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Environmental responsibility decisions of a supply chain under different channel leaderships

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ABSTRACT

Increasing concerns on environmental issues urge supply chain to be more sustainable. Channel leadership has a close relationship with the development of a sustainable supply chain. This paper employs game models of a sustainable supply chain, considering environmental responsibilities under different channel leaderships. We study how green-level, environmental responsibility, and performance are influenced by channel leaderships and environmental responsibility behavior. Analytical results indicate that if the manufacturer or the retailer are the leader of the channel, they might tend to lower environmental responsibility decisions. The retailer always wants to be the leader. But the manufacturer does not always want to be the leader of the channel, which also depends on consumer green-level sensitivity. Further, the impact of raw-material cost is negative for the manufacturer but positive for the retailer. Differently, the effect of environmental responsibility cost sensitivity on the manufacturer and the retailer are dependent on channel leadership. Besides, the manufacturer environmental responsibility behavior significantly affects green-level decisions, further offsets the manufacturer's first-mover disadvantage when consumer sensitivity is relatively small.

1. Introduction

With the long-term negative impact of traditional manufacturing on the environment, sustainable manufacturing has become a supply chain trend. Sustainability of a supply chain urges managers to pay their attention to pure profit and environmental effect of their operations. In practice, increasing enterprises (e.g., Adidas, Xerox, and Hewlett-Packard) focus on green manufacturing by adopting green-related measures to improve competitiveness and protect environment simultaneously. For example, Adidas, as a giant sports brand, reduces the environmental impact by greening its products (Banker et al., 1998). In addition to green manufacturing, some enterprises are concerning about environmental impact of their products during or after the usage, such as recycling and retreating waste product. This reflects the phenomenon that the manufacturer undertakes a proportion of the environmental responsibility of his product. The manufacturer's behavior towards environmental responsibility could affect the green-level decision significantly. This leads to the research questions: when considering environmental responsibility behavior, what the green-level decisions will be? And what about the effect of environmental responsibility behavior on the profits of players with different channel leaderships? This paper aims to address the above research questions.

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Along with the manufacturer's environmental responsibility, retailer's environmental responsibility is also becoming an essential priority for a supply chain. Firms may benefit from the environmental responsibility activities because of consumer's reward for their support of environmental programs. In practice, many retailers fulfill environmental responsibility in their operations. For instance, Best Buy, as one of the largest home appliance retailers, sells energy star certified products with superior energy efficiency (Li et al., 2016). This raises several interesting research questions, e.g., for the manufacturer and the retailer, what strategy can benefit both the profits and the environmental performance simultaneously? When considering corporate environmental responsibility of both the manufacturer and the retailer, how to depict these parameters or variables in the model, and what the appropriate decisions will be? When making decisions, both the manufacturer and the retailer should take opposite's strategies into consideration, which is the nature of game. How the game of the manufacturer and the retailer affects their optimal decisions?

In a game, channel leadership, which depends on channel players' ability to control the sequence of decision-making, significantly affects equilibrium outcomes and performance. Most enterprises would like to become channel leaders further get a lion share of the whole profit. In some scenarios, the manufacturer enjoys sufficient leadership as the channel leader and makes decisions first by anticipating the retailer's response, i.e., Manufacturer Stackelberg (*MS*), such as some giant manufacturer, Sports clothing brand, Adidas; Appliance enterprises, Gree, Midea, Haier, etc. Compared to some little retailer, they are the leader of supply chain and make their decisions first. However, in other scenarios, the increasing leadership of some retailers such as Tesco and Wal-Mart lead to the Retailer Stackelberg (*RS*) structure. They make their decisions first than some little manufacturer, such as organic food farmer, and organic cotton clothes manufacturer. Therefore, decision sequence of the game between the manufacturer and the retailer are different under different channel leaderships. Through maximizing own profits under different channel leaderships, the manufacturer and the retailer acquire their own optimal environmental responsibility decisions respectively. Therefore, a thorough understanding of how channel leaderships affect the green-level and environmental responsibility decisions and profitability of the players is the content of our research.

In this paper, a supply chain which consists of a manufacturer and a retailer is considered. Consumer demand is a linear function of consumers' environmental consciousness. On one hand, a relatively higher green-level or environmental responsibility can attract more consumers; however, it also means a higher cost of product, which may adverse to players' profit on the other hand. To maximize profit, the manufacturer and the retailer make tradeoff between the benefit and the cost. For the manufacturer, what green-level decision is optimal to himself and does not damage others' interests (e.g., the retailer and the environment)? Similar issues exist for the retailer. Therefore, we aim to answer the following two questions in this paper: (1) What is the green-level and environmental responsibility decisions of a supply chain in a perfectly competitive market when considering different channel leaderships? (2) Green initiatives by the manufacturer and the retailer: From a supply chain perspective, the manufacturer and the retailer who enjoy sufficient leadership in the channel? And which channel leadership structure is beneficial for the sustainability of the supply chain? Therefore, we model this aspect of the environmental supply chain by studying several channel leadership structures which are at play, one in which the manufacturer is the market leader, another the retailer is the leader.

This paper contributes to the literatures from the following aspects. This work reveals how channel leadership and consumers' environmental consciousness affect environmental responsibility decisions of the manufacturer and the retailer, and the performance of the system. We find that when the manufacturer or the retailer are the leader of the channel, they tend to make a relatively lower environmental responsibility decisions than when they are the follower of the channel. The effect of channel leadership on the manufacturer and the retailer are different. The retailer may have a first-mover advantage. But, the effect on the manufacturer depends on the consumer sensibility to green-level. Besides, the effect of channel leadership on environmental cost (*EC*) of the system also depends on consumer's environmental consciousness.

This work is organized as follows. We review related literature in Section 2. Section 3 presents assumptions and establishes the game models under different channel leaderships (*MS* or *RS* scenario). We compare the optimal equilibriums and performance of players in Section 4. Section 5 extents the model to the situation considering manufacturer environmental responsibility in the model, and further verifies the model by using numerical examples and robustness verification with different datasets. Finally, we draw conclusions and indicate the limitations of this research in Section 6.

2. Literature review

This work is related to three research streams: green manufacturing, corporate environmental responsibility, and channel leadership of supply chains.

One stream is green manufacturing. Green manufacturing is a mean of expressing green behavior of supply chain (Ogiemwonyi et al., 2020). Research on green manufacturing emphasizes how enterprises make their strategies to achieve competitiveness and environmental protection simultaneously. There are some studies focusing on green manufacturing, such as sustainable innovation (Borsatto and Bazani, 2020; Fung et al., 2021), green technologies (Dou and Choi, 2021), framework establishment of green manufacturing (Zhang et al., 2019), and green manufacturing agglomeration (Yuan et al., 2020), new energy vehicle recycle (Zhao et al., 2020), green supply chain coordination (Heydari et al., 2021). Unlike the studies in this stream, our paper investigates the roles of channel leadership and consumers' environmental consciousness play on environmental responsibility decisions of channel members, further analyzes the interaction between them.

Table 1
Comparison of previous researches with the proposed model.

