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Low carbon decision-making model under the combined effect of corporate social responsibility and overconfidence

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This paper explores the impact of retailers' corporate social responsibility (CSR) and manufacturers' overconfidence on manufacturers' carbon reduction in sustainable supply chains. We analyze the profits of manufacturers and retailers under different scenarios and explore the social welfare and environmental impacts under CSR. Our results suggest that retailers' CSR and manufacturers' overconfidence contribute positively to promoting carbon mitigation and reducing environmental impacts under certain conditions. However, with increasing CSR and manufacturer overconfidence levels, manufacturers are more likely to lead to worse environmental impacts and carbon emission reduction. In addition, we show that when the manufacturer's overconfidence level is high, manufacturers and retailers are more profitable and contribute to carbon emission reductions in the manufacturer without overconfidence (retailer without CSR) scenario. Moreover, we find that firms have the higher potential to capture optimal overall social welfare in the presence of retailers with CSR and manufacturer overconfidence.

1. Introduction

Nowadays, the problems of natural resource scarcity and ecological environment pollution becomes increasingly serious, and the pursuit of low-carbon or green production has become a mainstream development approach and an important topic for governments to achieve carbon neutrality and carbon dioxide peaking. Meanwhile, low-carbon and green sustainable development has also presented new challenges to the production and operation of enterprises. Moreover, numerous visionary companies are starting to consider how to actualize the target of carbon emission reduction and carbon neutrality. For example, well-known automotive companies such as *Geely* and *Volvo* have already embarked on producing low-carbon vehicles and achieving vehicle launches (Zhang & Huang, 2021; Shen et al., 2020; Wang et al., 2022; Qiu et al., 2020). With increasing consumer environmental awareness and concern about corporate social responsibility (CSR), numerous retailers have voluntarily chosen to integrate CSR into their corporate strategies to improve their business reputation and reduce corporate carbon emissions. For example, in 2014, Amazon launched a CSR program and initiative to drive reductions in greenhouse gas emissions. Moreover, Amazon has launched a 2 billion fund to help Amazon and other companies comply with its Climate Commitment Initiative, which launched in September 2019. The initiative commits the company and other companies that sign the pledge to become carbon neutral by 2040[1]. In addition, Walmart also has committed to reducing carbon emissions by

[1] https://corporate.walmart.com/planet/climate-change.

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1 billion metric tons by 2030 through its Project Gigaton program with suppliers[2] (see Figure 1 for recent years' carbon emissions reductions).

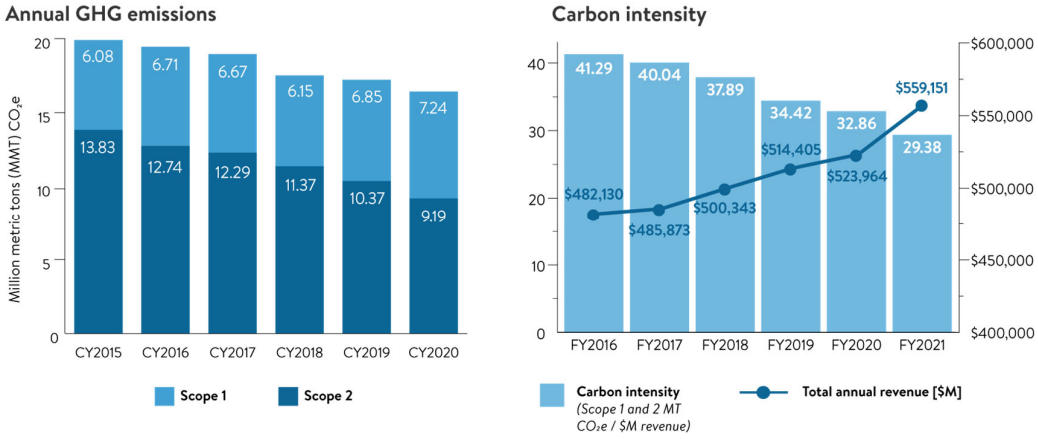

Fig. 1. Walmart's progress on operational emissions

While retailers' corporate social responsibility contributes to a positive impact on carbon emission reduction. However, manufacturers are not always rational in complex and uncertain environments (i.e., manufacturers often exhibit characteristics of bounded rationality in complex environments), such as overconfidence (Ren et al., 2017). This means that manufacturers' overconfidence may affect their profits and carbon emission reduction. For example, GE has been expanding its "outside" business, GE Capital, and over-relying on its financial business has stagnated the economy[3]. However, GE failed to learn the consequences of its overconfidence in non-renewable energy sources and overinvested in oil and gas, purchasing Alstom and Baker Hughes, which caused GE to struggle[4]. With the gradual recognition of renewable energy and carbon reduction as the future trend, GE started to consider the development of renewable energy and carbon emission reduction. For example, Jérôme Pécresse, CEO of GE Renewable Energy, said, "Energy efficiency and renewable energy will work together to reduce GE's operating costs. I believe that our process of achieving carbon neutrality will ultimately help us grow our business."[5]. Moreover, GE Renewable Energy announced that it would provide wind turbine facilities for the North Central Oklahoma Wind Energy Facility[6]. This naturally gives rise to an interesting and practically valuable question: how retailer corporate social responsibility and manufacturer overconfidence jointly affect the manufacturer's carbon emissions reduction and mitigation of environmental impact.

Following the above research motivation, we explore the joint effects of retailer CSR and manufacturer overconfidence on manufacturers' carbon emission reduction and social welfare. In addition, we further explore the environmental impacts of manufacturers' carbon mitigation under different scenarios. As a result, we propose the following research questions. How do retailer CSR and manufacturer overconfidence affect stakeholders' profit and manufacturer carbon mitigation? Are they conducive to improving manufacturers' carbon mitigation and reducing environmental impacts? Will retailer CSR and manufacturer overconfidence contribute to improved social welfare?

From the perspective of answering the above questions, we developed a sustainable supply chain with manufacturers and retailers and explored the impact of retailers' CSR and manufacturers' overconfidence on manufacturers' carbon mitigation. Moreover, we analyze and compare the equilibrium results of stakeholders. Furthermore, we explore the environmental impacts under different scenarios.

We can capture contributions from: First, few literatures have explored manufacturers' carbon mitigation under the joint effect of retailers' CSR and manufacturers' overconfidence. Moreover, our results provide significant insight into how manufacturers avoid the negative effects of overconfidence in their production operations. Second, we explore the impact of retailer CSR and manufacturer overconfidence on social welfare and the environment. Existing literature little considers the impact of the joint effect of retailer CSR and manufacturer overconfidence on the social environment. Finally, our results suggest that retailers' CSR contributes positively to reducing environmental impact and improving social welfare. Moreover, something counter-intuitive is that retailers are more likely to reduce environmental impacts when retailers without CSR and manufacturers are rational.

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https://corporate.walmart.com/newsroom/2020/09/21/walmart-sets-goal-to-become-a-regenerative-company.

[2] https://corporate.walmart.com/esgreport/esg-issues/climate-change

[3] https://www.sohu.com/a/401465378_120073184.

[4] https://www.sohu.com/a/401465378_120073184.

[5] https://www.ge.com/news/press-releases/ge-renewable-energy-announces-its-plan-become-carbon-neutral-2020.

[6] https://www.ge.com/news/press-releases/ge-renewable-energy-announce-over-1-gw-agreement-with-invenergy-for-north-central-wind-energy-facilities-oklahoma.

