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Chain-to-chain competition on product sustainability

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ABSTRACT

This paper studies the game model of two sustainable supply chains under competition in product sustainability, derives the equilibrium structures of the two-chain system and generates the managerial insights. When the supplier and manufacturer within the reverse supply chain are competitive, the sustainability degrees, demands and profits under three structures of this two-chain system are analyzed. It is found that although vertical integration is always a Nash equilibrium, it is Pareto optimal only when the competition degree is low. On the other hand, a more generalized case for the former model is investigated when the supplier and manufacturer are cooperative in bargaining the wholesale price, and the effects of bargaining power to the sustainability degrees, demands, and chain member profits are studied. It is further shown that the structure of vertical integration channels is not an equilibrium unless the two sustainable supply chains are independent.

1. Introduction

The importance of product sustainability in business practice has been increasingly acknowledged by both academy and industry. Many reports and researches have suggested that the image of product sustainability can improve companies' competitiveness, e.g., through the more efficient/green use of materials and energy, higher employee motivation, access to new market segments (such as green consumers), etc. In other words, companies can "do well by doing good" since consumers have strong willingness to purchase the more sustainable products (e.g., Porter and Kramer, 2006; Luchs et al., 2010; Grimmer and Bingham, 2013; Salimifard and Raeesi 2014).

This point of view is also upheld by industrial practitioners. Market force is driving companies to invest in sustainability and provide green information to the market to gain competitive edge and expand market share. For example, in the fashion apparel industry, companies such as H&M, Marks & Spencer, and Levis have taken many approaches to minimize carbon emission in its production process by adopting new technologies (Dong et al., 2014). Coca Cola and its bottling partners have also announced that 100% of their new vending machines and coolers will be HFC (hydrofluoro-carbon) free by 2015 (cn.mobile.reuters.com). Giant Retailers such as Tesco and Walmart have also initiated the newest sustainability programs such as carbon labeling and sustainable product index. A growing number of companies are using public announcements of sustainability goals as a means of signaling their commitment to become sustainability leaders, and to compete for superior positioning versus their rivals.

Motivated by the above facts, this paper explores a system of two supply chains under competition of product sustainability. Each supply chain consists of a supplier and a manufacturer. The product demand is increasing in the product sustainability of the particular supply chain while decreasing with its opponent. The market is supposed to be fully competitive so the product prices are regarded as given parameters for both supply chains. In a decentralized supply chain, the supplier offers a wholesale price contract under which the manufacturer determines the product sustainability to maximize his own profit. On the other hand, the supplier can offer a coordination contract and thus the whole system profit is maximized within the integrated supply chain. In combination of the above cases, three chain-to-chain structures are established and analyzed. It is found that although vertical integration is always Nash equilibrium, it is Pareto optimal only when the competition degree of product sustainability is low. When the competition degree is relatively high, the two-chain system falls into prisoner dilemma. When the competition degree is extremely high, decentralization for both chains is not only Pareto optimal but also Nash equilibrium. Therefore, from the perspective of sustainable supply chain governance, supply chain vertical coordination can only be effective when the chain-to-chain competition is of a low degree,

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otherwise the vertical integration cannot emerge as a stable coalition between supply chain members in such a dynamic and competitive business environment.

Furthermore, we also consider a more generalized scenario of the former model when the supplier and manufacturer are cooperative in bargaining the wholesale price. The methodology of Nash bargaining model is adopted, with the objective of maximizing the product of the power function of the profits for the two supply chain members. The analytical solutions of the product sustainability and system profits are obtained, with the unique Nash equilibrium derived and the effects of bargaining power studied. It is shown that the structure of vertical integration channels is not an equilibrium unless the two supply chains are totally independent. Therefore, from the perspective of sustainable supply chain governance, a contract stimulates proper profit allocation after bargaining, rather than a coordination scheme, is more appropriate for the sustainable supply chain under competition.

Our study is particularly related to those considering chain-to-chain competition. A seminal work in this field is McGuire and Staelin (1983), which considers a price competition between two suppliers each selling through an independent retailer and explores the effect of the level of product substitutability on optimal retailer distribution. A major result is that when products are highly substitutable the decentralization of supply chain is preferable by both manufacturers. Coughlan (1985) extends this research to a more general demand function and applies it to the electrical industry while Moorthy (1988) further explains the reason why supply chain decentralization can lead to higher profits and links it to the concept of strategic interaction. Wu and Chen (2003) consider a quantity competition of a duopoly where each chain includes a single manufacturer and two retailers facing a newsvendor demand. Baron et al. (2008) incorporate wholesale price bargaining into a two-chain competing system and show that both the traditional two-chain structures are special cases of Nash Bargaining on the wholesale price. Wu et al. (2009) further extend the work of Baron et al. (2008) to include uncertain demand and show that integration in both chains is the unique Nash Equilibrium over one period decision, while decentralization or bargaining on the wholesale price for both chains may be Nash equilibrium over infinitely many periods.

