

Shan Liu[1], Caiquan Duan[2,3,*], Jinyou Qiao[2] and Yan Sun[4]

Abstract. To achieve the ultimate objective of multi-dimensional sustainable development of the supply chain system, this paper examines the decision and coordination of the sustainable supply chain (SSC) from the dimensions of environment, society, and governance. Based on a dual-channel collecting structure, this study constructs six supply chain decision models considering two corporate social responsibility (CSR) implementers and three channel leadership structures. The findings reveal that in the SSC with a channel leader, it is most beneficial for the game follower to implement CSR from the perspective of maximising the total benefit to the supply chain and social welfare. The selection of the optimal channel leadership hinges on the trade-off between the collecting cooperation fees and the degree of the member's CSR implementation. Finally, this research proposes a revenue-responsibility sharing contract to achieve the perfect coordination of the SSC. Our results can function as guidelines for establishing an environmental-friendly SSC system.

Mathematics Subject Classification. 91A80, 91B06.

Received January 27, 2024. Accepted February 14, 2025.

1. Introduction

Nowadays, lack of resources, environmental pollution and financial constraints hinder the development of industrial enterprises. The stable operation of the supply chain, which is the carrier of enterprise production and product circulation, is key to the development of the enterprise [1,2]. In light of the increased importance of sustainable development, the supply chain system has begun to measure progress using the dimensions of "economic benefits, ecological environment, and social responsibility" [3,4]. In reality, the environmental, social and governance (ESG) multi-dimension evaluation system has attracted industry attention [5]. For example, Apple released an ESG report and proposed to strengthen ESG-based "Apple chain" governance by the end of 2021. Therefore, it has certain theoretical and practical significance to introduce the concept of ESG sustainable development into a supply chain system and study the reuse of resources, social responsibility and coordination of the system [6].

Keywords. Sustainable supply chain, dual-channel collecting, CSR, channel leadership, coordination.

[1] School of Management, Fudan University, Shanghai 200433, P.R. China.

[2] College of Engineering, Northeast Agricultural University, Harbin 150030, P.R. China.

[3] Postdoctoral Station for Agricultural and Forestry Economic Management, Northeast Agricultural University, Harbin 150030, P.R. China.

[4] Business School, Oxford Brookes University, Oxford OX3 0BP, UK.

*Corresponding author: duancaiquan@neau.edu.cn

In an SSC considering environmental dimension, this dimension is mainly to reuse resources from the "resource → consumption → collecting → remanufacturing" process, which helps to internalise negative environmental externalities [7,8]. However, it is difficult to collect waste products from consumers, and one-channel collecting cannot satisfy the complex and changing market collecting environment [9]. In reality, enterprises such as HP and Apple have adopted a dual-channel collecting structure involving the manufacturer and retailer. Studies have shown that multi-channel mixed collecting can significantly improve the scale effect of collecting and remanufacturing, especially the dual-channel collecting of the manufacturer and retailer [10]. Therefore, we conduct research based on the dual-channel collecting model of the manufacturer and retailer. Meanwhile, the corporate social responsibility (CSR) dimension requires enterprises to pay attention to their social responsibility [11], which can demonstrate social responsibility to consumers, guide consumers to balance their expenditure with the consumption of green products, and promote consumer loyalty to the enterprise brand [12]. Studies have shown that CSR can enhance brand value and bring additional benefits to enterprises [13]. Therefore, in the face of the different CSR implementers that may exist in an SSC system, choosing the optimal CSR implementer is key to realising the social sustainability of the system [14].

However, under the ESG sustainable development concept, the supply chain governance dimension also needs to be attached. In the field of supply chain governance, scholars have explored this theme from multiple angles such as social responsibility [15], digital platform technology [16], environmental governance [17], and coordination strategies [18]. Despite this breadth, these studies have typically focused on a singular dimension or primarily addressed the overall resilience and sustainability of the system. In contrast to the preceding studies, the supply chain governance explored in this paper exhibits multiple dimensions. On one hand, the effectiveness of different CSR implementers and channel leadership structures significantly influences the operational efficiency of the supply chain. Consequently, selecting suitable and efficient CSR implementation strategies and channel leaders represent a method to optimize SSC operations [6, 19]. On the other hand, the risk-sharing among members with diverse expectations, coupled with the varied decisions of multiple participants, necessitates a robust coordination mechanism. This mechanism is critical for enhancing supply chain governance capabilities and boosting system resilience [20]. Essentially, it involves identifying the optimal operational mode of the system, enabling the collective to utilize limited resources to maximize overall economic profit. Existing studies have also demonstrated that coordination mechanisms are crucial for optimizing supply chain operations [21]. The primary aim of this paper is to examine the integration of prominent research themes currently observed in SSC. These themes encompass SSC operation decision [8], as well as SSC modelling and optimization [22, 23], and supply chain coordination strategy [4, 19]. Additionally, introducing ESG concepts into SSC system and promoting ESG initiatives from the perspectives of "CSR implementer selection, channel leadership structure selection, and coordination mechanism" to achieve the ultimate goal of establishing an SSC system. The specific research objectives are as follows:

- Under different CSR implementers and channel leadership structures, what are the equilibrium strategies for the SSC operation?
- From the perspectives of the environment, social welfare and supply chain enterprise profit, when the channel leadership structure is determined, how can the optimal CSR implementer for the SSC be chosen?
- From the perspective of supply chain governance, when a CSR implementer is identified, what is the optimal channel leadership structure for the SSC operation? What factors influence the optimal channel leadership structure?
- Can designing a coordination mechanism improve the profit of members of the SSC system and allow members to better fulfil their environmental and social responsibilities?

To answer the above questions, we first use game theory to construct six SSC decision models that consider three channel leadership structures under the manufacturer (or retailer) implementing CSR, respectively. Analysis of the equilibrium results reveals that the collecting cooperation fees and the degree of CSR implementation are important parameters that affect members' production decisions and performance. Second, the research explores the interaction between collecting cooperation fees and the degree of CSR implementation and analyses their impact on the environment, social welfare and performance in the SSC. Third, by comparing the equilibrium results in different decision situations, this paper discusses the interaction between different channel leadership structures and the degree of CSR implementation, giving the optimal selection of channel leadership structure and CSR implementer of the supply chain from the perspectives of the economy, the environment and social welfare. Finally, to improve the overall governance level of the supply chain, this paper designs a revenue-responsibility sharing contract mechanism and presents specific coordination strategies that improve the profit of all members.

The contributions of this research are as follows. (1) Based on ESG sustainable development concept and supply chain management theory, from the perspective of different CSR implementers and channel leadership, this paper studies the operation decision and coordination of the SSC. This perspective is very meaningful. This is because it can realize the sustainable operation of supply chain from the dimensional of environment, society and governance. In addition, starting from the concept of sustainable development, this paper aims at the total profit of members seeking the maximisation of social welfare, through the logic of "the optimal CSR implementer, the optimal channel leadership, coordination mechanism" to promote the stable operation of the supply chain, which is a deep-level innovation in the field of SSCs. (2) We develop SSC decision models that consider different channel leadership structures and CSR implementers. Undoubtedly, these models can not only reflect the interaction between supply chain members, but also reflect the internal logical relationship between multiple factors (*i.e.* CSR implementers and channel leadership structure) and system operation decisions. Through analysing the models, the influence of the interaction of important parameters on profit, collecting rate and social welfare is given. In particular, to further realise supply chain governance, we use contract theory to design coordinating strategies to achieve the stable operation of the SSC. This can bridge the gap between research ideas and methodologies between disciplines and provide new ideas for research in the SSC field.

The remainder of the research proceeds as follows. Section 2 presents a literature review. Section 3 states the problem description and model assumptions. Sections 4 and 5 present the construction and solution analysis of the models. Section 6 designs a supply chain coordination mechanism. Section 7 outlines the conclusions and future research interests.

2. Literature review

In this section, we perform a literature review to validate the originality and significance of this research. Four streams of literature closed related to this study are reviewed.

The first stream of research related to this study focuses to closed-loop supply chain under different collecting channels of waste products. Since the introduction of the concept of closed-loop supply chains incorporating reverse logistics [24], the collection channels of closed-loop supply chains have garnered extensive attention from scholars. The first category of research explores the decision problem associated with one-channel closed-loop supply chain. Most scholars in this area have investigated the closed-loop supply chain decision problem in the context of the manufacturer collecting channel, such as Chen *et al.* [25], Luo *et al.* [26] and Chai *et al.* [27]. With the rapid rise of the remanufacturing industry, specialized remanufacturers such as Caterpillar Remanufacturing have emerged in the market. Consequently, from the perspective of remanufacturer collection channel, Hong *et al.* [28] compared and analysed the influence of fixed cost and a patent licence fee on the production decision and collecting level of supply chain members. From the perspective of retailer collection channel, Gong *et al.* [29] constructed a dual-channel closed-loop supply chain decision model considering consumer free-riding behaviour, clarifying the impact of such behaviour on offline/online supply chain operation decisions. To compare manufacturer collection, retailer collection, and third-party collection, Shan *et al.* [30] developed Stackelberg game models under three collection channels, each with service budget constraints and government subsidies. They ultimately found that the collecting rate is always highest under the retailer collection model. If collecting subsidies and service budgets can be observed, manufacturers are more willing to entrust collecting activities to retailers. However, one-channel collecting cannot satisfy the complex and changing market collecting environment [7]. The second category of this research involves studying the multichannel closed-loop supply chain decisions problem. Souza [31] contends that manufacturer should choose to collect waste products with other members of the supply chain to increase collection rate. In this context, scholars have studied the closed-loop supply chain decisions from the perspective of joint collecting between manufacturer and other members [32], entrusting other multilayer members to undertake collecting [33], and from the perspective of omni-channel collecting [34], finding that any kind of combined collecting can improve the collecting rate more than separate collecting. Comparing different types of multichannel collecting, Chen *et al.* [10] found that dual-channel collecting by manufacturer and retailer is more helpful for promoting the overall profitability of the system. To identify the optimal collection model in a closed-loop supply chain, Wan [35] established decision models based on manufacturer collection, retailer collection, and hybrid collection under single and dual channels. Through model solution analysis, they found that when the competition intensity for collecting is relatively low, customers, the environment, and manufacturers prefer the hybrid collection model. However, the above studies have primarily focused on environmental sustainability, often neglecting the CSR contributions of supply chain members and failing to demonstrate the overall impact on social welfare.

The second stream of research related to this research concerns supply chain decisions that consider CSR. CSR behaviour originates from the assumption of the irrational economic man, meaning that companies do not solely aim for their own economic interests but also consider environmental protection and social welfare. From the perspective of manufacturer CSR behaviour, Panda *et al.* [3] have studied the impact of manufacturer' CSR on pricing decision in a closed-loop supply chain, finding that the increase in CSR input can help expand social welfare. Viewing CSR as a demonstration of social charity, Modak *et al.* [36], Modak and Kelle [37] discuss the impact of manufacturer' CSR on supply chain pricing, and carbon the impact of emissions reductions from the perspective of donations. Considering the assumption of retailer implementing CSR, Zhang and Luo [38] constructed a poverty alleviation agricultural product supply chain decision model, proving that the CSR behaviour of retailer can effectively increase the profit of impoverished farmer. To compare the effectiveness of CSR implementation by manufacturer or retailer, Cheng *et al.* [39] analysed the supply chain game model and equilibrium results, demonstrating that under certain conditions, retailer CSR is more beneficial for overall system profitability and achieves Pareto improvement. The above studies have all aimed to determine the total profit by maximising social welfare. They have used game theory to design supply chain equilibrium models that consider CSR in different situations to analyse the impact of CSR on supply chain decisions. With the growing importance of sustainable development, ESG have gradually come to be regarded as a manifestation of the economy, environment, and society's triple sustainable operation within the supply chain [40, 41]. However, the above studies only consider the impact of CSR on supply chain operation decisions and assumes that the channel leader is fixed. Instead, we consider different channel leadership structures in the SSC.

The third stream of research related to this work is supply chain operation decisions under different leadership structures, which has achieved fruitful results. Studies in this stream can be further divided into two types. The first is supply chain operation decision under a single leadership structure, such as manufacturer channel leadership [42], retailer channel leadership [43] and recycler channel leadership [44]. However, the studies in this group did not consider the optimal leadership structure of the supply chain. The other type is the operation decision of supply chain under different leadership structures. Regarding the latter type, Choi *et al.* [20] and Zheng *et al.* [45] focused on single-channel and dual-channel closed-loop supply chains, respectively, and explored the collecting decision and supply chain coordination under manufacturer leadership, retailer leadership and recycler leadership structures, respectively. The authors found that the retailer channel leadership structure is more conducive to system operation. Gupta *et al.* [46] developed stochastic low-carbon supply chain decision models under the leadership structure of manufacturer, retailer, and supplier. Through comparative analysis of the equilibrium results, it was demonstrated that from a carbon reduction perspective, a retailer-led supply chain system is the optimal solution for manufacturer. From the perspective of fuzzy demand and different product quality levels, Liu *et al.* [47] established a closed-loop supply chain decision model under different leadership structures and found that the waste product collecting rate was the largest under the manufacturer leadership structure. From the perspective of manufacturer leadership, retailer leadership and no leadership structures, Zheng *et al.* [48] studied a closed-loop supply chain decision problem of the manufacturer encroaching on retail channels, finding that retailers gain most benefit under the manufacturer leadership structure. Taking the electric vehicle closed-loop supply chain as their research case, Liu *et al.* [49] constructed closed-loop supply chain decision models under supplier leadership and manufacturer leadership modes, respectively, clarifying the decisions and profit distribution of electric vehicle closed-loop supply chain under different collecting modes. Considering different leadership structures in electric vehicle collecting, Zhou *et al.* [50] constructed supply chain game models under the assumption of competition among an electric vehicle manufacturer, a professional recycler, and a third-party recycler, and obtained equilibrium results under different collecting leadership structures. Through comparative analysis, they found that adjusting the collecting leadership model is relatively challenging and requires technological advancements and government intervention. By incorporating government carbon reduction subsidies and collecting subsidies into a supply chain system, Zhang and Yu [51] constructed supply chain decision models under manufacturer-led, retailer-led, non-led, and centralized decision scenarios. They demonstrated that government subsidy mechanisms can significantly narrow the gap between manufacturer-led and retailer-led models. Additionally, they developed coordination contracts based on different power structures to further improve the overall performance of the supply chain. However, the above-mentioned studies considered the maximization of the economic performance of the system, and did not study the SSC operation from the dimensions of social responsibility and channel leadership. On the contrary, our research is carried out from the two dimensions to study the operation and coordination of the SSC system.

The fourth stream of research related to this work is SSC modelling and optimization. Prior research indicates that SSC systems are effective in addressing energy crises [52], reducing resource waste [53], enhancing social welfare [54], improving system resilience [22, 55], increasing operational efficiency [23], and bolstering resilience against uncertain risks [56]. Goli *et al.* [57] designed a SSC network optimization model and incorporated multiple factors that affect supply chain sustainability into a linear programming model. Numerical simulations demonstrated that the model can improve system optimization. From the perspective of sustainable waste collection, Tirkolaee *et al.* [58] identified reducing carbon emissions as key factor for improving social satisfaction and sustainability. They developed a new type of mixed integer programming model and applied practical examples or numerical examples to analyse and evaluate the effectiveness of the model. In addition, scholars have constructed different types of SSC optimization models for various supply chain types, focusing on specific sectors such as the dairy supply chain [59], sustainable pharmaceutical supply chain [60], sustainable petrochemical supply chain [23], agricultural supply chain [61], and perishable product supply chain [62]. These studies have provided insights into the optimal design of supply chain systems, optimal inventory allocation, product design combinations, path optimization, and operational decision-making. However, the above research did not study the operational issues of SSCs from the perspective of supply chain member games. By utilizing game theory, existing studies have been based on Nash non-cooperative game and Stackelberg game, and comprehensively applied the backward induction method to construct and solve the SSC game model, which has solved the equilibrium decision-making and profit distribution problems within the system, as demonstrated in studies such as Qian *et al.* [63] and Ma *et al.* [64]. However, the above research did not take SSC under dual channel collecting as the structure to study the optimal CSR implementer, channel leadership, and coordination issues.

Research gaps. The above studies have all achieved important research results. This paper has made some progress based on the above research. (1) The existing research on corporate social responsibility/channel leadership is based on the framework of single channel collecting, while dual channel collecting is common in reality. For example, the cooperation between Xerox, Eastman, Kodak, and retailers often runs through two aspects: product sales and waste collection. This can not only effectively improve the decision efficiency of enterprises, but also reduce channel costs [10]. Therefore, this paper uses dual channel collection as a benchmark to study the operational decision-making issues of SSCs, which is more in line with reality. (2) Different channel leadership structures and CSR implementers are important factors affecting the profit distribution of supply chain members [3]. Existing research has not fully explored the interaction between different channel leadership structures and different CSR implementers in the context of dual channel collection. (3) In existing research on SSC, scholars have constructed optimization models from various perspectives. However, the development of a game equilibrium model that simultaneously considers dual-channel collecting, CSR implementation, and channel leadership

TABLE 1. Comparison between this paper and the main related literature.