2. Literature review

2.1 Sustainable supply chain

In recent years, a remarkable amount of literature on sustainable supply chain management has yielded remarkable results (Ding et al., 2016; Gouda & Saranga, 2018; Saberi et al., 2019; Jin et al., 2021; Raj et al., 2021; Damberg et al., 2022). For example, Ding et al. (2016) constructed a quantitative model of a sustainably constrained supply chain in a competitive environment and investigated the interrelationship between government, firms, and consumers in reducing environmental externalities. Barbosa-Póvoa et al. (2018) review the trends and directions in the application of OR methods in achieving sustainable supply chains. Like Barbosa-Póvoa et al. (2018) comprehensive studies on various factors affecting sustainable supply chains were conducted and the results were documented (Manavalan et al., 2019). Ghadimi et al. (2019) analyzed sustainable supply chain modeling through the literature review. Kusi-Sarpong et al. (2019) analyzed sustainable supply chains of companies using the BW-MCDM model. Bag et al. (2020) investigated the approach of supply chain sustainability using big data techniques targeting the mining industry. Like the above literature, we explore sustainable supply chain management, but we mainly investigate sustainable supply chains under retailer corporate social responsibility and manufacturer overconfidence. In addition, we also concentrate on analyzing the carbon mitigation and environmental impact of manufacturers under sustainable supply chains, which is little considered in the literature.

2.2 Corporate social responsibility

Our article contributes to the exploration of research on corporate social responsibility (CSR). Previous literature shows that CSR plays an important role in influencing firm behavior, and one important manifestation of which is the promotion of carbon emission reduction by firms or manufacturers (Xia and Niu, 2021). Several studies have shown that CSR-minded policymakers have an intrinsic concern for social welfare apart from their profits (Bian et al., 2016; Chen et al., 2017; Wu et al., 2020; Li & Wu, 2020). In addition, CSR has an important influence on production and operational decisions in sustainable supply chains (Wang et al., 2019; Modak et al., 2019). Some scholars have also explored various problems of CSR and environment and corporate sustainability (Cruz 2013; Plambeck et al., 2015; Wu et al., 2017). Liu et al. (2019) evaluated environmental governance efficiencies and channel cooperation in tourist supply chains in the context of CSR. Lu et al. (2022) investigate the influence of CSR on the retail business, finding that the environmental dimension of CSR has a constructive impact on company performance. Wang et al. (2020) explore the impact of competition and CSR on supply chain systems and partner collaboration. Chen et al. (2017) evaluate alternative game models between two supply chain partners and consider the influence of social responsibility and mutual commitment on both sides' profitability. Sana (2020) investigates the influence of government policies and financial policies on stakeholders by using a supplier inventory model based on CSR green product marketing. Furthermore, some scholars have looked at the influence of social responsibility on stakeholders or firm operations in the face of information asymmetry (Ma et al., 2017; Raza 2018; Wu et al., 2020). The above literature has made a significant contribution to exploring the role of CSR. However, large parts of the literature have not investigated the impact of CSR and manufacturer overconfidence on social welfare and the environment. We concentrate on the combined effects of CSR and manufacturer overconfidence on carbon emission reduction and the environment. In addition, we analyze the impact of CSR on social welfare under different scenarios.

2.3 Overconfident behavior in the supply chain

Our study also concerns the overconfident behavior of decision-makers. Theoretically, most literature typically assumes that optimal decisions are made by rational decision-makers. However, numerous psychology and behavioral science research have revealed that rationality is limited by constraints such as knowledge, duration, and cognitive capacity (Simon 1979), resulting in departures from optimum behavior in various choice tasks (Sterman, 1989). Overconfidence is one of the most common causes of choice bias because people are likely to exaggerate external complexity while they overestimate their personal competence (Russo & Schoemaker 1992; Moore & Healy 2008). Liu et al. (2021) studies the effect of overconfidence on retailers' capital structure decisions, and his results showed that slight overconfidence could weaken the bargaining power of the platform, but confidence may lead to different results. Kirshner and Shao (2019) applied a probability weighting function from PT to analyze the effect of overconfidence on newsvendor ordering decisions. They show that greater overconfidence typically leads to lower profits. Like the findings of Kirshner (2019), Xiang (2020) shows that overconfidence may harm supplier and manufacturer profits. Chen et al. (2021) explore the omnichannel impact of the overconfident behavior problem in omnichannel by constructing a game-theoretic model and numerical analysis. However, there are significant differences between the results in terms of nominal and actual effects. In contrast to the above literature, some literature demonstrates that overconfidence does not always play a negative role (Li 2020; Lu et al., 2020; Bai et al., 2021). Lu (2015) shows that supplier overconfidence promotes suppliers to green production and increases retailer and supply chain profits. Xu et al. (2019) reveal that overconfidence would not necessarily damage operational performance.

We also explore the impact of overconfidence on stakeholders' profits. However, the above literature has little explored the joint impact of CSR and overconfidence on carbon mitigation and social welfare, which is the focus of our study. In addition, we also analyze the environmental impacts of retailer CSR and manufacturer overconfidence.

3. Model

Throughout satisfying the carbon reduction and carbon neutrality objectives, the producer commits to low carbon production and carbon mitigation in the production. Simultaneously, the manufacturer provides a low product and assesses its level of carbon emission reduction and wholesale price (w). Whereas during the sales season, the producer subsequently offers the low-carbon product to the final commodity market (i.e., the customer) through retailers. The retailer then selects the retail price (p) depending on market demand and wholesale pricing to maximize profits. We suppose that the unit manufacturing cost of a low-carbon product offered by a manufacturer is c, e represents the level of carbon reduction. This implies that with higher e, the more its production of low-carbon products is coherent with the government's carbon neutrality and carbon emission reduction targets. In addition, the manufacturer would invest in low carbon production technology to achieve low carbon production through reducing carbon emissions. As a result, the producer must take on the additional cost of carbon mitigation investment. We suppose that costs of carbon mitigation for manufacturers is a quadratic form function, which implies that the marginal benefit of carbon emission reduction investment decreases gradually ($C(e) = \frac{1}{2}ke^2$), where k is the carbon mitigation investment cost parameter (Savaskan & Van Wassenhove, 2006; Guo & Meng, 2015; Luo et al., 2016; Wang et al., 2021).

In the manufacturing operations literature, a similar market demand function is rather prevalent (Dong et al., 2016; Wang et al., 2021). Therefore, we denote the market demand function form as $D = a - p + \beta e$, where a represents the market potential, p indicates the retail price, β stands for the market demand elasticity coefficient of consumers for carbon abatement (i.e., consumers' low-carbon preference). In practice, manufacturers may engage in overconfidence, i.e., overestimating their carbon emission reduction levels. The manufacturer may be confident that its level of carbon reduction technology can produce lower carbon emissions and advertise its products. We use η to indicate the manufacturer's overconfidence level, and a larger η indicates that the manufacturer exhibits a higher level of overconfidence (Xu et al., 2019). The retailers are more likely to focus on social responsibility in response to carbon neutrality or carbon emission reduction policies. As explained by Panda (2014), corporate social responsibility (CSR) is calculated through the consumer surplus of its stakeholders. Consumer surplus is the difference between the maximum price a consumer is willing to pay for a given quantity of a product and the actual market price of those products (Panda et al., 2017). We use λ to denote the level of CSR of the retailer, i.e., $\lambda \int_{p_{min}}^{p_{max}} D dp = \frac{\lambda}{2}(a - p + \beta e)^2$. Since retailers are socially responsible, their profit function comprises profit obtained through the sale of products and consumer surplus obtained through corporate social responsibility practices.

4 Results

For convenience, we consider different scenarios of whether the retailer has a social responsibility and whether the manufacturer is over-confident. Therefore, we have four pairs of strategies, namely (S, N), (S, Y), (N, N), and (N, Y).

