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SOCIALLY RESPONSIBLE SUPPLY CHAINS WITH COST LEARNING EFFECTS

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Abstract. Corporate social responsibility (CSR) has been attracting increasing attention. This paper investigates the implications of CSR upon a two-period manufacturer–retailer supply chain with cost learning effects which have been widely observed in different industries. Two scenarios are under consideration: the retailer exhibits CSR in one and the manufacturer does in the other. The analytical results demonstrate that compared with no CSR, the implementation of CSR generates higher pure profit for the entire chain. In contrast to the scenario where the manufacturer shows CSR, in the scenario where the retailer exhibits CSR, the manufacturer charges higher wholesale prices while the retailer charges lower retail prices, resulting in a higher chain-wide profit. Moreover, two-part tariff contracts are designed to coordinate the socially responsible supply chains. When coordinated, if the retailer exhibits CSR the wholesale prices are equal to the realized production cost which results from cost learning effects, while the wholesale prices are lower than the realized production cost if the manufacturer shows CSR. Interestingly, cost learning effects impair the pure profit of the coordinated supply chain when the effect of CSR is sufficiently high.

Mathematics Subject Classification. 90Bxx, 91Axx.

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1. Introduction

Many manufacturers undergo reductions in production costs over time owing to previous production experience. This is because workers can learn much from the accumulation and repetition of production and become more familiar with their jobs, leading to improvements in the production process. This phenomenon, that production cost declines with the previous production quantity, is called learning-by-doing or the learning curve [10, 26, 31]. These *cost learning* effects have been widely observed in different industries such as aircraft manufacturing, automobile assembly, apparel manufacturing, and electronics. Wright [27] originally reported on cost learning effects and observed that with each doubling of cumulative production, the direct labor costs drop by 20% in airframe production. It is well known that Toyota applies the learning curve to its production system which focuses on the continuous improvement of processes [25]. CNBC said that Sony and Microsoft will ultimately benefit as the cost to produce their consoles decreases according to the normal learning curve dynamics in the electronics industry[1]. Cost learning effects have been studied widely in traditional supply chains

Keywords. Corporate social responsibility, cost learning effects, supply chain management, two-part tariff contract.

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[1] https://www.cnbc.com/2013/11/27/teardown-of-xbox-ps4-reveal-tight-margins.html

[7, 10, 29]. However, the implications of cost learning effects in socially responsible supply chains have not been explored.

In general, corporate social responsibility (CSR) implies that corporations should undertake the responsibility for stakeholders (consumers, employees, etc.) while creating profits for their shareholders. Instead of regarding traditional financial profit as their sole goal, socially responsible enterprises are concerned with the value of people in the production process and contribute to consumers and society. Spurred by the increasing pressure of governmental and non-governmental organizations, many companies have been actively engaged in responsible business conduct. For example, Sony takes its stakeholders' concerns seriously and works closely with its suppliers on initiatives in fields such as human rights, labor conditions, health and safety, and environmental protection[2]. The BMW Group considers the fulfillment of CSR as an indispensable part of its sustainable development strategy[3].

The issues of CSR have become increasingly crucial and the phenomenon of cost learning effects in supply chains is very common. Despite the popularity of CSR and cost learning effects in practice, their combination and interaction in a supply chain have not been investigated in the literature. Through their combination, the present study explores the implications of CSR upon a supply chain with cost learning effects and the property of cost learning effects in a socially responsible supply chain. In this study, the following questions are addressed:

(i) *How does CSR affect firms' pricing decisions in supply chains with cost learning effects?*
(ii) *What impacts do CSR and cost learning effects have on supply chain profitability?*
(iii) *Can two-part tariff contracts resolve channel conflict? If yes, what impacts do CSR have on two-part tariff contracts?*

To answer these questions, we consider a two-period Stackelberg game of a supply chain comprising a manufacturer with cost learning effects as the leader and a retailer as the follower. We use the decentralized scenario, where neither firm exhibits CSR, as a benchmark. Then, we investigate the scenario where the retailer alone is socially responsible, denoted R-CSR; and another where the manufacturer alone exhibits CSR, denoted M-CSR. For supply chain coordination, we also analyze the centralized scenario where the two firms act as an integrated firm to exhibit CSR. We examine the equilibrium behavior of each firm in the different scenarios and try to coordinate the socially responsible supply chains by adopting two-part tariff (TPT) contracts. Our main findings are: (i) Although either the manufacturer or the retailer exhibiting CSR is profitable to the supply chain, it is more profitable that the retailer be engaged in CSR. Compared with M-CSR, in R-CSR the wholesale prices are higher while the retail prices are lower. (ii) Cost learning effects and CSR can improve the profitability of the chain, but they cause greater double marginalization effects. (iii) We find out the conditions where TPT contracts can coordinate the socially responsible supply chains. When coordinated, in R-CSR the manufacturer chooses wholesale prices equaling the realized production cost resulting from learning effects, while in M-CSR the manufacturer will set the wholesale prices lower than the realized production cost. (iv) Cost learning effects might hurt the pure profit of the coordinated chain when the effect of CSR is sufficiently strong, whereas in each decentralized scenario, cost learning effects always benefit the chain-wide pure profit.

The remainder of this paper is organized as follows. The next section discusses the related literature and introduces our contribution. Section 3 elaborates our model development and parameter notation. We describe the aforementioned scenarios and give comparison analyses in Section 4. In Section 5, we utilize TPT contracts to coordinate socially responsible supply chains. Numerical analyses are carried out in Section 6. We make an extension in Section 7. Finally, some conclusions are presented in Section 8.

2. Literature review

This paper is mainly related to two streams of the literature, namely supply chain management with cost learning effects, and socially responsible supply chain. Cost learning effects have been studied widely in tra-

[2]https://www.sony.net/SonyInfo/csr-report/about/index.html
[3]http://www.bmw.com.cn/zh/topics/experience/csr/csr-overview.html

ditional supply chains. Gray *et al.* [7] explored the impact of cost learning effects on outsourcing decisions by considering a two-period game between an original equipment manufacturer and a powerful contract manufacturer, and they assumed both firms realize cost reduction due to learning effects. Xiao and Gaimon [29] examined the impacts of cost learning and integration investment on manufacturing outsourcing decisions by analyzing a two-period supply chain where both buyer and supplier experience cost reductions because of learning effects. Xu *et al.* [30] considered a single manufacturer–retailer supply chain where the manufacturer experiences cost reduction due to learning effects, and explored how the learning effects affect dynamic pricing strategies and channel efficiency. Li *et al.* [10] examined the impact of supply-side cost learning effects on pricing strategies, production decisions and procurement decisions in a two-period manufacturer–retailer supply chain. Considering a manufacturer–retailer green supply chain with the manufacturer as a leader, Zhang *et al.* [32] explored the impacts of learning effects on supply chain performance and profit distribution. Zhang *et al.* [33] investigated the impacts of cost learning effects when the retailer acts as a leader. Zhang and Zhang [31] explored contract preferences for a two-period supply chain where the supplier generates products with stochastic cost learning effects. Different from the existing literature which explores cost learning effects in traditional supply chains, we incorporate cost learning effects in socially responsible supply chains.

Although there are substantial studies on CSR from the individual firm perspective, studies on CSR in supply chains using OM models have just emerged in the last decade. Assuming a socially responsible retailer or a socially responsible manufacturer, Panda [20] investigated coordination of socially responsible supply chains by revenue-sharing contracts. Panda *et al.* [22] described a socially responsible three-layer supply chain and proposed a contract-bargaining process to cut out channel conflict. In a manufacturer–retailer supply chain with CSR, Panda *et al.* [23] considered two scenarios including the one where the retailer performs CSR, and the other in which the manufacturer does. In each scenario, a quantity discount contract is applied to resolve channel conflict. Furthermore, they used the Nash bargaining product to divide the surplus profit in the socially responsible chain. Panda and Modak [21] extended Panda *et al.* [23]'s study by considering that both the manufacturer and the retailer are socially responsible and they exhibit CSR in a proportion. Their study adopted subgame perfect equilibrium and extended alternating offer bargaining to investigate channel coordination and profit division between the two channel members. Modak *et al.* [15] considered a two-layer socially responsible supply chain consisting of a socially concerned manufacturer and two competitive retailers. They investigated two cases: the one where the two retailers play Cournot game, and the other where the retailers play Collusion game. Besides, in each case, they utilized TPT contracts to coordinate the chain, and used Nash bargaining to distribute the generated surplus profit from channel coordination. Panda *et al.* [24] examined channel coordination in a socially responsible closed-loop supply chain with product recycling. Using social work donation as a CSR practice, Modak *et al.* [16] studied a socially responsible closed-loop supply chain and explored three different channel structures based on who collects the used products for recycling, namely retailer collection, manufacturer collection or third-party collection. Moreover, they adopted TPT contracts to coordinate the chain. Biswas *et al.* [2] considered a two-layer sustainable supply chain which simultaneously involves CSR and green efforts, and investigated how these two kinds of sustainability responsibilities are allocated between channel members. Ni *et al.* [19] examined how CSR investment cost is allocated in a two-echelon supply chain with wholesale price contracts. Hsueh [8] provided a new revenue-sharing contract embedding CSR to coordinate a retailer-manufacturer supply chain where the manufacturer invests in CSR. Wu *et al.* [28] explored how an original equipment manufacturer mitigates an overseas supplier's social misconduct by setting CSR cost, and introduced a flexible quantity contract and a wholesale price incentive contract to improve supply chain performance. Ma *et al.* [13] designed optimal contracts for a supply chain with information asymmetry where the contract manufacturer can invest in CSR to increase demand. Nematollahi *et al.* [18] analyzed the coordination of decisions regarding CSR investment and order quantity, by considering a supplier-retailer supply chain in a newsvendor setup. Distinct from the previous literature which studies CSR in a static process, we investigate the implications of CSR in a dynamic process.

The current study incorporates cost learning effects into socially responsible supply chains and investigates how cost learning effects and CSR interact. To the best of our knowledge, such research is hitherto unexplored in

Table 1. Summary of notations.

Symbol	Definition
a	Market potential in each period
b	Price sensitivity of demand in each period
c_1	Production cost in the first period
β	Cost learning coefficient, also called cost learning rate
d_i^j	Demand in period i in scenario j
c_2^j	Production cost in the second period in scenario j
p_i^j	Retail price in period i in scenario j
w_i^j	Wholesale price in period i in scenario j
π_{dm}^j	Manufacturer's pure profit in scenario j
π_{dr}^j	Retailer's pure profit in scenario j
π^j	Chain-wide pure profit in scenario j
V_{dm}^j	Manufacturer's total profit in scenario j
V_{dr}^j	Retailer's total profit in scenario j
V^j	Chain-wide total profit in scenario j
*	Value of variables at equilibrium

Notes. j indicates different scenarios, where $j = c, r, m$, or n: c refers to Centralized scenario, r refers to R-CSR, m refers to M-CSR, and n refers to the scenario without CSR. i represents different selling periods, where $i = 1$ or 2.

the literature. Our study enriches the research on CSR and the literature on cost learning effects by considering the interactions between cost learning effects and CSR. We analyze socially responsible supply chains in a dynamic process with a two-period selling model. The previous CSR literature focused on a static process by assuming the products are sold in a single period. Furthermore, we investigate the coordination efficiency of TPT contracts in our setting and explore the impacts of CSR on TPT contracts.

3. Model development

Table 1 displays parameters and notations used in our model.

We consider a two-period Stackelberg game in a socially responsible supply chain consisting of a manufacturer ("he") as the leader and a retailer ("she") as the follower. One of the firms, either the manufacturer or the retailer, is socially concerned. In the first period, the manufacturer produces a product with unit cost c_1 and supplies it to the retailer at wholesale price w_1, and then the retailer sells it to consumers at retail price p_1. Due to cost learning effects, production cost c_1 drops to c_2 in the second period. In the second period, the manufacturer sells the product to the retailer at wholesale price w_2, and the retailer resells to consumers at retail price p_2. In line with [7, 10, 26], a linear cost learning effect is assumed so, specifically, c_2 equals $c_1 - \beta d_1$, where d_1 is the first-period selling quantity, and β denotes the cost learning coefficient.