Literature	PC		CSR			Leadership structure				RM	
	OC	MC	M-CSR	R-CSR	Other	M-led	R-led	N-led	Other	GT	OMRA
Panda *et al.* [3]	✓		✓			✓				✓	
Chen *et al.* [10],											
Zhao *et al.* [33],											
Wan [35]		✓				✓				✓	
Chen *et al.* [25],											
Shan *et al.* [30],											
Zheng *et al.* [48],	✓					✓	✓	✓		✓	
Zhang and Yu [51]											
Luo *et al.* [26],	✓					✓				✓	
Gong *et al.* [29],											
Chai *et al.* [27]	✓								✓	✓	
Hong *et al.* [28],											
Giovanni *et al.* [32],											
Liu *et al.* [49]		✓							✓	✓	
Modak *et al.* [36]		✓	✓			✓				✓	
Zhao and Luo [38]				✓			✓			✓	
Chen *et al.* [39]			✓	✓		✓				✓	
Huang and Wang [42]						✓				✓	
Yi *et al.* [43]		✓					✓			✓	
Miao *et al.* [44]		✓						✓		✓	
Zheng *et al.* [45],	✓					✓	✓		✓	✓	
Liu *et al.* [47]											
Gupta *et al.* [46]						✓	✓		✓	✓	
Zhou *et al.* [50]	✓					✓			✓	✓	
Tirkolaee *et al.* [53], Goli *et al.* [57],											
Tirkolaee and Aydin [62]											✓
Qian *et al.* [63]											
Ma *et al.* [64]									✓	✓	
This paper		✓	✓	✓		✓	✓	✓		✓	

Notes. PC: product collecting. RM: research method. OC: one-channel collecting. MC: multi-channel collecting. M-CSR: manufacturers implement CSR. R-CSR: retailer implement CSR. M-led: manufacturer-led. R-led: retailer-led. N-led: no-led. GT: game theory. OMRA: optimize models and related algorithms.

from a game-theoretic perspective has not yet been addressed. This gap presents a significant research opportunity for this paper. Therefore, based on the identified research gaps, the purpose of this study is to investigate the operational issues of SSC by considering the dual-channel collection structure of the manufacturer and the retailer as a scale effect of collection and remanufacturing. The study aims to clarify the selection of the CSR implementer, the choice of channel leadership structure, and the coordination mechanisms within the SSC. This research not only supplements the existing literature but also supports the operation and governance of supply chain systems. Specifically, a detailed comparison between this paper and the main related literature is presented in Table 1.

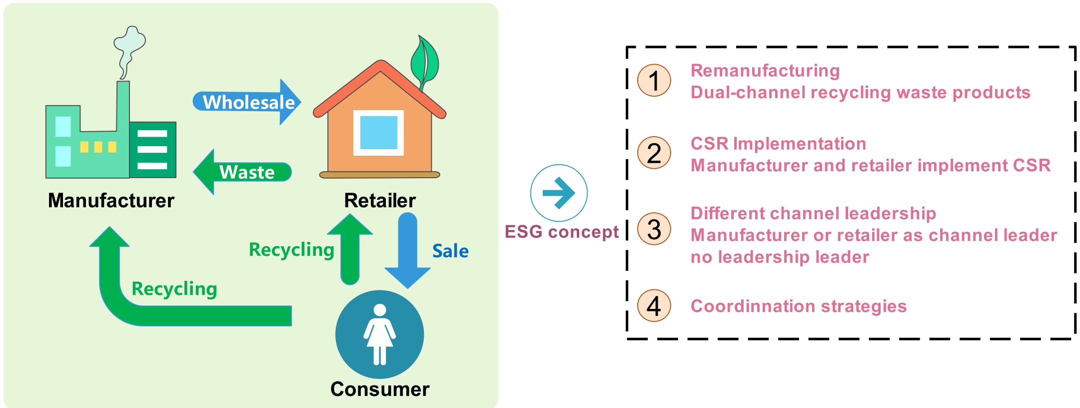

FIGURE 1. The SSC structure in this research.

3. Model preliminaries

3.1. Problem description

This research examines an SSC system consisting of a manufacturer and a retailer, both of whom possess symmetrical information [65]. The manufacturer utilizes raw materials to produce new products and also employs recycled waste materials to generate remanufactured products. The retailer is responsible for selling these products to consumers. Within the SSC system, the processes of waste collection and remanufacturing are considered integral to the environmental dimension, facilitating the internalization of negative environmental externalities. CSR practices adopted by the members are viewed as the social dimension of the system. This study further analyses the optimal CSR implementer selection strategy aimed at enhancing social welfare. From the perspective of supply chain governance, the research evaluates CSR implementer selection, channel leadership structure selection, and coordination strategies. Figure 1 illustrates the structure of this research.

3.2. Parameter definition and assumption

Table 2 summarizes the parameters and variables employed in this paper along with their respective descriptions. Following this, several basic assumptions are presented to support our theoretical model.

Assumption 3.1. *To realise the scale effect of collecting and remanufacturing, assume that the system adopts the dual-channel collecting structure of the manufacturer and retailer [10, 66]. Assuming b is the unit collecting cooperation fee paid by the manufacturer to the retailer to ensure that the remanufacturing is meaningful to the manufacturer, $c_m - c_r - b > 0$. Where c_m and c_r are the manufacturer's unit production cost and unit remanufacturing cost. Referring to Savaskan et al. [24] and Shekarian et al. [67], assume that $\tau_x = \sqrt{\frac{I_x^*}{k}}$, $x = \{m, r\}$ is the collection rate of the manufacturer or retailer, $I_x^* = k\tau_x^2$ is the effective cost of the manufacturer or retailer to collect waste products, and $k > 0$ is the collecting cost coefficient, representing the difficulty of collecting waste products.*

Assumption 3.2. *Assume that there is no difference between new products and remanufactured products in market sales [24, 28] and that the market demand of consumers for products meets the linear relationship – that is, $q = a - \beta p$, where a is the potential market capacity, p is the retail price and $\beta > 0$ is the sensitivity coefficient of consumer to product retail price.*

TABLE 2. Notations.

Symbols	Definitions
Indices	
$x = \{m, r, s\}$	Index of members, indicating the manufacturer, retailer and whole system
Parameters	
a	Potential market capacity
β	Sensitivity coefficient of consumer to product retail price
c_m	Unit production cost by using new materials
c_r	Unit remanufacturing cost by using recycled materials, $c_m > c_r$
$\Delta = c_m - c_r$	Unit production cost savings through remanufacturing
b	Unit collecting cooperation fee paid by the manufacturer to the retailer
k	Collecting cost coefficient
θ	Member's degree of CSR implementation
$\frac{z_1}{z_2}$	Contract parameters when the manufacturer/retailer implements CSR
Decision variables	
w	Wholesale price for products set by the manufacturer
p	Retail price for products set by the retailer
m	Unit profit set by the retailer
τ_x	Collection rate, $\tau_s = \tau_m + \tau_r$, $0 < \tau_s < 1$
Derived functions	
q	Market demand for products
π_x	Profit of each member, and $\pi_s = \pi_m + \pi_r$
V_x	Utility when the member implements CSR, and $V_s = V_m + \pi_r$ or $V_s = \pi_m + V_r$
CS	Consumer surplus, and $\text{CS} = \int_p^{p_{\max}} q\,\mathrm{d}p$
SW	Social welfare, and $\text{SW} = \pi_m + \pi_r + \text{CS}$

Notes. To enhance the readability, this paper uses the upper corner notation MM, MR and MN respectively represent the cases of manufacturer as the channel leader, the retailer as channel leader, and no channel leader when the manufacturer implements CSR. The upper corner notation RM, RR and RN respectively represent the cases of manufacturer as the channel leader, the retailer as channel leader, and no channel leader when the retailer implements CSR. The upper corner notation C, MS and RS respectively represent the cases of centralized decision, coordination when the manufacturer implements CSR, and coordination when retailer implements CSR. The superscript "*" indicates the equilibrium state.

Assumption 3.3. *According to Panda et al. [19] and Modak et al. [36], assume that the manufacturer and retailer can both implement CSR and that the CSR behaviour of the whole system is helpful to improve social welfare.*

Assumption 3.4. *According to Ranjbar et al. [68], assume that there are two types of games and three types of channel leadership relationships among the members of the system. The games are the Stackelberg game and the Nash game. The Stackelberg game explores the non-cooperative game between manufacturer and retailer, which the manufacturer as channel leader or the retailer as channel leader. The Nash game explores the non-cooperative game without the channel leader.*

3.3. Research method

This section will further introduce the main theoretical methods involved in the entire research process, in order to confirm the rationality of the model construction and the feasibility of the research results. For a simple supply chain system consisting of a manufacturer and a retailer, referring to Panda *et al.* [3], Choi *et al.* [20], and Savaskan *et al.* [24], this paper constructs decision models under different channel leadership using game theory, and then uses nonlinear optimization theory and backward induction to provide optimal strategies for the manufacturer and retailer. The advantage of using these research methods in this paper is that game theory can obtain the corresponding equilibrium strategy by studying the interaction between all possible behaviours of decision-makers. For example, in this study, we examine the manufacturer-led Stackelberg game, the retailer-led Stackelberg game, and the leaderless Nash game, respectively. Regardless of the game model, the players can reach an equilibrium point to keep the system in a relatively stable optimal state. In addition, the existence and uniqueness of the equilibrium strategy of manufacturer and retailer can be proved by using the basic method of nonlinear optimization and calculation techniques, and the optimal strategy of manufacturer and retailer can be solved by backward induction. At present, using game theory and backward induction to solve the optimal decision problem of a simple structured supply chain has been widely applied in the academic circle, such as in the works of Pal [2], Chai *et al.* [27], and Gong *et al.* [29].

3.4. Model construction

According to the above problem description, assumptions, and research methodology, this paper can construct the profit function of manufacturer and retailer respectively. The source of income for the manufacturer can be divided into two parts: the profit generated from selling the product to the retailer at price w, and the cost savings achieved through the collection and remanufacturing of waste products, which are collected both directly and from the retailer at price b. Hence, the manufacturer's profit function is given by:

$$\pi_m(w,\tau_m) = (w-c_m)(a-\beta p) + (c_m-c_r)\tau_m q + (c_m-c_r-b)\tau_r q - k\tau_m^2. \tag{3.1}$$

The retailer's sources of revenue can also be divided into two parts: the profit generated from selling the product to consumers at price p, and the price difference earned by reselling waste products collected from consumers to the manufacturer. Therefore, the retailer's profit function is given by:

$$\pi_r(p,\tau_r) = (p-w)q + b\tau_r q - k\tau_r^2. \tag{3.2}$$

This paper considers the decision-making of supply chain members in fulfilling their social responsibilities. In this context, the decision goal of the member implementing CSR is to maximize social welfare rather than simply maximize profit. Social welfare is typically regarded as the sum of consumer surplus and producer surplus. According to the general definition, consumer surplus refers to the difference between the highest price that consumers are willing to pay and the actual market price they pay for a product [17]. Accordingly, consumer surplus can be expressed as:

$$\mathrm{CS} = \int_{p}^{p_{\max}} q\,\mathrm{d}p = \int_{\frac{a-q}{\beta}}^{\frac{a}{\beta}} (a-\beta p)\,\mathrm{d}p = \frac{(a-\beta p)^2}{2\beta}\cdot \tag{3.3}$$

However, in supply chain management, due to the differences in channel leadership structure and member business roles, the implementation of CSR by different members within the same supply chain may yield varying effects. Therefore, this paper examines the scenarios in which either the manufacturer or the retailer implements CSR. When the manufacturer implements CSR, its objective function is given as follows:

$$V_m = \pi_m + \theta\mathrm{CS} = \pi_m + \frac{\theta(a-\beta p)^2}{2\beta}\cdot \tag{3.4}$$

When the retailer implements CSR, its objective function is given as follows:

$$V_r = \pi_r + \theta\mathrm{CS} = \pi_r + \frac{\theta(a-\beta p)^2}{2\beta} \tag{3.5}$$

where $0<\theta<1$ indicates the member's degree of CSR implementation, $\theta=0$ indicates that the member simply pursues maximum economic profit without considering CSR and $\theta=1$ indicates that the member pursues maximum social welfare and fully considers CSR.

4. Equilibrium result analysis

In this section, focusing on the research problem and based on the dual-channel collecting structure, six decision models of the SSC are constructed. These comprise two CSR implementation members (manufacturer and retailer) and three channel leadership structures (manufacturer leadership, retailer leadership, and without the channel leader). The equilibrium strategy of each decision situation is given.

4.1. Decision model of the manufacturer implementing CSR

When the manufacturer implements CSR, it will take the maximization of social welfare as the decision goal, and the manufacturer's objective function is as follows:

$$\max V_m(w,\tau_m) = (w-c_m)q + ((c_m-c_r)\tau_m + (c_m-c_r-b)\tau_r)q - k\tau_m^2 + \frac{\theta(a-\beta p)^2}{2\beta}\cdot \tag{4.1}$$

At this time, the objective function of the retailer is shown in equation (3.2).

4.1.1. Manufacturer as the channel leader (MM model)

In the MM model, the optimization problem of the SSC, as described in equations (3.2) and (4.1), is addressed by employing backward induction. The decision sequence of members is as follows: the manufacturer first determines the wholesale price w^{MM} and the collecting rate τ_m^{MM} according to its own utility maximisation; the retailer then determines the retail price p^{MM} and the collecting rate τ_r^{MM} based on the manufacturer's decisions. The specific optimal decisions for both the manufacturer and the retailer are as follows.

The optimal wholesale price and collecting rate set by the manufacturer are, respectively:

$$w^{\mathrm{MM}^*} = \frac{a\big(2k(2-\theta)-\beta\big(\Delta^2+2\Delta\mathrm{b}-b^2\big)\big)+\beta c_m\big(4k-\beta b^2\big)}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))} \text{ and } \tau_m^{\mathrm{MM}^*} = \frac{\Delta(a-\beta c_m)}{2k(4-\theta)-\beta\Delta(\Delta+2b)}\cdot$$

The optimal retail price and collecting rate set by the retailer are, respectively:

$$p^{\mathrm{MM}^*} = \frac{a\phi_9+2k\beta c_m}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))} \text{ and } \tau_r^{\mathrm{MM}^*} = \frac{b(a-\beta c_m)}{2k(4-\theta)-\beta\Delta(\Delta+2b)}\cdot$$

The retailer's unit profit m^{MM^*}, the total collecting rate $\tau_s^{\mathrm{MM}^*}$, and the market demand q^{MM^*} are, respectively:

$$m^{\mathrm{MM}^*} = \frac{\phi_2(a-\beta c_m)}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))}, \quad \tau_s^{\mathrm{MM}^*} = \frac{(\Delta+b)(a-\beta c_m)}{2k(4-\theta)-\beta\Delta(\Delta+2b)},$$
$$\text{and } q^{\mathrm{MM}^*} = \frac{2k(a-\beta c_m)}{2k(4-\theta)-\beta\Delta(\Delta+2b)}\cdot$$

By substituting the aforementioned equilibria into the profit functions of each member, the corresponding manufacturer's profit $\pi_m^{\mathrm{MM}^*}$, retailer's profit $\pi_r^{\mathrm{MM}^*}$, and the system's total profit $\pi_s^{\mathrm{MM}^*}$ can be derived. Further, it is straightforward to determine the consumer surplus $\mathrm{CS}^{\mathrm{MM}^*}$ and social welfare $\mathrm{SW}^{\mathrm{MM}^*}$.

Lemma 4.1. *To ensure that the expressions in the MM model have economic significance and the total collecting rate satisfies* $0 \le \tau_s^{\mathrm{MM}^*} \le 1$, *the parameters need to satisfy* $k > \frac{((\Delta+b)(a-\beta c_m)+\beta\Delta(\Delta+2b))}{2(4-\theta)}$.

4.1.2. Retailer as the channel leader (MR model)

In the MR model, backward induction is also used to solve the optimization problem of the SSC as described in equations (3.2) and (4.1). The decision sequence of members is as follows: the retailer first determines the unit profit m^{MR} and the collecting rate τ_r^{MR} according to its own profit maximisation. Subsequently, the manufacturer determines the wholesale price w^{MR} and the collecting rate τ_m^{MR} based on the retailer's decisions, aiming to maximize its own utility. The optimal decisions for both the manufacturer and the retailer are as follows.

The optimal wholesale price and collecting rate set by the manufacturer are, respectively:

$$w^{\mathrm{MR}^*}=\frac{a(2k(1-\theta)-\beta\Delta(2\Delta-b))+\beta c_m(2k(3-\theta)-\beta\Delta(\Delta+b))}{\beta(4k(2-\theta)-3\beta\Delta^2)}\ \text{ and }\ \tau_m^{\mathrm{MR}^*}=\frac{\Delta(a-\beta c_m)}{4k(2-\theta)-3\beta\Delta^2}.$$

The optimal unit profit and collecting rate set by the retailer are, respectively:

$$m^{\mathrm{MR}^*}=\frac{(2k(2-\theta)-\beta\Delta(\Delta+b))(a-\beta c_m)}{\beta(4k(2-\theta)-3\beta\Delta^2)}\ \text{ and }\ \tau_r^{\mathrm{MR}^*}=\frac{\Delta(a-\beta c_m)}{4k(2-\theta)-3\beta\Delta^2}.$$

The retailer's retail price p^{MR^*}, the total collecting rate $\tau_s^{\mathrm{MR}^*}$, and the market demand q^{MR^*} are, respectively:

$$p^{\mathrm{MR}^*}=\frac{a\big(2k(3-2\theta)-3\beta\Delta^2\big)+2k\beta c_m}{\beta(4k(2-\theta)-3\beta\Delta^2)},\quad \tau_s^{\mathrm{MR}^*}=\frac{2\Delta(a-\beta c_m)}{4k(2-\theta)-3\beta\Delta^2},$$
$$\text{and } q^{\mathrm{MR}^*}=\frac{2k(a-\beta c_m)}{4k(2-\theta)-3\beta\Delta^2}.$$

By substituting the aforementioned equilibria into the profit functions of each member, the corresponding manufacturer's profit $\pi_m^{\mathrm{MR}^*}$, retailer's profit $\pi_r^{\mathrm{MR}^*}$, and the system's total profit $\pi_s^{\mathrm{MR}^*}$ can be derived. Further, it is straightforward to determine the consumer surplus $\mathrm{CS}^{\mathrm{MR}^*}$ and social welfare $\mathrm{SW}^{\mathrm{MR}^*}$.

Lemma 4.2. *To ensure that the expressions in the* MR *model have economic significance and the total collecting rate satisfies* $0\le\tau_s^{\mathrm{MR}^*}\le 1$*, the parameters need to satisfy* $k>\frac{\Delta(2(a-\beta c_m)+3\beta\Delta)}{4(2-\theta)}$ *and* $0\le\theta<\frac{4k-\beta\Delta^2}{4k}$*.*

4.1.3. Without the channel leader (MN model)

In the MN model, the manufacturer and retailer have equal decision power and determine their respective variables simultaneously. The manufacturer's decision variables include the wholesale price w^{MN} and the collecting rate τ_m^{MN}, and the retailer's decision variables include the unit profit m^{MN} and the collecting rate τ_r^{MN}. The optimal decisions for both the manufacturer and the retailer are as follows.