Study	Echelons	Contract type	Decision Variables							Demand pattern			
			Retail Price	Order quantity	CER level	Wholesale price	Green level	emission abatement	CSR effort	Retail price	CER level	Green level	CSR effort
Dou and Choi (2021)	Two	Wholesale price	✓			✓		✓		✓			
Shi et al. (2020)	One	Game theory	✓						✓	✓			✓
Heydari et al. (2022)	Two	revenue-cost sharing/buyback		✓					✓		✓	✓	
Yang et al. (2019)	Two	Wholesale price	✓			✓	✓			✓		✓	
Heydari et al. (2021)	Two	greening cost g/revenue sharing	✓				✓			✓		✓	
Heydari and Rafiei (2020)	Two	Cost sharing			✓		✓			✓		✓	
This study	Two	Wholesale price			✓		✓				✓	✓	

Another stream is corporate environmental responsibility. Corporate environmental responsibility taking the environmental effects into consideration in corporate concerns has already become a notable issue for practitioners and academics. Environmental responsibility as the most essential aspect of social responsibility has attracted more attention than other aspects. For example, some literatures investigate the interaction between environmental and social responsibilities. Su and Swanson (2017) consider the destination social responsibility on tourist's environmental responsibility. Bulbul et al. (2020) investigate the relationship of environmental awareness or behaviors, and carbon footprint in households. Luo et al. (2020) study the influencing mechanism of social responsibility awareness on environmentally responsible behavior. There is also some literature focusing on the operation and coordination of an environmentally or socially responsible supply chain. Heydari and Mosanna (2018) and Heydari and Rafiei (2020) investigate the coordination of a sustainable supply chain by using greening cost sharing and revenue sharing contract. Yang et al. (2019) investigate the impact of CER on dual-channel strategies. Villena et al. (2021) investigate the untangling drivers of supplier environmental and social responsibility. Heydari et al. (2022) investigate the reconciling conflict of interests of a green retailing channel with green sales effort. Besides, as an extension, some literature assesses the impact of CSR. For example, Shi et al. (2020) explore the impacts of competition on CSR efforts in supply chains, and display that supply chain may reduce the CSR efforts level in duopoly scenario than monopoly scenario. Jajja et al. (2020) investigate the effect of social responsibility standards on performance of apparel supply chains. Isaksson and Kiessling (2021) investigate the implications of CSR on engineering management. Cai and Choi (2019) conduct a systematic review on extended producer responsibility from an operations management perspective. However, considering environmental responsible decisions of the manufacturer and the retailer simultaneously under different channel leaderships of a supply chain have not got sufficient attention, which is exactly our research content (see Table 1).

The third relevant research stream is on the implications of converting channel leadership. Channel leadership, which is also named channel power, is expressed as player's ability to impact the sequence of decision-making. Since Choi (1991) first considers non-cooperative games with different structures, channel leadership draws academics' attention. As an extension, Lee and Staelin (1997) study the role of vertical strategic interaction. Recently, Gao et al. (2016) study price and effort decisions of closed-loop supply chain with different channel power structures. Yang and Xiao (2017) study the pricing and green-level decisions with considering channel leadership. Chung and Lee (2018) reveal the effect of brand introduction on channel price leaderships. Shi (2019) investigates contract manufacturer's encroachment strategy under different channel leaderships. Jia et al. (2019) display the role of channel leadership on multi-tier sustainable supply chain management. Ranjbar et al. (2020) reveal the pricing and collecting decisions of a competitive dual recycling channel with different power structures. Liao et al. (2020) investigate the optimal store-brand quality considering channel price leadership. Wu et al. (2021) study the recycling price of closed-loop supply chain under different channel leadership and recycling channel. However, in an environmental responsible supply chain, which channel leadership scenario is better from the perspective of the system, consumers, or the environment has not been addressed.

It can be concluded from the literature review that this paper contributes to the literature by considering environmental responsibility and channel leadership of a sustainable supply chain simultaneously. By investigating two different game models, we reveal how the environmental responsibility decisions and performance of the supply chain depend on the channel leadership, consumer environmental consciousness, and cost sensitivities.

3. Models and equilibrium analysis under different channel structures

We consider a supply chain consist of one green manufacturer and one environmentally responsible retailer. The manufacturer produces green products and sells them to the retailer by predetermined wholesale price w. The retailer sells products to final consumers by the retail price $p(p > w)$. In a perfectly competitive market, the price is often determined by the market. Thus, in practice, every retailer is the taker (not the makers) of price. Since we emphasize the environmental responsibility decisions of the channel in a perfectly competitive market, following Shi et al. (2020), we consider the prices are constant across both channel leadership models.

We assume that consumers are sensitive to green-level of the product and environmental responsibility level of the supply chain. For convenience, we list all notations of this paper as follows.

Decision variables:
g: green-level of the product, which is the decision variable of the manufacturer, $g \geq 0$;
s: environmental responsibility level of the retailer, which is the decision variable of the retailer, $s \geq 0$.

Parameters:
a: market scale of product with non-green and environmental responsibility, which implies the certain amount if the consumers are not sensitive to the environmental issues;
p: the retail price of the green product, which is predetermined by the market;
w: the unit wholesale price of the green product, it is also predetermined by the contract;
c_0: the production cost of unit non-green product;
c_1: the increase of production cost if green-level increases by one unit;
α, β: green-level and environmental responsibility sensitivity coefficients of consumer;
λ, η: the cost multiplier of green investment and environmental responsibility;
D: demand of consumers on environmentally responsible product;
π_m: the environmental manufacturer's profit;
π_r: the environmentally responsible retailer's profit;
π_{SC}: profit of the environmentally responsible supply chain;
EC: the environmental cost of the system.

The manufacturer is responsible for the green-level of his products. Green-level is a measure of the degree of environmental impact of the product in the process from production to recycle. The larger of the green-level of the product (greener), the smaller the impact on the environment; conversely, the smaller of the green-level of the product, the greater the impact on the environment. In practice, there are many different forms of expression of green-level. Such as, the energy saving level of electrical appliances product, the carbon emission level of new energy vehicles, and the recovery of waste products. Green products generally have higher expenses than non-green products for the environmental-protect raw-materials. Therefore, we assume the manufacturing cost per green product is $c = c_0 + c_1 g$. The fixed production cost c_0 can be considered as the production cost of the non-green product. The variable portion dependent on the green-level reflects the increase of raw-material cost related to the green-level. Since we emphasize the impacts of production cost, we control for non-strategic factors. Specifically, we leave out of consideration of the green design cost invested in previous design stage.

Along with the manufacturer green initiatives, the retailer also undertakes some environmental responsibility, such as package, recycle, and green marketing efforts. Similar to Ghosh and Shah (2015), we assume the cost of environmental responsibility of the retailer is $\eta s^2/2$, which represents this phenomenon that when environmental responsibility increases per unit, the cost of the retailer will increase by a quadratic function.

Consumers are sensitive to the environmental responsibilities of both the manufacturer and the retailer. Hence, as decision variables, environmental responsibility levels affect the consumer demand. Following Heydari and Rafiei (2020), the demand function is defined as $D = a + \alpha g + \beta s$, where $g, s > 0$ are decision variables of the manufacturer and the retailer respectively.

Consumers' environmental responsibility consciousness affect consumer demand, further affect the green responsibility decisions through the interaction of players, which will influence the environmental cost of the supply chain. Therefore, we assume $EC = D/(g + s)$, which represents the impact of the products on the environment of the system under certain environmental responsibilities of the manufacturer and the retailer. This assumption is reasonable because environmental cost is positively related to the demand but negative related to the environmental responsibility levels of channel members.

The profits of the manufacturer and the retailer are as follows:

$$\pi_m = (w - (c_0 - c_1 g))(a + \alpha g + \beta s); \quad (1)$$

$$\pi_r = (p - w)(a + \alpha g + \beta s) - \eta s^2/2. \quad (2)$$

In the following of this subsection, we derive the optimal equilibriums of the supply chain under *MS* and *RS* game models successively.

3.1. MS game model

Under *MS* game model, the sequence of the game is as follows: (i) The manufacturer announces the green-level of the products firstly; (ii) After observing green-level of the products, the retailer determines his own environmental responsibility level.

We can solve this game model by using the backwards induction approach. From Eqs. (1) and (2), we can derive Lemma 1.

Lemma 1. *Under MS, we obtain the following equilibrium decisions:*

(i) The manufacturer's optimal green-level is

$$g^{MS*} = \frac{(\alpha (w - c_0) - ac_1)\,\eta - \beta^2 c_1 (p - w)}{2\alpha c_1 \eta};$$

(ii) The retailer's optimal environmental responsibility is

$$s^{MS*} = \frac{\beta (p - w)}{\eta}.$$

Proofs of all Lemmas and Propositions are provided in the Appendix.