In each period, we assume the demand at the retailer's end is deterministic and linear in retail price, formulated as $d_i = a_i - b_i p_i$. To ease exposition and focus on the impacts of CSR as well as cost learning effects on supply chain performance, we assume the potential market a_i in each period is the same and is denoted by a (where $a > c_1$), and the price sensitivity of demand in each period is also identical, denoted by b. To ensure nonnegativity of the demand function and production cost, we suppose $a - bc_1 > 0$ and $c_1 - a\beta > 0$, respectively. In each period, we consider a make-to-order setting, meaning that the retailer places her order based on the actual demand and the manufacturer arranges production according to the order of the retailer. In line with [4, 14], we assume the firms optimally choose all decisions before the selling season, and the decision flow is that the manufacturer decides the first-period wholesale price and the second-period wholesale price simultaneously, and afterwards the retailer makes decisions on the first-period retail price and the second-period retail price simultaneously. This assumption significantly simplifies the resulting equilibriums but does not change any of the qualitative insights on CSR. Also, to avoid complicated results, we assume each firm attaches the same importance to each period and does not consider any discount factor throughout this study, consistent with [3, 12, 14]. Then the manufacturer's financial profit, also called pure profit, is

$$\pi_{dm}^{j} = (a - bp_1)(w_1 - c_1) + (a - bp_2)(w_2 - c_2), \tag{3.1}$$

the retailer's pure profit is

$$\pi_{dr}^{j} = (a - bp_1)(p_1 - w_1) + (a - bp_2)(p_2 - w_2), \tag{3.2}$$

and the chain-wide pure profit under each decentralized scenario is

$$\pi^{j} = \pi_{dr}^{j} + \pi_{dm}^{j}. \tag{3.3}$$

The superscript j implies different scenarios, which can be n, r, or m. In the subscripts, d refers to a decentralized scenario, r means the retailer, and m denotes the manufacturer.

In keeping with previous publications [1, 2, 5, 6, 9, 11, 17, 24], a socially responsible firm's CSR in our model setting is accounted for in the form of a share of consumer surplus. The CSR firm's objective is to maximize her (or his) traditional pure profit plus a portion of consumer surplus accumulated from stakeholders. The consumer surplus is defined as the difference between the highest price which consumers are willing to pay and the retail price that they pay in fact, written as:

$$\mathrm{CS} = \int_{p_{\min}}^{p_{\max}} d\,\mathrm{d}p = \int_{(a-d)/b}^{a/b} d\,\mathrm{d}p = (a - bp)^2/2b. \tag{3.4}$$

We use $\theta \in (0, 1)$ as the fraction of consumer surplus which the socially responsible firm is concerned with. Then, the amount of consumer surplus embodied in her (or his) total profit in each period is $\theta(a - bp)^2/2b$.

The scenario without CSR, which is denoted by N-CSR, is a special case of R-CSR or M-CSR when $\theta = 0$. The profit function for each firm in N-CSR is exactly described in equations (3.1) and (3.2).

4. Analysis and discussion of scenarios

4.1. Centralized scenario

We first introduce the centralized scenario as a benchmark for supply chain coordination. The manufacturer and the retailer cooperate as a single firm which produces a product with cost learning effects and sells it to consumers over two periods (see Fig. 1). The total pure profit over two periods is:

$$\pi^{c} = (a - bp_1)(p_1 - c_1) + (a - bp_2)(p_2 - c_2). \tag{4.1}$$

Since the centralized firm is socially responsible, its total profit, *i.e.*, traditional pure profit plus a share of consumer surplus is

$$V^{c} = \pi^{c} + \theta(a - bp_1)^2/2b + \theta(a - bp_2)^2/2b. \tag{4.2}$$

The objective of the centralized firm is to determine p_1 and p_2 to maximize its total profit in equation (4.2). The optimal solutions are given in Table 2.

4.2. R-CSR scenario

In this subsection, we consider R-CSR scenario where the retailer is engaged in CSR and the manufacturer with cost learning effects is financially profit-maximizing (see Fig. 2). Since the retailer is socially responsible, her objective is to maximize her total profit including a portion of the consumer surplus and traditional pure profit. Her total profit is written as

$$V_{dr}^{r} = \pi_{dr}^{r} + \theta(a - bp_1)^2/2b + \theta(a - bp_2)^2/2b. \tag{4.3}$$

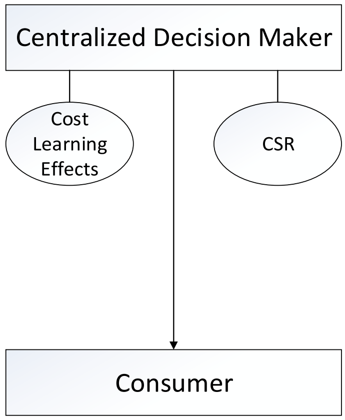


FIGURE 1. Structure of Centralized scenario.

TABLE 2. The optimal solutions for each scenario.

	Centralized	N-CSR	R-CSR	M-CSR
p_1^{j*}	$\frac{a(1-b\beta-\theta)+bc_1}{b(2-b\beta-\theta)}$	$\frac{3a-ab\beta+bc_1}{b(4-b\beta)}$	$\frac{a(3-b\beta-2\theta)+bc_1}{b(4-b\beta-2\theta)}$	$\frac{a(3-b\beta-\theta)+bc_1}{b(4-b\beta-\theta)}$
p_2^{j*}	$\frac{a(1-b\beta-\theta)+bc_1}{b(2-b\beta-\theta)}$	$\frac{3a-ab\beta+bc_1}{b(4-b\beta)}$	$\frac{a(3-b\beta-2\theta)+bc_1}{b(4-b\beta-2\theta)}$	$\frac{a(3-b\beta-\theta)+bc_1}{b(4-b\beta-\theta)}$
w_1^{j*}	Null	$\frac{a(2-b\beta)+2bc_1}{b(4-b\beta)}$	$\frac{a(2-b\beta-\theta)+b(2-\theta)c_1}{b(4-b\beta-2\theta)}$	$\frac{a(2-b\beta-\theta)+2bc_1}{b(4-b\beta-\theta)}$
w_2^{j*}	Null	$\frac{a(2-b\beta)+2bc_1}{b(4-b\beta)}$	$\frac{a(2-b\beta-\theta)+b(2-\theta)c_1}{b(4-b\beta-2\theta)}$	$\frac{a(2-b\beta-\theta)+2bc_1}{b(4-b\beta-\theta)}$
π_r^{j*}	Null	$\frac{2(a-bc_1)^2}{b(4-b\beta)^2}$	$\frac{2(1-\theta)(a-bc_1)^2}{b(4-b\beta-2\theta)^2}$	$\frac{2(a-bc_1)^2}{b(4-b\beta-\theta)^2}$
π_m^{j*}	Null	$\frac{(a-bc_1)^2}{b(4-b\beta)}$	$\frac{(a-bc_1)^2}{b(4-b\beta-2\theta)}$	$\frac{(4-b\beta-2\theta)(a-bc_1)^2}{b(4-b\beta-\theta)^2}$
π^{j*}	$\frac{(2-b\beta-2\theta)(a-bc_1)^2}{b(2-b\beta-\theta)^2}$	$\frac{(6-b\beta)(a-bc_1)^2}{b(4-b\beta)^2}$	$\frac{(6-b\beta-4\theta)(a-bc_1)^2}{b(4-b\beta-2\theta)^2}$	$\frac{(6-b\beta-2\theta)(a-bc_1)^2}{b(4-b\beta-\theta)^2}$
V_r^{j*}	Null	Null	$\frac{(2-\theta)(a-bc_1)^2}{b(4-b\beta-2\theta)^2}$	Null
V_m^{j*}	Null	Null	Null	$\frac{(a-bc_1)^2}{b(4-b\beta-\theta)}$
V^{j*}	$\frac{(a-bc_1)^2}{b(2-b\beta-\theta)}$	Null	$\frac{(6-b\beta-3\theta)(a-bc_1)^2}{b(4-b\beta-2\theta)^2}$	$\frac{(6-b\beta-\theta)(a-bc_1)^2}{b(4-b\beta-\theta)^2}$

The chain-wide total profit in R-CSR is

$$V^r = V_{dr}^r + \pi_{dm}^r. \tag{4.4}$$

By backward induction the equilibrium solutions were found; they are summarized in Table 2.

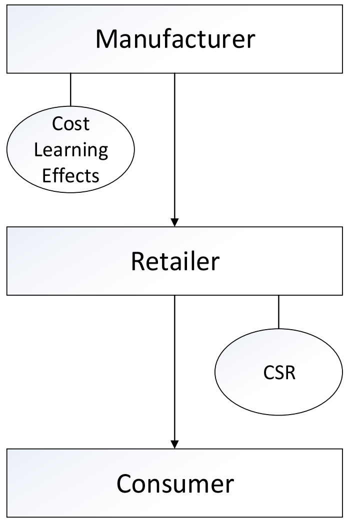


FIGURE 2. Structure of R-CSR Scenario.

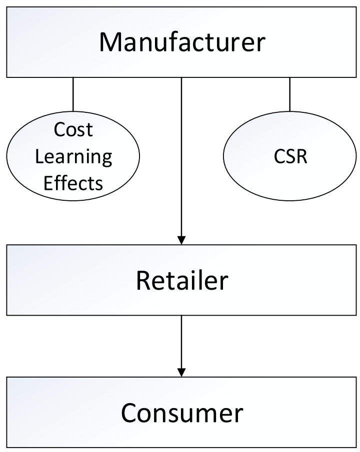


FIGURE 3. Structure of M-CSR Scenario.

4.3. M-CSR scenario

In M-CSR scenario where the manufacturer with cost learning effects is socially responsible and the retailer is financially profit-maximizing (see Fig. 3), the total profit function of the manufacturer is

$$V_{dm}^{m} = \pi_{dm}^{m} + \theta(a - bp_1)^2/2b + \theta(a - bp_2)^2/2b, \tag{4.5}$$

and the chain-wide total profit is

$$V^{m} = \pi_{dr}^{m} + V_{dm}^{m}. \tag{4.6}$$

Utilizing the backward induction approach, we derived the equilibrium solutions, which are given in Table 2.

4.4. Comparison analysis

In this subsection, we restrict our attention to the comparisons among these different scenarios and derive the following.

Proposition 4.1. *In each decentralized scenario, $p_1^{j*} = p_2^{j*} > w_1^{j*} = w_2^{j*} > c_1$, where j= n, r, or m. In the centralized scenario, $p_1^{c*} = p_2^{c*} > c_2^c$, and $p_1^{c*} < c_1$ if and only if $b\beta + \theta > 1$, otherwise $p_1^{c*} \geq c_1$.*

Proposition 4.1 indicates that there is no price change over two periods though the second-period production cost declines due to learning effects. This is due to the assumption that the manufacturer simultaneously decides his wholesale prices for the two periods. In the centralized decision, if the cost learning rate (modeled by β) is strong or if the effect of CSR (modeled by θ) is great, or both, the centralized firm will sacrifice first-period pure profit to obtain a higher second-period profit margin and higher consumer surplus by choosing a selling price below the first-period production cost. In contrast, in each decentralized scenario, each firm will maintain its financial profit margin in each period. This can be partially explained by the double marginalization effect between channel members.

Proposition 4.2. *For optimal retail prices in the different decentralized scenarios, we have $p_1^{n*} > p_1^{m*} > p_1^{r*}$. For optimal wholesale prices, we have $w_1^{n*} > w_1^{r*} > w_1^{m*}$. Also, $w_1^{r*} = w_1^{n*}$ if and only if $\beta = 0$.*

Proposition 4.2 sheds lights on the relationship of optimal price decisions among different decentralized scenarios. The retailer is close to consumers and has proximity to the market. When the retailer exhibits CSR, she has a direct motive to reduce the retail prices to attract more customers and improve consumer surplus. When the manufacturer is engaged in CSR, he induces the retailer to reduce retail prices by strategically choosing the wholesale prices. For the retailer, the former direct motive to cut prices is stronger than the latter motive to cut prices. Therefore, the retail prices in R-CSR are lower than those in M-CSR. It is intuitive that the retail prices in N-CSR, where neither of the two firms is concerned with CSR, are the highest since each firm pursues maximizing their respective pure profit without consideration of consumer surplus.

Considering optimal wholesale prices, to enhance consumer surplus, the CSR manufacturer has strong incentives to set low wholesale prices to induce the retailer to cut retail prices. Nevertheless, the optimal wholesale prices in R-CSR equal the ones in N-CSR if no cost learning effects exist. This implies that the retailer's concern for CSR has no impact on the manufacturer's decision when there are no cost learning effects. When cost learning effects exist, the wholesale prices in R-CSR will decrease with increasing θ as Figure 5b shows in Section 6. The reason behind this is that higher θ will drive up the first-period demand. The enhanced demand will augment the degree of cost reduction, resulting in wholesale prices lower than the ones in N-CSR. For the manufacturer, the motivation from CSR to cut wholesale prices in M-CSR is more significant, compared with the motivation from learning effects in R-CSR. Consequently, the optimal wholesale prices are in the order stated in Proposition 4.2. Proposition 4.2 suggests that different scenarios have different optimal price decisions for channel members. When firms make price decisions, they should carefully consider the scenario.