4.1 Without Corporate Social Responsibility

In this section, we consider the scenario where the retailers are without corporate social responsibility (i.e., the retailers are pure profit maximizers). We constructed a supply chain decision model in the scenario of whether the manufacturer is overconfident. To analyze the influence of manufacturer overconfidence on retailer or manufacturer profits and carbon mitigation levels, we analyze the equilibrium outcomes for retailers and manufacturers under different scenarios and investigate manufacturers' carbon mitigation levels.

Scenario NN: Retailers without CSR and manufacturers without overconfidence

In the scenario where retailers are without CSR, we explore the equilibrium outcomes of manufacturers' carbon abatement levels and participants under the without overconfidence scenario. Therefore, we construct the demand function under scenario NN:

$$D^{NN} = a - p + \beta e,$$

where superscript NN indicates without corporate social responsibility and overconfidence.

In scenario NN, We explore carbon abatement under the scenario of a retailer without CSR with a manufacturer without overconfidence and allow the supply chain players to perfectly align their targets. Therefore, we are present with the profit functions of the manufacturer and retailer under scenario NN:

$$\begin{aligned} \pi_R^{NN} &= (p - w)(a - p + \beta e), \\ \pi_M^{NN} &= (w - c)(a - p + \beta e) - ke^2/2, \end{aligned}$$

where the subscripts "M", "R" denote the manufacturers and retailers, respectively.
Using inverse induction, we can derive the optimal decisions of the participants under scenario NN by solving the equilibrium

results for each parameter (see Proposition 1).

Proposition 1: *Under scenario NN, we can obtain the equilibrium results for manufacturers and retailers:*

$$e^{NN} = \frac{\beta(a-c)}{4k-\beta^2}, w^{NN} = \frac{2k(a+c)-\beta^2 c}{4k-\beta^2}, p^{NN} = \frac{3ka+kc-\beta^2 c}{4k-\beta^2},$$
$$\pi_R^{NN} = \frac{k^2(a-c)^2}{(4k-\beta^2)^2}, \pi_M^{NN} = \frac{k(a-c)^2}{2(4k-\beta^2)}.$$

We demonstrate that in the scenario without CSR and overconfidence, the manufacturers and retailers' profits and the carbon reduction level, wholesale prices, and retail prices are more likely to be influenced by consumers' low-carbon preferences.

Corollary 1: *Under scenario NN, we have* $\frac{\partial e^{NN}}{\partial \beta} > 0, \frac{\partial w^{NN}}{\partial \beta} > 0, \frac{\partial p^{NN}}{\partial \beta} > 0.$

Corollary 1 suggests that the equilibrium outcomes for manufacturers and retailers improve as consumers' low-carbon preferences increase. On the one hand, the expansion of consumer market demand motivates manufacturers to set higher wholesale prices, which increases manufacturers' incentives to commit to carbon reduction. Therefore, if consumer low-carbon preferences increase, manufacturers have a higher incentive to improve the carbon abatement level of their products. On the other hand, retailers are able to obtain higher market retail prices, which makes retailers more inclined to sell products with high carbon abatement levels, which indirectly motivates manufacturers to reduce carbon emissions.

Scenario NY: Retailers without CSR and manufacturer overconfident

In the scenario where retailers are without CSR, we explore the equilibrium outcomes of manufacturers' carbon abatement levels and participants under the overconfidence scenario. In scenario NY, We explore carbon abatement under the scenario of a retailer without CSR with a manufacturer overconfidence and allow the supply chain players to perfectly align their targets. Therefore, we are present with the profit functions under scenario NY:

$$\pi_R^{NY} = (p-w)(a-p+\beta(1+\eta)e),$$
$$\pi_M^{NY} = (w-c)(a-p+\beta(1+\eta)e) - ke^2/2,$$

where superscript NY indicates the retailers without corporate social responsibility and the manufacturer's overconfidence. Therefore, we derive the optimal decisions of the participants under scenario NY by solving the equilibrium results for each parameter (see Proposition 2).

Proposition 2: *Under the scenario of retailers without CSR and manufacturer's overconfidence, we can obtain the equilibrium results for manufacturers and retailers:*

$$e^{NY} = \frac{\beta(1+\eta)(a-c)}{4k-\beta^2(1+\eta)^2}, w^{NY} = \frac{2k(a+c)-\beta^2(1+\eta)^2 c}{4k-\beta^2(1+\eta)^2}, p^{NY} = \frac{3ka+kc-\beta^2(1+\eta)^2 c}{4k-\beta^2(1+\eta)^2},$$
$$\pi_R^{NY} = \frac{k^2(a-c)^2}{(4k-\beta^2(1+\eta)^2)^2}, \pi_M^{NY} = \frac{k(a-c)^2}{2(4k-\beta^2(1+\eta)^2)}.$$

Proposition 2 shows the equilibrium results for retailers and manufacturers under scenario NY. We find that under the scenario considering manufacturer overconfidence, the equilibrium outcomes of retailers and manufacturers are jointly influenced by the manufacturer's overconfidence level and consumers' low-carbon preferences.

Corollary 2: *Comparing the manufacturers' carbon reduction level, manufacturers' profit, and retailers' profit under different scenarios, we have:*

(a) *If* $0 < \eta < -1 + 2\sqrt{\frac{k}{\beta^2}}$, $e^{NY} \geq e^{NN}$ *(*$\pi_M^{NY} \geq \pi_M^{NN}$*); Otherwise,* $e^{NY} < e^{NN}$ *(*$\pi_M^{NY} < \pi_M^{NN}$*).*

(b) *If* $0 < \eta < -1 + \sqrt{\frac{8k-\beta^2}{\beta^2}}$, $\pi_R^{NY} \geq \pi_R^{NN}$*; Otherwise,* $\pi_R^{NY} < \pi_R^{NN}$.

Corollary 2(a) suggests that when the level of overconfidence is small, manufacturers' carbon mitigation levels are better than the scenario without overconfidence. This implies that overconfidence may be beneficial to manufacturers for carbon emission reduction. Corollary 2(b) shows that under certain conditions, manufacturer overconfidence is conducive to enhancing participants' profits (i.e., manufacturers and retailers). However, when overconfidence levels are high (i.e., when manufacturers are blindly confident), manufacturer overconfidence would hurt manufacturer and retailer profits, which impedes manufacturers from pursuing carbon emission reductions.

4.2 Retailers with corporate social responsibility

In this section, we consider the scenario of a retailer with corporate social responsibility. We calculate the equilibrium decisions of stakeholders under various scenarios to investigate the influence of manufacturer overconfidence and retailer

CSR on retailer and manufacturer profits and carbon abatement levels.

Scenario SN: Retailers with CSR and manufacturer without overconfidence

In the scenario where retailers have CSR, we explore the equilibrium outcomes of participants in the absence of the overconfidence scenario. Under scenario SN, we explore carbon mitigation in the scenario where the retailer has a corporate social responsibility, and the manufacturer is without overconfidence. In scenario SN, the manufacturer (retailer) decides its carbon reduction level and wholesale price (retail price) to maximize profit. Therefore, we are present with the profit functions under scenario SN:

$$U_R^{SN} = \pi_R^{SN} + \lambda CS = (p-w)(a-p+\beta e) + \frac{\lambda}{2}(a-p+\beta e)^2,$$
$$\pi_M^{SN} = (w-c)(a-p+\beta e) - ke^2/2,$$

where the superscript SN indicates the retailers with corporate social responsibility (CSR) and the manufacturers without overconfidence. We further analyze the equilibrium results for the supply chain participants. We summarize the main results below (see Proposition 3).