Lemma 1 shows the green-level of the manufacturer and the environmental responsibility level of the retailer under *MS* scenario. From the results, we can intuitively obtain that consumer's sensibility to environmental responsibility of the retailer positively impacts the retailer's environmental responsibility level. But counter-intuitively, consumer's sensibility to environmental responsibility negatively impacts the green-level of the manufacturer. Unlike the consumer's sensibility to environmental responsibility of the retailer, the consumer sensibility to environmental responsibility positively impacts the green-level of the manufacturer. However, it does not impact the environmental responsibility level of the retailer.

Besides, from the proof process of Lemma 1, we obtain that the retailer's optimal decision function does not depend on the green-level decisions of the manufacturer. In other words, the *MS* model has the same results as the Nash equilibrium scenario, which is different from the findings in Yang and Xiao (2017). In Yang and Xiao (2017), the *MS* scenario and *VN* scenario have different equilibrium decisions. This result is partially because the Nash equilibrium model has no leadership in the supply chain and partially because the assumption of retailer's environmental responsibility cost, a quadratic of environmental responsibility, is independent of the demand and the green-level decisions. This type of environmental responsibility cost often occurs in practice. For example, the retailer invests a capital to promote environmental responsibility in advance.

3.2. RS game model

Under the *RS* game model, the sequence of the game is as follows: (i) The retailer announces his environmental responsibility level firstly; (ii) After observing the retailer's decision, the manufacturer sets the green-level of the product subsequently.

We solve this game model by using backwards induction. From Eqs. (1) and (2), we can derive Lemma 2.

Lemma 2. *Under RS, we have the following equilibrium decisions:*

(i) The manufacturer's optimal green-level is

$$g^{RS*} = \frac{2\,(\alpha (w - c_0) - ac_1)\,\eta - \beta^2 c_1 (p - w)}{4\alpha c_1 \eta};$$

(ii) The retailer's optimal environmental responsibility level is

$$s^{RS*} = \frac{\beta (p - w)}{2\eta}.$$

Lemma 2 shows the manufacturer's green-level and the retailer's environmental responsibility decisions in the *RS* scenario. From Lemmas 1 and 2, we can obtain the profits of the manufacturer and the retailer under different channel leaderships. From the first-order differential equation of the profits with respect to consumer sensibilities to the green-level and the environmental responsibility respectively, we can derive that consumer's sensibilities to green-level (α) and environmental responsibility (β) of the retailer positively impact profits of the manufacturer and the retailer.

4. Comparisons and sensitivity analyses

This section compares and analyzes the optimal equilibrium decisions obtained in Section 3, further reveals the effect of channel leadership on the green-level and environmental responsibility decisions. Some important management implications are derived.

Proposition 1. *For the equilibrium, we have* $g^{MS*} < g^{RS*}$, $s^{MS*} > s^{RS*}$.

Proposition 1 states that the retailer has a relatively higher environmental responsibility under *MS* than *RS* scenario, which indicates that a relatively higher channel leadership is detrimental to the environmental responsibility level of the retailer. This result is different from Chung and Lee (2018), in which the retailer pays more attention in vertical strategy interaction. It is also inconsistent with the result in Shi et al. (2020). Shi et al. (2020) consider that the supplier and buyer choose to be responsible if and only if the detection efficiency is sufficiently high in the monopoly scenario. However, this finding is similar to Heydari and Mosanna (2018) who consider that the donation size (a special form of social responsibility) will increase if the manufacturer's market domination decrease. This finding is counter-intuitive but explainable. The reason is that the cost of environmental responsibility hampers the retailer to increase its environmental responsibility, especially with a higher channel leadership. Similarly, the manufacturer has a relatively higher green-level under *RS* than *MS* scenario. This finding is also reasonable because the manufacturer with a higher channel leadership is prone to make a relative lower green-level because of the cost if there are no enough supports or interventions from planner. For example, there are many energy-intensive appliances in the home appliance market because such giant manufacturers have not impetus to improve the green-level of their product. Proposition 1 implies that both the manufacturer and the retailer are short of impetus to make decisions which may benefit the sustainability of the supply chain. In fact, it is difficult for both the manufacturer to voluntarily improve the green-level of products and the retailer to increase the environmental responsibility level. Therefore, appropriate interventions or subsidies from planner may be necessary to improve green-level and environmental responsibility level for manufacturer and retailer in practice.

Proposition 2. *For the profits of supply chain and its membership, we have*
(i) For any α and β, $\pi_R^{MS*} < \pi_R^{RS*}$;
(ii) If $\alpha \le \alpha_1$, then $\pi_M^{MS*} \le \pi_M^{RS*}$; if $\alpha > \alpha_1$, then $\pi_M^{MS*} > \pi_M^{RS*}$;
(iii) If $\alpha \le \alpha_2$, then $\pi_{SC}^{MS*} \le \pi_{SC}^{RS*}$; if $\alpha > \alpha_2$, then $\pi_{SC}^{MS*} > \pi_{SC}^{RS*}$;
Where

$$\alpha_1 = \frac{1}{4\left(w-c_0\right)^2\eta^2}\left(\beta^2 c_1\left(c_0-w\right)\left(p-w\right)\eta + \sqrt{c_1^2\eta^2\left(w-c_0\right)^2\left(11\beta^4\left(p-w\right)^2+24\alpha\beta^2\left(p-w\right)\eta+16\alpha^2\eta^2\right)}\right),$$

$$\alpha_2 = \frac{1}{8\left(w-c_0\right)^2\eta^2}\left(\beta^2 c_1\left(2c_0+p-3w\right)\left(p-w\right)\eta + \sqrt{c_1^2\eta^2\left(\beta^4\left(2c_0+p-3w\right)\left(p-w\right)^2+8\left(w-c_0\right)^2\left(5\beta^4\left(p-w\right)^2+12\alpha\beta^2\left(p-w\right)\eta+8\alpha^2\eta^2\right)\right)}\right).$$

Proposition 2(i) implies that the retailer can obtain a relatively higher profit under *RS* than under *MS* for any sensitivities to green-level and environmental responsibility of consumers, which represents that the retailer always has first-mover advantage. This finding is consistent with the result of Yang and Xiao (2017), in which the retailer also enjoys higher channel leadership. This finding implies that increase the market scale to capture the market further become the leader of the channel will be always better for the retailer. Different from Proposition 2(i), the manufacturer may have first-mover disadvantage when consumer's sensitivity to green-level is relatively small. However, the manufacturer may enjoy a relatively larger channel leadership when consumer's sensitivity to green-level is relatively high. This result is inconsistent with Yang and Xiao (2017) which present that the impact of channel leadership on manufacturer's profit depends on governmental intervention. This result is also different from Shi (2019) and Heydari and Mosanna (2018). Shi (2019) considers that the channel leadership does not impact the preference of contract manufacturer. However, Heydari and Mosanna (2018) consider that collaboration causes a more environmentally concerned supply chain than decentralization. Therefore, practically, increase the market scale will not be always benefit for the manufacturer. Besides, from Proposition 2(iii), when consumer's sensitivity to green-level is relatively high, *MS* scenario may be better than *RS* scenario for the system; otherwise, *RS* scenario is better. Proposition 2 reveals that the effect of channel leadership on the manufacturer and the retailer is different, but similar for the manufacturer and the entire system.