Another stream of research related to our paper is the study on sustainable supply chain. Du et al. (2011) examine a two-echelon supply chain in which the emission-dependent manufacturer trades with emission permit supplier under the cap-and-trade regulation. Swami and Shah (2013) study a two-echelon supply chain in which both supply chain members can design the greening effort, and find that a two-part tariff contract can coordinate the supply chain. Zhang and Liu (2013) investigate a supply chain in which the market demand correlates with the green degree of green product and find that the revenue sharing contract can coordinate the supply chain. Dong et al. (2014) study the sustainability investment on sustainable product with emission regulation consideration for decentralized and centralized supply chains. In addition, Amin and Zhang (2014) propose a mixed-integer linear programming model to configure a closed-loop supply chain network including multiple products, plants, recovery technologies, demand markets, and collection centres. Please see Alzaman (2014) for a recent literature review of this research stream.

Different from the above research, this paper contributes to the literature by constructing a model of two sustainable supply chains competing product sustainability and exploring the equilibrium structures for such a two-chain system. It is found that decentralization can prevail over integration when the competition degree is high, when the supplier and manufacturer act in a non-cooperative pattern. In addition, integration is never an equilibrium structure under competition when the chain members bargain on wholesale price. Hence, the coordination mechanisms that induce sustainable supply chains to act as if they are vertically integrated, such as Swami and Shah (2013) and Zhang and Liu (2013), should be treated with caution.

This paper is organized as follows. In Section 2, we propose the two-chain competition model. Section 3 derives optimal solutions for the sustainability degrees, demand, and supply chain member profits. Section 4 compares the equilibrium results among different structures and provides managerial insights. Section 5 incorporates Nash bargaining on wholesale price into the model and Section 6 concludes the paper.

2. Two-chain competition model

Consider that two supply chains, each one consisting of a supplier and a manufacturer. In each supply chain, the supplier provides raw material to the manufacturer who produces and sells substitutable product to market. The two chains compete on the sustainability degree of the product, which is invested in the process of product manufacturing and determined by the manufacturer. That is, the demand of the product is increased with its sustainability degree and decreased with the sustainability degree of its opponent product sold by the competing supply chain. This reflexes the fact that the consumers' environmental awareness raises their purchase willingness for more sustainable and eco-friendly products, and thus the product sustainability competition is emphasized. Since our main focus is on the competition on product sustainability and to highlight more on this core issue, the paper considers that the demand is only related on the competition on sustainability level and the market prices are given. This is for the tractability of our model and comparison of different channel structures. Moreover, this assumption is also rational in practice since markets in many resource-intensive industries have become almost price-deterministic and the competition nowadays is more on product brands, which closely relates to sustainability. The above actions of H&M in apparel industry and Coca Cola in food industry are fair examples since they have been grappling with sustainability issues for brand image while their product prices are very stable at the meantime.

Specifically, the demands for supply chain $i = 1{,}2$ are.

$$q_i = 1 + s_i - \theta s_j, \quad i = 1, 2; \; j = 3 - i. \tag{1}$$

In the above equation, 1 is the normalized market base, s_i is the sustainability level of product i and θ in [0,1) denotes the competition degree of the two products on sustainability; $\theta = 0$ implies two independent supply chains without any sustainability competition. Such linear demand functions regarding the sustainability level have been adopted by Swami and Shah (2013) and Dong et al. (2014). The sustainability level here, is a rather general concept that can be any eco-friendly factor or improvement embedded in the product. For example, s_i can represent the total amount of improvement of carbon emissions emitted per unit expressed in equivalent tons of carbon dioxide (CO2), which can be labeled as carbon footprint on the product. Such factor is relevant to the consumers' purchase willingness and can influence the market demand for the product. In addition, we also assume symmetry between the two supply chains. This is for the simplicity of the solution calculation of our model without loss of any generalization.