Proposition 3: *Under the scenario of retailers without CSR and manufacturer's overconfidence, we have the equilibrium outcomes for manufacturers and retailers:*

$$e^{SN} = \frac{\beta(a-c)}{2k(2-\lambda)-\beta^2}, w^{SN} = \frac{ka(2-\lambda)+kc(2-\lambda)-\beta^2 c}{2k(2-\lambda)-\beta^2}, p^{SN} = \frac{3ka-2k\lambda a+kc-\beta^2 c}{2k(2-\lambda)-\beta^2},$$
$$U_R^{SN} = \frac{k^2(a-c)^2(2-\lambda)}{(2k(2-\lambda)-\beta^2)^2}, \pi_M^{SN} = \frac{k(a-c)^2}{2(2k(2-\lambda)-\beta^2)}.$$

Corollary 3: *Comparing the manufacturers' carbon reduction level, manufacturers' profit, and retailers' profit under different scenarios, we have:*

(a) *If* $0 < \lambda < \frac{4k-\beta^2}{2k}$, $e^{SN} \geq e^{NN}$ *(*$\pi_M^{SN} \geq \pi_M^{NN}$*); Otherwise,* $e^{SN} < e^{NN}$ *(*$\pi_M^{SN} < \pi_M^{NN}$*).*

(b) *If* $0 < \lambda < \frac{(4k-\beta^2)(\beta^2+\sqrt{16k^2+\beta^4})}{8k^2}$, $U_R^{SN} \geq \pi_R^{NN}$*; Otherwise,* $U_R^{SN} < \pi_R^{NN}$.

Corollary 3(a) presents that when the retailers' CSR level is small, the level of carbon abatement of manufacturers is better than the scenario without CSR. This implies that CSR plays a positive role in promoting carbon mitigation by manufacturers. However, with increasing CSR levels, manufacturers' carbon emission reduction under scenario NN is more likely to be optimal (see Corollary 3(b)). The reason for this result is that retailers are more concerned about social responsibility and ask for a higher carbon emission reduction level from manufacturers, which makes manufacturers have to increase their low carbon investment. In other words, the higher retailer CSR may hurt the manufacturer's revenues and weaken the manufacturer's incentive to reduce carbon emissions. Corollary 3(b) shows that, under certain conditions, retailer CSR could benefit manufacturers and merchants increase their revenue. However, while CSR levels increase, manufacturers' profits are better under scenario NN than scenario SN. This implies that manufacturers have stronger incentives to reduce carbon emissions under scenario NN.

Scenario SY: Retailers with CSR and manufacturers overconfident

Under scenario SY, we explore carbon mitigation in the scenario where the retailer has a corporate social responsibility, and the manufacturer is overconfidence. Therefore, we are present with the profit functions under scenario SY:

$$U_R^{SY} = \pi_R^{SY} + \lambda CS = (p-w)(a-p+\beta(1+\eta)e) + \frac{\lambda}{2}(a-p+\beta(1+\eta)e)^2,$$
$$\pi_M^{SY} = (w-c)(a-p+\beta(1+\eta)e) - ke^2/2.$$

where the superscript SY denotes the retailer with CSR and manufacturer with overconfidence.

With inverse induction, we can solve the equilibrium outcomes of the supply chain participants under scenario SY. We summarize the main results as follows (see Proposition 4).

Proposition 4: *With retailers having CSR and manufacturers overconfident, the manufacturer's optimal profit, carbon mitigation level, wholesale price, and the retailer's optimal selling price are as follows:*

$$e^{SY} = \frac{\beta(1+\eta)(a-c)}{2k(2-\lambda)-\beta^2(1+\eta)^2}, w^{SY} = \frac{ka(2-\lambda)+kc(2-\lambda)-\beta^2(1+\eta)^2 c}{2k(2-\lambda)-\beta^2(1+\eta)^2}, p^{SY} = \frac{3ka-2k\lambda a+kc-\beta^2(1+\eta)^2 c}{2k(2-\lambda)-\beta^2(1+\eta)^2},$$

$$U_R^{SY} = \frac{k^2(a-c)^2(2-\lambda)}{(2k(2-\lambda)-\beta^2(1+\eta)^2)^2}, \pi_M^{SY} = \frac{k(a-c)^2}{2(2k(2-\lambda)-\beta^2(1+\eta)^2)}.$$

Comparing the equilibrium outcomes of manufacturers and retailers under different scenarios (scenario SY vs. scenario SN) and the manufacturers' carbon mitigation levels. The main comparison results we obtained are as follows:

Corollary 4: *Comparing the manufacturers' carbon mitigation level, manufacturers' profit, and retailers' profit under different scenarios, we have:*

(a) *If* $0 < \eta < -1 + \sqrt{2}\sqrt{\frac{2k-k\lambda}{\beta^2}}$, $e^{SY} \geq e^{SN}$ $(\pi_M^{SY} \geq \pi_M^{SN})$*; Otherwise,* $e^{SY} < e^{SN}$ $(\pi_M^{SY} < \pi_M^{SN})$.

(b) *If* $0 < \eta \leq -1 + \sqrt{\frac{8k-\beta^2-4k\lambda}{\beta^2}}$, $U_R^{SY} \geq \pi_R^{SN}$*; Otherwise,* $\pi_R^{SY} < \pi_R^{SN}$.

Like Corollary 2, Like Corollary 2, we find that when manufacturers have low overconfidence levels, manufacturers are more profitable under scenario NY than scenario SN. However, when the retailer has CSR and the manufacturer with high overconfidence level, the manufacturer is more likely to receive optimal profit under scenario SN and more inclined to commit to carbon emission reduction. Moreover, we present a comparison of the equilibrium findings for stakeholders' profit and the manufacturers' carbon reduction levels under scenario SY versus scenario NY. The main comparison results are summarized as follows.

Corollary 5: *Comparing the manufacturers' carbon reduction level, manufacturers' profit, and retailers' profit under different scenarios, we have:*

(a) *If* $0 < \lambda < \frac{4k-\beta^2-2\beta^2\eta-\beta^2\eta^2}{2k}$, $e^{SY} \geq e^{NY}$ $(\pi_M^{SY} \geq \pi_M^{NY})$*; Otherwise,* $e^{SY} < e^{NY}$ $(\pi_M^{SY} < \pi_M^{NY})$.

(b) *If* $0 < \lambda \leq \frac{(4k-\beta^2(1+\eta)^2)(-\beta^2(1+\eta)^2+\sqrt{16k^2+\beta^4(1+\eta)^4})}{8k^2}$, $U_R^{SY} \geq \pi_R^{NY}$*; Otherwise,* $\pi_R^{SY} < \pi_R^{NY}$.

We find from Corollary 5 that manufacturers are more inclined to carbon mitigation under scenario SY when they are overconfident, and retailers have a low level of CSR. However, as retailers are more concerned about CSR, manufacturers are preferred to carbon mitigation under scenario NY and receive optimal profits. Moreover, when the retailers' CSR level is high, the retailers' profits under scenario NY are better than in scenario SY. The reason for this result is that when the retailers' CSR is high, they are more concerned with optimizing social welfare as social welfare maximizers, which suggests a decrease in the retailers' profits. We further analyze the joint impact of CSR and overconfidence on manufacturers' and retailers' equilibrium decisions. Then, we analyze and elaborate on the results in different scenarios to yield the following propositions.

Proposition 5: *Comparing manufacturer carbon mitigation levels, manufacturer and retailer profits for the three scenarios (i.e., scenario SY, scenario SN and scenario NN), we have:*

(a) *When* $0 < \lambda < \lambda_1$ $(\lambda > \lambda_2)$*, the manufacturer's carbon mitigation level under scenario SY (scenario NN) is optimal; Otherwise, the manufacturer's carbon mitigation level under scenario SN outperformed the other scenario (i.e.,* $\lambda_1 < \lambda \leq \lambda_2$*), where* $\lambda_1 = \frac{4k-\beta^2-2\beta^2\eta-\beta^2\eta^2}{2k}$ *and* $\lambda_2 = \frac{4k-\beta^2}{2k}$.