Proposition 3. *For the environmental cost of the supply chain, we have: if $\alpha \le \frac{ac_1}{w-c_0}+\beta$ then $EC^{MS*} \ge EC^{RS*}$; if $\alpha > \frac{ac_1}{w-c_0}+\beta$, then $EC^{MS*} < EC^{RS*}$.*

Proposition 3 reveals the environmental cost of the system when the consumer's green-level consciousness is relatively low or high under different channel leaderships. From Proposition 3, the environmental cost of the system is also dependent on the channel leadership. Specifically, when consumer's green-level consciousness is relatively lower compared to environmental responsibility consciousness, the *EC* is larger under *MS* scenario than *RS*. However, when consumer's green-level consciousness is high, the *EC* is larger under *RS* than under *MS*. This result is inconsistent with Dou and Choi (2021) and Wu et al. (2021). Dou and Choi (2021) consider that retailer collect scheme may create higher level of economic benefit than manufacturer-collect. However, Wu et al. (2021) insist that manufacturer collect channel is the most effective recycling channel irrespective of the channel leadership when the recycling price is determined by the recycling party. However, this finding is reasonable because when consumer's environmental consciousness is relatively higher than consumer's environmental responsibility consciousness and raw-material cost sensitivity to green-level (*RCSG*), the demand will increase more quickly under *RS* than *MS* because of the low environmental responsibility decisions of the leaders which might be detrimental to the *EC*.

Proposition 4. *For the raw-material cost sensitivity to green-level (RCSG), we have*
(i) $\frac{\partial g^{MS*}}{\partial c_1} = \frac{\partial g^{RS*}}{\partial c_1} < 0$, $\frac{\partial s^{MS*}}{\partial c_1} = \frac{\partial s^{RS*}}{\partial c_1} = 0$;
(ii) $\frac{\partial \pi_M^{MS*}}{\partial c_1} < 0$, $\frac{\partial \pi_M^{RS*}}{\partial c_1} < 0$;
(iii) $\frac{\partial \pi_R^{MS*}}{\partial c_1} = \frac{\partial \pi_R^{RS*}}{\partial c_1} > 0$.

Proposition 4 displays the trend of equilibrium decisions and profits on *RCSG*. From Proposition 4(i), *RCSG* has no impact on retailer's environmental responsibility decision regardless of the channel leadership. In contrast, *RCSG* has a negative impact on manufacturer's green-level decisions regardless of the channel leadership structures. This result is intuitive because a relatively higher *RCSG* may be an obstacle for the manufacturer to increase his green-level, but may has no impact on retailer's environmental responsibility decisions. From Proposition 4(ii), we can obtain that *RCSG* also negatively impacts on the profit of the manufacturer. But interestingly, we can counter-intuitive derive that *RCSG* has a positive impact on the profit of the retailer. In other words, the retailer might benefit from the *RCSG* through the interaction with the manufacturer.

Proposition 5. *For the retailer's environmental responsibility cost sensitivity, we have*

(i) $\frac{\partial g^{MS*}}{\partial \eta} = \frac{2\partial g^{RS*}}{\partial \eta} > 0$, $\frac{\partial s^{MS*}}{\partial \eta} = \frac{2\partial s^{RS*}}{\partial c_1} < 0$;

(ii) $\frac{\partial \pi_M^{MS*}}{\partial \eta} < 0$, $\frac{\partial \pi_M^{RS*}}{\partial \eta} > 0$;

(iii) $\frac{\partial \pi_R^{MS*}}{\partial \eta} = 0$, $\frac{\partial \pi_R^{RS*}}{\partial \eta} < 0$.

Proposition 5 reveals the effect of the retailer's cost sensitivity to environmental responsibility (*RCSS*) on optimal equilibrium decisions and profits. Different from *RCSG* in Proposition 4, *RCSS* negatively impacts the environmental responsibility but positively impacts the green-level. This is because that a relatively higher *RCSS* can decrease retailer's environmental responsibility. Under this circumstance, a relatively higher green-level decision will be detrimental to the manufacturer. The impacts of *RCSS* on the profit of the manufacturer and the retailer are dependent on the channel leadership. Specifically, from Proposition 5(ii), under *MS*, *RCSS* has a positive impact on the profit of the manufacturer. But under *RS*, the effect of *RCSS* on the profit of the manufacturer is negative. Proposition 5(iii) shows that *RCSS* has a negative impact on the profit of the retailer under *RS*, but has no effect on retailer's profit under *MS*. This finding is explainable because a relatively higher *RCSS* will result in a higher environmental responsibility cost, which is detrimental to the retailer but beneficial for the manufacturer especially under *RS*. However, under *MS*, the effects of *RCSS* on the environmental responsibility decisions are weakened by the lower channel leadership of the retailer, further decrease the profits of both manufacturer and the retailer.

5. Extension of the models

Along with the green manufacturing, manufacturers undertake the environmental cost of their product, such as recycling and reprocessing. This environmental responsibility affects the decisions of the environmental responsible supply chain and further affects performance of the system with different channel leaderships. Therefore, we examine the effect of manufacturer environmental responsibility behavior on the equilibriums and performance of the supply chain in this section.

As similar to Yang et al. (2019), we assume the environmental cost of a unit green product is $e = (h_0 - h_1 g)$, where h_1 is the sensitivity of environmental cost to green-level (*SECG*), and h_0 is the environmental cost of a traditional product. Moreover, the sensitivity h_1 is small enough such that the environmental cost will be non-negative.

Let λ represent the environmental responsibility of the manufacturer, $0 \le \lambda \le 1$. $\lambda = 0$ indicates that the manufacturer has no environmental responsibility and cares his own profit only. $\lambda = 1$ means that the manufacturer takes the complete environmental cost into consideration (Wang and Sarkis, 2017). A higher λ means a higher environmental responsibility of the manufacturer. Therefore, $\lambda \cdot e$ is the environmental cost of a unit green product undertaken by the manufacturer.

With the above assumption, in the extended model, the profits of the manufacturer and the retailer are as follows.

$$\pi_m = (w - (c_0 - c_1 g) - \lambda (h_0 - h_1 g)) (a + \alpha g + \beta s); \quad (3)$$

$$\pi_r = (p - w) (a + \alpha g + \beta s) - \eta s^2/2. \quad (4)$$

We study optimal equilibrium decisions of the supply chain and examine the effect of the environmental responsibility behavior on the results under *MS* and *RS* scenarios in the following.

5.1. Equilibriums analyses considering manufacturer's environmental responsibility behavior

Under *MS* scenario, the game sequence of game is as same as the sequence in the subsection of 3.1. We solve this game model by using backwards induction. From Eqs. (3) and (4), we can derive Lemma 3.

Lemma 3. *Under MS, we obtain the following equilibrium decisions*

(i) The manufacturer's green-level is

$$g^{MS*} = \frac{(\alpha (w - (c_0 + h_1\lambda)) - a (c_1 - h_1\lambda)) \eta - \beta^2 (c_1 - h_1\lambda) (p - w)}{2\alpha (c_1 - h_1\lambda) \eta};$$

(ii) The retailer's environmental responsibility is

$$s^{MS*} = \frac{\beta\,(p-w)}{\eta}.$$

From Lemma 3, we can obtain that retailer's environmental responsibility decision is dependent on the manufacturer's environmental responsibility behavior.

Under *RS* scenario, the sequence of the game is as same as the subsection of 3.2. From Eqs. (3) and (4), we can derive Lemma 4 by using backwards induction.

Lemma 4. *Under RS, we obtain the following optimal equilibrium decisions:*
(i) The manufacturer's green-level is

$$g^{RS*} = \frac{(2\alpha\eta\,(w-(c_0+h_0\lambda)) - 2a\,(c_1-h_1\lambda)) - \beta^2\,(c_1-h_1\lambda)\,(p-w)}{4\alpha\,(c_1-h_1\lambda)\,\eta};$$

(ii) The retailer's environmental responsibility is

$$s^{RS*} = \frac{\beta\,(p-w)}{2\eta}.$$

From Lemmas 3 and 4, environmental responsibility behavior has a different impact on green-level decisions under different channel leadership structures. In other words, the effect of manufacturer's environmental responsibility behavior on equilibriums is dependent on the channel leaderships.