For notation convenience we assume the prices are same and denoted as$p$, but it can be relaxed to two different prices and all results generated will still apply. The unit cost for making raw material is c_s for the supplier. For the manufacturer, the unit manufacturing cost is $c_m + ks_i$ for product i, where c_m is the base production cost and ks_i is to denote the unit investment of offering sustainability degree s_i with k as a cost coefficient related to the sustainable production operation. Such a linear cost function is assumed for the tractability of our model, while it has also been adopted in the existing literature, e.g., see Porteus (1985) and Jiang and Klabjan (2012). The problems under more complex production functions are left for the future research and we conjecture that the insights obtained from this paper will apply to more complicated settings. We assume all cost and market parameters are common knowledge for the supply chain members.

Now we consider the supply chain structures. In a two chain model, each chain can be decentralized or centralized. In a decentralized chain i, supplier i first proposes wholesale price w_i to manufacturer i, who correspondingly determines the sustainability degree of the product s_i. Both the supplier and manufacturer maximize their own profit, respectively. Their interaction constitutes a leader-follower Stackelberg game, and the supply chain is called D (Decentralized). In practice, this is usually a common case because of the simplicity and convenience of the adoption of the wholesale price contract. On the other hand, in a centralized supply chain i, the supplier and manufacturer can be regarded as an integrated organization to maximize the total profit of the entire supply chain. The supply chain in this case is called I (Integrated). In practice, this can usually be achieved by adopting coordination schemes within the supply chain, as suggested by Swami and Shah (2013), Zhang and Liu (2013), and Dong et al. (2014). For example, to fulfill the 100% HFC free commitment, Coca Cola has collaborated with its bottling partners to investment in developing their new vending machines and coolers to accelerate the transition to HFC-free equipment (cn.mobile.reuters.com). UPS has also turned to technology suppliers to help reduce emissions and costs from its transportation fleet (MIT Sloan Management Review and Boston Consulting Group, 2013).

Hence, there can be 3 structures for a two-chain system: D–D, I–I and hybrid (D-I). In D–D structure, a complex 4-player game is conducted in the following way: The suppliers simultaneously and uncooperatively determine the wholesale prices within each supply chain, and accordingly, the suppliers simultaneously determine the sustainability degrees for their products. Hence, two Nash game connected with a Stackelbeg game should be formulated for this system. On the other hand, I–I structure corresponds to a 2-player Nash game, in which two integrated chains determine the sustainability degrees of their products simultaneously. Finally, in D-I structure, the supplier in the decentralized chain first proposes the wholesale price, and then her manufacturer and its opponent chain simultaneously determine the sustainability degrees to maximize their own profits, respectively.

3. Equilibrium derivation

In this section we derive equilibrium results for three 2-chain structures: D–D, I–I and hybrid.

3.1. D–D structure

We first consider D–D structure. In supply chain i, for given wholesale price w_i, the manufacturer determines sustainability s_i to maximize his profit

$$\max_{s_i} \pi_{Mi} = (p - w_i - c_m - ks_i)(1 + s_i - \theta s_j). \tag{2}$$

It is obvious that π_{Mi} is a concave function of e_i. Taking the first-order derivates and solving the joint equations for $i = 1,2$, it follows

$$s_i = \frac{(2+\theta)(p-k-c_m) - 2w_i - \theta w_j}{(4-\theta^2)k}, \tag{3}$$

which is the Nash equilibrium of the product sustainability between competing manufacturers .

Taking these equilibrium solutions into (1), it follows

$$q_i = \frac{(2-\theta-\theta^2)(p-c_m) + (2+\theta)k - (2-\theta^2)w_i + \theta w_j}{(4-\theta^2)k}, \tag{4}$$

As the Stackelberg leader, supplier i foresees the responses from the manufactures and chooses the wholesale price to maximize her own profit

$$\max_{w_i} \pi_{Si} = (w_i - c_s)q_i \tag{5}$$

Substituting (4) into (5), we have that π_{Si} is concave in w_i. Taking the first-order derivates and solving the joint equations for $i = 1,2$, it follows

$$w_i = \frac{2(p + c_s - c_m + k) - \theta(p - c_m - k) - \theta^2(p - c_s - c_m)}{4 - 2\theta^2 - \theta}, \tag{6}$$

for $i = 1,2$, which is the Nash equilibrium of the wholesale prices between competing suppliers .