(b) *When* $0 < \lambda < \lambda_1$ $(\lambda > \lambda_2)$*, the manufacturer's profit under scenario SY (scenario NN) is optimal; Otherwise, the manufacturer's profit under scenario SN is optimal (i.e.,* $\lambda_1 < \lambda \leq \lambda_2$*), where* $\lambda_1 = \frac{4k-\beta^2-2\beta^2\eta-\beta^2\eta^2}{2k}$ *and* $\lambda_2 = \frac{4k-\beta^2}{2k}$.

(c) *When* $0 < \lambda < \lambda_3$ $(\lambda > \lambda_4)$*, the retailer's profit under scenario SY (scenario NN) is optimal; Otherwise, the retailer's profit under scenario SN is optimal (i.e.,* $\lambda_3 < \lambda \leq \lambda_4$*), where* $\lambda_3 = \frac{8k-2\beta^2-2\beta^2\eta-\beta^2\eta^2}{4k}$ *and* $\lambda_4 = \frac{(4k-\beta^2)(\beta^2+\sqrt{16k^2+\beta^4})}{8k^2}$.

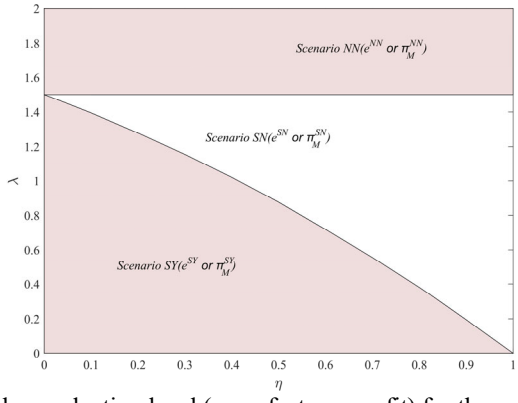

Fig. 2. Manufacturer carbon reduction level (manufacturer profit) for the combined effect of η and λ

From Proposition 5, we conclude that retailer CSR and manufacturer overconfidence are key factors affecting manufacturers'

carbon emission reduction levels, profits, and retailers' profits. Proposition 5(a) and Proposition 5(b) are intuitive. Under the joint impact of retailer CSR and manufacturer overconfidence, the carbon mitigation level (profit) under scenario SY is optimal if the CSR level is small (i.e., $\lambda < \lambda_1$). When λ is larger (i.e., $\lambda > \lambda_2$), the manufacturer's carbon abatement level (manufacturer profit) under scenario NN is optimal (see Fig. 2). When λ is moderate ($\lambda_1 < \lambda \leq \lambda_2$), the manufacturer's carbon abatement effect under scenario SN is better than in other scenarios (see Fig. 2). Proposition 5(c) also shows that retailer profits have similar results. In this section, considering the simulated data of Wang et al. (2021) and Song et al. (2021), we set $a = 10$, $c = 3$, $k = 2$, $\beta = 1$, and η (or λ) $= 0.5$.

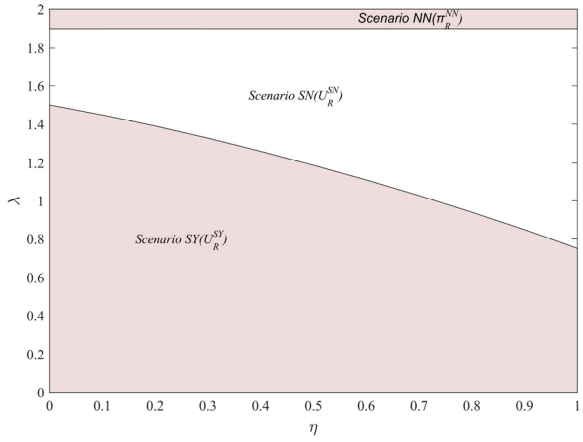

Fig. 3. The retailer's profit under the combined effect of η and λ

Fig. 3 shows that when the retailer CSR level (λ) is below the threshold, the retailer is more likely to receive optimal profits under scenario SY under the joint impacts of retailer CSR and manufacturer overconfidence. Moreover, we find that when the amount of manufacturer overconfidence increases, retailers' profits under scenario SN are better than other scenarios. Furthermore, we can observe that retailers have more potential to have optimal profits under scenaris NN when CSR level is above the threshold.

Proposition 6: *Comparing manufacturer carbon mitigation levels, manufacturer and retailer profits for the three scenarios (i.e., scenario SY, scenario NY and scenario NN), we have:*

(a) *When* $0 < \eta < \eta_1$ *(*$\eta > \eta_2$*), the manufacturer's carbon mitigation level under scenario SY (scenario NN) is optimal; Otherwise, the manufacturer's carbon abatement level under scenario NY outperformed the other scenario (i.e.,* $\eta_1 < \eta \leq \eta_2$*), where* $\eta_1 = -1 + \sqrt{2}\sqrt{\frac{2k-k\lambda}{\beta^2}}$ *and* $\eta_2 = -1 + 2\sqrt{\frac{k}{\beta^2}}$.

(b) *When* $0 < \eta < \eta_1$ *(*$\eta > \eta_2$*), the manufacturer's profit under scenario SY (scenario NN) is optimal; Otherwise, the manufacturer's profit under scenario NY is optimal (i.e.,* $\eta_1 < \eta \leq \eta_2$*), where* $\eta_1 = -1 + \sqrt{2}\sqrt{\frac{2k-k\lambda}{\beta^2}}$ *and* $\eta_2 = -1 + 2\sqrt{\frac{k}{\beta^2}}$.

(c) *When* $0 < \eta < \eta_3$ *(*$\eta > \eta_4$*), the retailer's profit under scenario SY (scenario NN) is optimal; Otherwise, the retailer's profit under scenario NY is optimal (i.e.,* $\eta_3 < \eta \leq \eta_4$*), where* $\eta_3 = -1 + \sqrt{2}\sqrt{\frac{(a-c)^2k\beta^2(-2+\lambda)+\sqrt{-(a-c)^4k^2\beta^4(-2+\lambda)\lambda^2}}{(a-c)^2\beta^4(-1+\lambda)}}$ *and* $\eta_4 = -1 + \sqrt{\frac{8k-\beta^2}{\beta^2}}$.

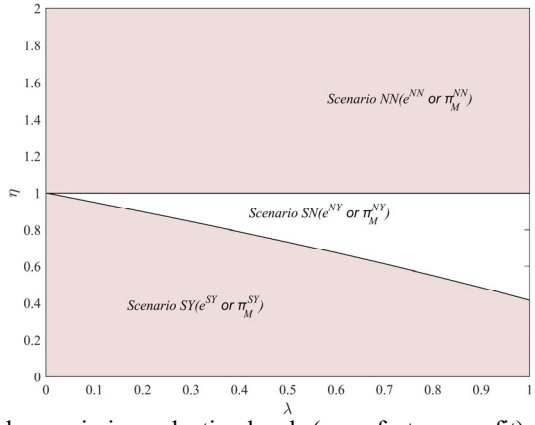

Fig. 4. Manufacturer carbon emission reduction levels (manufacturer profit) under different scenarios

Proposition 6 shows that manufacturers are more profitable under scenario SY when η is small ($\eta < \eta_1$) under the joint effect of retailer CSR and manufacturer overconfidence. When η is larger ($\eta > \eta_2$), manufacturers are more potential to capture the optimal profit and carbon mitigation levels under scenario NN (see Fig. 4). When η is moderate ($\eta_1 < \eta \leq \eta_2$), manufacturers will increase the level of carbon abatement, and they are more profitable under scenario NY than other scenarios (see Figure 4). (see Fig. 4). Proposition 6(c) also shows that retailer profits have similar results.