5.2. Comparisons and sensitivity analyses under manufacturer environmental responsibility

In the following, we make comparisons of the equilibriums derived from Section 5.1. Then we analyze the impact of manufacturer's environmental responsibility on the optimal decisions and profits. Finally, we develop numerical examples with different datasets to confirm accuracy and robustness of the model, further generate more management insights.

Proposition 6. *By comparing the equilibriums and profits under two different channel leadership scenarios, we have*
(i) $g^{MS*} < g^{RS*}$, $s^{MS*} > s^{RS*}$;
(ii) $\pi_M^{MS*} > \pi_M^{RS*}$, $\pi_R^{MS*} < \pi_R^{RS*}$.

Proposition 6 makes a comparison of optimal equilibriums and profits of the manufacturer and the retailer under different leaderships with considering the manufacturer's environmental responsibility. Proposition 6(i) reveals that the manufacturer and the retailer are prone to a relatively lower decision when they are the leader of the channel, which is similar to on optimal equilibriums cannot surpass the effect of channel leadership. Under this circumstance, it is the channel leadership (the decision sequence in a supply chain) which plays a key role in the decisions of the two players. From Proposition 6(ii), the manufacturer and the retailer both have the first-mover advantage, which is different from Proposition 2. This is explainable because manufacturer's environmental responsibility affects manufacturer's decision significantly and further offsets the manufacturer's first-mover disadvantage when consumer sensitivity is relatively small.

Proposition 7. *For the environmental responsibility behavior of the manufacturer to the equilibriums, we have*
(i) If $h_1 \geq \frac{c_1 h_0}{w-c_0}$, *then* $\frac{\partial g^{MS*}}{\partial \lambda} \geq 0$; *if* $h_1 < \frac{c_1 h_0}{w-c_0}$, *then* $\frac{\partial g^{MS*}}{\partial \lambda} < 0$;
(ii) $\frac{\partial s^{MS*}}{\partial \lambda} = \frac{\partial s^{RS*}}{\partial \lambda} = 0$.

Proposition 7(i) implies that the effect of manufacturer's environmental responsibility behavior on green-level decision depends on the *SECG*. Specifically, when *SECG* is relatively high, it has a positive impact on the green-level decision; but when *SECG* is relatively low, the impact is negative. This result is counter-intuitive but explainable. The effect of manufacturer's environmental responsibility on the green-level decision is dependent on multiple parameters. Proposition 7(ii) reveals that manufacturer's environmental responsibility has no effect on retailer's environmental responsibility decision under both *MS* and *RS* channel leadership structures.

Proposition 8. *For the profits of the manufacturer and the retailer concerning environmental responsibility behavior, we have*
(i) If $h_1 \geq \frac{c_1 h_0}{w-c_0}$, *then* $\frac{\partial \pi_R^{MS*}}{\partial \lambda} \geq 0$ $\left(\frac{\partial \pi_R^{RS*}}{\partial \lambda} \geq 0\right)$; *if* $h_1 < \frac{c_1 h_0}{w-c_0}$, *then* $\frac{\partial \pi_R^{MS*}}{\partial \lambda} < 0$ $\left(\frac{\partial \pi_R^{RS*}}{\partial \lambda} < 0\right)$;
(ii) If $\lambda > \lambda_1$ *and* $\alpha < \alpha_3$, *or* $\lambda \leq \lambda_1$, *then* $\frac{\partial \pi_M^{MS*}}{\partial \lambda} \leq 0$ $\left(\frac{\partial \pi_M^{RS*}}{\partial \lambda} \leq 0\right)$; *otherwise, then* $\frac{\partial \pi_M^{MS*}}{\partial \lambda} > 0$ $\left(\frac{\partial \pi_M^{RS*}}{\partial \lambda} > 0\right)$;
Where $\lambda_1 = \frac{2c_1h_0 + c_0h_1 - wh_0}{h_0h_1}$, $\alpha_3 = \frac{\beta^2 h_1(c_1-h_1\lambda)(p-w) + ah_1(c_1-h_1\lambda)\eta}{(2c_1h_0+c_0h_1-h_1(w+h_0\lambda))\eta}$.

Proposition 8 displays the effect of environmental responsibility on the profits of the manufacturer and the retailer. From Proposition 8(i), the impact of environmental responsibility behavior on the profit of the retailer depends on *SECG* (sensitivity of environmental cost to green-level). Specifically, when *SECG* is relatively small, the environmental

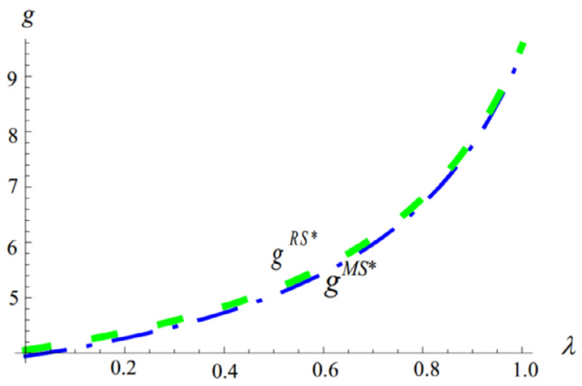

Fig. 1. Green-level decision concerning environmental responsibility (h_1 is relatively high).

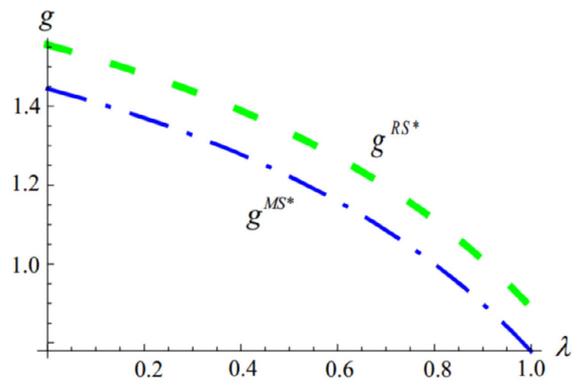

Fig. 2. Green-level decision concerning environmental responsibility (h_1 is relatively low).

responsibility negatively impacts the retailer; when *SECG* is relatively high, the impact is positive. This is explainable because a relatively higher *SECG* often means a higher green-level from Proposition 7, which will benefit to the retailer. Proposition 8(ii) reveals that the impact of environmental responsibility behavior on the profit of the manufacturer depends on the environmental responsibility and the consumer green-level sensitivity. If the environmental responsibility is low enough, or although the environmental responsibility is relatively high, the consumer green-level sensitivity is low enough, the environmental responsibility behavior will negatively impact the manufacturer. However, if environmental responsibility or *SECG* is relatively high, the environmental responsibility will positively impact the manufacturer, which is an insightful result.

5.3. Numerical results and robustness

In this subsection, we provide numerical examples to analyze the difference of the equilibriums and profits of the supply chain under different channel leaderships further illustrate the robust of the models and results by using different datasets.

In order to reveal the impact of key parameters on decision variables and revenues clearly, we adopt the parameters based on the following two imperative conditions: (a) the optimal solutions of game models are unique; (b) all variables are non-negative. We first assume $a = 10$, $\alpha = 1.5$, $\beta = 1$, $\eta = 1.5$, $c_0 = 1$, $c_1 = 0.2$, $h_0 = 1.7$, $h_1 = 0.15$, $p = 5$, and $w = 4$ (*SECG* is relatively higher than *RCSG* under these parameters). Then, we vary the parameters to generate more management implications. We reset $c_1 = 0.3$. Other parameters remain unchanged (*SECG* is lower than *RCSG*). We draw graphs of green-level decisions regarding environmental responsibility behavior under two channel leadership structures with different parameters, as displayed in Figs. 1 and 2.

From Figs. 1 and 2, green-level decision under *RS* is higher than under *MS*. However, the effect of environmental responsibility behavior on the green-level decision is dependent on other parameters. When *SECG* is relatively higher than *RCSG*, the impact is positive; but when *SECG* is lower than *RCSG*, the impact is negative. This result confirms Propositions 5 and 6. Besides, by the comparison of Figs. 1 and 2, the difference of green-level decisions under two channel leaderships is larger when *SECG* is lower than *RCSG*.