Proposition 4.3. *For chain-wide profits under the decentralized scenarios, we have $V^{r*} > \max(V^{m*}, \pi^{r*}) > \pi^{m*} > \pi^{n*}$. Also $\pi^{r*} \geq V^{m*}$ if and only if $\theta \leq b\beta(4 - b\beta)/(2 + b\beta)$.*

Proposition 4.3 reflects the fact that exhibiting CSR is beneficial from the chain-wide viewpoint. The chain-wide pure profit in N-CSR is outperformed by both R-CSR and M-CSR. The reason for higher profitability of the chain with CSR lies in the fact that the implementation of CSR brings enhanced demand and augmented cost reduction. Proposition 4.3 also states that the chain-wide performance, regardless of total profit or pure profit in R-CSR, overtakes that in M-CSR. As Proposition 4.2 describes, the optimal retail price in R-CSR is the lowest among the three decentralized scenarios. Thus, the first-period demand in R-CSR is the largest, resulting in the biggest cost reduction, which greatly benefits the whole chain. Consequently, the total chain-wide profit in R-CSR dominates. Even the chain-wide pure profit in R-CSR outweighs the total profit in M-CSR when the effect of CSR is sufficiently small. However, if there are no cost learning effects, this never happens. With the increasing effect of CSR (*i.e.*, higher θ), the ratio of pure profit to the total profit decreases. When θ goes beyond a certain threshold, the pure profit in R-CSR is overtaken by the total profit in M-CSR. There is a widespread belief among practitioners that the cost of CSR might lead to profit loss. Our results indicate that CSR improves supply chain performance irrespective of pure profit or total profit, and it is more profitable for the overall supply chain if the retailer undertakes CSR.

Proposition 4.4. *For the manufacturer's profit, we have* $\pi_{dm}^{r*} > V_{dm}^{m*} > \pi_{dm}^{n*} > \pi_{dm}^{m*}$. *For the retailer's profit, we have* $V_{dr}^{r*} > \pi_{dr}^{m*} > \max(\pi_{dr}^{r*}, \pi_{dr}^{n*})$. *Also,* $\pi_{dr}^{r*} \geq \pi_{dr}^{n*}$ *if and only if* $\theta \leq b\beta(4 - b\beta)/4$.

First, we analyze the results of comparisons between M-CSR and N-CSR. When the manufacturer is socially concerned, he will sacrifice his pure profit to optimize his total profit involving a portion of consumer surplus. In such a setting, the retailer is better off since she can obtain lower wholesale prices. In addition, regarding the comparisons between R-CSR and N-CSR, if there are no cost learning effects, the retailer's pure profit in R-CSR is always worse off. In contrast, if cost learning effects exist, the retailer can improve pure profit when θ is below a certain threshold. This is because the degree of cost reduction in R-CSR is larger than that in N-CSR, and she can indirectly benefit from the enhanced cost reduction through the manufacturer's lower wholesale prices. When θ is above the threshold, however, the retailer in R-CSR will optimize her total profit at the expense of her pure profit. As for the manufacturer, he will benefit much from the greater demand in R-CSR. Therefore, compared with N-CSR, his profit in R-CSR is greater, even surpassing the total profit in M-CSR. In contrast to M-CSR, the retailer in R-CSR gains greater total profit at the expense of her pure profit.

Combining Propositions 4.3 and 4.4, we find that no matter from the perspective of the entire chain or each firm, it is beneficial to exhibit CSR, and it is more profitable if the retailer is engaged in CSR. These results can provide managerial guidelines for supply chain managers and firms. The supply chain managers should urge retailers to pay attention to CSR, and traditional firms are advised to choose firms which are socially concerned as their partners.

Corollary 4.5. $\partial \Delta p^j/\partial\beta > 0$ *and* $\partial \Delta p^j/\partial\theta > 0$, *where* $\Delta p^j = p_1^{j*} - p_1^{c*} > 0$, $j = r$ *or* m.

Corollary 4.5 implies that the double marginalization problem in R-CSR or M-CSR becomes more severe with a greater learning rate (greater β) or increasing effect of CSR (higher θ). The manufacturer with greater β will expect the retailer to set a lower retail price to enhance the degree of cost reduction. To optimize her profit, the retailer will not set retail prices as low as the manufacturer desires, resulting in fiercer channel conflict. In the centralized scenario and each decentralized scenario, higher θ will induce a drop of retail prices to generate more consumer surplus. On the other hand, in each decentralized scenario, the degree of retail price fall is also influenced by the wholesale price of the manufacturer. With higher θ, the decrement rate of retail price in the centralized scenario is greater than that in each decentralized scenario. Therefore, combined with the result that the retail price in each decentralized scenario is greater than the price in the centralized case, the retail price differences between the centralized and each decentralized scenario increase, intensifying double marginalization.

Corollary 4.6.

(i) $\partial\pi^{r*}/\partial\theta > 0$, $\partial\pi^{m*}/\partial\theta > 0$, $\partial\pi^{c*}/\partial\theta < 0$.
(ii) $\partial\pi^{n*}/\partial\beta > 0$, $\partial\pi^{r*}/\partial\beta > 0$, $\partial\pi^{m*}/\partial\beta > 0$, *and* $\partial\pi^{c*}/\partial\beta > 0$ *if and only if* $\theta < (2 - b\beta)/3$, *otherwise* $\partial\pi^{c*}/\partial\beta \leq 0$.

Corollary 4.6(i) shows with the increasing effect of CSR, the pure profit in the centralized scenario decreases, while the chain-wide pure profit in each decentralized scenario increases. When two firms act as an integrated firm, the integrated firm will improve its total profit at the cost of pure profit. With higher θ, the integrated firm has stronger motivations to enlarge consumer surplus, leading to a smaller pure profit. When the two firms make their respective decisions independently, the one firm which is socially responsible will give up its pure profit to increase the stakeholders' welfare, but the other firm seeking to maximize financial profit can obtain more pure profit due to the enhanced demand and cost reduction. For the decentralized scenarios, the increment of pure profit of the traditional firm overcompensates for the decrement of pure profit of the CSR firm. As a result, the chain-wide pure profit in the decentralized cases increases with higher θ.

Corollary 4.6(ii) states the chain-wide pure profit in each decentralized case increases with a higher learning rate. Nevertheless, the pure profit in the centralized scenario goes down with greater β when the effect of CSR is sufficiently high. When the integrated firm focuses on CSR, the firm will pursue greater consumer surplus by cutting prices. In such a setting, a higher learning rate will aggravate the degree of price markdown, resulting in greater loss of pure profit. In each decentralized scenario, with greater β, the decline rate of retail price is small due to double marginalization effect, and the profit gain from the increased cost reduction overcompensates for the profit loss from the retail price reduction. Therefore, greater β will always bring about larger pure profit in the decentralized scenarios.

Corollary 4.7. *For the impact of* θ *on the pure profit of the CSR firm, we have* $\partial\pi_{dm}^{m*}/\partial\theta < 0$. *Also,* $\partial\pi_{dr}^{r*}/\partial\theta > 0$ *if and only if* $\theta < b\beta/2$.

When the socially concerned manufacturer concentrates more on CSR, his pure profit declines, which is intuitive. If no cost learning effects exist, when the socially responsible retailer puts more effort into CSR, her pure profit drops, which is also intuitive. Interestingly, when cost learning effects exist, her pure profit will firstly increase and then decrease with the increasing effect of CSR. The reason can be described as follows: higher θ will motivate the CSR retailer to lower her retail price to attract more demand, resulting in enhanced demand and amplified cost reduction. When θ is sufficiently small (below $b\beta/2$), the negative impact of CSR on her pure profit is not significant. For her pure profit, the loss from the negative impact of CSR is overwhelmed by the gain from the enhanced demand and cost reduction. Therefore, the CSR retailer's pure profit improves. However, with increasing θ, the negative impact of CSR on her pure profit becomes more and more significant. When θ is sufficiently large, her pure profit declines with greater θ. In M-CSR, with greater θ, the CSR manufacturer will decrease his wholesale prices to induce the retailer to mark down prices. As mentioned earlier, the retailer will not choose the retail prices which the manufacturer expects due to double marginalization effect. For the CSR manufacturer, the pure profit gain from an enlarged demand and cost reduction cannot compensate for the direct loss of pure profit due to the fall of wholesale prices. Accordingly, his pure profit will be lower with higher θ.

5. TPT contracts for decentralized scenarios with CSR

From the above section, we know that there is channel conflict in R-CSR and M-CSR. To eliminate channel conflict, here we introduce two-part tariff (TPT) contracts to coordinate the socially responsible supply chains. Under TPT contracts, the manufacturer as the leader proposes contract parameters (w_1, w_2, F) where F refers to the lump-sum fee (also called the franchise fee) that the retailer transfers to the manufacturer. The retailer follows by setting retail prices p_1 and p_2. In this setting, the manufacturer's and the retailer's pure profit are

$$\pi_{tm} = (a - bp_1)(w_1 - c_1) + (a - bp_2)(w_2 - c_2) + F \tag{5.1}$$

$$\pi_{tr} = (a - bp_1)(p_1 - w_1) + (a - bp_2)(p_2 - w_2) - F. \tag{5.2}$$

In the equations above, the subscript t refers to a scenario with a TPT contract. Next, we analyze R-CSR and M-CSR with TPT contracts.

5.1. TPT contract for R-CSR

In this setting, the socially responsible retailer's total profit function including a portion of the consumer surplus is

$$V_{tr}^{r} = \pi_{tr} + \theta(a - bp_1)^2/2b + \theta(a - bp_2)^2/2b. \tag{5.3}$$

TABLE 3. Optimal TPT contracts for R-CSR and M-CSR.

	R-CSR with TPT contract	M-CSR with TPT contract
π_{tr}^{j*}	$\frac{2(1-\theta)(a-bc_1)^2}{b(2-b\beta-\theta)^2} - F$	$\frac{2(a-bc_1)^2}{b(2-b\beta-\theta)^2} - F$
π_{tm}^{j*}	$F - \frac{\beta(a-bc_1)^2}{(2-b\beta-\theta)^2}$	$F - \frac{(b\beta+2\theta)(a-bc_1)^2}{b(2-b\beta-\theta)^2}$
V_{tr}^{j*}	$\frac{(2-\theta)(a-bc_1)^2}{b(2-b\beta-\theta)^2} - F$	Null
V_{tm}^{j*}	Null	$F - \frac{(b\beta+\theta)(a-bc_1)^2}{b(2-b\beta-\theta)^2}$
F_1^{j*}	$\frac{(2-\theta)^2(a-bc_1)^2}{b(2-b\beta-\theta)^2(4-b\beta-2\theta)}$	$\frac{4(a-bc_1)^2}{b(4-b\beta-\theta)(2-b\beta-\theta)^2}$
F_2^{j*}	$\frac{(2-\theta)^2(6-2b\beta-3\theta)(a-bc_1)^2}{b(2-b\beta-\theta)^2(4-b\beta-2\theta)^2}$	$\frac{8(3-b\beta-\theta)(a-bc_1)^2}{b(4-b\beta-\theta)^2(2-b\beta-\theta)^2}$

The CSR retailer's goal is to determine retail prices p_1 and p_2 to optimize her total profit in equation (5.3). Given the specified contract, we can obtain her best response p_{t1}^{r*} and p_{t2}^{r*} through solving her optimization problem. Anticipating the retailer's best response, the manufacturer will set such wholesale prices which make the retailer choose retail prices equaling the optimal prices in the centralized scenario in Section 4.1, namely $p_{t1}^{r*} = p_1^{c*}$ and $p_{t2}^{r*} = p_2^{c*}$. Then we can derive the wholesale prices under R-CSR with a TPT contract, as Proposition 5.1(i) describes. To ensure that the manufacturer and the CSR retailer comply with such a contract, it is necessary to guarantee that both channel members obtain more with the TPT contract than without such a contract. Thus, we require $\pi_{tm}^{r*} \geq \pi_{dm}^{r*}$ and $V_{tr}^{r*} \geq V_{dr}^{r*}$, namely a win-win result for both firms. We use F_1^j and F_2^j to denote the lower bound and the upper bound on the franchise fee under scenario j with a TPT contract where $j = r$ or m. The specific values of these bounds on F are exhibited in Table 3.

5.2. TPT contract for M-CSR

The socially responsible manufacturer's total profit function is

$$V_{tm}^m = \pi_{tm}^m + \theta(a-bp_1)^2/2b + \theta(a-bp_2)^2/2b. \tag{5.4}$$

Using a similar analysis method to that of Section 5.1, we derive the optimal wholesale prices of the TPT contract for M-CSR, given in Proposition 5.1(ii). To have each firm voluntarily comply with the TPT contract, the fixed transfer fee needs to satisfy $\pi_{tr}^{m*} \geq \pi_{dr}^{m*}$ and $V_{tm}^{m*} \geq V_{dm}^{m*}$, as Proposition 5.1(ii) demonstrates.

5.3. Analysis of TPT contracts under R-CSR and M-CSR

To coordinate these two kinds of socially responsible supply chains with TPT contracts, the wholesale prices and the lump-sum transfer fee need to satisfy the following conditions.

Proposition 5.1.

(i) *The TPT contract can coordinate the R-CSR supply chain if and only if* $w_{t1}^{r*} = w_{t2}^{r*} = ((2-\theta)c_1 - a\beta)/(2 - b\beta - \theta)$ *and* $F_1^r \leq F \leq F_2^r$.