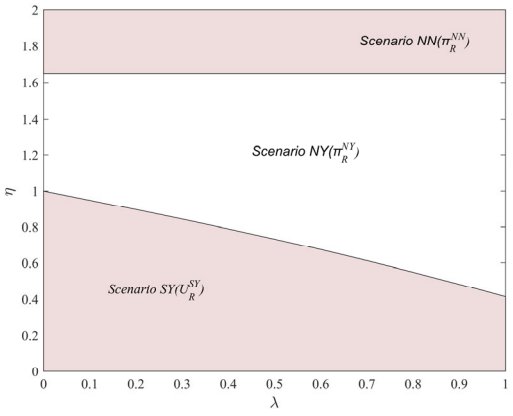

Fig. 5. The retailer's profit under the combined effect of η and λ

Fig. 5 shows that when the manufacturer overconfidence level (η) is below the threshold, retailers are more potential to receive optimal profits under scenario SY under the joint impacts of retailer CSR and manufacturer overconfidence. Moreover, we find that as the retailer CSR level increases, the profits of retailers under scenario NY are better than in other scenarios. Furthermore, we can observe that retailers have more potential to have optimal profits under scenario NN when the manufacturer's overconfidence level is above the threshold.

5. Discussion

The retailer's CSR may play a positive role in disciplining manufacturers to mitigate carbon output to engage in low-carbon production. Considering the joint influence of manufacturer overconfidence and retailer CSR, it remains to be explored whether they are conducive to promoting carbon emission reduction, increasing social welfare, and mitigating environmental impacts. Therefore, we focus on the impact of retailer CSR and overconfidence of manufacturers on social welfare and the environment in this section. In this section, considering the simulated data of Wang et al. (2021) and Song et al. (2021), we set $a = 10$, $c = 3$, $k = 2$, $\beta = 1$, $\eta \sim (0,1)$, and $\lambda \sim (0,1)$.

5.1 Consumer surplus

We calculate and analyze the consumer surplus (CS). As a result, according to the consumer surplus function, we have the CS function for the benchmark scenario (i.e., scenario NN).

$$CS^{NN} = \int_{p_{min}}^{p_{max}} D^{NN} dp = \frac{k^2(a-c)^2}{2(4k-\beta^2)^2}.$$

Similarly, we have access to the consumer surplus under scenario NY.

$$CS^{NY} = \int_{p_{min}}^{p_{max}} D^{NY} dp = \frac{k^2(a-c)^2}{2(4k-\beta^2(1+\eta)^2)^2}.$$

When the retailer has CSR, we have the consumer surplus under scenario SN and scenario SY, respectively.

$$CS^{SN} = \int_{p_{min}}^{p_{max}} D^{SN} dp = \frac{k^2(a-c)^2}{2(2k(2-\lambda)-\beta^2)^2},$$
$$CS^{SY} = \int_{p_{min}}^{p_{max}} D^{SY} dp = \frac{k^2(a-c)^2}{2(2k(2-\lambda)-\beta^2(1+\eta)^2)^2}.$$

From Fig. 6, we can observe that consumer surplus is better under scenario SY than in other scenarios. Under scenario NN, the consumer surplus is probably the worst. Under the joint impact of CSR and manufacturer's overconfidence level, consumer surplus increases with increasing λ and η for scenario SN (scenario NY). The reason is that as the CSR and overconfidence levels increase, consumers are able to obtain more extra utility value from low-carbon products, which increases consumers' perceived product value and willingness to pay. However, consumer surplus under scenario SN (scenario NY) has more potential to be better than under scenario NY (scenario SN) as CSR (manufacturer overconfidence level) increases.

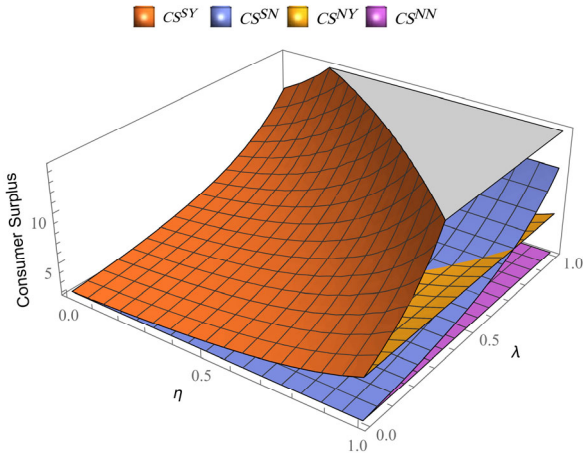

Fig. 6. Comparison of consumer surplus under different scenarios

5.2 Environmental effects

In this section, we analyze the influence of retailers' CSR and manufacturers' overconfidence on the environment. We measured the environmental impact of carbon mitigation with the parameter ϕ multiplied by q and e. This indicates the amount of carbon released in the manufacturer's production process and the degree to which the product is low carbon (Krass et al., 2013). Therefore, we then acquire the impact of retailers' CSR and manufacturers' overconfidence on the environment under different scenarios.

$$EI^{NN}(q^{NN}) = \phi e^{NN} q^{NN}, EI^{NY}(q^{NY}) = \phi e^{NY} q^{NY},$$
$$EI^{SN}(q^{SN}) = \phi e^{SN} q^{SN}, EI^{SY}(q^{SY}) = \phi e^{SY} q^{SY}.$$

Substituting the equilibrium outcome for the stakeholders, we have:

$$EI^{NN} = \frac{(a-c)^2 k\beta\phi}{(4k-\beta^2)^2}, EI^{NY} = \frac{(a-c)^2 k\beta(1+\eta)\phi}{(4k-\beta^2(1+\eta)^2)^2},$$
$$EI^{SN} = \frac{(a-c)^2 k\beta\phi}{(2k(2-\lambda)-\beta^2)^2}, EI^{SY} = \frac{(a-c)^2 k\beta(1+\eta)\phi}{(2k(2-\lambda)-\beta^2(1+\eta)^2)^2}.$$

We analyze the environmental impact under different situations. The results reveal that the environmental impact of manufacturers is jointly affected by the CSR and overconfidence levels. We can observe in Fig. 7 that wherever the level of CSR is low, the environmental impact gradually increases as the manufacturers' overconfidence levels increase (i.e., scenario NY). This means that manufacturer overconfidence damages the ecological environment and is not conducive to achieving sustainable development. The reason is that manufacturers' blind optimism reduces the carbon emission reduction level, which causes manufacturers to release more carbon emission pollutants with larger environmental impact. As retailers' CSR increases, the quality of manufacturers' products is regulated by retailers (i.e., the retailer is concerned about maximizing social welfare and becoming more corporate socially responsible), which increases the incentive for manufacturers to pursue carbon emission reductions and reduce their environmental impact. However, with increasing retailer CSR concerns, we find that manufacturers produce larger environmental impacts in scenario SY. Moreover, we also find that under the joint affected of λ and η, the manufacturer produces smaller environmental impacts under scenario NN.