We further illustrate the difference of the manufacturer and the retailer's profits, and the *EC* concerning environmental responsibility behavior under two channel leadership structures with different parameters in Figs. 3–6.

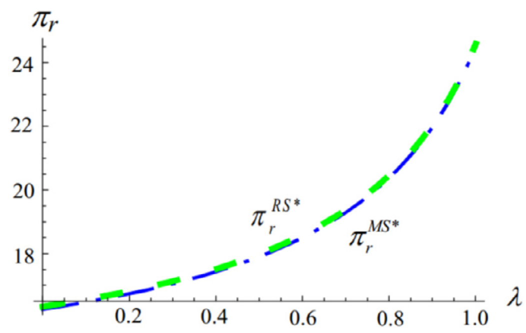

Fig. 3. Retailer's profit concerning environmental responsibility (h_1 is relatively high).

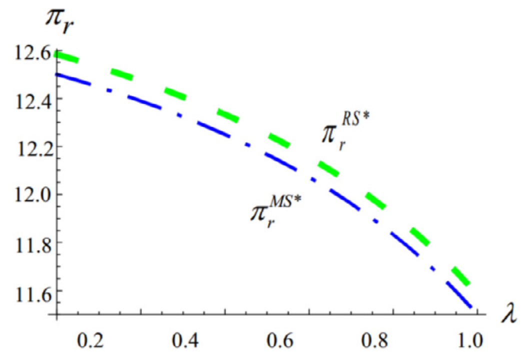

Fig. 4. Retailer's profit concerning environmental responsibility (h_1 is relatively low).

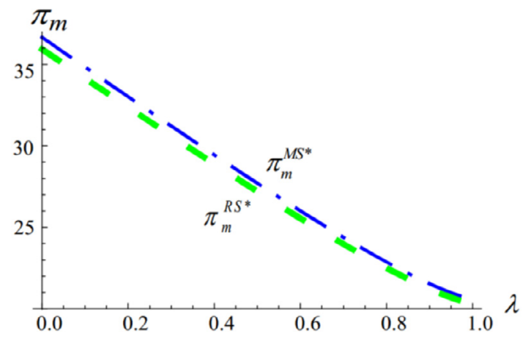

Fig. 5. Manufacturer's profit concerning environmental responsibility (h_1 is relatively low).

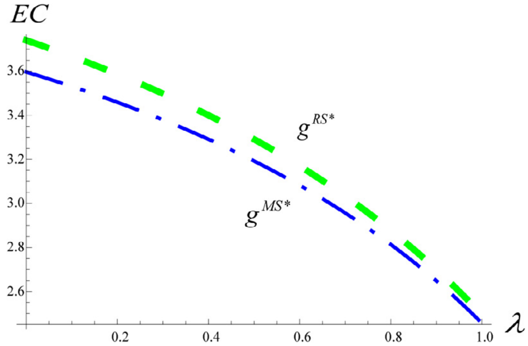

Fig. 6. *EC* concerning environmental responsibility (h_1 is relatively low).

Table 2
The optimal decisions and profits versus the sensitivity of environmental cost to green-level (*SECG*).

h_1	g^{MS*}	s^{MS*}	π_M^{MS*}	π_R^{MS*}	EC^{MS*}	g^{RS*}	s^{RS*}	π_M^{RS*}	π_R^{RS*}	EC^{RS*}
0.03	2.26	0.67	24.34	13.72	4.81	2.37	0.33	23.77	13.80	5.14
0.06	2.77	0.67	24.89	14.49	4.31	2.88	0.33	24.33	14.57	4.56
0.09	3.38	0.67	25.59	15.40	3.89	3.49	0.33	25.05	15.49	4.07
0.12	4.12	0.67	26.50	16.52	3.52	4.23	0.33	25.99	16.60	3.65
0.15	5.04	0.67	27.70	17.90	3.19	5.16	0.33	27.20	17.98	3.20

Table 3
The optimal decisions and profits versus the unit increase of production cost with green-level.

c_1	g^{MS*}	s^{MS*}	π_M^{MS*}	π_R^{MS*}	EC^{MS*}	g^{RS*}	s^{RS*}	π_M^{RS*}	π_R^{RS*}	EC^{RS*}
0.15	10.78	0.67	36.00	26.50	2.34	10.89	0.33	35.56	26.58	2.38
0.20	5.04	0.67	27.70	17.90	3.19	5.16	0.33	27.20	17.98	3.29
0.25	2.59	0.67	24.69	14.21	4.47	2.70	0.33	24.13	14.30	4.74
0.30	1.22	0.67	23.44	12.17	6.62	1.33	0.33	22.82	12.25	7.40
0.35	0.35	0.67	22.98	10.86	10.98	0.46	0.33	22.31	10.95	13.82

Table 4
The optimal decisions and profits versus green-level sensitivity coefficient.

α	g^{MS*}	s^{MS*}	π_M^{MS*}	π_R^{MS*}	EC^{MS*}	g^{RS*}	s^{RS*}	π_M^{RS*}	π_R^{RS*}	EC^{RS*}
0.4	1.0	0.67	22.96	10.73	6.64	1.42	0.33	22.28	10.82	6.23
0.6	5.44	0.67	24.27	13.60	2.28	5.72	0.33	23.69	13.68	2.27
0.8	7.67	0.67	26.46	16.47	2.02	7.88	0.33	25.94	16.55	2.03
1.0	9.00	0.67	29.01	19.33	2.03	9.17	0.33	28.52	19.42	2.05
1.2	9.89	0.67	31.73	22.20	2.13	10.03	0.33	31.27	22.28	2.15

Figs. 3 and 4 display the trend of the retailer's profit concerning manufacturer's environmental responsibility behavior. Similar to the green-level decision, the trend of the retailer's profit depends on the relative difference of *SECG* and *RCSG*. When *SECG* is relatively higher than *RCSG*, the impact of environmental responsibility on the retailer's profit is positive. When *SECG* is lower than *RCSG*, the impact is negative. This finding is consistent with Proposition 8. Besides, the retailer has a greater first-mover advantage when *SECG* is lower than *RCSG*. Fig. 5 shows the tendency of the manufacturer's profit with its environmental responsibility behavior when *SECG* is lower than *RCSG*. As is displayed, the manufacturer's first-mover advantage may not be obvious under this circumstance. Fig. 6 reveals that when h_1 is relatively low, *EC* is higher under *RS* than *MS* scenario. However, the difference decreases with the manufacturer's environmental responsibility behavior.

To illustrate the robust of the result, we further calculate the optimal decisions and profits by varying key parameters with different steps, and compare the difference of the results under different datasets. Then, we make comparison of the results with former theoretical results. We use tables to display the results in the following.

Tables 2 and 3 describe the optimal decisions and profits with the variation of the *SECG* and the unit increase of production cost with green-level. Considering the non-negativity of all variables and the uniqueness of the optimal decisions, we increase *SECG* (h_1) by step 0.03 in Table 2, and increase c_1 by step 0.05 in Table 3. Other parameters are as same as those mentioned above. As is displayed, the manufacturer has a relatively higher green-level under *RS*, and the retailer has a relatively higher environmental responsibility under *MS* instead, which verify the correctness of Propositions 1 and 6. Besides, with the increase of c_1, the optimal green-level increases, the environmental responsibility is constant, and the optimal profits of the manufacturer and the retailer decrease regardless of the channel leadership. This finding is consistent with Propositions 1, 2 and 4

Table 4 reveals the optimal decisions and profits with the variation of green-level sensitivity coefficient α. As depicted, under considering the non-negativity and uniqueness, we vary α and β by step 0.2 from 0.4 to 1.2 respectively. Other parameters are as same as those mentioned above. From Table 4, we can arrive the following results: both the manufacturer and the retailer enjoy channel power to become the leader of the channel. However, when the manufacturer and the retailer is the leader of the channel, they tend to make a relatively lower environmental responsibility decision than they are the follower. These findings are consistent with Propositions 1 and 6. Besides, α has a positive impact on green-level and profits of the manufacturer and the retailer under both channel leadership structures. But β has a negative impact on the optimal green-level of the manufacturer and a positive impact on the environmental responsibility of the retailer. In addition, for the *EC*, we can obtain that when α is relatively low, the *EC* is higher under *MS* than under *RS*; but when α is relatively high, the *EC* is higher under *RS* than under *MS*. This finding is consistent with Proposition 3 (see Table 5).