(ii) *The TPT contract can coordinate the M-CSR supply chain if and only if* $w_{t1}^{m*} = w_{t2}^{m*} = (2bc_1 - a(b\beta + \theta))/(b(2 - b\beta - \theta))$ *and* $F_1^m \leq F \leq F_2^m$.

Proposition 5.1 reveals the conditions under which TPT contracts can coordinate socially responsible supply chains. Under coordination conditions, the wholesale price in each period is the same, like Proposition 4.1. The lower bound on the fixed fee determines the constraint condition below which the manufacturer would not like to comply with the contract, and the upper bound on the fixed fee defines the constraint beyond which the retailer will not be willing to take part. The specific amount of the franchise fee paid by the retailer hinges on the relative bargaining power of the two firms.

Corollary 5.2.

(i) $w_{t1}^{r*} = c_2^c$; $w_{t1}^{m*} < c_2^c$; $w_{t1}^{m*} < 0$ *if and only if* $\theta > b(2c_1 - a\beta)/a$; *and* $w_{t1}^{r*} = w_{t1}^{m*} = c_2^c$ *if and only if* $\theta = 0$.

(ii) $\partial w_{t1}^{j*}/\partial\theta < 0$, $\partial w_{t1}^{j*}/\partial\beta < 0$, $\partial F_k^j/\partial\theta > 0$, $\partial F_k^j/\partial\beta > 0$ *where j= r or m, and k =1 or 2.*

From Corollary 5.2(i), we know that the wholesale price in R-CSR with a TPT contract is identical to the realized production cost in the second period, in line with the situation without CSR. In M-CSR with a TPT contract, the wholesale price is below the realized production cost and may even be negative when the effect of CSR is sufficiently high. This is explained by the following: When the retailer exhibits CSR, swelling consumer surplus will be favorable to maximize her goal, so she has the incentive to lower retail prices to enlarge demand. Thus, the profit-maximizing manufacturer does not need to set the wholesale prices below the realized production cost to motivate the retailer to cut retail prices, and he behaves the same as in a traditional supply chain. Inversely, when the manufacturer is engaged in CSR, the profit-maximizing retailer is less motivated to cut retail prices. To stimulate the retailer to choose retail prices equaling the prices in the centralized case, the CSR manufacturer charges wholesale prices lower than the second-period production cost, even subsidizing the retailer for per unit of product. The manufacturer obtains no financial profit from the product sales, but he attains revenue from the lump-sum transfer payment paid by the retailer as compensation for coordination. Consequently, with a TPT contract, both firms can gain more profits than without the contract.

Corollary 5.2(ii) shows how the effect of CSR and the learning rate affect the wholesale prices and the bounds on the franchise fee. Irrespective of which member is socially conscious, the wholesale prices when coordinated will decrease with higher θ or greater β. This is because higher θ will motivate the CSR firm to enlarge consumer surplus by lowering prices. Greater β will reduce the second-period production cost, which leads to a markdown of prices. The decline of wholesale prices results in a loss in the manufacturer's financial profit and a gain in the retailer's profit. Therefore, the retailer needs to transfer a greater fixed fee to the manufacturer as compensation.

Regarding the comparison of TPT contracts between R-CSR and M-CSR, the following corollary is obtained.

Corollary 5.3.

(i) *With the same* F, *the following hold:* $\pi_{tm}^{r*} > V_{tm}^{m*}$ *and* $\pi_{tr}^{m*} > V_{tr}^{r*}$.

(ii) *For the range of franchise fee, the following hold:* $F_1^r < F_1^m$ *and* $F_2^r < F_2^m$.

Corollary 5.3(i) indicates that given an identical fixed transfer fee, the manufacturer in R-CSR with a TPT contract is more profitable, compared with M-CSR with a TPT contract. As for the retailer, she is better off in M-CSR with a TPT contract. The reason is that the wholesale prices in M-CSR with a TPT contract are lower than those in R-CSR with a TPT contract. Lower wholesale prices will benefit the retailer but impair the manufacturer. Therefore, the retailer prefers to participate in a TPT contract under M-CSR where wholesale prices are lower, and the manufacturer is more willing to take part in a TPT contract under R-CSR where wholesale prices are higher. Corollary 5.3(ii) shows, in contrast to R-CSR with a TPT contract, both the lower bound and the upper bound on the fixed fee are higher in M-CSR with a TPT contract. That is because, for channel coordination, the manufacturer in M-CSR gives up more revenue from the product sales and he needs more compensation from the franchise fee. The retailer in M-CSR greatly benefits from the channel coordination and hence she has greater added profit with which to compensate the manufacturer.

6. Numerical analysis

In this section, numerical examples will be presented to corroborate and supplement the preceding developments. The results of comparisons between different scenarios can be displayed clearly by the numerical analysis. This analysis enables us to understand how θ and β affect each firm's decisions and profitability. The following common values for exogenous parameters are chosen: $a = 40$, $b = 3$, and $c_1 = 8$. In addition, if it is not specifically stated, β is set at 0.15 when we discuss the impacts of θ on optimums, and θ is set at 0.3 when we discuss the impacts of β on optimums.

For a given β, Figure 4a shows the retail prices will decrease as θ increases for all scenarios with CSR. The decrement rate of retail prices in the three CSR scenarios are in the following order: $\partial p_1^{c*}/\partial\theta > \partial p_1^{r*}/\partial\theta > \partial p_1^{m*}/\partial\theta$. The retail price in the centralized scenario is most sensitive to θ. In Figure 4b, for a given θ, the retail prices in all scenarios will decline with greater β. We can observe the decrement rate in the centralized case is the largest again. For the decentralized scenarios, the decrement rate of retail prices is in the following order: $\partial p_1^{r*}/\partial\beta > \partial p_1^{m*}/\partial\beta > \partial p_1^{n*}/\partial\beta$.

Figure 5 illustrates that the wholesale prices under decentralized scenarios have negative relationships with θ and β. From Figure 5, we know that the wholesale price under M-CSR is most sensitive to the change of θ or β. Figure 5b also indicates the wholesale price in R-CSR equals that in N-CSR if there are no cost learning effects, as Proposition 4.2 describes. Combining Figures 4 and 5, we can summarize that among the three decentralzied scenarios, the price decision of the socially concerned firm is most sensitive to the change of θ or β.

Figure 6a illustrates how θ influences the chain-wide pure profit in different scenarios. In each decentralized scenario, the chain-wide pure profit will be better off with higher θ. In the centralized case, the pure profit decreases with the growth of θ. These results are consistent with Corollary 4.6(i). Moreover, from Figure 6a, we observe that the pure profit in the centralized scenario is greater than each decentralized scenario when θ is small, while the pure profit in the centralized scenario is gradually dominated by each decentralized scenario with increasing θ.

Figures 6b and 6c show the impact of β on chain-wide pure profit in different scenarios for a given θ. Under all decentralized scenarios, the chain-wide pure profit always has a positive relationship with β. In the centralized scenario, when θ is sufficiently small (0.3 in Fig. 6b), the pure profit has a positive relationship with β, while a negative relationship with β when θ is sufficiently large (0.65 in Fig. 6c). These results have been explained in Corollary 4.6.

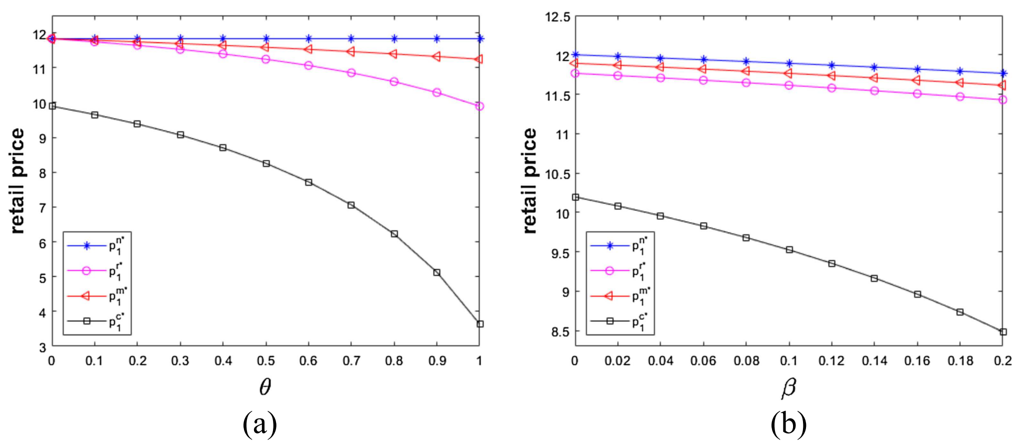


Figure 4. Effects of θ and β on optimal retail prices.

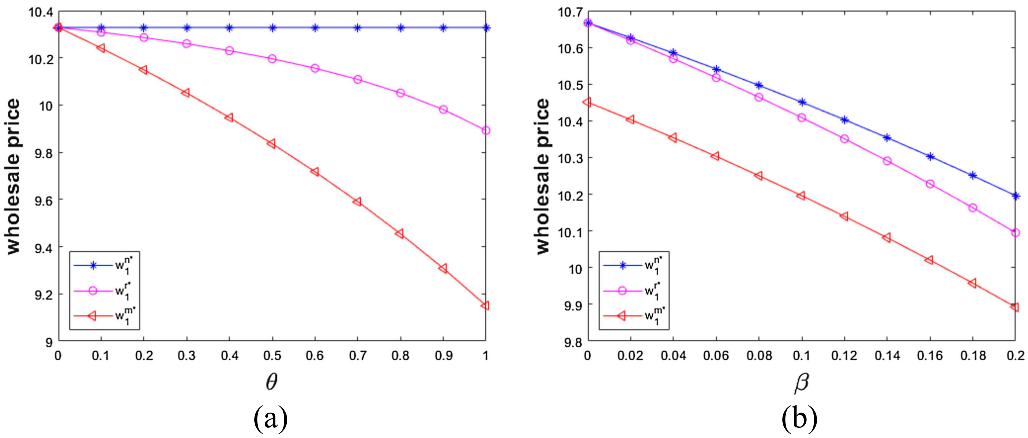


FIGURE 5. Effects of θ and β on optimal wholesale prices.