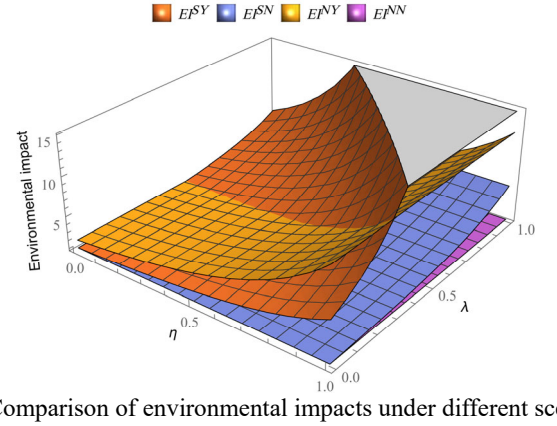

Fig. 7. Comparison of environmental impacts under different scenarios

5.3 Social welfare

We evaluate the influence of the combined effects of retailer CSR and manufacturer overconfidence on social welfare (SW). We explore the optimal social welfare based on the equilibrium outcomes of stakeholders and environmental impacts. While drawing on Atasu et al. (2009) and Kras et al. (2013), we incorporate the following components of social welfare.

$$Social\ welfare\ =\ Manufacturer's\ profit\ +Retailer's\ profit+\ Consumer\ surplus\ -\ Environmental\ impact.$$

Then, we can capture the social welfare of different scenarios.

$$SW^{NN}=\frac{(a-c)^2k(7k-\beta(\beta+2\phi))}{2(-4k+\beta^2)^2},$$

$$SW^{NY}=\frac{(a-c)^2k(13k-2\beta(1+\eta)(\beta+\beta\eta+2\phi))}{4(-4k+\beta^2(1+\eta)^2)^2},$$

$$SW^{SN}=\frac{(a-c)^2}{4k}\left(-\frac{2k^2(\beta^2+k(-9+4\lambda))}{(\beta^2+2k(-2+\lambda))^2}-\frac{\phi}{\beta^3(-2+\lambda)^2}\right),$$

$$SW^{SY}=\frac{(a-c)^2}{4k}\left(-\frac{2k^2}{\beta^2(1+\eta)^2+2k(-2+\lambda)}-\frac{2k^3(-5+2\lambda)}{(\beta^2(1+\eta)^2+2k(-2+\lambda))^2}-\frac{\phi}{\beta^3(1+\eta)^3(-2+\lambda)^2}\right).$$

Finally, we analyzed social welfare in different scenarios. However, due to the complexity of the results, we could not obtain a specific solution to the analysis. Therefore, we performed an extensive numerical study (see Fig. 8).

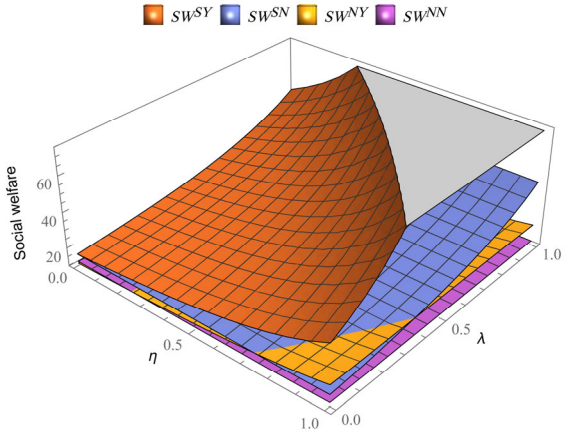

Fig. 8. Comparison of social welfare in different scenarios

Fig. 8 illustrates the joint impact of retailer CSR and manufacturer overconfidence on social welfare. We reveal that SW increases with retailer CSR and manufacturer overconfidence levels. Moreover, we present that the SW under scenario SY is superior to other scenarios. Furthermore, the findings demonstrate that SW under scenario SN (scenario NY) increases with λ (η). However, when λ is low, we find that social welfare under scenario NY outperformed scenario SN with increasing η. It is worth noting that social welfare under scenario NN outperforms scenario NY when the manufacturer's overconfidence level is low.

6. Conclusions

6.1 Concluding remarks

First, we find that under the joint impact of retailers' CSR and manufacturers' overconfidence, manufacturers' carbon emission reduction levels and profits shift from scenario SY to scenario SN (scenari NY) and finally to scenario NN as the retailers' CSR level (manufacturers' overconfidence level) increases (see Proposition 5, Proposition 6). However, when the retailer's CSR level is below the threshold, the manufacturer's profits under scenario SN exceed the other scenarios along with the increase in the manufacturer's overconfidence level (see Fig. 2). In addition, we also reveal that when the CSR level (manufacturer's level of overconfidence) is above the threshold, manufacturer profits and carbon mitigation levels are always optimal under scenario NN, whatever the manufacturer overconfidence level (retailers' CSR level) varies (see Proposition 5, Proposition 6, Fig. 1 and Fig. 2).

Second, we find that retailers are more profitable under scenario SY when the CSR or manufacturer overconfidence level is low. As the CSR or manufacturer overconfidence level increases, retailers are more profitable under scenario NN when the CSR or manufacturer overconfidence level is above the threshold. In addition, retailers are more potential to receive optimal profits under scenario SN or scenario NY when CSR or manufacturer overconfidence levels are moderate.

Third, our results demonstrate that environmental impacts are lowest under scenario NN, followed by scenario SN, suggesting that manufacturers are easier to protect the ecological environment under scenario NN and scenario SN. Something surprising is that we also find that higher retailer CSR is not always beneficial for carbon emission reduction and reduced environmental impact. Moreover, we find that environmental impacts are higher under scenario SY under the joint impact of CSR or manufacturer overconfidence levels. However, we find that when the CSR level is below the threshold, the environmental impact of scenario NY is higher than scenario SY as the level of manufacturer overconfidence increases. This implies that manufacturers have a higher probability of increasing carbon pollutants and harming the ecological environment when they are out of the regulatory constraints of retailers' products.

Finally, we explore social welfare under different scenarios. Our findings suggest that social welfare always prevails under scenario SY with respect to other scenarios. Moreover, our outcomes demonstrate that social welfare in the scenario SN is better than in other scenarios (i.e., scenario NY, scenario NN) under the joint effect of CSR and manufacturer overconfidence level. However, we find that social welfare under scenario NY outperforms scenario NN when manufacturers have higher levels of overconfidence and retailers have lower CSR. It is worth noting that social welfare under scenario NY outperforms scenario NN when the level of manufacturer overconfidence is low.

6.2 Future research

There are several interesting and valuable directions worth investigating in the future. First, we consider retailer CSR and manufacturer overconfidence in the absence of competition. Therefore, considering retailer competition or competition from multiple manufacturers may yield some interesting findings. Second, we consider that market information is symmetric, while demand information or cost information in the market may be informationally asymmetric. It is an interesting problem to consider the influence of retailers' CSR on carbon abatement and environment under information asymmetry. Third, governments usually implement various government policies to promote carbon emission reduction and preserve the ecological environment, such as government subsidies, tax policies, or carbon cap-and-trade policies. Therefore, considering carbon emission reduction and environmental impacts under various government policies may lead to interesting results.

Appendix

Proof of Proposition 1.

$$\pi_R^{NN} = (p - w)(a - p + \beta e), \quad (1)$$
$$\pi_M^{NN} = (w - c)(a - p + \beta e) - ke^2/2, \quad (2)$$

According to the profit function of the retailer under scenario NN: $\pi_R^{NN} = (p - w)q = (p - w)(a - p + \beta e)$. After we take the first derivative of p with respect to Eq. (2), we can derive

$$p = \frac{a+\beta e+w}{2}. \quad (A1)$$

substituting (A1) into Eq. (2) and taking the first order derivatives of w and e in Eq. (2), we can obtain,

$$e^{NN} = \frac{\beta(a-c)}{4k-\beta^2}, w^{NN} = \frac{2k(a+c)-\beta^2 c}{4k-\beta^2}. \quad (A2)$$

we can get:

$$p^{NN} = \frac{3ka+kc-\beta^2 c}{4k-\beta^2}. \quad (A3)$$

we can derive:

$$\pi_M^{NN} = \frac{k(a-c)^2}{2(4k-\beta^2)}, \pi_R^{NN} = \frac{k^2(a-c)^2}{(4k-\beta^2)^2}. \quad (A4)$$

Proof of Corollary 1.