Substituting the above equilibrium into (3) and (4) yields,

$$s_i = \frac{(2-\theta^2)(p-c_s-c_m) - 2k(3-\theta^2)}{(2-\theta)(4-2\theta^2-\theta)k} \tag{7}$$

$$q_i = \frac{(2-\theta^2)[(1-\theta)(p-c_s-c_m)+k]}{(2-\theta)(4-2\theta^2-\theta)k} \tag{8}$$

Substituting the above results into (2) and (5) yields,

$$\pi_{Si} = \frac{(2+\theta)(2-\theta^2)[(1-\theta)(p-c_s-c_m)+k]^2}{(2-\theta)(4-2\theta^2-\theta)^2 k} \tag{9}$$

$$\pi_{Mi} = \frac{(2-\theta^2)^2[(1-\theta)(p-c_s-c_m)+k]^2}{(2-\theta)^2(4-2\theta^2-\theta)^2 k} \tag{10}$$

The entire supply chain profit is

$$\pi_i = \frac{2(2-\theta^2)(3-\theta^2)[(1-\theta)(p-c_s-c_m)+k]^2}{(2-\theta)^2(4-2\theta^2-\theta)^2 k}, \tag{11}$$

for $i = 1,2$.

Note that in the above results, the wholesale price, sustainability degree, demand and profits for the two chains are identical. This is because of our symmetric assumption on the cost and market parameters between the two chains.

3.2. I–I structure

For I–I structure, each chain i determines the sustainability degree s_i to maximize the profit of the supply chain,

$$\max_{e_i} \pi_i = (p - c_s - c_m - ks_i)(1 + s_i - \theta s_j) \tag{12}$$

It is obvious that π_i is a concave function of e_i. Taking the first-order derivates and solving the joint equations for $i = 1,2$, it follows

$$s_i = \frac{p - c_s - c_m - k}{(2-\theta)k}, \tag{13}$$

for $i = 1,2$. Substituting them into the demand and objective functions yields,

$$q_i = \frac{(1-\theta)(p - c_s - c_m) + k}{(2-\theta)k}, \tag{14}$$

and

$$\pi_i = \frac{[(1-\theta)(p - c_s - c_m) + k]^2}{(2-\theta)^2 k}. \tag{15}$$

3.3. Hybrid structure

The equilibrium derivation for hybrid structure is similar to the above two structures. Suppose that chain 1 is D (decentralized) and chain 2 is I (integrated). Jointly solving problem (2) for manufacturer 1 and problem (12) for chain 2 yields

$$\begin{cases} s_1 = \dfrac{2(c_m + k - p + w_1) + \theta(c_m + c_s + k - p)}{k(\theta^2 - 4)} \\ s_2 = \dfrac{\theta(c_m + k - p + w_1) + 2(c_m + c_s + k - p)}{k(\theta^2 - 4)} \end{cases} \tag{16}$$

Substituting (16) into $\max_{w_1} \pi_{S1} = (w_1 - c_s)q_1$, and taking the first-order derivative, we have

$$w_i = \frac{(\theta^2 - 4)(p + c_s - c_m) + \theta(p - c_m - c_s - k) - 2k}{2(\theta^2 - 4)}, \tag{17}$$

Substituting the above solution into (16) yields

$$\begin{cases} s_1 = \dfrac{(1+\theta-\theta^2)(p - c_s - c_m) - (3-\theta^2)k}{(2-\theta)(2-\theta^2)k} \\ s_2 = \dfrac{(4-\theta-\theta^2)(p - c_s - c_m) - (4+\theta-2\theta^2)k}{2(2-\theta)(2-\theta^2)k} \end{cases}, \tag{18}$$

and further

$$\begin{cases} q_1 = \dfrac{[(1-\theta)(p - c_s - c_m) + k]}{2(2-\theta)k} \\ q_2 = \dfrac{(-2\theta^2 + \theta + 4)\left[(1-\theta)(p - c_s - c_m) + k\right]}{2(2-\theta)(2-\theta^2)k}, \end{cases} \tag{19}$$

which is the equilibrium solution of the two-chain system under hybrid structure.

Substituting it into the objective functions yields

$$\pi_{S1} = \frac{(2+\theta)[(1-\theta)(p - c_s - c_m) + k]^2}{4(2-\theta^2)(2-\theta)k} \tag{20}$$

$$\pi_{M1} = \frac{[(1-\theta)(p - c_s - c_m) + k]^2}{4(2-\theta)^2 k} \tag{21}$$

$$\pi_1 = \frac{(3-\theta^2)[(1-\theta)(p - c_s - c_m) + k]^2}{2(2-\theta)^2(2-\theta^2)k} \tag{22}$$

$$\pi_2 = \frac{(-2\theta^2 + \theta + 4)^2[(1-\theta)(p - c_s - c_m) + k]^2}{4(2-\theta)^2(2-\theta^2)^2 k} \tag{23}$$

Table 1 summarizes the sustainability degree, demand, and profits of the supply chain members under different two-chain structures, which are related to three parameters: k,θ, and $\Delta = p - c_s - c_m$. Especially, the demand in each structure is the product of $\frac{(1-\theta)\Delta + k}{k}$ and a function of θ, and the profit in each structure is the product of $\frac{[(1-\theta)\Delta + k]^2}{k}$ and a function of θ. This provides great convenience for our further analysis.