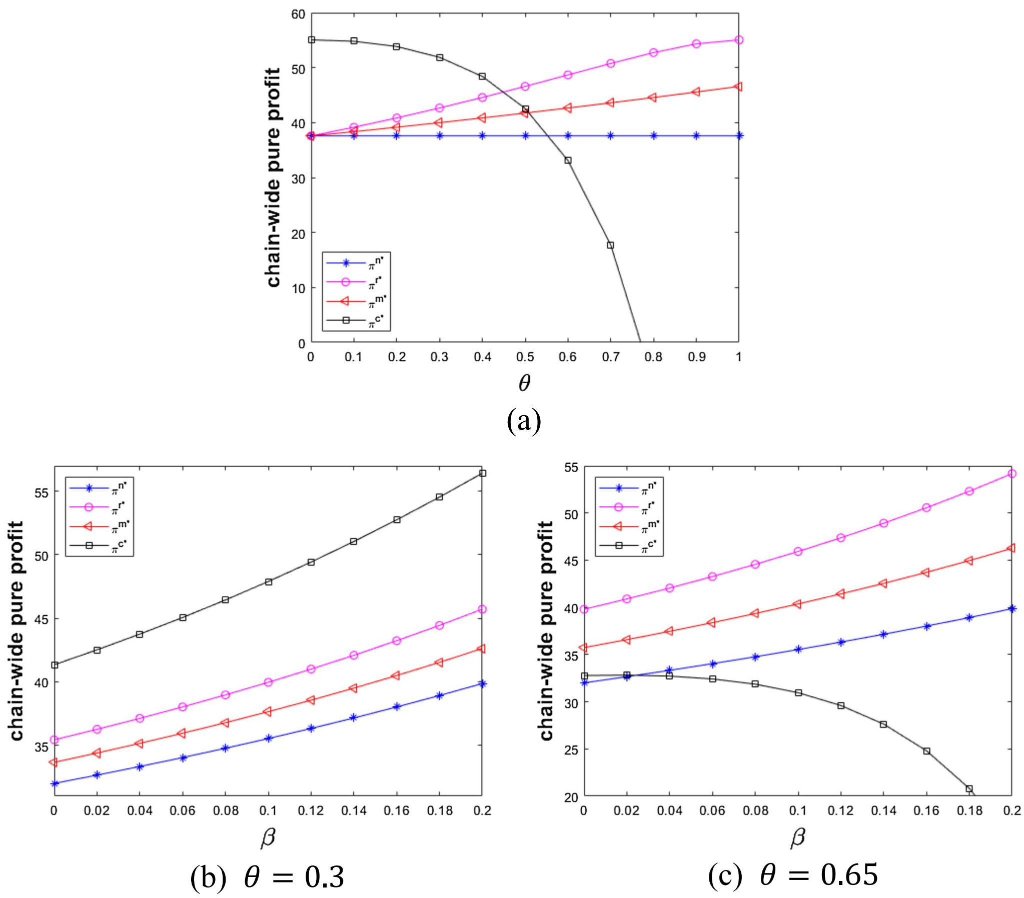
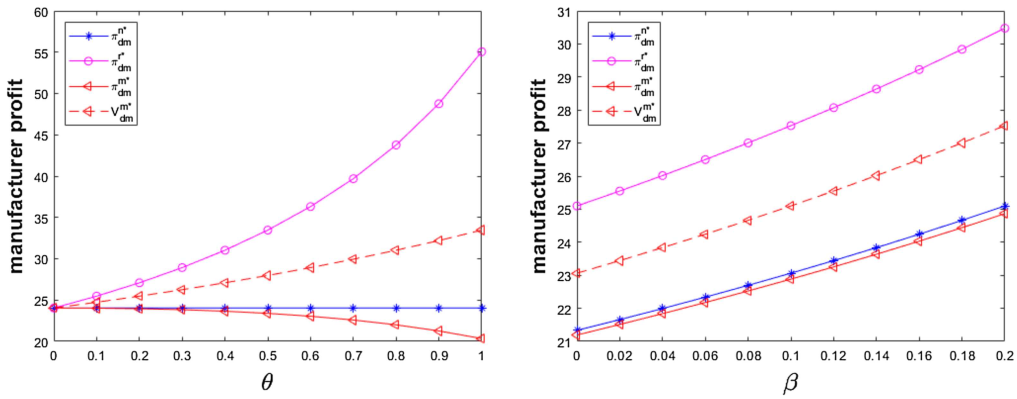
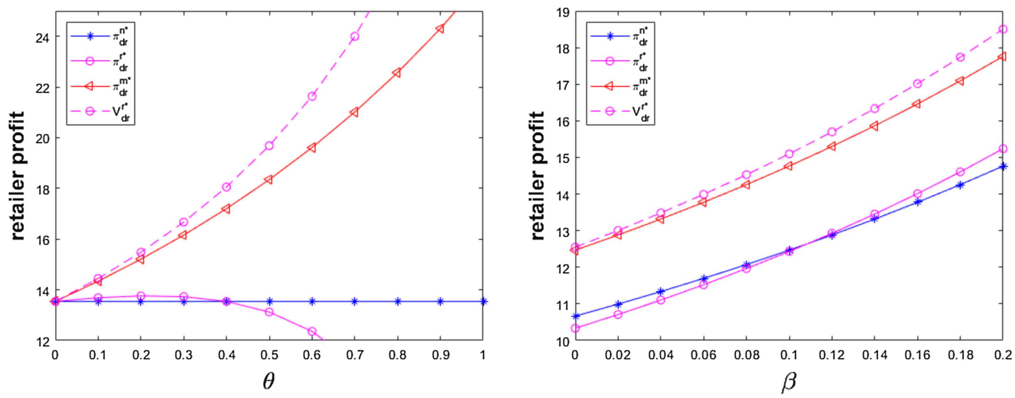


FIGURE 6. Effects of θ and β on chain-wide profits.



(a) (b)

FIGURE 7. Effects of θ and β on the manufacturer's profits.



(a) (b)

FIGURE 8. Effects of θ and β on the retailer's profits.

Figure 7 depicts how θ or β affects the manufacturer's performance in each decentralized scenario. From Figure 7a, we observe that with the increase of θ, the manufacturer's profit in R-CSR will be higher, and in M-CSR the manufacturer's pure profit will decrease and his total profit will increase. Figure 7b illustrates that with increasing β, the total or pure profit of the manufacturer in all decentralized cases will increase.

The impacts of θ and β on the retailer's optimal profits are graphed in Figure 8. In Figure 8a, we find with greater θ, the pure profit of the CSR retailer increases first and then decreases, but her total profit increases all the time. The profit of the retailer in M-CSR becomes better off with greater θ. The increase of β benefits the retailer in all the three decentralized scenarios.

7. EXTENSION

In the above sections, we have assumed the same level of concern of the socially responsible firm for the first period and the second period. In this section, we relax the assumption and analyze the situation in which there are different levels of socially responsible concerns in two different periods. We use θ_1 and θ_2 to indicate the effect of CSR in the first period and the second period, respectively. Using the same method as above, we derive the firms' equilibrium decisions in Centralized, R-CSR, and M-CSR scenarios, respectively (see Tab. C.1). Due to the complexity of the profit expressions at equilibrium, it is complicated to compare the optimal profits in different scenarios. Therefore, we focus on the comparisons of firms' optimal price decisions. And then some results which differ from the main body are obtained. Besides, in this new model setting, since the results when the chain is coordinated by TPT contract are similar to the main body, we omit the discussion about the coordination by TPT contract.

Proposition 7.1. *For optimal retail prices in Centralized, R-CSR and M-CSR scenarios, we have $p_1^{j*} < p_2^{j*}$ if and only if $\theta_1 > \theta_2$, where $j = c,\ r,\ m$. For optimal wholesale prices, we have $w_1^{r*} < w_2^{r*}$ if and only if $\theta_1 < \theta_2$; and $w_1^{m*} < w_2^{m*}$ if and only if $\theta_1 > \theta_2$.*

As can be seen in Proposition 7.1, if the CSR firm is more socially concerned in the first period than that in the second period, the first-period retail price would be lower than the second-period one. The reason behind this is that a higher effect of CSR directly or indirectly induces the retailer or the centralized firm to reduce the retail price, resulting in a higher consumer surplus. Although there is cost reduction in the second period, the impact of CSR on retail prices is greater than the impact of cost reduction on retail prices. Therefore, when the effect of CSR in the first period is stronger than that in the second period, the first-period retail price is lower than the second-period one.

For wholesale prices, when the retailer is socially concerned and she puts more weight on CSR in the second period than in the first period, the first-period retail price is relatively higher, leading to a low first-period demand. In order to enhance the first-period demand and enlarge the degree of cost reduction, the manufacturer would charge the retailer a lower wholesale price in the first period. However, when the retailer puts more weight on CSR in the first period than in the second period, the retailer per se has the motivation to mark down the first-period retail price. The manufacturer does not need to induce her with a lower first-period wholesale price. Hence, the first-period wholesale price is higher than the second-period one in this case. However, under M-CSR, for the manufacturer, CSR plays a greater role than cost learning effects. Thus, when $\theta_1 > \theta_2$, in the first period he would strategically set a lower wholesale price to motivate the retailer to choose a low first-period retail price, and *vice versa*.

Proposition 7.2. *For optimal retail prices in different scenarios, we have $p_i^{n*} > p_i^{m*} > p_i^{r*} > p_i^{c*}$. For optimal wholesale prices, we have $w_i^{n*} > w_i^{r*} > w_i^{m*}$ if and only if $\theta_i > \theta_i'$, otherwise $w_i^{n*} > w_i^{m*} \geq w_i^{r*}$ (θ_i' is given in appendix). What's more, if $\beta = 0$, then we always have $w_i^{n*} = w_i^{r*} > w_i^{m*}$, where $i = 1$ or 2.*

In line with the main body, Proposition 7.2 suggests that the double marginalization is weaker in R-CSR than that in M-CSR. Interestingly, the relationship of wholesale prices in R-CSR and M-CSR is different from that when the effects of CSR are the same over periods. It is intuitive that the wholesale prices in N-CSR are higher than the ones with CSR. When the effects of CSR are strong, the wholesale prices in M-CSR are lower than the ones in R-CSR, similar to the explanation made in Proposition 4.2. Nevertheless, when the effects of CSR are sufficiently weak, the wholesale prices in M-CSR are higher than those in R-CSR. The reason for this difference is that CSR plays a less significant role than the cost learning effects when the effects of CSR are sufficiently weak. The first-period demand in R-CSR is greater than that in M-CSR, therefore, the degree of cost reduction in R-CSR is greater than that in M-CSR. In this condition, the manufacturer in R-CSR can benefit more from the cost reduction than in M-CSR. Coupled with a less significant CSR, the greater cost reduction in R-CSR motivates the manufacturer to charge lower wholesale prices than those in M-CSR. Without cost learning effects, the wholesale prices in R-CSR is always higher than those in M-CSR, which highlights the important role of cost learning effects.

8. Conclusion

In this paper, we consider a two-period Stackelberg game in a socially responsible supply chain where the manufacturer achieves cost reduction due to learning effects. With cost learning effects, we regard the scenario where no firms are engaged in CSR as a benchmark, and investigate a single manufacturer–retailer setup where one of the firms, either the manufacturer or the retailer, is socially concerned. In line with previous literature, we use a share of consumer surplus to specify CSR. Our study explores the implications of CSR on supply chain with cost learning effects and compares the equilibrium results of different scenarios. Moreover, we utilize two-part tariff contracts to coordinate the socially responsible supply chains. The major findings are drawn as follows.

Our analysis proves that from the chain-wide viewpoint, the implementation of CSR is beneficial, and it is more profitable if the retailer (rather than the manufacturer) exhibits CSR since the double marginalization in R-CSR is less severe than in M-CSR. From the perspective of each firm, it is also profitable to exhibit CSR even though the socially concerned firm might have to sacrifice pure profit to optimize total profit. Although CSR and cost learning effects will improve supply chain profitability in each decentralized scenario, these two factors strengthen channel conflict between channel members. The channel conflict can be eliminated by TPT contracts. When a TPT contract coordinates R-CSR supply chain, the wholesale prices are equal to the realized production cost in the second period, which is consistent with the scenario without CSR. When a TPT contract coordinates M-CSR supply chain, however, the wholesale prices are lower than the realized production cost and may even be negative. Interestingly, cost learning effects might impair the pure profit of the coordinated chain if the effect of CSR is sufficiently high.

These findings can provide managerial guidelines for managers. The optimal values we derive in different scenarios will be helpful to manufacturers and retailers to make strategic decisions to optimize their objectives. In our analysis, we discuss the impacts of CSR and cost learning effects, and compare different scenarios, which can help firms develop a better understanding of CSR and cost learning effects. The implementation of CSR is found to benefit the pure profit of the supply chain, which is contrary to the widespread belief that CSR leads to profit loss; Supply chain managers should encourage firms to undertake CSR. Firms are encouraged to choose socially concerned firms as their partners, since this choice will bring them great benefit. Additionally, our results will also enable practitioners to strategize coordination policy for socially responsible supply chains.

Though the proposed model leads to several insightful findings, it has some limitations which could be overcome in future research. Firstly, for analytical simplification, we assume the demand is deterministic and linear in the retail price. Models with stochastic demand functions deserve attention. Secondly, the cost reduction from learning effects is assumed to be linear in the previous production quantity, but other functions might describe the cost learning effects more comprehensively. Thirdly, our study utilizes TPT contracts to coordinate socially responsible supply chains. Other contracts, such as quantity discount and sales-rebate contracts are also worthy of investigation. Finally, extension from two periods to multiple periods or infinite periods also needs further study.

Appendix A. Summary of solutions

A.1. Equilibrium in Centralized scenario

The total profit function of the integrated firm is

$$V^c = (a - bp_1)(p_1 - c_1) + (a - bp_2)(p_2 - c_2) + \frac{\theta (a - bp_1)^2}{2b} + \frac{\theta (a - bp_2)^2}{2b}\cdot \tag{A.1}$$

The Hessian matrix of V^c with respect to (w.r.t.) p_1 and p_2 is given by $\mathrm{H}_1 = \begin{bmatrix} b(\theta-2) & b^2\beta \\ b^2\beta & b(\theta-2)\end{bmatrix}$. Assuming $a - bc_1 > 0$, $c_1 - a\beta > 0$, and $a > c_1$, we have $b\beta < 1$ so $\det[\mathrm{H}_{11}] = b(\theta - 2) < 0$ and $\det[\mathrm{H}_{12}] = b^2(2 - \theta - b\beta)(2 - \theta + b\beta) > 0$. The Hessian H_1 is negative definite. Hence the profit function is jointly concave in p_1 and p_2. By the first-order conditions, we obtain the optimums of the centralized scenario, as summarized in Table 2.

A.2. Equilibrium in N-CSR

By the backward induction approach, we first solve the optimization problem of the retailer whose profit function is given by

$$\pi_{dr}^n = (a - bp_1)(p_1 - w_1) + (a - bp_2)(p_2 - w_2)\,. \tag{A.2}$$

The Hessian matrix of π_{dr}^{n} w.r.t. p_1 and p_2 is $\mathrm{H}_2 = \begin{bmatrix} -2b & 0 \\ 0 & -2b \end{bmatrix}$. The Hessian H_2 is negative definite. The first-order conditions yield $p_1^* = (a + bw_1)/2b$ and $p_2^* = (a + bw_2)/2b$. The manufacturer's profit function in N-CSR is

$$\pi_{dm}^{n} = (a - bp_1)(w_1 - c_1) + (a - bp_2)(w_2 - c_2). \tag{A.3}$$

Substituting the derived prices into equation (A.3) and calculating the Hessian matrix of π_{dm}^{n} w.r.t. w_1 and w_2, we can derive $\mathrm{H}_3 = \begin{bmatrix} -b & b^2\beta/4 \\ b^2\beta/4 & -b \end{bmatrix}$. The following hold: $\det[\mathrm{H}_{31}] = -b < 0$ and $\det[\mathrm{H}_{32}] = b^2(4 - b\beta)(4 + b\beta)/16 > 0$. The Hessian H_3 is negative definite. By the first-order conditions, we obtain w_1^* and w_2^*. Then, substituting them into the price, demand, and profit functions, the optimums in N-CSR are derived, as summarized in Table 2.