The optimal wholesale price and collecting rate set by the manufacturer are, respectively:

$$w^{\mathrm{MN}^*}=\frac{a\big(2k(1-\theta)-\beta\big(\Delta^2+\Delta\mathrm{b}-b^2\big)\big)+\beta c_m\big(4k-\beta b^2\big)}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))}\ \text{ and }\ \tau_m^{\mathrm{MN}^*}=\frac{\Delta(a-\beta c_m)}{2k(3-\theta)-\beta\Delta(\Delta+b)}.$$

The optimal unit profit and collecting rate set by the retailer are, respectively:

$$m^{\mathrm{MN}^*}=\frac{\big(2k-\beta b^2\big)(a-\beta c_m)}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))}\ \text{ and }\ \tau_r^{\mathrm{MN}^*}=\frac{b(a-\beta c_m)}{2k(3-\theta)-\beta\Delta(\Delta+b)}.$$

The retailer's retail price p^{MN^*}, the total collecting rate $\tau_s^{\mathrm{MN}^*}$, and the market demand q^{MN^*} are, respectively:

$$p^{\mathrm{MN}^*}=\frac{a(2k(2-\theta)-\beta\Delta(\Delta+b))+2k\beta c_m}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))},\quad \tau_s^{\mathrm{MN}^*}=\frac{(\Delta+b)(a-\beta c_m)}{2k(3-\theta)-\beta\Delta(\Delta+b)},$$
$$\text{and } q^{\mathrm{MN}^*}=\frac{2k(a-\beta c_m)}{2k(3-\theta)-\beta\Delta(\Delta+b)}.$$

By substituting the aforementioned equilibria into the profit functions of each member, the corresponding manufacturer's profit $\pi_m^{\mathrm{MN}^*}$, retailer's profit $\pi_r^{\mathrm{MN}^*}$, and the system's total profit $\pi_s^{\mathrm{MN}^*}$ can be derived. Further, it is straightforward to determine the consumer surplus $\mathrm{CS}^{\mathrm{MN}^*}$ and social welfare $\mathrm{SW}^{\mathrm{MN}^*}$.

Lemma 4.3. *To ensure that the expressions in the* MN *model have economic significance and the total collecting rate satisfies* $0\le\tau_s^{\mathrm{MN}^*}\le 1$*, the parameters need to satisfy* $k>\frac{(\Delta+b)(a-\beta c_m+\beta\Delta)}{2(3-\theta)}$ *and* $0\le\theta<\frac{4k-\beta\Delta^2}{4k}$*.*

4.2. Decision model of the retailer implementing CSR

Similarly, when the retailer implements CSR, it will take the maximization of social welfare as the decision goal, and the retailer's objective function is as follows:

$$\max V_r(p,\tau_r) = (p-w)(a-\beta p) + b\tau_r(a-\beta p) - k\tau_r^2 + \frac{\theta(a-\beta p)^2}{2\beta}\cdot \tag{4.2}$$

The manufacturer aims to maximize profit, and its objective function is presented in equation (3.1).

4.2.1. Manufacturer as the channel leader (RM model)

In the RM model, the optimization problem of the SSC, as described in equations (3.1) and (4.2), is addressed by employing backward induction. The decision sequence of the members is as follows: the manufacturer first determines the wholesale price w^{RM} and the collecting rate τ_m^{RM}; then, according to the manufacturer's decision, the retailer maximizes its own utility by determining the retail price p^{RM} and the collecting rate τ_r^{RM}. The optimal decisions for both the manufacturer and the retailer are as follows.

The optimal wholesale price and collecting rate set by the manufacturer are, respectively:

$$w^{\mathrm{RM}^*} = \frac{a\big(2k(2-\theta)-\beta\big(\Delta^2+2\Delta\mathrm{b}-b^2\big)\big)+\beta c_m\big(2k(2-\theta)-\beta b^2\big)}{\beta(4k(2-\theta)-\beta\Delta(\Delta+2b))} \quad\text{and}\quad \tau_m^{\mathrm{RM}^*} = \frac{\Delta(a-\beta c_m)}{4k(2-\theta)-\beta\Delta(\Delta+2b)}\cdot$$

The optimal retail price and collecting rate set by the retailer are, respectively:

$$p^{\mathrm{RM}^*} = \frac{a(2k(3-\theta)-\beta\Delta(\Delta+2b))+2k\beta c_m}{\beta(4k(2-\theta)-\beta\Delta(\Delta+2b))} \quad\text{and}\quad \tau_r^{\mathrm{RM}^*} = \frac{b(a-\beta c_m)}{4k(2-\theta)-\beta\Delta(\Delta+2b)}\cdot$$

The retailer's unit profit m^{RM^*}, the total collecting rate $\tau_s^{\mathrm{RM}^*}$, and the market demand q^{RM^*} are, respectively:

$$m^{\mathrm{RM}^*} = \frac{\big(2k(1-\theta)-\beta b^2\big)(a-\beta c_m)}{\beta(4k(2-\theta)-\beta\Delta(\Delta+2b))},\quad \tau_s^{\mathrm{RM}^*} = \frac{(\Delta+b)(a-\beta c_m)}{4k(2-\theta)-\beta\Delta(\Delta+2b)},$$
$$\text{and } q^{\mathrm{RM}^*} = \frac{2k(a-\beta c_m)}{4k(2-\theta)-\beta\Delta(\Delta+2b)}\cdot$$

By substituting the aforementioned equilibria into the profit functions of each member, the corresponding manufacturer's profit $\pi_m^{\mathrm{RM}^*}$, retailer's profit $\pi_r^{\mathrm{RM}^*}$, and the system's total profit $\pi_s^{\mathrm{RM}^*}$ can be derived. Further, it is straightforward to determine the consumer surplus $\mathrm{CS}^{\mathrm{RM}^*}$ and social welfare $\mathrm{SW}^{\mathrm{RM}^*}$.

Lemma 4.4. *To ensure that the expressions in the* RM *model have economic significance and the total collecting rate satisfies* $0 \le \tau_s^{\mathrm{RM}^*} \le 1$, *the parameters need to satisfy* $k > \frac{((\Delta+b)(a-\beta c_m)+\beta\Delta(\Delta+2b))}{4(2-\theta)}$ *and* $0 \le \theta < \frac{2k-\beta b^2}{2k}$.

4.2.2. Retailer as the channel leader (RR model)

In the RR model, the retailer first determines the unit profit m^{RR} and the collecting rate τ_r^{RR} according to its own utility maximisation, and then the manufacturer determines the wholesale price w^{RR} and the collecting rate τ_m^{RR}. The optimal decisions for both the manufacturer and the retailer are as follows.

The optimal wholesale price and collecting rate set by the manufacturer are, respectively:

$$w^{\mathrm{RR}^*} = \frac{a(2k-\beta\Delta(2\Delta-b))+\beta c_m(2k(3-\theta)-\beta\Delta(\Delta+b))}{\beta(2k(4-\theta)-3\beta\Delta^2)} \quad\text{and}\quad \tau_m^{\mathrm{RR}^*} = \frac{\Delta(a-\beta c_m)}{2k(4-\theta)-3\beta\Delta^2}\cdot$$

The optimal unit profit and collecting rate set by the retailer are, respectively:

$$m^{\mathrm{RR}^*} = \frac{(2k(2-\theta)-\beta\Delta(\Delta+b))(a-\beta c_m)}{\beta(2k(4-\theta)-3\beta\Delta^2)} \quad\text{and}\quad \tau_r^{\mathrm{RR}^*} = \frac{\Delta(a-\beta c_m)}{2k(4-\theta)-3\beta\Delta^2}\cdot$$

The retailer's retail price p^{RR^*}, the total collecting rate $\tau_s^{\mathrm{RR}^*}$, and the market demand q^{RR^*} are, respectively:

$$p^{\mathrm{RR}^*} = \frac{a\big(2k(3-\theta) - 3\beta\Delta^2\big) + 2k\beta c_m}{\beta(2k(4-\theta) - 3\beta\Delta^2)}, \quad \tau_s^{\mathrm{RR}^*} = \frac{2\Delta(a-\beta c_m)}{2k(4-\theta) - 3\beta\Delta^2},$$
$$\text{and } q^{\mathrm{RR}^*} = \frac{2k(a-\beta c_m)}{2k(4-\theta) - 3\beta\Delta^2}.$$

By substituting the aforementioned equilibria into the profit functions of each member, the corresponding manufacturer's profit $\pi_m^{\mathrm{RR}^*}$, retailer's profit $\pi_r^{\mathrm{RR}^*}$, and the system's total profit $\pi_s^{\mathrm{RR}^*}$ can be derived. Further, it is straightforward to determine the consumer surplus $\mathrm{CS}^{\mathrm{RR}^*}$ and social welfare $\mathrm{SW}^{\mathrm{RR}^*}$.

Lemma 4.5. *To ensure that the expressions in the* RR *model have economic significance and the total collecting rate satisfies* $0 \le \tau_s^{\mathrm{RR}^*} \le 1$, *the parameters need to satisfy* $k > \frac{\Delta(2(a-\beta c_m)+3\beta\Delta)}{2(4-\theta)}$.

4.2.3. Without the channel leader (RN model)

In the RN model, the manufacturer and the retailer decide on their own variables simultaneously. The manufacturer's decision variables include the wholesale price w^{RN} and the collecting rate τ_m^{RN}, and the retailer's decision variables include the unit profit m^{RN} and the collecting rate τ_r^{RN}. The optimal decisions for both the manufacturer and the retailer are as follows.

The optimal wholesale price and collecting rate set by the manufacturer are, respectively:

$$w^{\mathrm{RN}^*} = \frac{a\big(2k - \beta\big(\Delta^2 + \Delta \mathrm{b} - b^2\big)\big) + \beta c_m\big(2k(2-\theta) - \beta b^2\big)}{\beta(2k(3-\theta) - \beta\Delta(\Delta+b))} \text{ and } \tau_m^{\mathrm{RN}^*} = \frac{\Delta(a-\beta c_m)}{2k(3-\theta) - \beta\Delta(\Delta+b)}.$$

The optimal unit profit and collecting rate set by the retailer are, respectively:

$$m^{\mathrm{RN}^*} = \frac{\big(2k(1-\theta) - \beta b^2\big)(a-\beta c_m)}{\beta(2k(3-\theta) - \beta\Delta(\Delta+b))} \text{ and } \tau_r^{\mathrm{RN}^*} = \frac{b(a-\beta c_m)}{2k(3-\theta) - \beta\Delta(\Delta+b)}.$$

The retailer's retail price p^{RN^*}, the total collecting rate $\tau_s^{\mathrm{RN}^*}$, and the market demand q^{RN^*} are, respectively:

$$p^{\mathrm{RN}^*} = \frac{a(2k(2-\theta) - \beta\Delta(\Delta+b)) + 2k\beta c_m}{\beta(2k(3-\theta) - \beta\Delta(\Delta+b))}, \quad \tau_s^{\mathrm{RN}^*} = \frac{(\Delta+b)(a-\beta c_m)}{2k(3-\theta) - \beta\Delta(\Delta+b)},$$
$$\text{and } q^{\mathrm{RN}^*} = \frac{2k(a-\beta c_m)}{2k(3-\theta) - \beta\Delta(\Delta+b)}.$$

By substituting the aforementioned equilibria into the profit functions of each member, the corresponding manufacturer's profit $\pi_m^{\mathrm{RN}^*}$, retailer's profit $\pi_r^{\mathrm{RN}^*}$, and the system's total profit $\pi_s^{\mathrm{RN}^*}$ can be derived. Further, it is straightforward to determine the consumer surplus $\mathrm{CS}^{\mathrm{RN}^*}$ and social welfare $\mathrm{SW}^{\mathrm{RN}^*}$.

Lemma 4.6. *To ensure that the expressions in the* RN *model have economic significance and the total collecting rate satisfies* $0 \le \tau_s^{\mathrm{RN}^*} \le 1$, *the parameters need to satisfy* $k > \frac{(\Delta+b)(a-\beta c_m+\beta\Delta)}{2(3-\theta)}$ *and* $0 \le \theta < \frac{2k-\beta b^2}{2k}$.

5. Analysis and comparison of equilibrium results

Research on using numerical simulation technology to solve sustainable supply chain (SSC) optimization problems is currently divided into two main categories. The first category focuses on maximizing total profit or minimizing total cost. This involves constructing SSC optimization models under different scenarios and employing various methods, such as the accelerated Benders decomposition algorithm [59], colony optimization algorithm [69], and new variants of metaheuristic algorithms [22], to optimize and analyse these models. This approach clarifies the optimal design, inventory allocation, product design combination, path optimization, and operational decisions of the system. In contrast, the second category utilizes game theory to construct supply chain decision models, obtain equilibrium results, and employ numerical simulation techniques to verify the rationality of the model construction and the correctness of the equilibrium results. Examples of this approach include the research conducted by Panda *et al.* [3], Chai *et al.* [27], and Gong *et al.* [29]. Therefore, based on game theory, this paper constructs SSC game models under different behaviours and decision goals, and compares and analyses the obtained equilibrium price, market demand, waste recycling rate, enterprise performance, and social welfare to determine the optimal conditions of the system. In addition, this paper uses Matlab numerical simulation technology to visualize the obtained equilibrium results and conduct sensitivity analysis, in order to verify the effectiveness of the model and the feasibility of the research conclusions.

5.1. Comparison of channel leadership structure when the manufacturer implements CSR

Proposition 5.1. *When the manufacturer implements CSR,* (a) $w^{\mathrm{MM}^*} > w^{\mathrm{MN}^*} > w^{\mathrm{MR}^*}$. (b) $p^{\mathrm{MM}^*} > p^{\mathrm{MR}^*} \geq p^{\mathrm{MN}^*}$, $q^{\mathrm{MM}^*} < q^{\mathrm{MR}^*} \leq q^{\mathrm{MN}^*}$, *if* $0 \leq \theta \leq \frac{2k-\beta\Delta(2\Delta-b)}{2k}$; $p^{\mathrm{MM}^*} > p^{\mathrm{MN}^*} > p^{\mathrm{MR}^*}$, $q^{\mathrm{MM}^*} < q^{\mathrm{MN}^*} < q^{\mathrm{MR}^*}$, *if* $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$.

Proposition 5.1(a) shows that the wholesale price w^* is the lowest when the manufacturer is the channel leader and the highest when the retailer is the channel leader; it has nothing to do with the CSR implementation degree θ of the manufacturer. This suggests that a socially responsible manufacturer will sacrifice more profit in favour of a downstream company under its own leadership structure. Proposition 5.1(b) shows that when the CSR implementation degree θ is low, the structure without channel leadership is most beneficial to minimise p^* and maximise q^*; when θ is higher, the retailer channel leadership structure is best, otherwise the manufacturer as the channel leader is always the most unfavourable situation.

Proposition 5.2. *When the manufacturer implements CSR,* (a) $\tau_m^{\mathrm{MN}^*} \geq \tau_m^{\mathrm{MR}^*} > \tau_m^{\mathrm{MM}^*}$, *if* $0 < \theta \leq \frac{2k-\beta\Delta(2\Delta-b)}{2k}$; $\tau_m^{\mathrm{MR}^*} > \tau_m^{\mathrm{MN}^*} > \tau_m^{\mathrm{MM}^*}$, *if* $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$. (b) $\tau_r^{\mathrm{MR}^*} \geq \tau_r^{\mathrm{MN}^*} > \tau_r^{\mathrm{MM}^*}$, *if* $0 < b \leq \frac{(6k-\beta\Delta^2)\Delta}{8k-2\beta\Delta^2}$; $\tau_r^{\mathrm{MN}^*} > \tau_r^{\mathrm{MR}^*} > \tau_r^{\mathrm{MM}^*}$, *if* $\frac{(6k-\beta\Delta^2)\Delta}{8k-2\beta\Delta^2} < b < \Delta$. (c) $\tau_s^{\mathrm{MR}^*} > \tau_s^{\mathrm{MN}^*} > \tau_s^{\mathrm{MM}^*}$, *if* $0 < b \leq \frac{\Delta(4k+\beta\Delta^2)}{8k-\beta\Delta^2}$; $\tau_s^{\mathrm{MN}^*} \geq \tau_s^{\mathrm{MR}^*} > \tau_s^{\mathrm{MM}^*}$, *if* $\frac{\Delta(4k+\beta\Delta^2)}{8k-\beta\Delta^2} < b < \Delta$ *and* $0 \leq \theta \leq \frac{4k(2b-\Delta)-\beta\Delta^2(\Delta+b)}{4kb}$; $\tau_s^{\mathrm{MR}^*} >_s^{\mathrm{MN}^*} > \tau_s^{\mathrm{MM}^*}$, *if* $\frac{\Delta(4k+\beta\Delta^2)}{8k-\beta\Delta^2} < b < \Delta$ *and* $\frac{4k(2b-\Delta)-\beta\Delta^2(\Delta+b)}{4kb} \leq \theta < \frac{4k-\beta\Delta^2}{4k}$.

Proposition 5.2 compares the collecting level of each member and the whole system from the perspective of an environment under the three channel leadership structures. First, for the manufacturer, its CSR implementation degree is the important factor that influences its choice of the optimal channel leadership structure. When θ is low, τ_m^* is the highest under the structure without channel leadership, and when θ exceeds a certain threshold, the retailer channel leadership structure is more favourable for maximising τ_m^*. Second, for the retailer, the collecting cooperation fees b have a greater impact on τ_r^*: when b is low, τ_r^* is the highest under the retailer's channel leadership structure; when b is higher, the structure without channel leadership is the most favourable. Finally, from the perspective of the whole system, τ_s^* will be affected by b and θ: if b is low, τ_s^* is always the highest under the retailer channel leadership structure; if b is high and θ is low, τ_s^* will be higher under the structure without channel leadership structure; if b and θ are high, τ_s^* will be higher under the retailer channel leadership structure.

Example 5.1. Table 3 and Figure 2 provide some illustrations of parameter values and corresponding outcomes under different channel leadership structures when the manufacturer implements CSR. The parameter settings should satisfy the assumptions in the theoretical model, so assuming that $a = 260$, $\beta = 2$, $c_m = 50$, $c_r = 20$, $k = 7000$.