4. Analysis and insights

In this section we compare the equilibrium results among different structures of the two-chain systems, and provide insights on some research questions.

4.1. For the supply chain

(1) Research Question 1: Does the integrated supply chain always generate a higher profit than the decentralized one?

It is well-known that the integration always generally leads to a higher profit for a supply chain than the decentralization with a wholesale price contract, which is referred to the effect of "Double Marginalization" (Spengler, 1950). In consequence, various coordination contracts have been developed to achieve integrated supply chain decisions, see Cachon (2003). Swami and Shah (2013) reports similar result for a supply chain with sustainability investment and designs coordination scheme to achieve sustainable supply chain integration. However, the above researches do not consider supply chain competition on sustainability. For the two-chain system, we have the following result:

If $\theta > (<) 0.482$, then $\pi^{RS-RS} > (<) \pi^{VI-VI}$.

That is, if the competition on sustainability is sufficiently fierce ($\theta > 0.482$), the profit for the decentralized supply chain is higher than that for the integrated supply chain. This result is different for that for a single supply chain without any competition. On the other hand, if the competition on sustainability is not so fierce ($\theta < 0.482$), the result becomes similar to that in the scenario of single supply chain, that is, integration prevails decentralization.

This seemingly counter-intuitive result reflexes the influence of sustainability competition. For a single supply chain, double marginalization leads to a lower sustainability degree which results in a lower profit for the decentralized chain. However, such a lower sustainability degree is beneficial to the other chain for D–D structure.

Table 1
Sustainability degrees, demands and supply chain member profits under different structures.

	D–D	D in Hybrid	I in Hybrid	I–I
s	$\frac{(2-\theta^2)\Delta - 2k(3-\theta^2)}{(2-\theta)(4-2\theta^2-\theta)k}$	$\frac{(1+\theta-\theta^2)\Delta - (3-\theta^2)k}{(2-\theta)(2-\theta^2)k}$	$\frac{(4-\theta-\theta^2)\Delta - (4+\theta-2\theta^2)k}{2(2-\theta)(2-\theta^2)k}$	$\frac{\Delta - k}{(2-\theta)k}$
q	$\frac{(2-\theta^2)[(1-\theta)\Delta + k]}{(2-\theta)(4-2\theta^2-\theta)k}$	$\frac{[(1-\theta)\Delta + k]}{2(2-\theta)k}$	$\frac{(-2\theta^2+\theta+4)[(1-\theta)\Delta + k]}{2(2-\theta)(2-\theta^2)k}$	$\frac{(1-\theta)\Delta + k}{(2-\theta)k}$
π_S	$\frac{(2+\theta)(2-\theta^2)[(1-\theta)\Delta + k]^2}{(2-\theta)(4-2\theta^2-\theta)^2 k}$	$\frac{(2+\theta)[(1-\theta)\Delta + k]^2}{4(2-\theta^2)(2-\theta)k}$	N/A	N/A
π_M	$\frac{(2-\theta^2)^2[(1-\theta)\Delta + k]^2}{(2-\theta)^2(4-2\theta^2-\theta)^2 k}$	$\frac{[(1-\theta)\Delta + k]^2}{4(2-\theta)^2 k}$	N/A	N/A
π	$\frac{2(2-\theta^2)(3-\theta^2)[(1-\theta)\Delta + k]^2}{(2-\theta)^2(4-2\theta^2-\theta)^2 k}$,	$\frac{(3-\theta^2)[(1-\theta)\Delta + k]^2}{2(2-\theta)^2(2-\theta^2)k}$	$\frac{(-2\theta^2+\theta+4)^2[(1-\theta)\Delta + k]^2}{4(2-\theta)^2(2-\theta^2)^2 k}$	$\frac{[(1-\theta)\Delta + k]^2}{(2-\theta)^2 k}$

$\Delta = p - c_s - c_m$.