A.3. Equilibrium in R-CSR

The objective function of each firm in R-CSR is

$$V_{dr}^{r} = (a - bp_1)(p_1 - w_1) + (a - bp_2)(p_2 - w_2) + \frac{\theta (a - bp_1)^2}{2b} + \frac{\theta (a - bp_2)^2}{2b} \tag{A.4}$$

$$\pi_{dm}^{r} = (a - bp_1)(w_1 - c_1) + (a - bp_2)(w_2 - c_2). \tag{A.5}$$

With the backward induction approach, we first solve the optimization problem of the socially concerned retailer regarding p_1 and p_2. The Hessian matrix of V_{dr}^{r} w.r.t. p_1 and p_2 is $\mathrm{H}_4 = \begin{bmatrix} b(\theta-2) & 0 \\ 0 & b(\theta-2) \end{bmatrix}$. The Hessian H_4 is negative definite. The first-order conditions generate $p_1^* = (a - a\theta + bw_1)/(2b - b\theta)$ and $p_2^* = (a - a\theta + bw_2)/(2b - b\theta)$. Substituting them into equation (A.5) and calculating the Hessian matrix of π_{dm}^{r} w.r.t. w_1 and w_2, we derive $\mathrm{H}_5 = \begin{bmatrix} 2b/(\theta-2) & b^2\beta/(2-\theta)^2 \\ b^2\beta/(2-\theta)^2 & 2b/(\theta-2) \end{bmatrix}$. We have $\det[\mathrm{H}_{51}] = 2b/(\theta - 2) < 0$ and $\det[\mathrm{H}_{52}] = b^2(4 - 2\theta + b\beta)(4 - 2\theta - b\beta)/(2-\theta)^4$. Since $4 - 2\theta - b\beta = (3 - 2\theta) + (1 - b\beta) > 0$ with $0 < \theta < 1$ and $0 < b\beta < 1$, we know $\det[\mathrm{H}_{52}] > 0$. Thus, π_{dm}^{r} is jointly concave in w_1 and w_2. Letting $\partial \pi_{dm}^{r}/\partial w_1 = 0$ and $\partial \pi_{dm}^{r}/\partial w_2 = 0$, we obtain w_1^{r*} and w_2^{r*}. Then substituting them into the price, demand, and profit functions, we get the optimums in R-CSR.

A.4. Equilibrium in M-CSR

The retailer's profit function is written as equation (A.2). The total profit of the CSR manufacturer is

$$V_{dm}^{m} = (a - bp_1)(w_1 - c_1) + (a - bp_2)(w_2 - c_2) + \frac{\theta (a - bp_1)^2}{2b} + \frac{\theta (a - bp_2)^2}{2b}. \tag{A.6}$$

With the backward induction approach, the optimization problem of the retailer w.r.t.p_1 and p_2 is analyzed first. The Hessian matrix of π_{dr}^{m} w.r.t. p_1 and p_2 is $\mathrm{H}_6 = \begin{bmatrix} -2b & 0 \\ 0 & -2b \end{bmatrix}$. The Hessian H_6 is negative definite. The equations $p_1^* = (a + bw_1)/2b$ and $p_2^* = (a + bw_2)/2b$ are derived from the first-order conditions. Substituting them into equation (A.6) and calculating the Hessian matrix of V_{dm}^{m} with respect to w_1 and w_2, we derive the Hessian matrix $\mathrm{H}_7 = \begin{bmatrix} b(\theta-4)/4 & b^2\beta/4 \\ b^2\beta/4 & b(\theta-4)/4 \end{bmatrix}$, $\det[\mathrm{H}_{71}] = b(\theta - 4)/4 < 0$, and $\det[\mathrm{H}_{72}] = b^2(4 - \theta + b\beta)(4 - \theta - b\beta)/16$. Because $4 - \theta - b\beta = 2 + (1 - \theta) + (1 - b\beta) > 0$, we know $\det[\mathrm{H}_{72}] > 0$. The Hessian H_7 is negative definite. We obtain w_1^{m*} and w_2^{m*} from the first-order conditions and the other optimums in M-CSR, as Table 2 shows.

Appendix B. Proofs

B.1. Proof of Proposition 4.1.

Since $4 - b\beta - 2\theta = 1 + (1 - b\beta) + 2(1 - \theta) > 0$ and $2 - b\beta - \theta = (1 - b\beta) + (1 - \theta) > 0$, the following relationships hold: $p_1^{r*} - w_1^{r*} = (1 - \theta)(a - bc_1)/(b(4 - b\beta - 2\theta)) > 0$, $w_1^{r*} - c_1 = (2 - b\beta - \theta)(a - bc_1)/(b(4 - b\beta - 2\theta)) >$

0, $p_1^{m*} - w_1^{m*} = (a - bc_1)/(b(4 - b\beta - \theta)) > 0$, $w_1^{m*} - c_1 = (2 - b\beta - \theta)(a - bc_1)/(b(4 - b\beta - \theta)) > 0$, and $p_2^{c*} - c_2^c = (1 - \theta)(a - bc_1)/(b(2 - b\beta - \theta)) > 0$. Note that $p_1^{c*} - c_1 = (1 - b\beta - \theta)(a - bc_1)/(b(2 - b\beta - \theta))$. If $b\beta + \theta > 1$, then $1 - b\beta - \theta < 0$, and otherwise $1 - b\beta - \theta \geq 0$. Thus, if $b\beta + \theta > 1$, then $p_1^{c*} - c_1 < 0$, and otherwise $p_1^{c*} - c_1 \geq 0$. Q.E.D.

B.2. Proof of Proposition 4.2.

Considering the comparisons of optimal retail prices among the scenarios, we have $p_1^{n*} - p_1^{m*} = \theta(a - bc_1)/(b(4 - b\beta)(4 - b\beta - \theta))$ and $p_1^{m*} - p_1^{r*} = \theta(a - bc_1)/(b(4 - b\beta - \theta)(4 - b\beta - 2\theta))$. In the proof of Proposition 4.1, we have proved $4 - b\beta - 2\theta > 0$. Combining with $a - bc_1 > 0$, since the denominators and the numerators are both positive, we have $p_1^{n*} - p_1^{m*} > 0$ and $p_1^{m*} - p_1^{r*} > 0$. Hence, $p_1^{n*} > p_1^{m*} > p_1^{r*}$.

Considering the comparisons of optimal wholesale prices, note that $w_1^{n*} - w_1^{r*} = \beta\theta(a - bc_1)/((4 - b\beta)(4 - b\beta - 2\theta))$ and $w_1^{r*} - w_1^{m*} = \theta(2 - b\beta - \theta)(a - bc_1)/(b(4 - b\beta - \theta)(4 - b\beta - 2\theta))$. The denominators $(4 - b\beta)(4 - b\beta - 2\theta)$ and $b(4 - b\beta)(4 - b\beta - 2\theta)$ are both positive, and since $2 - b\beta - \theta > 0$, the numerators are positive as well. Therefore, $w_1^{n*} - w_1^{r*} > 0$ and $w_1^{r*} - w_1^{m*} > 0$, which implies $w_1^{n*} > w_1^{r*} > w_1^{m*}$. Q.E.D.

B.3. Proof of Proposition 4.3.

As for the comparison of the chain-wide profit between R-CSR and M-CSR, we have $\pi^{r*} - \pi^{m*} = \theta(16 - 2\theta(9 - 2\theta) - b\beta(4 - 3\theta))(a - bc_1)^2/(b(4 - b\beta - \theta)^2(4 - b\beta - 2\theta)^2)$. Whether $\pi^{r*} - \pi^{m*}$ is positive or negative depends on $16 - 2\theta(9 - 2\theta) - b\beta(4 - 3\theta)$. Because $\partial(16 - 2\theta(9 - 2\theta) - b\beta(4 - 3\theta))/\partial\theta = -18 + 3b\beta + 8\theta = -7 - 3(1 - b\beta) - 8(1 - \theta) < 0$, a negative relationship between $16 - 2\theta(9 - 2\theta) - b\beta(4 - 3\theta)$ and θ holds. When $\theta = 1$, $16 - 2\theta(9 - 2\theta) - b\beta(4 - 3\theta)$ has the minimal value, which is $16 - 2(9 - 2) - b\beta(4 - 3) = 2 - b\beta > 0$. Therefore, when $\theta \in (0, 1)$, we have $16 - 2\theta(9 - 2\theta) - b\beta(4 - 3\theta) > 2 - b\beta > 0$ and $\pi^{r*} - \pi^{m*} > 0$. For the comparison of the chain-wide profit between M-CSR and N-CSR, note that $\pi^{m*} - \pi^{n*} = (16 - b\beta(4 - \theta) - 6\theta)\theta(a - bc_1)^2/(b(4 - b\beta)^2(4 - b\beta - \theta)^2)$. Since $16 - b\beta(4 - \theta) - 6\theta = 6 + 4(1 - b\beta) + 6(1 - \theta) + b\beta\theta > 0$, we obtain $\pi^{m*} - \pi^{n*} > 0$. Note that $\pi^{r*} - V^{m*} = \theta(b\beta(4 - b\beta - \theta) - 2\theta)(a - bc_1)^2/(b(4 - b\beta - \theta)^2(4 - b\beta - 2\theta)^2)$. Letting $b\beta(4 - b\beta - \theta) - 2\theta = 0$, we get $\theta = b\beta(4 - b\beta)/(2 + b\beta)$. The relation $\partial(b\beta(4 - b\beta - \theta) - 2\theta)/\partial\theta = -(2 + b\beta) < 0$ holds, which implies $b\beta(4 - b\beta - \theta) - 2\theta$ is decreasing in θ. Hence, if $\theta \leq b\beta(4 - b\beta)/(2 + b\beta)$, then $b\beta(4 - b\beta - \theta) - 2\theta \geq 0$, leading to $\pi^{r*} - V^{m*} \geq 0$, otherwise $b\beta(4 - b\beta - \theta) - 2\theta < 0$ and $\pi^{r*} - V^{m*} < 0$. Through the above analysis, we can derive $\pi^{r*} > \pi^{m*} > \pi^{n*}$. In addition to π^{m*}, V^{m*} includes a share of consumer surplus, so $V^{m*} > \pi^{m*}$. In the same way, $V^{r*} > \pi^{r*}$. Thus, we have $V^{r*} > \max(\pi^{r*}, V^{m*}) > \pi^{m*} > \pi^{n*}$. Q.E.D.

B.4. Proof of Proposition 4.4.

In the proof of Proposition 4.1, we have proved $4 - b\beta - 2\theta > 0$, so the following hold: $\pi_{dm}^{r*} - V_{dm}^{m*} = \theta(a - bc_1)^2/(b(4 - b\beta - \theta)(4 - b\beta - 2\theta)) > 0$, $V_{dm}^{m*} - \pi_{dm}^{n*} = \theta(a - bc_1)^2/(b(4 - b\beta)(4 - b\beta - \theta)) > 0$, and $\pi_{dm}^{n*} - \pi_{dm}^{m*} = \theta^2(a - bc_1)^2/(b(4 - b\beta)(4 - b\beta - \theta)^2) > 0$. Consequently, $\pi_{dm}^{r*} > V_{dm}^{m*} > \pi_{dm}^{n*} > \pi_{dm}^{m*}$.