Table 3 and Figure 2 verify the research results of Propositions 5.1 and 5.2 and analyse the influence of the CSR implementation degree θ of manufacturer and collecting cooperation fees b on the equilibrium results under different channel leadership structures.

TABLE 3. Parameter values and w, p, m, q when the manufacture implements CSR.

Parameter		$L = $ MM			$L = $ MR			$L = $ N		
		θ								
Decision	b	0.05	0.50	0.92	0.05	0.50	0.92	0.05	0.50	0.92
w^{L^*}	10	87.98	87.33	86.18	67.64	70.18	73.33	74.27	78.96	85.33
	20	87.94	87.25	86.01	68.60	71.28	74.60	74.65	79.50	86.14
p^{L^*}	10	108.29	101.28	88.88	107.56	104.31	100.31	101.21	95.64	88.08
	20	107.78	100.37	86.99	107.56	104.31	100.31	100.76	95.00	87.12
m^{L^*}	10	20.31	13.95	2.70	39.92	34.13	26.98	26.94	16.69	2.75
	20	19.84	13.12	0.99	38.96	33.03	25.71	26.11	15.50	0.97
q^{L^*}	10	43.41	57.44	82.23	44.89	51.38	59.38	57.58	68.71	83.83
	20	44.44	59.26	86.02	44.89	51.38	59.38	58.49	70.00	85.76

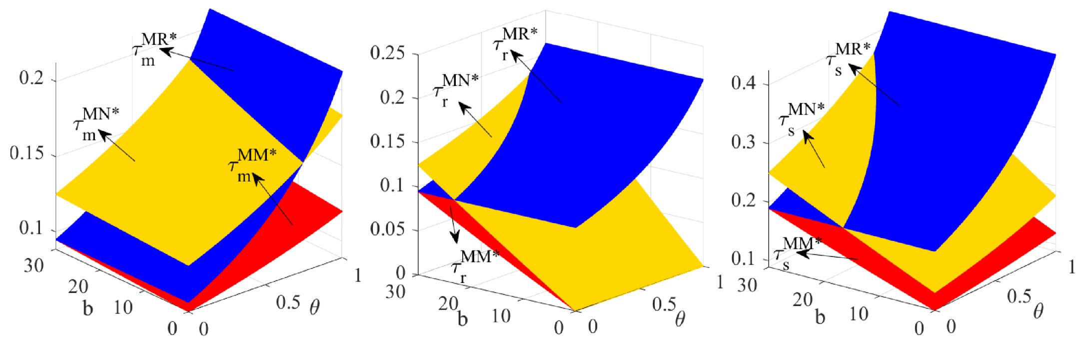

FIGURE 2. Parameter values and τ_m, τ_r, τ_s when the manufacture implements CSR.

First, when b is fixed, for any channel leadership structure, w^* and p^* decrease in θ while q^*, τ_m^*, τ_r^* and τ_s^* increase in θ. This is because the manufacturer implements CSR to benefit the retailer by reducing its own price, thus prompting the retailer to reduce the price for consumer to stimulate consumption and improve consumer surplus. Moreover, improving the collecting efficiency of waste products reflects the effect of members implementing CSR to a strong extent. Hence, the manufacturer and retailer as collectors will strive to improve their own collecting level of waste products to reflect their CSR behaviour and ultimately increase the collecting level of the whole supply chain system. We further find that under the channel structure of manufacturer leadership or without leadership, the retailer's unit profit m^* is always increasing in θ; however, under the retailer channel leadership structure, m^* is also affected by b. This reveals that when the retailer has strong bargaining power, the collecting cooperation fees b paid by the manufacturer are an important factor influencing the retailer's decision.

Note that when θ is determined, under the manufacturer channel leadership or without channel leadership structure, the increase of b reduces p^*, q^*, τ_m^*, τ_r^* and τ_s^*, while under the retailer channel leadership structure, b will not affect these values. We also reach the interesting conclusion that m^* always decreases in b under any channel leadership structure. This shows that in the process of reverse collecting, the manufacturer can effectively motivate the retailer to collect waste products by setting higher collecting cooperation fees. At the same time, the retailer does not hesitate to sacrifice its own unit profit through lower pricing strategies to increase market demand, expand the market scale of waste product collecting and finally form a virtuous circle development of SSC system.

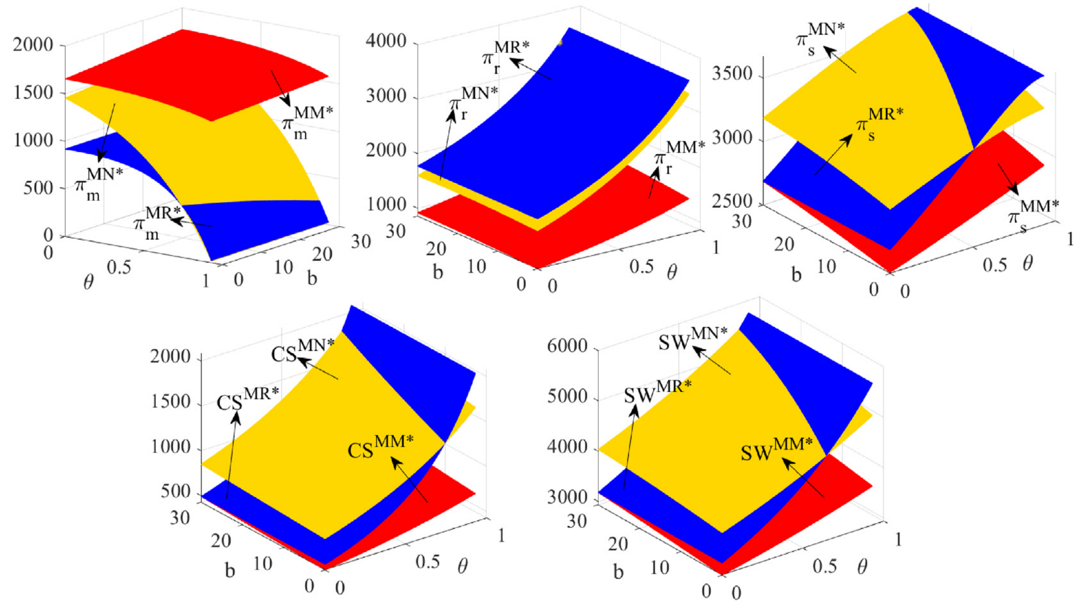

FIGURE 3. Parameter values and π_m, π_r, π_s, CS, SW when the manufacturer implements CSR.

Proposition 5.3. *When the manufacturer implements CSR,* (a) $\pi_r^{\mathrm{MR}^*} > \pi_r^{\mathrm{MN}^*} > \pi_r^{\mathrm{MM}^*}$. (b) $\pi_m^{\mathrm{MM}^*} > \pi_m^{\mathrm{MN}^*} \geq \pi_m^{\mathrm{MR}^*}$, *if* $0 \leq \theta \leq \frac{2k-\beta\Delta(2\Delta-b)}{2k}$; $\pi_m^{\mathrm{MM}^*} > \pi_m^{\mathrm{MR}^*} > \pi_m^{\mathrm{MN}^*}$, *if* $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$. (c) $\mathrm{CS}^{\mathrm{MN}^*} \geq \mathrm{CS}^{\mathrm{MR}^*} > \mathrm{CS}^{\mathrm{MM}^*}$, *if* $0 \leq \theta \leq \frac{2k-\beta\Delta(2\Delta-b)}{2k}$; $\mathrm{CS}^{\mathrm{MR}^*} > \mathrm{CS}^{\mathrm{MN}^*} > \mathrm{CS}^{\mathrm{MM}^*}$, *if* $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$.

Propositions 5.3(a) and 5.4(b) illustrate that from the perspective of members' profit, both the manufacturer and retailer obtain the maximum profit under their own channel leadership structure, and both have nothing to do with the manufacturer's degree of CSR implementation. For consumers, the manufacturer's degree of CSR implementation manufacturer will have a certain impact on their choice of the optimal channel leadership structure. When θ is low, consumer surplus is the maximum under the structure without channel leadership, while when θ is high, the retailer's channel leadership structure is more favourable for consumer surplus maximisation.

Example 5.2. Figure 3 illustrates some parameter values and the trend of π_m, π_r, π_s, CS, and SW under different channel leadership structures; the parameter setting is the same as that in Example 5.1.

To verify Proposition 5.3, Figure 3 further analyses the influence of CSR implementation degree θ and the collecting cooperation fees b on the profit and utility of members, consumer surplus and total social welfare. When b is fixed, the retailer's profit π_r^*, the supply chain's total profit π_s^*, the consumer surplus CS^* and the total social welfare SW^* all increase in θ for any channel leadership structure. However, in most cases, the profit of the manufacturer implementing CSR will decrease in θ. This reveals that to maximise social welfare, the manufacturer chooses to sacrifice its own profit to benefit other stakeholders (such as the retailer) and contribute to consumers and society. However, compared with θ, the effect of b is not significant. In most cases, the structure without channel leadership is more favourable for maximising π_s^* and SW^*; the retailer channel leadership structure is more dominant only when the manufacturer implements a relatively high degree of CSR.

Proposition 5.4. *When the manufacturer implements CSR, compare the profit relationship between manufacturer and retailer under the three channel leadership structures:*

(a) *Under the manufacturer channel leadership structure,* $\pi_m^{\mathrm{MM}^*} \geq \pi_r^{\mathrm{MM}^*}$, *if* $0 \leq \theta \leq \frac{4k-\beta\left(\Delta^2+2\Delta \mathrm{b}-b^2\right)}{4k}$, $\pi_m^{\mathrm{MM}^*} < \pi_r^{\mathrm{MM}^*}$, *if* $\frac{4k-\beta\left(\Delta^2+2\Delta \mathrm{b}-b^2\right)}{4k} < \theta < \frac{4k-\beta\Delta^2}{4k}$.
(b) *Under the retailer channel leadership structure,* $\pi_m^{\mathrm{MR}^*} < \pi_r^{\mathrm{MR}^*}$.
(c) *Under without channel leadership structure,* $\pi_m^{\mathrm{MN}^*} < \pi_r^{\mathrm{MN}^*}$.

Proposition 5.4(a) first illustrates that under the manufacturer channel leadership structure, when the manufacturer's CSR implementation degree θ is low, the manufacturer will obtain more profit than the retailer; conversely, if θ is high, the retailer's profit will be higher than that of the dominant manufacturer. Then, combining (b) and (c) means that with the weakening of the manufacturer's leadership, no matter what θ is, the retailer's profit is always higher than that of the manufacturer under the retailer channel leadership structure or without channel leadership structure.

5.2. Comparison of channel leadership structure when the retailer implements CSR

Proposition 5.5. *When the retailer implements CSR,* (a) $w^{\mathrm{RM}^*} \geq w^{\mathrm{RN}^*} > w^{\mathrm{RR}^*}$, *if* $0 \leq \theta \leq \frac{2k-\beta b\Delta}{2k}$; $w^{\mathrm{RN}^*} > w^{\mathrm{RM}^*} > w^{\mathrm{RR}^*}$, *if* $\frac{2k-\beta b\Delta}{2k} < \theta \leq \frac{2k-\beta b^2}{2k}$. (b) $p^{\mathrm{RM}^*} \geq p^{\mathrm{RR}^*} > p^{\mathrm{RN}^*}$, $q^{\mathrm{RM}^*} \leq q^{\mathrm{RR}^*} < q^{\mathrm{RN}^*}$, *if* $0 \leq \theta \leq \frac{\beta\Delta(\Delta-b)}{k}$; $p^{\mathrm{RR}^*} > p^{\mathrm{RM}^*} \geq p^{\mathrm{RN}^*}$, $q^{\mathrm{RR}^*} < q^{\mathrm{RM}^*} \leq q^{\mathrm{RN}^*}$, *if* $\frac{\beta\Delta(\Delta-b)}{k} < \theta \leq \frac{2k-\beta b\Delta}{2k}$; $p^{\mathrm{RR}^*} > p^{\mathrm{RN}^*} > p^{\mathrm{RM}^*}$, $q^{\mathrm{RR}^*} < q^{\mathrm{RN}^*} < q^{\mathrm{RM}^*}$, *if* $\frac{2k-\beta b\Delta}{2k} < \theta < \frac{2k-\beta b^2}{2k}$.

Proposition 5.5 compares pricing strategies and market demand under the three channels of leadership structures when the retailer implements CSR. First, (a) shows under its own leadership structure, the retailer can obtain a lower wholesale price from the manufacturer and not be affected by its own CSR implementation degree, which reveals that channel leaders in the supply chain have a unique advantage in pricing decisions. Further, in the analysis of (b), when the retailer implements CSR influence on its own retail price and the market demand is significant, combined with the numerical results in Table 4, a general structure without channel leadership is more advantageous to lowering retail price and improving market demand; only when the CSR implementation degree θ is higher will the pricing strategy and market demand be better under the manufacturer channel leadership structure.

Proposition 5.6. *When the retailer implements CSR,* (a) $\tau_m^{\mathrm{RN}^*} > \tau_m^{\mathrm{RR}^*} \geq \tau_m^{\mathrm{RM}^*}$, *if* $0 < \theta \leq \frac{\beta\Delta(\Delta-b)}{k}$; $\tau_m^{\mathrm{RN}^*} \geq \tau_m^{\mathrm{RM}^*} > \tau_m^{\mathrm{RR}^*}$, *if* $\frac{\beta\Delta(\Delta-b)}{k} < \theta \leq \frac{2k-\beta b\Delta}{2k}$; $\tau_m^{\mathrm{RM}^*} > \tau_m^{\mathrm{RN}^*} > \tau_m^{\mathrm{RR}^*}$, *if* $\frac{2k-\beta b\Delta}{2k} < \theta < \frac{2k-\beta b^2}{2k}$.

(b-1) $\tau_r^{\mathrm{RR}^*} \geq \tau_r^{\mathrm{RM}^*}$, *if* $0 < b \leq \frac{\left(4k-\beta\Delta^2\right)\Delta}{6k-\beta\Delta^2}$ *or* $\frac{\left(4k-\beta\Delta^2\right)\Delta}{6k-\beta\Delta^2} < b < \Delta$ *and* $0 \leq \theta \leq \frac{\left(8k-\beta\Delta^2\right)(\Delta-b)}{2k(2\Delta-b)}$; $\tau_r^{\mathrm{RM}^*} > \tau_r^{\mathrm{RR}^*}$, *if* $\frac{\left(4k-\beta\Delta^2\right)\Delta}{6k-\beta\Delta^2} < b < \Delta$ *and* $\frac{\left(8k-\beta\Delta^2\right)(\Delta-b)}{2k(2\Delta-b)} < \theta < \frac{2k-\beta b^2}{2k}$; (b-2) $\tau_r^{\mathrm{RN}^*} \geq \tau_r^{\mathrm{RM}^*}$, *if* $0 \leq \theta \leq \frac{2k-\beta b\Delta}{2k}$; $\tau_r^{\mathrm{RM}^*} > \tau_r^{\mathrm{RN}^*}$, *if* $\frac{2k-\beta b\Delta}{2k} < \theta < \frac{2k-\beta b^2}{2k}$; (b-3) $\tau_r^{\mathrm{RR}^*} \geq \tau_r^{\mathrm{RN}^*}$, *if* $0 < b \leq \frac{\left(4k-\beta\Delta^2\right)\Delta}{6k-2\beta\Delta^2}$ *or* $\frac{\left(4k-\beta\Delta^2\right)\Delta}{6k-2\beta\Delta^2} < b < \frac{\left(6k-\beta\Delta^2\right)\Delta}{8k-2\beta\Delta^2}$ *and* $0 \leq \theta \leq \frac{2k(3\Delta-4b)-\beta\Delta^2(\Delta-2b)}{2k(\Delta-b)}$; $\tau_r^{\mathrm{RN}^*} > \tau_r^{\mathrm{RR}^*}$, *if* $\frac{\left(4k-\beta\Delta^2\right)\Delta}{6k-2\beta\Delta^2} < b < \frac{\left(6k-\beta\Delta^2\right)\Delta}{8k-2\beta\Delta^2}$ *and* $\frac{2k(3\Delta-4b)-\beta\Delta^2(\Delta-2b)}{2k(\Delta-b)} < \theta < \frac{2k-\beta b^2}{2k}$ *or* $\frac{\left(6k-\beta\Delta^2\right)\Delta}{8k-2\beta\Delta^2} \leq b < \Delta$.

(c-1) $\tau_s^{\mathrm{RR}^*} \geq \tau_s^{\mathrm{RM}^*}$, *if* $0 < b \leq \frac{\left(2k+\beta\Delta^2\right)\Delta}{6k+\beta\Delta^2}$ *or* $\frac{\left(2k+\beta\Delta^2\right)\Delta}{6k+\beta\Delta^2} < b < \Delta$ *and* $0 \leq \theta \leq \frac{8k(\Delta-b)-\beta\Delta^2(\Delta-b)}{2k(3\Delta-b)}$; $\tau_s^{\mathrm{RM}^*} > \tau_s^{\mathrm{RR}^*}$, *if* $\frac{\left(2k+\beta\Delta^2\right)\Delta}{6k+\beta\Delta^2} < b < \Delta$ *and* $\frac{8k(\Delta-b)-\beta\Delta^2(\Delta-b)}{2k(3\Delta-b)} < \theta < \frac{2k-\beta b^2}{2k}$; (c-2) $\tau_s^{\mathrm{RN}^*} \geq \tau_s^{\mathrm{RM}^*}$, *if* $0 \leq \theta \leq \frac{2k-\beta b\Delta}{2k}$; $\tau_s^{\mathrm{RM}^*} > \tau_s^{\mathrm{RN}^*}$, *if* $\frac{2k-\beta b\Delta}{2k} < \theta < \frac{2k-\beta b^2}{2k}$; (c-3) $\tau_s^{\mathrm{RR}^*} \geq \tau_s^{\mathrm{RN}^*}$, *if* $0 < b \leq \frac{\left(2k+\beta\Delta^2\right)\Delta}{6k-\beta\Delta^2}$ *or* $\frac{\left(2k+\beta\Delta^2\right)\Delta}{6k-\beta\Delta^2} < b < \frac{\left(4k+\beta\Delta^2\right)\Delta}{8k-\beta\Delta^2}$ *and* $0 \leq \theta \leq \frac{4k(\Delta-2b)+\beta\Delta^2(\Delta+b)}{2k(\Delta-b)}$; $\tau_s^{\mathrm{RN}^*} > \tau_s^{\mathrm{RR}^*}$, *if* $\frac{\left(2k+\beta\Delta^2\right)\Delta}{6k-\beta\Delta^2} < b < \frac{\left(4k+\beta\Delta^2\right)\Delta}{8k-\beta\Delta^2}$ *and* $\frac{4k(\Delta-2b)+\beta\Delta^2(\Delta+b)}{2k(\Delta-b)} < \theta < \frac{2k-\beta b^2}{2k}$ *or* $\frac{\left(4k+\beta\Delta^2\right)\Delta}{8k-\beta\Delta^2} \leq b < \Delta$.