According to the results of (A2) and (A3), for which we solve the first order derivative, we obtain

$$\frac{\partial e^{NN}}{\partial \beta} = \frac{(a-c)(4k+\beta^2)}{(-4k+\beta^2)^2} > 0, \frac{\partial p^{NN}}{\partial \beta} = \frac{6(a-c)k\beta}{(-4k+\beta^2)^2} > 0, \frac{\partial w^{NN}}{\partial \beta} = \frac{4(a-c)k\beta}{(-4k+\beta^2)^2} > 0.$$

Proof of Proposition 2.

$$\pi_R^{NY} = (p-w)(a-p+\beta(1+\eta)e), \tag{3}$$
$$\pi_M^{NY} = (w-c)(a-p+\beta(1+\eta)e) - ke^2/2, \tag{4}$$

With the similar proof of Proposition 1, we derive the equilibrium results under scenario NY.

$$p^{NY} = \frac{3ka+kc-\beta^2(1+\eta)^2c}{4k-\beta^2(1+\eta)^2}. \tag{A5}$$
$$w^{NY} = \frac{2k(a+c)-\beta^2(1+\eta)^2c}{4k-\beta^2(1+\eta)^2}, e^{NY} = \frac{\beta(1+\eta)(a-c)}{4k-\beta^2(1+\eta)^2}. \tag{A6}$$

Substituting (A5) and (A6) into Eq. (3) and Eq. (4), we can derive:

$$\pi_R^{NY} = \frac{k^2(a-c)^2}{(4k-\beta^2(1+\eta)^2)^2}, \pi_M^{NY} = \frac{k(a-c)^2}{2(4k-\beta^2(1+\eta)^2)}.$$

Proof of Corollary 2.

According to the manufacturer profit and carbon mitigation level under scenario NN and scenario NY, we have $\pi_M^{NY} - \pi_M^{NN} = \frac{(a-c)^2k\beta^2\eta(2+\eta)}{2(4k-\beta^2)(4k-\beta^2(1+\eta)^2)}$. Solving for $\pi_M^{NY} - \pi_M^{NN} \geq 0$. Therefore, we can get if $0 < \eta < -1 + 2\sqrt{\frac{k}{\beta^2}}$, we have $\pi_M^{NY} \geq \pi_M^{NN} \geq 0$. Otherwise, $\pi_M^{NY} < \pi_M^{NN}$. Similarly, we can prove that $e^{NY} \geq e^{NN}$, thus it is omitted here.
According to the profits of retailers under situation NN and situation NY, we have $\pi_R^{NY} - \pi_R^{NN} = (a-c)^2k^2(-\frac{1}{(-4k+\beta^2)^2} + \frac{1}{(-4k+\beta^2(1+\eta)^2)^2})$. Solving for $\pi_M^{NY} - \pi_M^{NN} \geq 0$. Therefore, we can get if $0 < \eta < -1 + \sqrt{\frac{8k-\beta^2}{\beta^2}}$, we have $\pi_R^{NY} \geq \pi_R^{NN}$. Otherwise, $\pi_M^{NY} < \pi_M^{NN}$.

Proof of Proposition 3.

$$U_R^{SN} = \pi_R^{SN} + \lambda CS = (p-w)(a-p+\beta e) + \frac{\lambda}{2}(a-p+\beta e)^2, \tag{5}$$
$$\pi_M^{SN} = (w-c)(a-p+\beta e) - ke^2/2, \tag{6}$$

With the similar proof of Proposition 1, we derive the equilibrium results under scenario SN:

$$p^{SN} = \frac{3ka-2k\lambda a+kc-\beta^2c}{2k(2-\lambda)-\beta^2}. \tag{A7}$$
$$w^{SN} = \frac{ka(2-\lambda)+kc(2-\lambda)-\beta^2c}{2k(2-\lambda)-\beta^2}, e^{SN} = \frac{\beta(a-c)}{2k(2-\lambda)-\beta^2}. \tag{A8}$$

Substituting (A7) and (A8) into Eq. (5) and Eq. (6), we can derive:

$$\pi_M^{SN} = \frac{k(a-c)^2}{2(2k(2-\lambda)-\beta^2)}, U_R^{SN} = \frac{k^2(a-c)^2(2-\lambda)}{(2k(2-\lambda)-\beta^2)^2}. \tag{A9}$$

Proof of Corollary 3.

The subsequent solution process of Corollary 3 with the similarity to Corollary 2's proof is therefore omitted here.

Proof of Proposition 4.

$$U_R^{SY} = \pi_R^{SY} + \lambda CS = (p-w)(a-p+\beta(1+\eta)e) + \frac{\lambda}{2}(a-p+\beta(1+\eta)e)^2, \tag{7}$$
$$\pi_M^{SY} = (w-c)(a-p+\beta(1+\eta)e) - ke^2/2, \tag{8}$$

With the similar proof of Proposition 1, we derive the equilibrium results under scenario SY:

$$p^{SY} = \frac{3ka-2k\lambda a+kc-\beta^2(1+\eta)^2c}{2k(2-\lambda)-\beta^2(1+\eta)^2}. \tag{A10}$$
$$w^{SY} = \frac{ka(2-\lambda)+kc(2-\lambda)-\beta^2(1+\eta)^2c}{2k(2-\lambda)-\beta^2(1+\eta)^2}, e^{SY} = \frac{\beta(1+\eta)(a-c)}{2k(2-\lambda)-\beta^2(1+\eta)^2}. \tag{A11}$$

Substituting (A10) and (A11) into Eq. (7) and Eq. (8), we can derive:

$$\pi_M^{SY} = \frac{k(a-c)^2}{2(2k(2-\lambda)-\beta^2(1+\eta)^2)}, U_R^{SY} = \frac{k^2(a-c)^2(2-\lambda)}{(2k(2-\lambda)-\beta^2(1+\eta)^2)^2}. \quad \text{(A12)}$$

Proof of Corollary 4 and Corollary 5.

The subsequent solution process of Corollary 3 with the similarity to Corollary 2's proof is therefore omitted here.

Proof of Proposition 5.

Under different scenarios, we first compare the carbon mitigation levels under scenario SY and scenario SN. $e^{SY} - e^{SN} = \frac{(a-c)\beta\eta(\beta^2(1+\eta)-2k(-2+\lambda))}{(\beta^2+2k(-2+\lambda))(\beta^2(1+\eta)^2+2k(-2+\lambda))}$. Solving for $e^{SY} - e^{SN} \geq 0$, we have $0 < \lambda < \frac{4k-\beta^2-2\beta^2\eta-\beta^2\eta^2}{2k}$, $e^{SY} \geq e^{SN}$; otherwise, $e^{SY} < e^{SN}$. Next, we compare the carbon mitigation levels under scenario SN and scenario NN. we have $e^{SN} - e^{NN} = -\frac{2(a-c)k\beta\lambda}{(4k-\beta^2)(\beta^2+2k(-2+\lambda))}$, by solving $e^{SN} - e^{NN} \geq 0$, we can get $\frac{4k-\beta^2-2\beta^2\eta-\beta^2\eta^2}{2k} < k \leq \frac{4k-\beta^2}{2k}$, $e^{SN} - e^{NN}$; otherwise, $e^{SN} < e^{NN}$. Similarly, we can prove Proposition 5 (b) and (c).

Proof of Proposition 6.

The solution process of Proposition 6 with the similarity to Proposition 5's proof is therefore omitted here.

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