Note that $V_{dr}^{r*} - \pi_{dr}^{m*} = \theta\left(2b\beta(2 - \theta) + (2 - \theta)\theta - b^2\beta^2\right)(a - bc_1)^2/(b(4 - b\beta - \theta)^2(4 - b\beta - 2\theta)^2)$ and the sign of $V_{dr}^{r*} - \pi_{dr}^{m*}$ depends on $2b\beta(2 - \theta) + (2 - \theta)\theta - b^2\beta^2$. There is $2b\beta(2 - \theta) + (2 - \theta)\theta - b^2\beta^2 = b\beta(4 - 2\theta - b\beta) + (2 - \theta)\theta = b\beta(2(1 - \theta) + (2 - b\beta)) + (2 - \theta)\theta > 0$, so $V_{dr}^{r*} - \pi_{dr}^{m*} > 0$. Note that $\pi_{dr}^{m*} - \pi_{dr}^{r*} = 2\theta\left(8 + b^2\beta^2 - 2b\beta(3 - \theta) - (5 - \theta)\theta\right)(a - bc_1)^2/(b(4 - b\beta - \theta)^2(4 - b\beta - 2\theta)^2)$. Because $8 + b^2\beta^2 - 2b\beta(3 - \theta) - (5 - \theta)\theta = (2 - b\beta)^2 + (1 - \theta)(2(1 - b\beta) + (2 - \theta)) > 0$, we have $\pi_{dr}^{m*} - \pi_{dr}^{r*} > 0$. $\pi_{dr}^{m*} - \pi_{dr}^{n*} = 2\theta(8 - 2b\beta - \theta)(a - bc_1)^2/(b(4 - b\beta)^2(4 - b\beta - \theta)^2) > 0$ since $8 - 2b\beta - \theta > 0$. Through the above analyses, we have $V_{dr}^{r*} > \pi_{dr}^{m*} > \max(\pi_{dr}^{r*}, \pi_{dr}^{n*})$. For π_{dr}^{r*} and π_{dr}^{n*}, there is $\pi_{dr}^{r*} - \pi_{dr}^{n*} = 2\theta(b\beta(4 - b\beta) - 4\theta)(a - bc_1)^2/(b(4 - b\beta)^2(4 - b\beta - 2\theta)^2)$. The sign of $\pi_{dr}^{r*} - \pi_{dr}^{n*}$ depends on $b\beta(4 - b\beta) - 4\theta$. We know $\partial(b\beta(4 - b\beta) - 4\theta)/\partial\theta = -4 < 0$, so $b\beta(4 - b\beta) - 4\theta$ is negatively related to θ. Then letting $b\beta(4 - b\beta) - 4\theta = 0$, we get that the solution for θ is $b\beta(4 - b\beta)/4$. Therefore, if $\theta \leq b\beta(4 - b\beta)/4$, we know $b\beta(4 - b\beta) - 4\theta \geq 0$ and $\pi_{dr}^{r*} - \pi_{dr}^{n*} \geq 0$, otherwise $\pi_{dr}^{r*} - \pi_{dr}^{n*} < 0$. Q.E.D.

B.5. Proof of Corollary 4.5.

Comparing the optimal retail prices in the decentralized scenarios with the ones in the centralized case, and differentiating the price differences with θ and β, we have the following: $\Delta p^r = p_1^{r*} - p_1^{c*} = (2-\theta)(a-bc_1)/(b(2-b\beta-\theta)(4-b\beta-2\theta)) > 0$, $\partial\Delta p^r/\partial\theta = (2(2-\theta)^2 - b^2\beta^2)(a-bc_1)/(b(2-b\beta-\theta)^2(4-b\beta-2\theta)^2)$, and $\partial\Delta p^r/\partial\beta = (2-\theta)(6-2b\beta-3\theta)(a-bc_1)/((2-b\beta-\theta)^2(4-b\beta-2\theta)^2)$. Since $2(2-\theta)^2 - b^2\beta^2 = (2-\theta)^2 + (2-\theta-b\beta)(2-\theta+b\beta) > 0$, we know $\partial\Delta p^r/\partial\theta > 0$. Since $6-2b\beta-3\theta = 1+2(1-b\beta)+3(1-\theta) > 0$, we have $\partial\Delta p^r/\partial\beta > 0$. In M-CSR, we have $\Delta p^m = p_1^{m*} - p_1^{c*} = 2(a-bc_1)/(b(4-b\beta-\theta)(2-b\beta-\theta)) > 0$, $\partial\Delta p^m/\partial\theta = 4(3-b\beta-\theta)(a-bc_1)/(b(4-b\beta-\theta)^2(2-b\beta-\theta)^2)$, and $\partial\Delta p^m/\partial\beta = 4(3-b\beta-\theta)(a-bc_1)/((4-b\beta-\theta)^2(2-b\beta-\theta)^2)$. Note that $3-b\beta-\theta = 1+(1-b\beta)+(1-\theta) > 0$, therefore $\partial\Delta p^m/\partial\theta > 0$ and $\partial\Delta p^m/\partial\beta > 0$. Q.E.D.

B.6. Proof of Corollary 4.6.

Differentiating the chain-wide pure profits w.r.t. θ and β, we obtain: $\partial\pi^{r*}/\partial\theta = 8(1-\theta)(a-bc_1)^2/(b(4-b\beta-2\theta)^3) > 0$, $\partial\pi^{m*}/\partial\theta = 2(2-\theta)(a-bc_1)^2/(b(4-b\beta-\theta)^3) > 0$, and $\partial\pi^{c*}/\partial\theta = -2\theta(a-bc_1)^2/(b(2-b\beta-\theta)^3) < 0$. We have $\partial\pi^{r*}/\partial\beta = (8-b\beta-6\theta)(a-bc_1)^2/((4-b\beta-2\theta)^3)$ and $8-b\beta-6\theta = (2-b\beta)+6(1-\theta) > 0$, so $\partial\pi^{r*}/\partial\beta > 0$. There are $\partial\pi^{m*}/\partial\beta = (8-b\beta-3\theta)(a-bc_1)^2/((4-b\beta-\theta)^3) > 0$ and $\partial\pi^{n*}/\partial\beta = (8-b\beta)(a-bc_1)^2/((4-b\beta)^3) > 0$. Note that $\partial\pi^{c*}/\partial\beta = (2-b\beta-3\theta)(a-bc_1)^2/((2-b\beta-\theta)^3)$. The sign of $\partial\pi^{c*}/\partial\beta$ depends on $2-b\beta-3\theta$. If $\theta < (2-b\beta)/3$, then $2-b\beta-3\theta > 0$ and $\partial\pi^{c*}/\partial\beta > 0$, otherwise $2-b\beta-3\theta \le 0$ and $\partial\pi^{c*}/\partial\beta \le 0$. Q.E.D.

B.7. Proof of Corollary 4.7.

Differentiating the pure profit of the CSR firm w.r.t. θ, we derive $\partial\pi_{dm}^{m*}/\partial\theta = -2\theta(a-bc_1)^2/(b(4-b\beta-\theta)^3) < 0$ and $\partial\pi_{dr}^{r*}/\partial\theta = 2(b\beta-2\theta)(a-bc_1)^2/(b(4-b\beta-2\theta)^3)$. If $\theta < b\beta/2$, then $b\beta-2\theta > 0$ and $\partial\pi_{dr}^{r*}/\partial\theta > 0$, otherwise $b\beta-2\theta \le 0$ and $\partial\pi_{dr}^{r*}/\partial\theta \le 0$. Q.E.D.

B.8. Proof of Proposition 5.1.

The solution process of optimums under a TPT contract has been described in Section 5. Here we omit it.

(i) To ensure that both channel members voluntarily participate in the contract, the following need to be satisfied: $\pi_{tm}^{r*} - \pi_{dm}^{r*} = -(2-\theta)^2(a-bc_1)^2/(b(2-b\beta-\theta)^2(4-b\beta-2\theta)) + F \ge 0$ and $V_{tr}^{r*} - V_{dr}^{r*} = (2-\theta)^2(6-2b\beta-3\theta)(a-bc_1)^2/(b(2-b\beta-\theta)^2(4-b\beta-2\theta)^2) - F \ge 0$. Then we get the constraints on F in R-CSR with a TPT contract: $(2-\theta)^2(a-bc_1)^2/(b(2-b\beta-\theta)^2(4-b\beta-2\theta)) \le F \le (2-\theta)^2(6-2b\beta-3\theta)(a-bc_1)^2/(b(2-b\beta-\theta)^2(4-b\beta-2\theta)^2)$.

(ii) Similarly, it is necessary to guarantee that $\pi_{tr}^{m*} - \pi_{dr}^{m*} = 8(3-b\beta-\theta)(a-bc_1)^2/(b(4-b\beta-\theta)^2(2-b\beta-\theta)^2) - F \ge 0$ and $V_{tm}^{m*} - V_{dm}^{m*} = -4(a-bc_1)^2/(b(4-b\beta-\theta)(2-b\beta-\theta)^2) + F \ge 0$ hold. Then we obtain these constraints on F in M-CSR with a TPT contract: $4(a-bc_1)^2/(b(4-b\beta-\theta)(2-b\beta-\theta)^2) \le F \le 8(3-b\beta-\theta)(a-bc_1)^2/(b(4-b\beta-\theta)^2(2-b\beta-\theta)^2$. Q.E.D.

B.9. Proof of Corollary 5.2.

(i) Comparing the wholesale price with the realized cost in the second period, we have $w_{t1}^{r*} - c_2^c = 0$ and $w_{t1}^{m*} - c_2^c = -\theta(a-bc_1)/(b(2-b\beta-\theta)) < 0$.

(ii) Considering the sensitivity analyses of w regarding θ and β, the following hold: $\partial w_{t1}^{r*}/\partial\theta = -\beta(a-bc_1)/((2-b\beta-\theta)^2) < 0$, $\partial w_{t1}^{m*}/\partial\theta = -2(a-bc_1)/(b(2-b\beta-\theta)^2) < 0$, $\partial w_{t1}^{r*}/\partial\beta = -(2-\theta)(a-bc_1)/(2-b\beta-\theta)^2 < 0$, and $\partial w_{t1}^{m*}/\partial\beta = -2(a-bc_1)/((2-b\beta-\theta)^2) < 0$.

Considering the bounds on F, note that $\partial F_1^r/\partial\theta = 2(b\beta(2-\theta-b\beta)+(2-\theta)^2)(2-\theta)(a-bc_1)^2/(b(2-b\beta-\theta)^3(4-b\beta-2\theta)^2) > 0$ and $\partial F_1^m/\partial\theta = 4(10-3b\beta-3\theta)(a-bc_1)^2/(b(4-b\beta-\theta)^2(2-b\beta-\theta)^3) > 0$. We have $\partial F_2^r/\partial\theta = (4b^3\beta^3 - 9b^2\beta^2(2-\theta) + b\beta(2-\theta)^2 + 6(2-\theta)^3)(2-\theta)(a-bc_1)^2/(b(2-b\beta-\theta)^3(4-b\beta-2\theta)^3)$. Whether $\partial F_2^r/\partial\theta$ is negative or positive depends on $4b^3\beta^3 - 9b^2\beta^2(2-\theta) + b\beta(2-\theta)^2 + 6(2-\theta)^3$. There exists $4b^3\beta^3 -$

$9b^2\beta^2(2-\theta)+b\beta(2-\theta)^2+6(2-\theta)^3=(2-\theta)^3+5(2-\theta)(2-b\beta-\theta)(2+b\beta-\theta)+b\beta(2-2b\beta-\theta)^2>0$, so $\partial F_2^r/\partial\theta>0$. Because $\left(28+3b^2\beta^2-6b\beta(3-\theta)-3(6-\theta)\theta\right)=3(3-b\beta)((1-b\beta)+2(1-\theta))+1+3\theta^2>0$, we have $\partial F_2^m/\partial\theta=8(28+3b^2\beta^2-6b\beta(3-\theta)-3(6-\theta)\theta)(a-bc_1)^2/(b(4-b\beta-\theta)^3(2-b\beta-\theta)^3)>0$. Since $5(2-\theta)-3b\beta=5(1-\theta)+3(1-b\beta)+2>0$, we have $\partial F_1^r/\partial\beta=(5(2-\theta)-3b\beta)(2-\theta)^2(a-bc_1)^2/((2-b\beta-\theta)^3(4-b\beta-2\theta)^2)>0$. Since $\partial F_1^m/\partial\beta=4(10-3b\beta-3\theta)(a-bc_1)^2/((4-b\beta-\theta)^2(2-b\beta-\theta)^3)$ and $10-3b\beta-3\theta=4+3(1-\theta)+3(1-b\beta)>0$, we derive $\partial F_1^m/\partial\beta>0$. There is $\partial F_2^r/\partial\beta=2(3b^2\beta^2-9b\beta(2-\theta)+7(2-\theta)^2)(2-\theta)^2(a-bc_1)^2/((2-b\beta-\theta)^3(4-b\beta-2\theta)^3)$. Since $3b^2\beta^2-9b\beta(2-\theta)+7(2-\theta)^2=3(2-\theta-b\beta)^2+(2-\theta)(1+4(1-\theta)+3(1-b\beta))>0$, we obtain $\partial F_2^r/\partial\beta>0$. We have already proved $28+3b^2\beta^2-6b\beta(3-\theta)-3(6-\theta)\theta>0$, so $\partial F_2^m/\partial\beta=8(28+3b^2\beta^2-6b\beta(3-\theta)-3(6-\theta)\theta)(a-bc_1)^2/((4-b\beta-\theta)^3(2-b\beta-\theta)^3)>0$. Q.E.D.

B.10. Proof of Corollary 5.3.

(i) Considering a given F, $\pi_{tm}^{r*}-V_{tm}^{m*}=\theta(a-bc_1)^2/(b(2-b\beta-\theta)^2)>0$ and $\pi_{tr}^{m*}-V_{tr}^{r*}=\theta(a-bc_1)^2/(b(2-b\beta-\theta)^2)>0$.