Proposition 5.6 analyses in detail the collecting efficiency of each member and the whole system under the three channel leadership structures when the retailer implements CSR. It also presents the conditions for

TABLE 4. Parameter values and w, p, m, q when the retailer implements CSR.

	Parameter	$L = \text{RM}$			$L = \text{RR}$			$L = \text{RN}$		
		θ								
Decision	b	0.05	0.50	0.92	0.05	0.50	0.92	0.05	0.50	0.92
w^{L^*}	10	87.98	87.33	86.18	67.64	70.18	73.33	74.27	78.96	85.33
	20	87.94	87.25	86.01	68.60	71.28	74.60	74.65	79.50	86.14
p^{L^*}	10	108.29	101.28	88.88	107.56	104.31	100.31	101.21	95.64	88.08
	20	107.78	100.37	86.99	107.56	104.31	100.31	100.76	95.00	87.12
m^{L^*}	10	20.31	13.95	2.70	39.92	34.13	26.98	26.94	16.69	2.75
	20	19.84	13.12	0.99	38.96	33.03	25.71	26.11	15.50	0.97
q^{L^*}	10	43.41	57.44	82.23	44.89	51.38	59.38	57.58	68.71	83.83
	20	44.44	59.26	86.02	44.89	51.38	59.38	58.49	70.00	85.76

selecting the optimal channel leadership structure. Results show that τ_m^* is mainly affected by the retailer's CSR implementation degree θ, and τ_r^* and τ_s^* are affected not only by θ but also by the collecting cooperation fees b paid by the manufacturer to the retailer. For the manufacturer, in most cases, the structure without channel leadership achieves higher collecting level, and it is only when θ and b are higher that the manufacturer is likely to achieve higher collecting level under its own channel leadership structure. For the retailer and the whole system, when b is relatively low, the collecting level is usually higher under the retailer channel leadership structure; when b improves, the structure without channel leadership is more conducive to a higher collecting level for retailer and the whole supply chain; the manufacturer leadership structure is superior only when both θ and b are high.

Example 5.3. Table 4 and Figure 4 present some illustrations of parameter values and corresponding outcomes under different channel leadership structures when the retailer implements CSR; the parameter setting is the same as that in Example 5.1.

According to Table 4 and Figure 4, the conclusions of Propositions 5.5 and 5.6 can be verified. The influence of the retailer's CSR implementation degree θ and collecting cooperation fees b on the equilibrium results under different channel leadership structures is also analysed. First, when b is fixed, the effect of the retailer's CSR implementation degree θ on product price p^*, market demand q^* and the collecting level of waste products τ_m^*, τ_r^* and τ_s^* is the same as that when the manufacturer implements CSR. The difference is that under the retailer channel leadership or without channel leadership structure, w^* increases in θ when the retailer implements CSR. This result illustrates that when manufacturer acts as the channel leader, it will lower the wholesale price to benefit the retailer who is implementing CSR; but under the retailer channel leadership or without channel leadership structure, the manufacturer will engage in "free ride" behaviour and take the opportunity to gain more profit by raising the price. In addition, the influence of b is similar to that of the manufacturer implementing CSR, which indicates that the influence of b on members' decisions does not change qualitatively with different CSR implementation members.

Proposition 5.7. *When the retailer undertakes CSR,* (a) $\pi_m^{\text{RM}^*} > \pi_m^{\text{RN}^*} > \pi_m^{\text{RR}^*}$. (b) $\pi_r^{\text{RR}^*} > \pi_r^{\text{RN}^*} \geq \pi_r^{\text{RM}^*}$, *if* $0 \leq \theta \leq \frac{2k-\beta b\Delta}{2k}$; $\pi_r^{\text{RR}^*} > \pi_r^{\text{RM}^*} > \pi_r^{\text{RN}^*}$, *if* $\frac{2k-\beta b\Delta}{2k} < \theta \leq \frac{2k-\beta b^2}{2k}$. (c) $\text{CS}^{\text{RN}^*} > \text{CS}^{\text{RR}^*} \geq \text{CS}^{\text{RM}^*}$, *if* $0 \leq \theta \leq \frac{\beta\Delta(\Delta-b)}{k}$; $\text{CS}^{\text{RN}^*} \geq \text{CS}^{\text{RM}^*} > \text{CS}^{\text{RR}^*}$, *if* $\frac{\beta\Delta(\Delta-b)}{k} < \theta \leq \frac{2k-\beta b\Delta}{2k}$; $\text{CS}^{\text{RM}^*} > \text{CS}^{\text{RN}^*} > \text{CS}^{\text{RR}^*}$, *if* $\frac{2k-\beta b\Delta}{2k} < \theta < \frac{2k-\beta b^2}{2k}$.

Propositions 5.7(a) and 5.7(b) show that in most cases, both the manufacturer and retailer obtain more profit under their own leadership structure and the least profit under the other party's leadership structure. (c) shows that for consumers, when the retailer's CSR implementation degree θ is low, the structure without

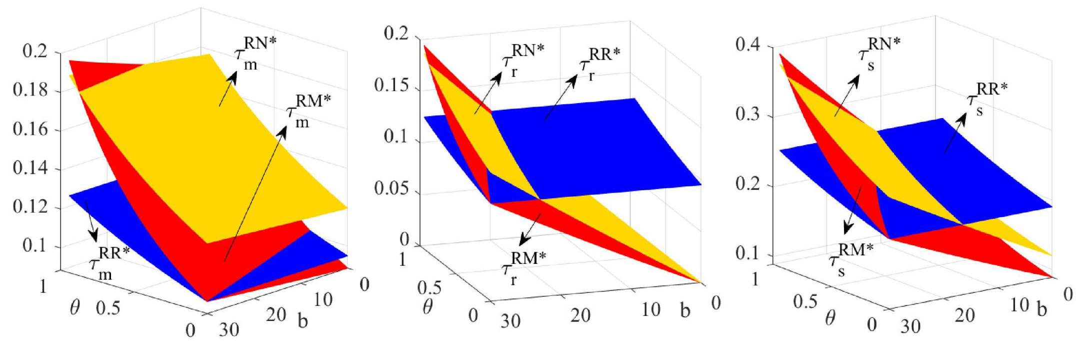

FIGURE 4. Parameter values and τ_m, τ_r, τ_s when the retailer implements CSR.

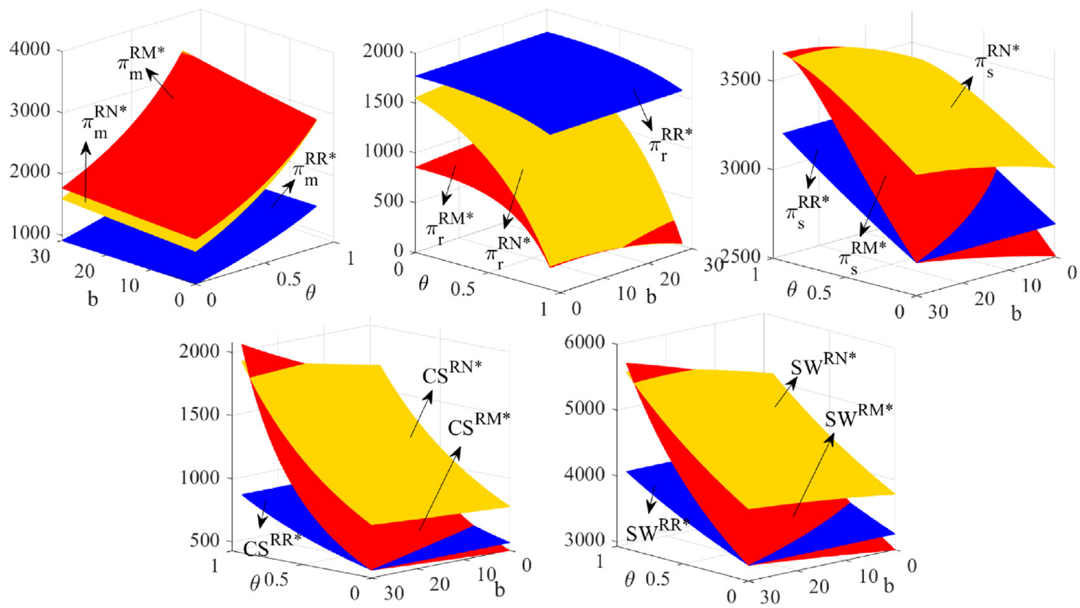

FIGURE 5. Parameter values and π_m, π_r, π_s, CS, SW when the retailer implements CSR.

channel leadership is the most beneficial to maximise consumer surplus; as θ increases, the manufacturer channel leadership structure is optimal for consumers when it exceeds a certain threshold.

Example 5.4. Figure 5 presents illustrations of parameter values and the trend of π_m, π_r, π_s, CS, and SW under different channel leadership structures; the parameter setting is the same as that in Example 5.1.

In addition, the conclusion in Proposition 5.7 is verified through numerical simulation, as illustrated in Figure 5. This study further compares the total profit of the whole supply chain and social welfare under the three channel leadership structures. This analysis reveals that, in most cases, the structure without channel leadership is the most beneficial. The advantage of the manufacturer channel leadership structure becomes evident only when the retailer's CSR implementation degree θ and the collecting cooperation fees b are both relatively high.

Proposition 5.8. *When the retailer implements CSR, the profit relationship between the manufacturer and the retailer under the three different channel leadership structures satisfies the following:* (a) *Under the manufacturer channel leadership structure,* $\pi_m^{\mathrm{RM}^*} > \pi_r^{\mathrm{RM}^*}$. (b) *Under the retailer channel leadership structure,* $\pi_m^{\mathrm{RR}^*} \le \pi_r^{\mathrm{RR}^*}$, *if* $0 \le \theta \le \frac{2k-\beta\Delta^2}{2k}$; $\pi_m^{\mathrm{RR}^*} > \pi_r^{\mathrm{RR}^*}$, *if* $\frac{2k-\beta\Delta^2}{2k} < \theta \le 1$. (c) *Under without channel leadership structure,* $\pi_m^{\mathrm{RN}^*} \le \pi_r^{\mathrm{RN}^*}$, *if* $0 \le \theta \le \frac{\beta(\Delta^2-b^2)}{4k}$; $\pi_m^{\mathrm{RN}^*} > \pi_r^{\mathrm{RN}^*}$, *if* $\frac{\beta(\Delta^2-b^2)}{4k} < \theta < \frac{2k-\beta b^2}{2k}$.

Proposition 5.8 shows that the retailer's profit is always lower than that of the manufacturer under the manufacturer channel leadership structure. Further, under without channel leadership structure, when the retailer's degree of CSR implementation is low, the retailer will obtain more profit than the manufacturer, otherwise, it will obtain less profit than the manufacturer. Under the retailer channel leadership structure, when the retailer's CSR implementation degree is higher, the retailer's profit is lower than that of the manufacturer. This conclusion reveals that when the retailer channel leadership is enhanced, its bargaining and profitability in the supply chain also improve, which is conducive to improving its CSR implementation degree.

5.3. Comparison of CSR implementers under different channel leadership structures

Proposition 5.9. *Comparing the equilibrium strategies of different members implementing CSR under the three channel leadership structures satisfies the following:*

(a) *Under the manufacturer channel leadership structure,* (1) $w^{\mathrm{MM}^*} < w^{\mathrm{RM}^*}$, $p^{\mathrm{MM}^*} > p^{\mathrm{RM}^*}$, $q^{\mathrm{MM}^*} < q^{\mathrm{RM}^*}$, $\tau_m^{\mathrm{MM}^*} < \tau_m^{\mathrm{RM}^*}$, $\tau_r^{\mathrm{MM}^*} < \tau_r^{\mathrm{RM}^*}$, $\tau_s^{\mathrm{MM}^*} < \tau_s^{\mathrm{RM}^*}$; (2) $\pi_m^{\mathrm{MM}^*} < \pi_m^{\mathrm{RM}^*}$, $\pi_r^{\mathrm{MM}^*} > \pi_r^{\mathrm{RM}^*}$, $\pi_s^{\mathrm{MM}^*} < \pi_s^{\mathrm{RM}^*}$, $\mathrm{CS}^{\mathrm{MM}^*} < \mathrm{CS}^{\mathrm{RM}^*}$.

(b) *Under retailer channel leadership structure,* (1) $w^{\mathrm{MR}^*} < w^{\mathrm{RR}^*}$, $p^{\mathrm{MR}^*} < p^{\mathrm{RR}^*}$, $q^{\mathrm{MR}^*} > q^{\mathrm{RR}^*}$, $\tau_m^{\mathrm{MR}^*} > \tau_m^{\mathrm{RR}^*}$, $\tau_r^{\mathrm{MR}^*} > \tau_r^{\mathrm{RR}^*}$, $\tau_s^{\mathrm{MR}^*} > \tau_s^{\mathrm{RR}^*}$; (2) $\pi_m^{\mathrm{MR}^*} < \pi_m^{\mathrm{RR}^*}$, $\pi_r^{\mathrm{MR}^*} > \pi_r^{\mathrm{RR}^*}$, $\pi_s^{\mathrm{MR}^*} > \pi_s^{\mathrm{RR}^*}$, $\mathrm{CS}^{\mathrm{MR}^*} > \mathrm{CS}^{\mathrm{RR}^*}$.

(c) *Under without channel leadership structure,* (1) $w^{\mathrm{MN}^*} < w^{\mathrm{RN}^*}$, $p^{\mathrm{MN}^*} = p^{\mathrm{RN}^*}$, $q^{\mathrm{MN}^*} = q^{\mathrm{RN}^*}$, $\tau_m^{\mathrm{MN}^*} = \tau_m^{\mathrm{RN}^*}$, $\tau_r^{\mathrm{MN}^*} = \tau_r^{\mathrm{RN}^*}$, $\tau_s^{\mathrm{MN}^*} = \tau_s^{\mathrm{RN}^*}$; (2) $\pi_m^{\mathrm{MN}^*} < \pi_m^{\mathrm{RN}^*}$, $\pi_r^{\mathrm{MN}^*} > \pi_r^{\mathrm{RN}^*}$, $\pi_s^{\mathrm{MN}^*} = \pi_s^{\mathrm{RN}^*}$, $\mathrm{CS}^{\mathrm{MN}^*} = \mathrm{CS}^{\mathrm{RN}^*}$.

Propositions 5.9(a) and 5.9(b) show that when a channel leader exists in the supply chain, the effect is better when the follower implements CSR, whether from the perspective of reducing the price of new products, expanding market demand, enhancing the level of environmental protection or improving consumer surplus. Proposition 5.9(c) reveals that under the structure without channel leadership, the difference of CSR implementation members only affects the profit of members at the node of the supply chain but will not affect the pricing strategy of the whole supply chain system, the waste product collection level and the consumer surplus. In summary, for Propositions 5.9(a)–5.9(c), from the perspective of maximising profit, no matter whether there is a channel leader in the supply chain, each member hopes that the other party can assume social responsibilities to gain more profit for itself. This conclusion reveals that supply chain members often lack motivation to take the initiative to undertake CSR; coupled with the inconsistency between decision goals and the maximisation of individual interests, this makes the supply chain system unable to operate steadily. Therefore, it is necessary to study the coordination strategy of the SSC system.

6. Coordination strategies of the sustainable supply chain

6.1. Centralised decision model (C model)

The supply chain under centralised decision is an ideal market structure. All members in the supply chain will make centralised decisions and complete the operation of the whole supply chain system with the highest efficiency. In this case, the overall objective function of the supply chain system implementing CSR can be expressed as:

$$\max V_s^{\mathrm{C}}(p,\tau_m,\tau_r) = (p-c_m)q + (c_m-c_r)(\tau_m+\tau_r)q - k\left(\tau_m^2+\tau_r^2\right) + \frac{\theta(a-\beta p)^2}{2\beta}\cdot \tag{6.1}$$

In the C model, the manufacturer and the retailer jointly determine the p^{C}, τ_m^{C} and τ_r^{C}. Through calculation, it can be determined that equation (6.1) is the joint concave function of p^{C}, τ_m^{C} and τ_r^{C}, and there exists a unique optimal solution. The equilibrium strategy in the C model can be obtained as follows: $p^{\mathrm{C}^*} = \frac{a\left(k(1-\theta)-\beta\Delta^2\right)+k\beta c_m}{\beta(k(2-\theta)-\beta\Delta^2)}$, $\tau_m^{\mathrm{C}^*} = \frac{\Delta(a-\beta c_m)}{2(k(2-\theta)-\beta\Delta^2)}$, $\tau_r^{\mathrm{C}^*} = \frac{\Delta(a-\beta c_m)}{2(k(2-\theta)-\beta\Delta^2)}$, $\tau_s^{\mathrm{C}^*} = \frac{\Delta(a-\beta c_m)}{k(2-\theta)-\beta\Delta^2}$, $q^{\mathrm{C}^*} = \frac{k(a-\beta c_m)}{k(2-\theta)-\beta\Delta^2}$, $V_s^{\mathrm{C}^*} = \frac{k(a-\beta c_m)^2}{2\beta(k(2-\theta)-\beta\Delta^2)}$.