Table 6(a) and (b) reveal the optimal decisions and profits with the variation of the cost multiplier of green investment λ. With considering the non-negativity and uniqueness, under h_1 is relatively low or high, we vary λ by step 0.2 from 0.4 to 1.8 respectively. We leave the other parameters unchanged. With the comparison of green-levels on λ with different h_1 (low or high), we can arrive that when h_1 is relatively low, λ has a negative impact on the green-level; but when

Table 5
The optimal decisions and profits versus environmental responsibility sensitivity coefficient.

β	g^{MS*}	s^{MS*}	π_M^{MS*}	π_R^{MS*}	EC^{MS*}	g^{RS*}	s^{RS*}	π_M^{RS*}	π_R^{RS*}	EC^{RS*}
0.4	0.54	0.27	21.85	10.86	13.53	0.56	0.13	21.74	10.88	15.75
0.6	0.50	0.40	22.12	10.86	12.26	0.54	0.20	21.87	10.89	14.85
0.8	0.43	0.53	22.49	10.86	11.46	0.50	0.27	22.06	10.92	14.22
1.0	0.35	0.67	22.98	10.86	10.98	0.46	0.33	22.31	10.95	13.82
1.2	0.26	0.80	23.59	10.86	10.74	0.42	0.40	22.60	10.98	13.61

Table 6
The optimal decisions and profits versus the cost multiplier of green investment.

(a) When h_1 is relatively low ($h_1 = 0.15$).										
λ	g^{MS*}	s^{MS*}	π_M^{MS*}	π_R^{MS*}	EC^{MS*}	g^{RS*}	s^{RS*}	π_M^{RS*}	π_R^{RS*}	EC^{RS*}
0.2	0.60	0.67	28.55	11.23	9.13	0.71	0.33	27.73	11.32	10.91
0.4	0.44	0.67	24.83	11.00	10.20	0.56	0.33	24.11	11.08	12.56
0.6	0.25	0.67	21.14	10.71	12.02	0.36	0.33	20.51	10.79	16.62
0.8	0.01	0.67	17.49	10.34	15.79	0.12	0.33	16.95	10.43	23.15
(b) When h_1 is relatively high ($h_1 = 0.3$).										
λ	g^{MS*}	s^{MS*}	π_M^{MS*}	π_R^{MS*}	EC^{MS*}	g^{RS*}	s^{RS*}	π_M^{RS*}	π_R^{RS*}	EC^{RS*}
0.2	1.03	0.67	28.84	11.88	7.20	1.14	0.33	28.05	11.95	8.16
0.4	1.49	0.67	25.51	12.57	5.99	1.60	0.33	24.86	12.65	6.59
0.6	2.27	0.67	22.43	13.74	4.80	2.38	0.33	21.90	13.82	5.13
0.8	3.90	0.67	20.00	16.18	3.62	4.01	0.33	19.60	16.27	3.76

Table 7
The optimal decisions and profits versus the cost multiplier of environmental responsibility.

η	g^{MS*}	s^{MS*}	π_M^{MS*}	π_R^{MS*}	EC^{MS*}	g^{RS*}	s^{RS*}	π_M^{RS*}	π_R^{RS*}	EC^{RS*}
1	0.24	1.00	23.67	10.86	9.15	0.41	0.50	22.64	10.99	12.23
1.5	0.35	0.67	22.98	10.86	10.97	0.46	0.20	22.31	10.95	13.82
2.0	0.41	0.50	22.64	10.86	12.23	0.49	0.25	22.14	10.93	14.80
2.5	0.44	0.40	22.44	10.86	13.13	0.51	0.40	22.04	10.91	15.46
3	0.46	0.33	22.31	10.86	13.82	0.52	0.16	21.97	10.91	15.94

h_1 is relatively high, λ has a positive impact on the green-level. Besides, λ has also negative impact on the profits of the manufacturer and the retailer, but no any impact on the environmental responsibility decisions of the retailer. This finding is consistent with Proposition 7. Therefore, Table 6(a) and (b) can explain the robust of Proposition 7.

Table 7 displays the optimal decisions and profits with the variation of the cost multiplier of environmental responsibility η. Similar to the former tables, we vary η by step 0.5 from 1 to 3. As depicted in Table 7, we can obtain that η has a positive impact on the green-level decisions but negative impact on the environmental responsibility decisions. Besides, η has a negative impact on the profit of the manufacturer under *MS* but positive impact under *RS*. However, η has a negative impact on the profit of the retailer under *RS*, but no impact under *MS*. This finding is absolutely consistent with Proposition 7.

By the comparison of the results under different channel leadership structures, we can arrive that the key parameters have different impact on the optimal decisions and the profits. Numerical examples illustrate the robust of the models and the theoretical results.

6. Conclusions

By considering environmental responsibilities of both the manufacturer and the retailer simultaneously, we develop a two-stage game models of supply chain. We study the optimal equilibriums under different channel leaderships further examine the effect of channel leadership. Some managerial insights are generated.

Our results have practical implications for making optimal decisions for environmental initiative manufacturer, environmentally responsible retailer, and the planner. Results show that channel leadership affects the equilibrium decisions further influences performance of the supply chain. Specifically, (i) if the manufacturer or the retailer are the leader of the channel, they might tend to low environmental responsibility decisions. The manufacturer makes a low green-level, and the retailer makes a low environmental responsibility, respectively. In practice, it is difficult for the manufacturer and the retailer to voluntarily improve the green-level of products to maintain the sustainability of the supply chain. Therefore, appropriate interventions or subsidies from planner may be necessary to improve green-level and environmental responsibility for large manufacturer and retailer in practice. (ii) The effect of channel leadership on the manufacturer and the retailer are different. The retailer has the first-mover advantage, which implies that increase the market scale will be always better for the retailer. But sometimes the manufacturer may have the first-mover disadvantage, which still depends on green-level and environmental responsibility sensitivity coefficients of consumers. Therefore, practically, increase the market scale will not be always benefit for the manufacturer. Manufacturer should consider other key parameters when they intend to expand its scale for the priority in decision making in the channel. In practice, some manufacturers enjoy to be a follower sometimes. (iii) When *RCSG*'s (consumers' sensitivity of environmental cost to green-level) is high, *RCSG*'s impacts on the manufacturer and the retailer are positive, otherwise, the impacts are negative. So, take some effective measures to improve *RCSG* is necessary for both the manufacturer and the retailer, such as presale to increase personal experience, publicity to inform the greenness of the product. (iv) However, *RCSS*'s (retailer's cost sensitivity to environmental responsibility) effects on the manufacturer and the retailer are related to channel leadership. If *RCSS* is high, the manufacturer is prone to make a high green-level. And when the manufacturer is the leader, a high *RCSS* will benefit for the manufacturer, but when the manufacturer is the follower, a high *RCSS* may detrimental to the manufacturer. However, *RCSS* has a negative impact on the environmental responsibility of the retailer. When the retailer is the leader, a high *RCSS* might benefit for the retailer. Besides, manufacturer's environmental responsibility behavior affects green-level decision significantly further alters manufacturer's first-mover disadvantage when consumer sensitivity is relatively small. Numerical examples with different datasets illustrate the correctness and robustness of the models and the findings.