(ii) For the comparisons of the bounds of F, note that $F_1^r-F_1^m=-((6-\theta)(2-\theta)-b\beta(4-\theta))\theta(a-bc_1)^2/(b(4-b\beta-\theta)(2-b\beta-\theta)^2(4-b\beta-2\theta))$. Since $(6-\theta)(2-\theta)-b\beta(4-\theta)>5\times1-4=1>0$, we have $F_1^r-F_1^m<0$. Considering the upper bound on F, we have $F_2^r-F_2^m=\theta((2b^3\beta^3(4-\theta)+4b\beta(6-\theta)(2-\theta)(5-2\theta)-(2-\theta)^2(64-3(10-\theta)\theta)-b^2\beta^2(76-\theta(50-7\theta))))(a-bc_1)^2/(b(4-b\beta-\theta)^2(2-b\beta-\theta)^2(4-b\beta-2\theta)^2)$. The sign of $F_2^r-F_2^m$ depends on $(2b^3\beta^3(4-\theta)+4b\beta(6-\theta)(2-\theta)(5-2\theta)-(2-\theta)^2(64-3(10-\theta)\theta)-b^2\beta^2(76-\theta(50-7\theta)))$, which we denote as g. We have$\partial g/\partial\theta=2(-b^3\beta^3+b^2\beta^2(25-7\theta)-4b\beta(32-3(7-\theta)\theta)+(2-\theta)(94-51\theta+6\theta^2))$, which we denote as h. Then $\partial h/\partial\theta=-2(196+7b^2\beta^2+18(-7+\theta)\theta+12b\beta(-7+2\theta))$, which we denote as k. Since $\partial k/\partial\theta=12(21-4b\beta-6\theta)>0$, we know k is increasing in θ. When $\theta=1$, we can derive the maximum of k, this is, $k_{\max}=-2\left(88-60b\beta+7b^2\beta^2\right)<0$, therefore, $k<0$ and $\partial h/\partial\theta<0$ so h is decreasing in θ. When $\theta=1$, we can derive the minimum of h, namely $h_{\min}=98-2b\beta(14-b\beta)(4-b\beta)$. Because $\partial(h_{\min})/\partial(b\beta)=-112+72b\beta-6b^2\beta^2=-40-72(1-b\beta)-6b^2\beta^2<0$, when $b\beta=1$, we derive $(h_{\min})_{\min}=20>0$ and $h_{\min}>0$, and moreover $\partial g/\partial\theta=h>h_{\min}>0$. Hence, g is increasing in θ. When $\theta=1$, we derive the maximum of g, namely $g_{\max}=-37+3b\beta(20-b\beta(11-2b\beta))$. Note that $\partial(g_{\max})/\partial(b\beta)=6(2-b\beta)(5-3b\beta)>0$. Therefore, when $b\beta=1$, we derive the maximum of $g_{\max}$, namely $(g_{\max})_{\max}=-4<0$. Then we have $g<0$ and $F_2^r-F_2^m<0$. Q.E.D.

Appendix C. Proofs of extension

Because the analytical process when the effects of CSR over two periods are different is similar to the main body, we omit the solution process. If required, we can provide. The firms' equilibrium decisions in Centralized, R-CSR and M-CSR scenarios are exhibited in Table C.1.

C.1. Proof of Proposition 7.1.

For optimal retail prices, we have $p_1^{c*}-p_2^{c*}=(a-bc_1)(\theta_2-\theta_1)/(b\left(4-b^2\beta^2-\theta_1(2-\theta_2)-2\theta_2\right))$, $p_1^{r*}-p_2^{r*}=2(a-bc_1)(\theta_2-\theta_1)/(b(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2))$, and $p_1^{m*}-p_2^{m*}=(a-bc_1)(\theta_2-\theta_1)/(b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2))$. Since $4-b^2\beta^2-\theta_1(2-\theta_2)-2\theta_2=(2-\theta_1)(2-\theta_2)-b^2\beta^2>0$, $16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2=4(2-\theta_1)(2-\theta_2)-b^2\beta^2>0$, and $16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2=(4-\theta_1)(4-\theta_2)-b^2\beta^2>0$, the sign of $p_1^{j*}-p_2^{j*}$ depends on $\theta_2-\theta_1$. If $\theta_1>\theta_2$, then $p_1^{j*}<p_2^{j*}$, otherwise $p_1^{j*}\geq p_2^{j*}$.

For optimal wholesale prices, note that $w_1^{r*}-w_2^{r*}=\beta(a-bc_1)(\theta_1-\theta_2)/(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2)$ and $w_1^{m*}-w_2^{m*}=2(a-bc_1)(\theta_2-\theta_1)/(b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2))$. If $\theta_1>\theta_2$, then $w_1^{r*}>w_2^{r*}$ and $w_1^{m*}<w_2^{m*}$, otherwise $w_1^{r*}\leq w_2^{r*}$ and $w_1^{m*}\geq w_2^{m*}$. Q.E.D.

C.2. Proof of Proposition 7.2.

With the help of Mathematica, we can derive $p_1^{n*}-p_1^{m*}=(a-bc_1)(\theta_1(4-\theta_2)+b\beta\theta_2)/(b(4-b\beta)(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2))>0, p_1^{m*}-p_1^{r*}=(a-bc_1)(4(4+b\beta)\theta_1+(4+b\beta)(b\beta-3\theta_1)\theta_2+$

TABLE C.1. The optimal solutions with different levels of CSR over two periods.

	Centralized	R-CSR	M-CSR
p_1^{j*}	$\frac{bc_1(2+b\beta-\theta_2)+a(2-b\beta-b^2\beta^2-\theta_1(2-\theta_2)-\theta_2)}{b(4-b^2\beta^2-\theta_1(2-\theta_2)-2\theta_2)}$	$\frac{bc_1(4+b\beta-2\theta_2)+a((3-b\beta)(4+b\beta)-4\theta_1(2-\theta_2)-6\theta_2)}{b(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2)}$	$\frac{bc_1(4+b\beta-\theta_2)+a((3-b\beta)(4+b\beta)-\theta_1(4-\theta_2)-3\theta_2)}{b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2)}$
p_2^{j*}	$\frac{bc_1(2+b\beta-\theta_1)+a(2-b\beta-b^2\beta^2-\theta_1-(2-\theta_1)\theta_2)}{b(4-b^2\beta^2-\theta_1(2-\theta_2)-2\theta_2)}$	$\frac{bc_1(4+b\beta-2\theta_1)+a((3-b\beta)(4+b\beta)-\theta_1(6-4\theta_2)-8\theta_2)}{b(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2)}$	$\frac{bc_1(4+b\beta-\theta_1)+a((3-b\beta)(4+b\beta)-\theta_1(3-\theta_2)-4\theta_2)}{b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2)}$
w_1^{j*}	Null	$\frac{bc_1(2-\theta_1)(4+b\beta-2\theta_2)+a((2-b\beta)(4+b\beta)-4\theta_2-\theta_1(4-b\beta-2\theta_2))}{b(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2)}$	$\frac{2bc_1(4+b\beta-\theta_2)+a((2-b\beta)(4+b\beta)-\theta_1(4-\theta_2)-2\theta_2)}{b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2)}$
w_2^{j*}	Null	$\frac{bc_1(4+b\beta-2\theta_1)(2-\theta_2)+a((2-b\beta)(4+b\beta)-2\theta_1(2-\theta_2)-(4-b\beta)\theta_2)}{b(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2)}$	$\frac{2bc_1(4+b\beta-\theta_1)+a((2-b\beta)(4+b\beta)-\theta_1(2-\theta_2)-4\theta_2)}{b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2)}$

$2\theta_1\theta_2^2)/(b(16 - b^2\beta^2 - \theta_1(4-\theta_2) - 4\theta_2)(16 - b^2\beta^2 - 4\theta_1(2-\theta_2) - 8\theta_2)) > 0$, and $p_1^{r*} - p_1^{c*} = (a-bc_1)(2-\theta_2)((2+b\beta)(4+b\beta) - 4\theta_2 - \theta_1(4+3b\beta-2\theta_2))/(b\left(4-b^2\beta^2-\theta_1(2-\theta_2)-2\theta_2\right)(16 - b^2\beta^2 - 4\theta_1(2-\theta_2) - 8\theta_2)) > 0$. So we have $p_1^{n*} > p_1^{m*} > p_1^{r*} > p_1^{c*}$. By the same way, we can derive $p_2^{n*} - p_2^{m*} = (a-bc_1)(b\beta\theta_1 - (4-\theta_1)\theta_2)/(b(4-b\beta)\left(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2\right)) > 0$, $p_2^{m*} - p_2^{r*} = (a-bc_1)\left((4+b\beta)\theta_1(b\beta-3\theta_2) + 4(4+b\beta)\theta_2 + 2\theta_1^2\theta_2\right)/(b\left(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2\right)(16-b^2\beta^2 - 4\theta_1(2-\theta_2)-8\theta_2)) > 0$, and $p_2^{r*}-p_2^{c*} = (a-bc_1)(2-\theta_1)((2+b\beta)(4+b\beta) - 2\theta_1(2-\theta_2) - (4+3b\beta)\theta_2)/(b(4-b^2\beta^2 - \theta_1(2-\theta_2)-2\theta_2)(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2)) > 0$. Hence, we have $p_2^{n*} > p_2^{m*} > p_2^{r*} > p_2^{c*}$.

Note that $w_1^{n*} - w_1^{r*} = \beta(a-bc_1)(b\beta\theta_1 + 2(2-\theta_1)\theta_2)/((4-b\beta)\left(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2\right)) > 0$, $w_1^{n*} - w_1^{m*} = 2(a-bc_1)(\theta_1(4-\theta_2)+b\beta\theta_2)/(b(4-b\beta)\left(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2\right)) > 0$, and $w_1^{r*} - w_1^{m*} = (a-bc_1)(\theta_1((4+b\beta)(8-b^2\beta^2) - 2(3-b\beta)(4+b\beta)\theta_2 + 4\theta_2^2) - \theta_1^2(4+b\beta-2\theta_2)(4-\theta_2) - 2b\beta(4+b\beta)\theta_2)/(b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2)(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2))$. Through Mathematica, we find that there exists θ_1' and if $\theta_1 > \theta_1'$, then $w_1^{r*} > w_1^{m*}$, otherwise $w_1^{r*} \le w_1^{m*}$, where

$$\theta_1' = \frac{(4+b\beta)(8-b^2\beta^2)-2\theta_2((3-b\beta)(4+b\beta)+2\theta_2)-\sqrt{(4+b\beta)^2(b^2\beta^2-8)^2-4\theta_2((4+b\beta)^2(24-b^2\beta^2(3-b\beta))-\theta_2((4+b\beta)(52+b\beta(9-b\beta(2-b\beta)))-4\theta_2(3(4+b\beta)-\theta_2)))}}{(4+b\beta-2\theta_2)(4-\theta_2)}.$$

We have $w_2^{n*} - w_2^{r*} = \beta(a-bc_1)(2\theta_1(2-\theta_2)+b\beta\theta_2)/((4-b\beta)\left(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2\right)) > 0$, $w_2^{n*} - w_2^{m*} = 2(a-bc_1)(b\beta\theta_1+(4-\theta_1)\theta_2)/(b(4-b\beta)\left(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2\right)) > 0$, and $w_2^{r*} - w_2^{m*} = ((a-bc_1)(2\theta_1^2(2-\theta_2)\theta_2 + (4+b\beta)\theta_2(8-b^2\beta^2-4\theta_2) - \theta_1(2b\beta(4+b\beta)+\theta_2(2(3-b\beta)(4+b\beta)-(12+b\beta)\theta_2))))/(b(16-b^2\beta^2-\theta_1(4-\theta_2)-4\theta_2)(16-b^2\beta^2-4\theta_1(2-\theta_2)-8\theta_2))$. By Mathematica, we find there exists θ_2', and if $\theta_2 > \theta_2'$, then $w_2^{r*} > w_2^{m*}$, otherwise $w_2^{r*} \le w_2^{m*}$, where

$$\theta_2' = \frac{(4+b\beta)(8-b^2\beta^2)-2\theta_1((3-b\beta)(4+b\beta)-2\theta_1)-\sqrt{(4+b\beta)^2(-8+b^2\beta^2)^2+4\theta_1(-(4+b\beta)^2(24+b^2\beta^2(-3+b\beta))+\theta_1((4+b\beta)(52+b\beta(9+b\beta(-2+b\beta)))+4\theta_1(-3(4+b\beta)+\theta_1)))}}{2(4+b\beta-2\theta_1)(4-\theta_1)}.$$

What's more, it is easy to find $w_1^{n*} - w_1^{r*} = 0$ and $w_2^{n*} - w_2^{r*} = 0$ if $\beta = 0$. And by Mathematica, we find $\theta_1' = 0$ and $\theta_2' = 0$ if $\beta = 0$. Q.E.D.

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Compliance with ethical standards

The authors declare that they have no conflict of interest. This article does not contain any studies with human participants or animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study. The study is approved by all authors for publication.

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