Lemma 6.1. *To ensure that the expressions in the C model have certain economic significance, the collecting rate should be satisfied* $0 \le \tau_s^{\mathrm{C}} \le 1$ *and the parameters should be satisfied* $k > \frac{\Delta(a-\beta c_m+\beta\Delta)}{2-\theta}$.

Proposition 6.1. *Equilibrium results under decentralised decision compared with centralised decision:* $p^{\mathrm{C}^*} < p^{L^*}$, $q^{\mathrm{C}^*} > q^{L^*}$, $\tau_s^{\mathrm{C}^*} > \tau_s^{L^*}$, $V_s^{\mathrm{C}^*} > V_s^{L^*}$, $\mathrm{CS}^{\mathrm{C}^*} > \mathrm{CS}^{L^*}$, $\mathrm{SW}^{\mathrm{C}^*} > \mathrm{SW}^{L^*}$, *where* $L = \{\mathrm{MM}, \mathrm{MR}, \mathrm{MN}, \mathrm{RM}, \mathrm{RR}, \mathrm{RN}\}$.

Proposition 6.1 shows that regardless of whether the manufacturer or retailer implements CSR, compared with centralised decision, decentralised decision will result in higher product price, lower market demand and waste product collection level, and significantly less consumer surplus and total social welfare. This is because the "double marginal" effect under decentralised decision leads to low efficiency in supply chain operation. The inconsistency in supply chain members' decision objectives is also an important factor in the loss of decision efficiency. Therefore, supply chain members should design effective contracts to control the losses caused by the "double marginal" effect on the supply chain; simultaneously, this can effectively motivate each member to actively fulfil its social responsibilities and consider the maximisation of social welfare. This research provides an effective governance mechanism for the decentralised decision of different members' CSR implementation and offer specific coordination strategies under different channel leadership structures to improve each member's profit and social welfare.

6.2. Coordination strategies when the manufacturer implements CSR (MS model)

When the manufacturer implements CSR, the specific process is that the retailer and manufacturer will share the retailer's sales revenue and the manufacturer's social responsibility according to the same ratio: z_1 and $1-z_1$, $z_1 \in (0,1)$. In the MS model, the contract objective functions of the manufacturer and retailer are respectively transformed into:

$$\max V_m^{\mathrm{MS}}(w,\tau_m) = (w-c_m)(a-\beta p) + ((c_m-c_r)\tau_m + (c_m-c_r-b)\tau_r)(a-\beta p) - k\tau_m^2 + (1-z_1)(p-w)(a-\beta p) + (1-z_1)\frac{\theta(a-\beta p)^2}{2\beta} \tag{6.2}$$

$$\max \pi_r^{\mathrm{MS}}(p,\tau_r) = z_1(p-w)(a-\beta p) + b\tau_r(a-\beta p) - k\tau_r^2 + z_1\frac{\theta(a-\beta p)^2}{2\beta}\cdot \tag{6.3}$$

After contract coordination, the wholesale price of products in the MS model is $w^{\mathrm{MS}*} = \frac{a\Delta(b-2\Delta z_1)+c_m(2kz_1(2-\theta)-\beta b\Delta)}{2z_1(k(2-\theta)-\beta\Delta^2)}$, the manufacturer's utility after implementing CSR is $V_m^{\mathrm{MS}*} = \frac{k(2k(2-\theta)(1-z_1)-\beta\Delta^2)(a-\beta c_m)^2}{4\beta(k(2-\theta)-\beta\Delta^2)^2}$ and the retailer's profit is $\pi_r^{\mathrm{MS}*} = \frac{k(2kz_1(2-\theta)-\beta\Delta^2)(a-\beta c_m)^2}{4\beta(k(2-\theta)-\beta\Delta^2)^2}$, which is $V_s^{\mathrm{MS}*} = V_m^{\mathrm{MS}*} + \pi_r^{\mathrm{MS}*} = V_s^{\mathrm{C}^*}$.

To make each member in the supply chain accept the contract, the following conditions need to be satisfied: $V_m^{\mathrm{MS}*} \ge V_m^{L^*}$, $\pi_r^{\mathrm{MS}*} \ge \pi_r^{L^*}$, where $L = \{\mathrm{MM}, \mathrm{MR}, \mathrm{MN}\}$ and the value range of contract parameters z_1 under different channel leadership structures can be obtained.

(1) Under the manufacturer channel leadership structure, the value range of contract parameter z_1 can be obtained as:

$$z_1^{\text{MS-M}} \ge \frac{16k^3(2-\theta)^2 + 4k^2\beta B_1 + 4k\beta^2\Delta^2 B_2 + \beta^3\Delta^5(4b+\Delta)}{2k(2-\theta)(2k(4-\theta)-\beta\Delta(2b+\Delta))^2},$$

$$z_1^{\text{MS-M}} \leq \frac{4k(2-\theta)(2k-\beta b\Delta)+\beta\Delta^2(4k(1-\theta)-\beta\Delta(3\Delta-2b))}{2k(2-\theta)(2k(4-\theta)-\beta\Delta(2b+\Delta))},$$

where $B_1=\Delta^2\theta^2-b^2(2-\theta)^2$, $B_2=\Delta^2\theta-2b\Delta(4-\theta)+2b^2(2-\theta)$.

(2) Under the retailer channel leadership structure, the value range of contract parameter z_1 can be obtained as:

$$\frac{(2k(2-\theta)-\beta\Delta^2)^2}{2k(2-\theta)(4k(2-\theta)-3\beta\Delta^2)} \leq z_1^{\text{MS-R}} \leq \frac{(6k(2-\theta)-5\beta\Delta^2)(2k(2-\theta)-\beta\Delta^2)^2}{2k(2-\theta)(4k(2-\theta)-3\beta\Delta^2)^2}.$$

(3) Under without channel leadership structure, the value range of contract parameter z_1 can be obtained as:

$$z_1^{\text{MS-N}} \geq \frac{16k^3(2-\theta)^2-4k^2\beta B_3+4k\beta^2\Delta^2 B_4+\beta^3\Delta^5(4b+\Delta)}{(2-\theta)(2k(3-\theta)-\beta b\Delta)^2},$$

$$z_1^{\text{MS-N}} \leq \frac{(2k+\beta\Delta(\Delta-b))\big(2k(2-\theta)-\beta\Delta^2\big)(2k(5-2\theta)-\beta\Delta(3\Delta+b))}{2k(2-\theta)(2k(3-\theta)-\beta\Delta(\Delta+b))^2},$$

where $B_3=\Delta^2(7-2\theta-\theta^2)+b^2(2-\theta)^2$, $B_4=\Delta^2(1+\theta)-b\Delta(3-\theta)+2b^2(2-\theta)$.

6.3. Coordination strategies when the retailer implements CSR (RS model)

When the retailer implements CSR, at this time, the retailer and the manufacturer share the retailer's sales revenue and social responsibility according to the same ratio z_2 and $1-z_2$, $z_2\in(0,1)$. In the RS model, the contract objective functions of the manufacturer and retailer are transformed into:

$$\max \pi_m^{\text{RS}}(w,\tau_m)=(w-c_m)(a-\beta p)+((c_m-c_r)\tau_m+(c_m-c_r-b)\tau_r)(a-\beta p) - k\tau_m^2++(1-z_2)(p-w)(a-\beta p)+(1-z_2)\frac{\theta(a-\beta p)^2}{2\beta} \tag{6.4}$$

$$\max\ V_r^{\text{RS}}(p,\tau_r)=z_2(p-w)(a-\beta p)+b\tau_r(a-\beta p)-k\tau_r^2+z_2\frac{\theta(a-\beta p)^2}{2\beta}\cdot \tag{6.5}$$

After contract coordination, the wholesale price of products in the RS model is $w^{\text{RS}^*}=\frac{a\Delta(b-2\Delta z_2)+c_m(2kz_2(2-\theta)-\beta b\Delta)}{2z_2(k(2-\theta)-\beta\Delta^2)}$, the manufacturer's profit is $\pi_m^{\text{RS}^*}=\frac{k(2k(2-\theta)(1-z_2)-\beta\Delta^2)(a-\beta c_m)^2}{4\beta(k(2-\theta)-\beta\Delta^2)^2}$ and the utility of the retailer after implementing CSR is $V_r^{\text{RS}^*}=\frac{k(2kz_2(2-\theta)-\beta\Delta^2)(a-\beta c_m)^2}{4\beta(k(2-\theta)-\beta\Delta^2)^2}$, which is $V_s^{\text{RS}^*}=\pi_m^{\text{RS}^*}+V_r^{\text{RS}^*}=V_s^{\text{C}^*}$

To make each member in the supply chain accept the contract, the following conditions need to be satisfied: $\pi_m^{\text{RS}^*}\geq\pi_m^{L^*}$, $V_r^{\text{RS}^*}\geq V_r^{L^*}$, where $L=\{\text{RM},\text{RR},\text{RN}\}$ and the value range of contract parameters z_2 under different channel leadership structures can be obtained.

(1) Under the manufacturer channel leadership structure, the value range of the contract parameters z_2 can be obtained as:

$$z_2^{\text{RS-M}} \geq \frac{8k^3(2-\theta)^3-4k^2\beta b^2(2-\theta)^2-8kb\beta^2\Delta^2(2-\theta)(2\Delta-b)+\beta^3\Delta^5(\Delta+4b)}{2k(2-\theta)(4k(2-\theta)-\beta\Delta(\Delta+2b))^2},$$

$$z_2^{\text{RS-M}} \leq \frac{4k^2(2-\theta)^2+2k\beta\Delta(2-\theta)(\Delta-2b)-\beta^2\Delta^3(3\Delta-2b)}{2k(2-\theta)(4k(2-\theta)-\beta\Delta(\Delta+2b))}.$$

(2) Under the retailer channel leadership structure, the value range of the contract parameters z_2 can be obtained as:

$$z_2^{\text{RS-R}} \geq \frac{4k^2(2-\theta)^2-2k\beta\Delta^2(4-3\theta)+\beta^2\Delta^4}{2k(2-\theta)(2k(4-\theta)-3\beta\Delta^2)},$$

$$z_2^{\text{RS-R}} \leq \frac{8k^3(2-\theta)\big(12-6\theta+\theta^2\big)-8k^2\beta\Delta^2\big(22-16\theta+3\theta^2\big)+2k\beta^2\Delta^4-5\beta^3\Delta^6}{2k(2-\theta)(2k(4-\theta)-3\beta\Delta^2)^2}.$$

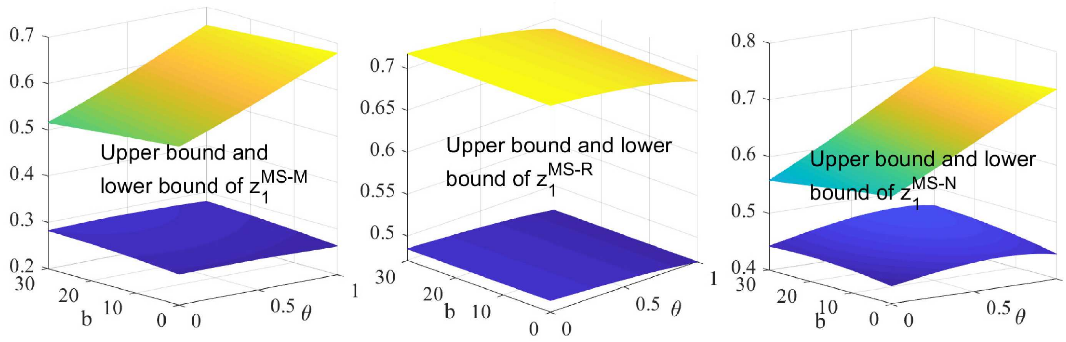

FIGURE 6. Parameter values and contract parameter z_1 when the manufacturer implements CSR.

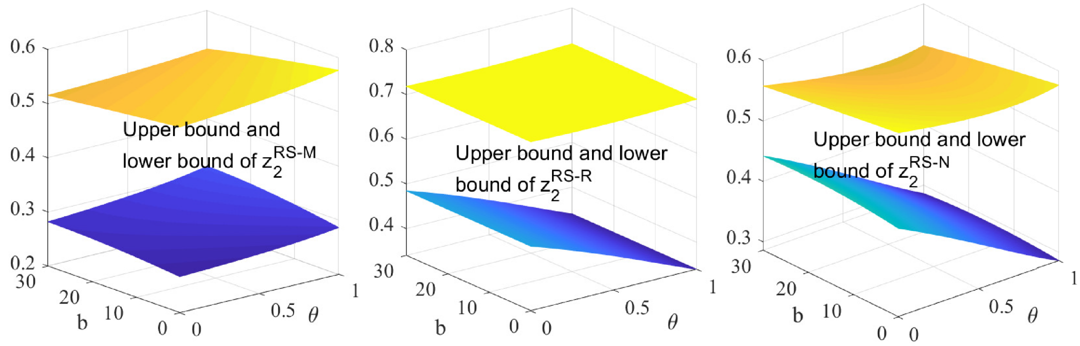

FIGURE 7. Parameter values and contract parameter z_2 when the retailer implements CSR.

(3) Under without channel leadership structure, the value range of the contract parameters z_2 can be obtained as:

$$z_2^{\text{RS-N}} \geq \frac{8k^3(2-\theta)^3 - 4k^2\beta B_5 + 4k\beta^2\Delta^2 B_6 + \beta^3\Delta^4 B_7}{2k(2-\theta)(2k(3-\theta)-\beta\Delta(\Delta+b))^2},$$
$$z_2^{\text{RS-N}} \leq \frac{8k^3(2-\theta)\left(5-4\theta+\theta^2\right) - 4k^2\beta\Delta B_8 - 2k\beta^2\Delta^2 B_9 + \beta^3\Delta^4 B_{10}}{2k(2-\theta)(2k(3-\theta)-\beta\Delta(\Delta+b))^2},$$

where $B_5 = \Delta^2(1-\theta)(7-3\theta) + b^2(2-\theta)^2$, $B_6 = \Delta^2(1-\theta) - b\Delta(3-\theta) + 2b^2(2-\theta)$, $B_7 = \Delta^2 + 2b\Delta - 3b^2$, $B_8 = \Delta\left(1-4\theta+2\theta^2\right) + 2b(2-\theta)(3-\theta)$, $B_9 = 3\Delta^2 - 2b\Delta - b^2$, $B_10 = \Delta^2(8-\theta) - 2b\Delta(5-2\theta) - b^2(2-\theta)$.

Example 6.1. In Figures 6 and 7, some illustrations of parameter values and contract parameter z_1 and z_2 are provided under different channel leadership structures; the parameter setting is the same as that in Example 5.1.

To further verify the effectiveness of the revenue-responsibility sharing contract, this study first assume that $b = 20$ and $\theta = 0.5$. Combined with Figures 6 and 7, the value range of contract parameters z_1 and z_2 under different channel leadership structures can be obtained.

When the manufacturer implements CSR, the value range of the contract parameters under different channel leadership structures is set as $z_1^{\text{MS-M}} \in (0.281, 0.592)$, $z_1^{\text{MS-R}} \in (0.480, 0.708)$ and $z_1^{\text{MS-N}} \in (0.469, 0.644)$. Table 5 shows the equilibrium results under the different decision models.

TABLE 5. Equilibrium results when the manufacturer implements CSR.

	z_1	w	p	q	τ_s	π_m	π_r	π_s	V_m	V_s
C	–	–	65.6	128.7	0.552	–	–	–	–	5149.4
MM	–	81.4	105	50	0.179	1687.5	1214.3	2901.8	2000	3214.3
MR	–	60.1	99.4	61.2	0.262	816	2448.1	3264.1	1284.2	3732.3
MN	–	62	95	70	0.471	1067.5	2380	3447.5	1680	4060
MS − M	0.4	47.2	65.6	128.7	0.552	1953.2	1953.2	3906.4	3196.2	5149.4
MS − R	0.5	44.5	65.6	128.7	0.552	1538.9	2574.7	4113.6	2574.7	5149.4
MS − N	0.6	42.6	65.6	128.7	0.552	1124.6	3196.2	4320.8	1953.2	5149.4

TABLE 6. Equilibrium results when the retailer implements CSR.

	z_2	w	p	q	τ_s	π_m	π_r	π_s	V_r	V_s
C	–	–	65.6	128.7	0.552	–	–	–	–	5149.4
RM	–	87.2	100.4	59.3	0.212	2370.4	827.7	3198.1	1266.7	3637.1
RR	–	71.3	104.3	51.4	0.22	1234.9	1725.1	2960	2055	3290
RN	–	79.5	95	70	0.25	2292.5	1155	3447.5	1767.5	4060
RS − M	0.35	49.2	65.6	128.7	0.552	3506.9	917.4	4424.3	1642.5	5149.4
RS − R	0.45	45.7	65.6	128.7	0.552	2885.4	1331.7	4217.1	2264	5149.4
RS − N	0.5	44.5	65.6	128.7	0.552	2574.7	1538.9	4113.6	2574.7	5149.4

When the retailer implements CSR, the value range of the contract parameters under different channel leadership structures is set as $z_2^{\text{RS-M}} \in (0.290, 0.533)$, $z_2^{\text{RS-R}} \in (0.416, 0.716)$, $z_2^{\text{RS-N}} \in (0.370, 0.545)$. Table 6 shows the equilibrium results under the different decision models.

According to the data analysis in Tables 5 and 6, as long as it is within the feasibility range of the given contract parameters, no matter what channel leadership structure, the revenue-responsibility sharing contract can effectively realise the perfect coordination of the SSC that simultaneously considers the economy, environment and society. The retail price, market demand, collection level and the total utility of the supply chain all reach the level of centralised decision, and the profit of each member in the supply chain is improved. In addition, it is worth explaining that with the increase of contract parameter z_1 (z_2), the manufacturer's profit decrease while the retailer's profit increase, which mainly depends on their bargaining power under different channel leadership structures. The conclusion of this paper provides some theoretical reference for the coordination strategy of the ESG multi-dimensional SSC.