This paper contributes to the literature by considering the environmental responsibilities of both the manufacturer and the retailer in a supply chain simultaneously. There are inherent limitations due to the assumptions. This work assumes the information is complete. However, some information is private. Incomplete information may be an interesting extension. Besides, we assume that the demand function is a linear function to the green-level and environmental responsibility, and the wholesale and retail prices are given. In reality, the demand is more complex and requires further research.

CRediT authorship contribution statement

Deyan Yang: Investigation, Writing – original draft, Software, Project administration. **Dongping Song:** Conceptualization, Funding acquisition, Supervision. **Cunfang Li:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Proofs of propositions

Proof of Lemma 1. According to Eq. (2), the first-order and the second-order partial derivatives of $\pi_R(g,s)$ with respect to s are as follows

$$\frac{\partial \pi_R(g,s)}{\partial s} = \beta(p-w) - s\eta,$$
$$\frac{\partial^2 \pi_R(g,s)}{\partial s^2} = -\eta < 0. \tag{A.1}$$

By Eq. (A.1), we can obtain that $\pi_R(g,s)$ is concave in s. By solving the first-order condition $\frac{\partial \pi_R(g,s)}{\partial s} = 0$ for s, we can get the optimal retail's social responsibility

$$s^{MS}(g) = \frac{\beta(p-w)}{\eta}. \tag{A.2}$$

Then, expecting the retailer's social responsibility reaction, the manufacturer sets his green-level g to maximize his profit $\pi_M\left(g, s^{MS}(g)\right)$. We rewrite $\pi_M\left(g, s^{MS}(g)\right)$ as $\pi_M^{MS}(g)$.

Substituting Eq. (A.2) into Eq. (1), we have

$$\pi_M^{MS}(g) = (w-(c_0+c_1 g))\left(a+\alpha g+\frac{\beta^2(p-w)}{\eta}\right). \tag{A.3}$$

It follows from Eq. (A.3) that the first-order and the second-order partial derivatives of $\pi_M^{MS}(g)$ with respect to g can be shown as

$$\frac{\partial \pi_M^{MS}(g)}{\partial g} = \alpha\left(w-(c_0+c_1 g)\right) - c_1\left(a+\alpha g+\frac{\beta^2(p-w)}{\eta}\right), \tag{A.4}$$

$$\frac{\partial^2 \pi_M^{MS}(g)}{\partial g^2} = -2\alpha c_1. \tag{A.5}$$

By Eq. (A.5), the profit $\pi_M^{MS}(g)$ is concave with respect to g. By solving the first-order condition $\frac{\partial \pi_M^{MS}(g)}{\partial g}=0$, we obtain Lemma 1(i) and (ii). ■

Proof of Lemma 2. According to Eq. (1), the first-order and the second-order partial derivatives of $\pi_M(g,s)$ concerning g are as follows

$$\frac{\partial \pi_M(g,s)}{\partial g} = \alpha\left(w-(c_0+c_1 g)\right) - c_1\left(a+\alpha g+\beta s\right), \tag{A.6}$$

$$\frac{\partial^2 \pi_M(g,s)}{\partial g^2} = -2\alpha c_1 < 0. \tag{A.7}$$

By Eq. (A.7), we can see that $\pi_M(g,s)$ is concave to g. By solving the first-order condition $\frac{\partial \pi_M(g,s)}{\partial g}=0$ for g, we can obtain the optimal manufacturer's green-level

$$g^{RS}(s) = \frac{\alpha(w-c_0)-c_1(a-\beta s)}{2\alpha c_1}. \tag{A.8}$$

Then, expecting the manufacturer's green-level reaction, the retailer sets his social responsibility s to maximize his profit $\pi_R\left(s, g^{RS}(s)\right)$. We rewrite $\pi_R\left(s, g^{RS}(s)\right)$ as $\pi_R^{RS}(s)$.

Substituting Eq. (A.8) into Eq. (2), we have

$$\pi_R^{RS}(s) = \frac{1}{2}\left(\frac{(p-w)\left(c_1(\alpha+\beta s)+\alpha(w-c_0)\right)}{c_1} - s^2\eta\right). \tag{A.9}$$

From Eq. (A.9), the first-order and the second-order partial derivatives of $\pi_R^{RS}(s)$ concerning s can be shown as

$$\frac{\partial \pi_R^{RS}(s)}{\partial s} = \frac{\beta(p-w)-2s\eta}{2}, \tag{A.10}$$

$$\frac{\partial^2 \pi_R^{RS}(s)}{\partial s^2} = -\eta. \tag{A.11}$$

By Eq. (A.11), the profit $\pi_R^{RS}(s)$ is concave with respect to s. By solving the first-order condition $\frac{\partial \pi_R^{RS}(s)}{\partial s}=0$, we obtain Lemma 2 (ii). Substituting Lemma 2(ii) into Eq. (A.8), we have Lemma 2(i). ■

Proof of Proposition 1. The difference of green-level and social responsibility decisions under different channel leaderships are

$$s^{MS*} - s^{RS*} = \frac{\beta(p-w)}{2\eta} > 0,$$

$$g^{MS*} - g^{RS*} = -\frac{\beta^2(p-w)}{4\alpha\eta} < 0.$$

We can easily obtain Proposition 1. ■

Proof of Proposition 2. The difference of the profits of manufacturer and retailer under different scenarios are

$$\pi_R^{MS*} - \pi_R^{RS*} = -\frac{\beta^2(p-w)^2}{8\eta}$$

$$\pi_M^{MS*} - \pi_M^{RS*} = \frac{1}{16\alpha c_1\eta^2}\left(-5\beta^4 c_1^2(p-w)^2 + 4\beta^2 c_1\left(3ac_1+\alpha(w-c_0)(p-w)\eta + 8\left(-a^2c_1^2+\alpha^2(w-c_0)^2\eta^2\right)\right)\right).$$

We use $f(a) = -5\beta^4 c_1^2(p-w)^2 + 4\beta^2 c_1\left(3ac_1+\alpha(w-c_0)(p-w)\eta + 8\left(-a^2c_1^2+\alpha^2(w-c_0)^2\eta^2\right)\right)$. Then $f(0)<0$, and $\frac{\mathrm{d}^2 f(\alpha)}{\mathrm{d}\alpha^2}>0$. So, $\exists \alpha_1$, such that when $0<\alpha<\alpha_1$, we have $\pi_M^{MS*} \le \pi_M^{RS*}$; when $\alpha>\alpha_1$, we have $\pi_M^{MS*} > \pi_M^{RS*}$. Proposition 2 is proved. ■

Proof of Proposition 3. From Lemmas 1–2, we can easily get the differences of the *ESC* between the two channel leadership structures. Then Proposition 3 is proved. ■

Proof of Proposition 4. From Lemmas 1–2, first-order partial derivatives of equilibriums and the profits of manufacturer and retailer under different channel leaderships with respect to c_1, we obtain Proposition 4. ■

Proof of Proposition 5. The first-order partial derivatives of the equilibriums and optimal profits of the manufacturer and the retailer under different channel leadership structures with respect to η, we obtain Proposition 5. ■

Proof of Lemma 3. The process of the proof of Lemma 3 is similar to the proof of Lemma 1. ■

Proof of Lemma 4. The process of the proof of Lemma 4 is similar to the proof of Lemma 2. ■

Proof of Proposition 6. From Lemmas 3 and 4, we can get the differences of green-level and social responsibility decisions, and the profits of manufacturer and retailer under different leaderships. Then Proposition 6 is obtained. ■

Proof of Proposition 7. From Lemmas 3 and 4, first-order partial differential of green-level and social responsibility under different channel structures concerning λ, we can obtain Proposition 7. ■

Proof of Proposition 8. Similar to the proof of Proposition 7, The first-order partial differential of the profits of the manufacturer and the retailer under different channel leaderships concerning λ, we can obtain Proposition 8. ■

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