7. Conclusions, managerial insights and future directions

7.1. Conclusions

This research investigates the decision-making and coordination mechanisms within an SSC system through the lens of the ESG sustainable development framework. The study aims to identify the most effective CSR implementer, the optimal channel leadership structure, and the corresponding coordination strategies for an SSC. Under the assumption of dual-channel collecting by both the manufacturer and the retailer, game theory is employed to construct six supply chain decision models, taking into account two CSR implementers and three channel leadership structures. These models are solved, followed by a comparative analysis of the equilibrium results, to determine the optimal conditions for selecting the CSR implementer and channel leadership structure. Finally, coordination models and strategies are formulated for various combinations of CSR implementers and channel leadership structures.

The main conclusions of this research are as follows: (1) In the SSC system, members actively implement CSR to help reduce product price, increase market demand, and improve the efficiency of waste product collection. Additionally, the implementation of CSR by any member enhances social welfare and boosts the profit of other members. (2) When the CSR implementer within the system is determined, both the manufacturer and retailer achieve greater economic profits under their own channel leadership. From an environmental and social perspective, the efficient collection of waste products and overall social welfare are influenced by the manufacturer's collection cooperation fees and the degree of CSR implementation by the members. (3) When the channel leadership structure of the supply chain is determined, the retailer's implementation of CSR is more conducive to higher total profits for the manufacturer. Similarly, the manufacturer's implementation of CSR helps the retailer gain more profit. From an environmental and social perspective, having the channel follower implement CSR, rather than the channel leader, is more effective in improving social welfare and the efficient collection of waste products. Notably, in the absence of a channel leader, the implementation of CSR by either the manufacturer or the retailer has an equal impact on the environment and society. (4) From a supply chain governance perspective, the revenue-responsibility sharing coordination mechanism not only achieves perfect coordination within the SSC but also enhances each member's profit. Additionally, it effectively encourages members to implement environmental and social responsibilities.

7.2. Managerial insights

Drawing on the findings presented above, this paper offers a set of management recommendations aimed at enhancing the sustainability of the supply chain system.

First, this research indicates that within SSC system, when members proactively engage in CSR initiatives, it can lead to a reduction in product prices, an escalation in market demand, and enhanced efficiency in waste collection. Therefore, it is imperative for supply chain members to formulate well-defined CSR strategies and objectives, integrating them within their broader development agendas. Furthermore, members are advised to create a specific department or team tasked with the development and execution of CSR initiatives. Particularly, enterprises can bolster transparency and foster community trust by consistently publishing CSR reports that detail the execution and impact of their CSR initiatives. Concurrently, it is imperative that enterprises motivate employees and supply chain collaborators to engage in CSR endeavours by providing training and offering incentives. Through these strategies, enterprises can not only augment their market competitiveness and financial performance but also contribute positively to societal welfare and environmental sustainability, thereby enhancing their commitment to social responsibility and capabilities for sustained development.

Second, enterprises can conduct a cost-benefit analysis of various channel leadership structures, identify the most effective structure, and establish appropriate cooperation mechanisms. This ensures that all members not only fulfil their social responsibilities but also achieve economic gains. By making informed decisions and refining channel leadership configurations, enterprises can secure a competitive edge and foster the sustainable growth of the supply chain. Furthermore, this research indicates that once the leadership hierarchy within a supply chain is established, the adoption of CSR initiatives by channel followers significantly enhances social welfare and the effective collection of waste. It is imperative for businesses to motivate channel followers to embrace CSR proactively. In terms of operational specifics, enterprises can define the CSR obligations and benchmarks for channel followers *via* contractual designs, incentive schemes, and collaborative agreements. Additionally, channel leader may offer technical assistance and training programs to bolster the CSR execution skills of channel follower. It is worth noting that channel leader should establish supervision and evaluation mechanisms, regularly inspect and evaluate the CSR implementation of channel follower, and reward or improve based on the evaluation results. By encouraging channel follower to implement CSR, leader can improve the overall social welfare and environmental benefits of the system, and enhance the sustainable development capability of the supply chain.

Third, the research revealed that the mechanism for distributing benefits and responsibilities not only facilitates the ideal coordination within SSC members but also enhances the profitability of each participant. Furthermore, it effectively motivates members to assume a certain level of environmental and social responsibility.

These findings offer significant managerial insights for businesses. Therefore, it is necessary to actively implement a mechanism for sharing and coordinating benefits and responsibilities to optimize the overall performance of the supply chain. Specifically, supply chain members can establish a fair and reasonable mechanism for sharing benefits and responsibilities through contract design, profit sharing, and cost sharing. For instance, manufacturers can markedly enhance the efficiency and competitiveness of the entire supply chain by implementing a lean production system and collaborating on cost and benefit sharing with supply chain partners. Moreover, enterprises should formulate specific profit and responsibility sharing schemes tailored to the characteristics and cooperative relationships of the supply chain members, ensuring an equitable balance of interests among all stakeholders. Concurrently, it is imperative for enterprises to enhance the oversight and appraisal of coordination mechanisms, making timely adjustments and optimizations to guarantee their efficacy and durability. Through the establishment of a mechanism that facilitates the sharing and coordination of revenue and responsibility, enterprises are able to augment the overall efficacy of the supply chain system, thereby reaping multifaceted benefits across economic, societal, and environmental dimensions.

7.3. Limitations and future direction

A Although our model has yielded some preliminary results, there are still numerous directions that are worth further exploration in future studies. First, this study assumes that consumer demand is certain. However, in practice, predicting market demand is often challenging due to various internal and external factors. The uncertainty of demand also significantly impacts the recycling of waste products. Therefore, it would be beneficial to investigate decision-making and coordination strategies in an SSC under conditions of uncertain demand. Second, this research primarily addresses information symmetry among members. It remains unclear whether the same conclusions would hold in the presence of information asymmetry. Thus, examining the operation of the SSC under conditions of information asymmetry constitutes an interesting future research direction. Finally, this paper focuses on an SSC system with a "one-to-one" structure, without considering multilevel network structures. Future research could explore the equilibrium problems of supply chain networks within the ESG multi-dimensional framework.

Funding

This research is supported by the National Social Science Fund of China (Grant Number 22BJY240).

Data availability statement

The research data associated with this article are included in the article.

References

[1] L. Yang, Y. Hu and L. Huang, Collecting mode selection in a remanufacturing supply chain under cap-and-trade regulation. *Eur. J. Oper. Res.* **287** (2020) 480–496.
[2] B. Pal, Optimal pricing and offering reward decisions in a competitive closed-loop dual-channel supply chain with recycling and remanufacturing. *RAIRO – Oper. Res.* **56** (2022) 1763–1780.
[3] S. Panda, N.M. Modak and L.E. Cárdenas-Barrón, Coordinating a socially responsible closed-loop supply chain with product recycling. *Int. J. Prod. Econ.* **188** (2017) 11–21.
[4] Y. Yan, F. Yao and J. Sun, Manufacturer's cooperation strategy of closed-loop supply chain considering corporate social responsibility. *RAIRO – Oper. Res.* **55** (2021) 3639–3659.
[5] C. Busco, C. Consolandi, R.G. Eccles and E. Sofra, A preliminary analysis of SASB reporting: disclosure topics, financial relevance, and the financial intensity of ESG materiality. *J. Appl. Corp. Finan.* **32** (2020) 117–125.
[6] R. Stekelorum, The roles of SMEs in implementing CSR in supply chains: a systematic literature review. *Int. J. Logist. Res. App.* **23** (2020) 228–253.
[7] K. Govindan, H. Soleimani and D. Kannan, Reverse logistics and closed-loop supply chain: a comprehensive review to explore the future. *Eur. J. Oper. Res.* **240** (2015) 603–626.
[8] M. Sarkar, A. Majumder, S. Bhattacharya and B. Sarkar, Optimization of energy cycle under a sustainable supply chain management. *RAIRO – Oper. Res.* **57** (2023) 2177–2196.

[9] L. Liu, Z. Wang, L. Xu, X. Hong and K. Govindan, Collection effort and reverse channel choices in a closed-loop supply chain. *J. Clean. Prod.* **144** (2017) 492–500.
[10] X. Chen, M. Goh, B. Li and Y. Cheng, Collection strategies and pricing decisions for dual channel EOL products. *Comput. Ind. Eng.* **159** (2021) 107477.
[11] N.M. Modak, S. Panda, S.S. Sana and M. Basu, Corporate social responsibility, coordination and profit distribution in a dual-channel supply chain. *Pac. Sci. Rev.* **16** (2014) 235–249.
[12] Y. Xia, X. Zu and C. Shi, A profit-driven approach to building a "people-responsible" supply chain. *Eur. J. Oper. Res.* **241** (2015) 348–360.
[13] H. Servaes and A. Tamayo, The impact of corporate social responsibility on firm value: the role of customer awareness. *Manage. Sci.* **59** (2013) 1045–1061.
[14] C.S. Tang, Socially responsible supply chains in emerging markets: some research opportunities. *J. Oper. Manag.* **57** (2018) 1–10.
[15] M.M. Hohn and C.F. Durach, Additive manufacturing in the apparel supply chain – impact on supply chain governance and social sustainability. *Int. J. Oper. Prod. Manag.* **41** (2021) 1035–1059.
[16] T. Gruchmann, Theorizing the impact of network characteristics on multitier sustainable supply chain governance: a power perspective. *Int. J. Logist. Manag.* **33** (2022) 170–192.
[17] Y. Li, Q. Deng, C. Zhou and L. Feng, Environmental governance strategies in a two-echelon supply chain with tax and subsidy interactions. *Ann. Oper. Res.* **290** (2020) 439–462.
[18] Y. Liu, Q. Xu and Z.Y. Liu, A coordination mechanism through value-added profit distribution in a supply chain considering corporate social responsibility. *Manag. Decis. Econ.* **41** (2020) 586–598.
[19] S. Panda, N.M. Modak and D. Pradhan, Corporate social responsibility, channel coordination and profit division in a two-echelon supply chain. *Int. J. Manag. Sci. Eng.* **11** (2016) 22–33.
[20] T.M. Choi, Y. Li and L. Xu, Channel leadership, performance and coordination in closed loop supply chains. *Int. J. Prod. Econ.* **146** (2013) 371–380
[21] A.C. Braz and A.M. De Mello, Circular economy supply network management: a complex adaptive system. *Int. J. Prod. Econ.* **243** (2022) 108317.
[22] G.W. Weber, A. Goli and E.B. Tirkolaee, Logistics and operations modelling and optimization for sustainable supply chain. *Sustainability* **15** (2023) 12727.
[23] A. Goli and H. Mohammadi, Developing a sustainable operational management system using hybrid shapley value and multimoora method: case study petrochemical supply chain. *Environ. Dev. Sustain.* **24** (2022) 10540–10569.
[24] R.C. Savaskan, S. Bhattacharya and L.N. Van Wassenhove, Closed-loop supply chain models with product remanufacturing. *Manage. Sci.* **50** (2004) 239–252.
[25] H. Chen, Z. Dong, G. Li and K. He, Remanufacturing process innovation in closed-loop supply chain under cost-sharing mechanism and different power structures. *Comput. Ind. Eng.* **162** (2021) 107743.
[26] R. Luo, L. Zhou, Y. Song and T. Fan, Evaluating the impact of carbon tax policy on manufacturing and remanufacturing decisions in a closed-loop supply chain. *Int. J. Prod. Econ.* **245** (2022) 108408.
[27] J. Chai, Z. Qian, F. Wang and J. Zhu, Process innovation for green product in a closed loop supply chain with remanufacturing. *Ann. Oper. Res.* **333** (2024) 533–555.
[28] X. Hong, K. Govindan, L. Xu and P. Du, Quantity and collection decisions in a closed-loop supply chain with technology licensing. *Eur. J. Oper. Res.* **256** (2017) 820–829.
[29] D. Gong, H. Gao, L. Ren and X. Yan, Consumers' free riding: pricing and retailer service decisions in a closed-loop supply chain. *Comput. Ind. Eng.* **181** (2023) 109285.
[30] R. Shan, L. Luo and B. Shi, The choice of recycling strategies for decision-makers based on government subsidy and service budget. *Environ. Dev. Sustain.* **25** (2023) 1441–1472.
[31] G.C. Souza, Closed-loop supply chains: a critical review, and future research. *Decis. Sci.* **44** (2013) 7–38.
[32] P.D. Giovanni, P.V. Reddy and G. Zaccour, Incentive strategies for an optimal recovery program in a closed-loop supply chain. *Eur. J. Oper. Res.* **249** (2016) 605–617.
[33] Y. Zhao, W. Wang and Y. Ni, EPR system based on a reward and punishment mechanism: producer-led product recycling channels. *Waste Manage.* **103** (2020) 198–207.
[34] L. Tombido and I. Baihaqi, Dual and multi-channel closed-loop supply chains: a state of the art review. *J. Remanuf.* **12** (2022) 89–123.
[35] N. Wan, Impacts of sales mode and recycling mode on a closed-loop supply chain. *Int. J. Syst. Sci. Oper. Logist.* **10** (2023) 2221076.

[36] N.M. Modak, N. Kazemi and L.E. Cárdenas-Barrón, Investigating structure of a two-echelon closed-loop supply chain using social work donation as a Corporate Social Responsibility practice. *Int. J. Prod. Econ.* **207** (2019) 19–33.

[37] N.M. Modak and P. Kelle, Using social work donation as a tool of corporate social responsibility in a closed-loop supply chain considering carbon emissions tax and demand uncertainty. *J. Oper. Res. Soc.* **72** (2021) 61–77.

[38] Q. Zhang and T. Luo, Socially responsible retailer's service provision strategies for poverty and inequity alleviation in the supply chain. *Comput. Ind. Eng.* **187** (2024) 109770.

[39] Y. Cheng, J. Pan and Y. Gong, Who will undertake corporate social responsibility in supply chain encroachment? Manufacturer or retailer. *Manag. Decis. Econ.* **45** (2024) 1511–1527.

[40] I. Tamayo-Torres, L. Gutierrez-Gutierrez and A. Ruiz-Moreno, Boosting sustainability and financial performance: the role of supply chain controversies. *Int. J. Prod. Res.* **57** (2019) 3719–3734.

[41] R. Rajesh and C. Rajendran, Relating environmental, social, and governance scores and sustainability performances of firms: an empirical analysis. *Bus. Strat. Environ.* **29** (2020) 1247–1267.

[42] Y. Huang and Z. Wang, Pricing and production decisions in a closed-loop supply chain considering strategic consumers and technology licensing. *Int. J. Prod. Res.* **57** (2019) 2847–2866.

[43] P. Yi, M. Huang, L. Guo and T. Shi, Dual recycling channel decision in retailer oriented closed-loop supply chain for construction machinery remanufacturing. *J. Clean. Prod.* **137** (2016) 1393–1405.

[44] S. Miao, T. Wang and D. Chen, System dynamics research of remanufacturing closed-loop supply chain dominated by the third party. *Waste Manage. Res.* **35** (2017) 379–386.

[45] B. Zheng, C. Yang, J. Yang and M. Zhang, Dual-channel closed loop supply chains: forward channel competition, power structures and coordination. *Int. J. Prod. Res.* **55** (2017) 3510–3527.

[46] R. Gupta, M. Goswami, Y. Daultani, B. Biswas and V. Allada, Profitability and pricing decision-making structures in presence of uncertain demand and green technology investment for a three tier supply chain. *Comput. Ind. Eng.* **179** (2023) 109190.

[47] W. Liu, W. Liu, N. Shen, Z. Xu, N. Xie, J. Chen and H. Zhou, Pricing and collection decisions of a closed-loop supply chain with fuzzy demand. *Int. J. Prod. Econ.* **245** (2022) 108409.

[48] B. Zheng, N. Yu, L. Jin and H. Xia, Effects of power structure on manufacturer encroachment in a closed-loop supply chain. *Comput. Ind. Eng.* **137** (2019) 106062.

[49] C.Y. Liu, H. Wang, J. Tang, C.T. Chang and Z. Liu, Optimal recovery model in a used batteries closed-loop supply chain considering uncertain residual capacity. *Transp. Res. Part E Logist. Transp. Rev.* **156** (2021) 102516.

[50] Y. Zhou, Y. Zhang, M.I.M. Wahab and M. Goh, Channel leadership and performance for a closed-loop supply chain considering competition. *Transp. Res. Part E Logist. Transp. Rev.* **175** (2023) 103151.

[51] Z. Zhang and L. Yu, Dynamic decision-making and coordination of low-carbon closed-loop supply chain considering different power structures and government double subsidy. *Clean Technol. Environ.* **25** (2023) 143–171.

[52] S.S. Ali, G.W. Weber, E.B. Tirkolaee and A. Goli, Circular economy practices in the context of emerging economies. *Sustainability* **16** (2024) 1417.

[53] E.B. Tirkolaee, A. Goli, M. Pahlevan and R.M. Kordestanizadeh, A robust bi-objective multi-trip periodic capacitated arc routing problem for urban waste collection using a multi-objective invasive weed optimization. *Waste Manag. Res.* **37** (2019) 1089–1101.

[54] E.B. Tirkolaee, A. Goli, H. Golpîra and E.D.R.S. Gonzalez, Sustainable global supply chain management from an international perspective. *Sustainability* **15** (2023) 12154.

[55] A. Goli, Integration of blockchain-enabled closed-loop supply chain and robust product portfolio design. *Comput. Ind. Eng.* **179** (2023) 109211.

[56] E.B. Tirkolaee, I. Mahdavi, M.M.S. Esfahani and G.W. Weber, A robust green location–allocation–inventory problem to design an urban waste management system under uncertainty. *Waste Manag.* **102** (2020) 340–350.

[57] A. Goli, E.B. Tirkolaee, A.M. Golmohammadi, Z. Atan, G.W. Weber and S.S. Ali, A robust optimization model to design an iot-based sustainable supply chain network with flexibility. *Cent. Eur. J. Oper. Res.* (2023). DOI: 10.1007/s10100-023-00870-4.

[58] E.B. Tirkolaee, A. Goli, A. Faridnia, M. Soltani and G.W. Weber, Multi-objective optimization for the reliable pollution-routing problem with cross-dock selection using pareto-based algorithms. *J. Clean. Prod.* **276** (2020) 122927.

[59] A. Goli and E.B. Tirkolaee, Designing a portfolio-based closed-loop supply chain network for dairy products with a financial approach: accelerated benders decomposition algorithm. *Comput. Oper. Res.* **155** (2023) 106244.

[60] E.B. Tirkolaee, A. Goli and S. Mirjalili, Circular economy application in designing sustainable medical waste management systems. *Environ. Sci. Pollut. Res.* **29** (2022) 79667–79668.
[61] E.B. Tirkolaee, Z. Dashtian, G.W. Weber, H. Tomaskova, M. Soltani and N.S. Mousavi, An integrated decision-making approach for green supplier selection in an agri-food supply chain: threshold of robustness worthiness. *Mathematics* **9** (2021) 1304.
[62] E.B. Tirkolaee and N.S. Aydin, Integrated design of sustainable supply chain and transportation network using a fuzzy bi-level decision support system for perishable products. *Expert Syst. Appl.* **195** (2022) 116628.
[63] X. Qian, F.T.S. Chan, J. Zhang, M. Yin and Q. Zhang, Channel coordination of a two-echelon sustainable supply chain with a fair-minded retailer under cap-and-trade regulation. *J. Clean. Prod.* **244** (2020) 118715.
[64] S. Ma, Y. He, R. Gu and S. Li, Sustainable supply chain management considering technology investments and government intervention. *Transp. Res. Part E Logist. Transp. Rev.* **149** (2021) 102290.
[65] Q. He, N. Wang, Z. Yang, Z. He and B. Jiang, Competitive collection under channel inconvenience in closed-loop supply chain. *Eur. J. Oper. Res.* **275** (2019) 155–166.
[66] M. Chen and C.I. Chang, The co-opetitive strategy of a closed-loop supply chain with remanufacturing. *Transp. Res. Part E Logist. Transp. Rev.* **48** (2012) 387–400.
[67] E. Shekarian, A. Marandi and J. Majava, Dual-channel remanufacturing closed-loop supply chains under carbon footprint and collection competition. *Sustain. Prod. Consum.* **28** (2021) 1050–1075.
[68] Y. Ranjbar, H. Sahebi, J. Ashayeri and A. Teymouri, A competitive dual recycling channel in a three-level closed loop supply chain under different power structures: pricing and collecting decisions. *J. Clean. Prod.* **272** (2020) 122623.
[69] E.B. Tirkolaee, I. Mahdavi, M.M.S. Esfahani and G.W. Weber, A hybrid augmented ant colony optimization for the multi-trip capacitated arc routing problem under fuzzy demands for urban solid waste management. *Waste Manag. Res.* **38** (2020) 156–172.

Appendix A.

Proof of Lemma 4.1. This paper uses the backward induction method to solve it. First, calculate the Hessian of $\pi_r^{\mathrm{MM}}(p,\tau_r)$ with respect to p^{MM} and τ_r^{MM} is given by $\left|H^{\mathrm{MM}}\right| = \begin{vmatrix} -2\beta & -\beta b \\ -\beta b & -2k \end{vmatrix}$; the first-order principal is $H_1^{\mathrm{MM}} = -2\beta < 0$ and the second-order principal is $H_2^{\mathrm{MM}} = \beta(4k - \beta b^2)$; so when $4k - \beta b^2 > 0$, $\pi_r^{\mathrm{MM}}(p,\tau_r)$ is a joint concave function of p^{MM} and τ_r^{MM}. Based on the first-order conditions, the optimal feedback functions of the retailer can be obtained as $p^{\mathrm{MM}} = \frac{a(2k-\beta b^2)+2k\beta w}{\beta(4k-\beta b^2)}$, $\tau_r^{\mathrm{MM}} = \frac{b(a-\beta w)}{4k-\beta b^2}$. Substituting p^{MM} and τ_r^{MM} into equation (4.1), it is easy to prove that $V_m^{\mathrm{MM}}(w,\pi_m)$ is a joint concave function of w^{MM} and τ_m^{MM}. According to the first-order conditions, the optimal decision variables w^{MM^*} and $\tau_m^{\mathrm{MM}^*}$ of the manufacturer can be obtained. Further, substitute w^{MM^*} and $\tau_m^{\mathrm{MM}^*}$ into the retailer's feedback function p^{MM} and τ_r^{MM}; the optimal decision variables p^{MM^*} and $\tau_r^{\mathrm{MM}^*}$ can be obtained. Then, according to the demand function, the maximum market demand q^{MM^*} can be obtained. Finally, the above decision variables are substituted into equations (3.1)–(3.3): $\pi_m^{\mathrm{MM}^*}$, $\pi_r^{\mathrm{MM}^*}$, and $\mathrm{CS}^{\mathrm{MM}^*}$ are obtained. □

Proof of Lemma 4.2. First, let $p^{\mathrm{MR}} = w^{\mathrm{MR}} + m^{\mathrm{MR}}$, m^{MR} is the unit profit of the retailer, substitute $p^{\mathrm{MR}} = w^{\mathrm{MR}} + m^{\mathrm{MR}}$ into equations (3.2) and (4.1), calculate the Hessian of $V_m^{\mathrm{MR}}(w,\tau_m)$ with respect to w^{MR}, and τ_m^{MR} is given by $\left|H^{\mathrm{MR}}\right| = \begin{vmatrix} -\beta(2-\theta) & -\beta\Delta \\ -\beta\Delta & -2k \end{vmatrix}$; the first-order principal is $H_1^{\mathrm{MR}} = -\beta(2-\theta) < 0$ and the second-order principal is $H_2^{\mathrm{MR}} = \beta(2k(2-\theta) - \beta\Delta^2)$, so when $2k(2-\theta) - \beta\Delta^2 > 0$, $V_m^{\mathrm{MR}}(w, \tau_m)$ is a joint concave function of w^{MR} and τ_m^{MR}. Based on the first-order conditions, the optimal feedback functions of the manufacturer can be obtained as $w^{\mathrm{MR}} = \frac{(2k(1-\theta)-\beta\Delta^2)(a-\beta m)+2k\beta(c_m-\tau_r(\Delta-b))}{\beta(2k(2-\theta)-\beta\Delta^2)}$. Substitute w^{MR} and τ_m^{MR} into equation (3.2) and it is easy to prove that $\pi_r^{\mathrm{MR}}(m, \tau_r)$ is a joint concave function of m^{MR} and τ_r^{MR}. According to the first-order conditions, the optimal decision variables m^{MR^*} and $\tau_r^{\mathrm{MR}^*}$ of the retailer can be obtained. Then, substitute m^{MR^*} and $\tau_r^{\mathrm{MR}^*}$ inverse back into the expressions w^{MR} and τ_m^{MR}; the optimal decision variables w^{MR^*} and $\tau_m^{\mathrm{MR}^*}$ can be obtained, and according to $p^{\mathrm{MR}} = w^{\mathrm{MR}} + m^{\mathrm{MR}}$, obtain the p^{MR^*}. Then, based on the demand function, obtain the q^{MR^*}. Finally, the above variables are substituted into equations (3.1)–(3.3): $\pi_m^{\mathrm{MR}^*}$, $\pi_r^{\mathrm{MR}^*}$, and $\mathrm{CS}^{\mathrm{MR}^*}$ are obtained. □

Proof of Lemma 4.3. First, let $p^{\mathrm{MN}} = w^{\mathrm{MN}} + m^{\mathrm{MN}}$, substitute $p^{\mathrm{MN}} = w^{\mathrm{MN}} + m^{\mathrm{MN}}$ into equations (3.2) and (4.1), calculate the Hessian of $V_m^{\mathrm{MN}}(w, \tau_m)$ with respect to w^{MN} and τ_m^{MN} is given by $\left|H^{\mathrm{MN}}\right| = \begin{vmatrix} -\beta(2-\theta) & -\beta\Delta \\ -\beta\Delta & -2k \end{vmatrix}$; the first-order principal is $H_1^{\mathrm{MN}} = -\beta(2-\theta) < 0$ and the second-order principal is $H_2^{\mathrm{MN}} = \beta(2k(2-\theta) - \beta\Delta^2)$, so when $2k(2-\theta) - \beta\Delta^2 > 0$, $V_m^{\mathrm{MN}}(w, \tau_m)$ is a joint concave function of w^{MN} and τ_m^{MN}. Similarly, it can be proved that $\pi_r^{\mathrm{MN}}(m, \tau_r)$ is a joint concave function with respect to its own decision variables m^{MN} and τ_r^{MN}; by the first-order conditions, simultaneous $\frac{\partial V_m^{\mathrm{MN}}(w,\tau_m)}{\partial w} = 0$, $\frac{\partial V_m^{\mathrm{MN}}(w,\tau_m)}{\partial \tau_m} = 0$, $\frac{\partial \pi_r^{\mathrm{MN}}(m,\tau_r)}{\partial m} = 0$ and $\frac{\partial \pi_r^{\mathrm{DMN}}(m,\tau_r)}{\partial \tau_r} = 0$, the optimal variables w^{MN^*}, $\tau_m^{\mathrm{MN}^*}$, m^{MN^*} and $\tau_r^{\mathrm{MN}^*}$ of the manufacturer and retailer, respectively, can be obtained. Then, based on the demand function, obtain the q^{MN^*}. Substituting the above decision variables into equations (3.1)–(3.3), $\pi_m^{\mathrm{MN}^*}$, $\pi_r^{\mathrm{MN}^*}$, and $\mathrm{CS}^{\mathrm{MN}^*}$ are obtained. □

The proof processes for Lemmas 4.4–4.6 and Lemma 6.1 are similar to that for Lemmas 4.1–4.3, which are omitted.

Proof of Proposition 5.1. (a) According to the w^* under the three power structures in Table 1, it is easy to obtain $w^{\mathrm{MM}^*} - w^{\mathrm{MN}^*} = \frac{(4k-\beta b^2)(2k-\beta b\Delta)(a-\beta c_m)}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))(2k(4-\theta)-\beta\Delta(\Delta+2b))} > 0$, $w^{\mathrm{MN}^*} - w^{\mathrm{MR}^*} = \frac{(4k(k(1-\theta)^2-\beta b\Delta(3-\theta))+4k\beta(\Delta^2\theta+b^2(2-\theta))+\beta^2\Delta^2(\Delta^2+2b\Delta-2b^2))(a-\beta c_m)}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))(4k(2-\theta)-3\beta\Delta^2)} > 0$. (a) is proved.

(b) Taking the p^* as an example, according to the p^* under the three power structures in Table 1, it is obtain $p^{\mathrm{MM}^*} - p^{\mathrm{MR}^*} = \frac{4k(k\theta+\beta\Delta(\Delta-b))(a-\beta c_m)}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))(4k(2-\theta)-3\beta\Delta^2)} > 0$, $p^{\mathrm{MM}^*} - p^{\mathrm{MN}^*} = \frac{2k(2k-\beta b\Delta)(a-\beta c_m)}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))(2k(4-\theta)-\beta\Delta(\Delta+2b))} > 0$; $p^{\mathrm{MR}^*} - p^{\mathrm{MN}^*} = \frac{2k(2k(1-\theta)-\beta\Delta(2b-\Delta))(a-\beta c_m)}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))(4k(2-\theta)-3\beta\Delta^2)}$, let $l_4(\theta) = \frac{2k(2k(1-\theta)-\beta\Delta(2b-\Delta))(a-\beta c_m)}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))(4k(2-\theta)-3\beta\Delta^2)} = 0$, could find a non-negative root $\theta = \frac{2k-\beta\Delta(2\Delta-b)}{2k}$; when $0 \le \theta \le \frac{2k-\beta\Delta(2\Delta-b)}{2k}$, $l_4(\theta) \ge 0$, which is $p^{\mathrm{MR}^*} \ge p^{\mathrm{MN}^*}$, when $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$, $l_4(\theta) < 0$, which $p^{\mathrm{MN}^*} > p^{\mathrm{MR}^*}$. Sum up that: when $0 \le \theta \le \frac{2k-\beta\Delta(2\Delta-b)}{2k}$, $p^{\mathrm{MM}^*} > p^{\mathrm{MR}^*} \ge p^{\mathrm{MN}^*}$, when $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$, $p^{\mathrm{MM}^*} > p^{\mathrm{MN}^*} > p^{\mathrm{MR}^*}$. The conclusion of q^* is the opposite of p^*, it would not repeat here. (b) is proved. □

The proof process for Proposition 5.2 is similar to that for Proposition 5.1, which is omitted.

Proof of Proposition 5.3. (a) According to π_r^* under the three power structures in Table 1, it is easy to obtain $\pi_r^{\mathrm{MR}^*} - \pi_r^{\mathrm{MN}^*} = \frac{k(4k(k(1-\theta)^2-\beta b\Delta(3-\theta))+4k\beta(\Delta^2\theta+b^2(2-\theta))+\beta^2\Delta^2(\Delta^2+2b\Delta-2b^2))(a-\beta c_m)^2}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))^2(4k(2-\theta)-3\beta\Delta^2)} > 0$, $\pi_r^{\mathrm{MN}^*} - \pi_r^{\mathrm{MM}^*} = \frac{k(4k-\beta b^2)(2k-\beta b\Delta)(2k(7-\theta)-\beta\Delta(2\Delta+3b))(a-\beta c_m)^2}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))^2(4k(2-\theta)-3\beta\Delta^2)^2} > 0$. (a) is proved.

(b) Taking the π_m^* as an example, according to π_m^* under the three power structures in Table 1, it is easy to obtain $\pi_m^{\mathrm{MM}^*} - \pi_m^{\mathrm{MR}^*} = \frac{2k(2k(2-\theta)(4-3\theta)-\beta\Delta^2(9-5\theta)+\beta b\Delta(2k(2-\theta)-\beta\Delta^2)+4\beta^2\Delta^4)(a-\beta c_m)^2}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))(4k(2-\theta)-3\beta\Delta^2)^2} > 0$, $\pi_m^{\mathrm{MM}^*} - \pi_m^{\mathrm{MN}^*} = \frac{k(2k-\beta b\Delta)^2(a-\beta c_m)^2}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))^2(2k(4-\theta)-\beta\Delta(\Delta+2b))} > 0$.
Then, let $l_5(\theta) = \pi_m^{\mathrm{MN}^*} - \pi_m^{\mathrm{MR}^*} = \frac{k(2k(2-\theta)-\beta\Delta^2)(2k(7-3\theta)-\beta\Delta(4\Delta+b))(2k(1-\theta)-\beta\Delta(2\Delta-b))(a-\beta c_m)^2}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))^2(4k(2-\theta)-3\beta\Delta^2)^2} = 0$. By solving, one could obtain a non-negative real root of $\theta = \frac{2k-\beta\Delta(2\Delta-b)}{2k}$. When $0 \le \theta \le \frac{2k-\beta\Delta(2\Delta-b)}{2k}$, $l_5(\theta) \ge 0$, which is $\pi_m^{\mathrm{MN}^*} \ge \pi_m^{\mathrm{MR}^*}$, when $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$, $l_5(\theta) < 0$, which is $\pi_m^{\mathrm{MR}^*} > \pi_m^{\mathrm{MN}^*}$. Therefore, when $0 \le \theta \le$

$\frac{2k-\beta\Delta(2\Delta-b)}{2k}, \pi_m^{\mathrm{MM}^*} > \pi_m^{\mathrm{MN}^*} \geq \pi_m^{\mathrm{MR}^*}$; when $\frac{2k-\beta\Delta(2\Delta-b)}{2k} < \theta < \frac{4k-\beta\Delta^2}{4k}$, $\pi_m^{\mathrm{MM}^*} > \pi_m^{\mathrm{MR}^*} > \pi_m^{\mathrm{MN}^*}$. The proof process for CS^* is similar to that for π_m^*. (b) is proved.

□

The proof process for (c) is similar to that for (b), which is omitted.

Proof of Proposition 5.4. (a) According to the $\pi_m^{\mathrm{MM}^*}$ and $\pi_r^{\mathrm{MM}^*}$ in Table 1, could obtain that $\pi_m^{\mathrm{MM}^*} - \pi_r^{\mathrm{MM}^*} = \frac{k(4k(1-\theta)-\beta(\Delta^2+2b\Delta-b^2))(a-\beta c_m)^2}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))^2}$, let $l_6(\theta) = \pi_m^{\mathrm{MM}^*} - \pi_r^{\mathrm{MM}^*} = \frac{k(4k(1-\theta)-\beta(\Delta^2+2b\Delta-b^2))(a-\beta c_m)^2}{\beta(2k(4-\theta)-\beta\Delta(\Delta+2b))^2} = 0$, could obtain a non-negative real root $\theta = \frac{4k-\beta(\Delta^2+2\Delta \mathrm{b}-b^2)}{4k}$, when $0 \leq \theta \leq \frac{4k-\beta(\Delta^2+2\Delta \mathrm{b}-b^2)}{4k}$, $l_6(\theta) \geq 0$, which is $\pi_m^{\mathrm{MM}^*} \geq \pi_r^{\mathrm{MM}^*}$, when $\frac{4k-\beta(\Delta^2+2\Delta \mathrm{b}-b^2)}{4k} < \theta < \frac{4k-\beta\Delta^2}{4k}$, $l_6(\theta) < 0$, which is $\pi_m^{\mathrm{MM}^*} < \pi_r^{\mathrm{MM}^*}$. (a) is proved. (b) According to the $\pi_m^{\mathrm{MR}^*}$ and $\pi_r^{\mathrm{MR}^*}$ in Table 1, it is easy to obtain $\pi_m^{\mathrm{MR}^*} - \pi_r^{\mathrm{MR}^*} = \frac{-2k(2k-\beta\Delta^2)(a-\beta c_m)^2}{\beta\left(4k(2-\theta)-3\beta\Delta^2\right)^2} < 0$. (b) is proved. (c) According to the $\pi_m^{\mathrm{MN}^*}$ and $\pi_r^{\mathrm{MN}^*}$ in Table 1, it is easy to obtain $\pi_m^{\mathrm{MN}^*} - \pi_r^{\mathrm{MN}^*} = \frac{-k(4k\theta+\beta(\Delta^2+b^2))(a-\beta c_m)^2}{\beta(2k(3-\theta)-\beta\Delta(\Delta+b))^2} < 0$. (c) is proved. □

The proof process for Propositions 5.5–5.8 is similar to that for Propositions 5.1–5.4, which are omitted. Propositions 5.9 and 6.1 can be proved by simple mathematical calculation; these are not repeated here.