This benefit grows as the competition becomes more fierce, and when $\theta > 0.482$, the benefit brought about by competition between two chains covers the loss of profit due to double marginalization with a single chain. In this case, D—D structure is more preferable than I—I structure from the supply chain perspective.

(2) Since D—D might be preferable, is it profitable for a decentralized supply chain to transfer into an integrated one when its opponent is decentralized?

We have the following result on this question:
If $\theta<(>)0.771$, then $\pi^{I-D}>(<)\pi^{D-D}$.

That is, if the sustainability competition is not very fierce ($\theta < 0.771$), then a supply chain should be coordinated into an integrated one when its opponent is decentralized; if the sustainability competition is not very fierce ($\theta > 0.771$), then decentralization prevails over integration for a supply chain whose opponent is decentralized.

This result shows that one supply chain could have incentive to keep decentralized if the other one is decentralized. This is because transferring into I from D will lead to a higher sustainability degree, which further results in a higher sustainability degree of its opponent chain. The resulting profit loss for this transferring supply chain exceeds the benefit from eliminating double marginalization effect, when the competition is very fierce.

(3) Symmetric to Question 2, is it profitable for an integrated supply chain to transfer into a decentralized one when its opponent is integrated?

We have the following result on this question:
For any $0 \le \theta < 1$, we have $\pi^{I-I} > \pi^{D-I}$.

That is, integration is always an optimal policy for a supply chain whose component is adopting integration rather than decentralization. This result holds for any degree of sustainability competition.

(4) Which structure is a stable equilibrium for two-chain system?

From the above 3 questions, we can make the following observations on equilibrium structure.

(a) Hybrid structure is never a Nash equilibrium, while I—I is always a Nash equilibrium.

This can be seen from the remark to question 3. On the one hand, the decentralized chain in Hybrid structure always has incentive to transfer into an integrated one, so the hybrid structure is not stable. On the other hand, an integrated chain in I—I structure never has incentive for decentralization, so I—I structure is always a Nash equilibrium.

(b) If $\theta > 0.771$, D—D is a Nash equilibrium; otherwise it is not.

This can be seen from the remark to question 3. If and only if $\theta > 0.771$, a chain will choose decentralization rather than integration given its opponent is decentralized. Hence, D—D is a Nash equilibrium if and only if $\theta > 0.771$.

(c) If $0 \le \theta < 0.482$, I—I is a unique Nash equilibrium and also Pareto optimal; If $0.482 < \theta < 0.771$, I—I is a unique Nash equilibrium but D—D is Pareto optimal, so Prison-dilemma occurs; If $\theta > 0.771$, I—I and D—D are Nash equilibriums and D—D is Pareto optimal.

This can be concluded from the remark from question 1 as well as results (a) and (b). First, we have seen that I—I is a unique Nash equilibrium if $\theta < 0.771$ and D—D becomes a Nash equilibrium if $\theta > 0.771$, according to results (a) and (b). Second, D—D (I—I) is Pareto optimal if and only if $\theta>(<)0.482$ according to the remark from question 1.

4.2. For the social welfare and market

In this subsection we compare the two-chain structures from the perspectives of social welfare and market. First, the social welfare is related to product sustainability. In this regard, we have,

$$s^{D-D} < s^{D-I} < s^{I-D} < s^{I-I}.$$

That is, the sustainability degree is highest in I—I structure, and lowest in D—D structure. In Hybrid structure, the integrated chain produces a more sustainable product than that in the decentralized chain. Therefore, I—I is the most preferable structure from the perspective of social welfare. Swami and Shah (2013) claims that the integrated supply chain is more sustainable than the decentralized one under the single-chain environment. Our observation confirms that such a result can be extended to the two-chain competition scenario.

In addition, demand is the most important factor in marketing. In this regard, we have.

$$q^{RS-VI} \le q^{RS-RS} < q^{VI-VI} \le q^{VI-RS} \text{ and}$$

$$2q^{RS-RS} < 2q^{VI-VI} < q^{VI-RS} + q^{RS-VI},$$

in which, "$\le$" holds if and only if $\theta = 0$.

This suggests that a chain in I—I structure generates a higher demand than that in D—D structure. Hybrid structure, on the other hand, makes an extreme case in which the integrated chain yields the highest demand while the decentralized chain yields the lowest demand. Furthermore, the total demand of the two chains in Hybrid structure exceeds that in I—I structure.

Finally, we conclude this section with that all the equilibrium results on two-chain structure is only related to the sustainability competition degree θ and has no relationship with other parameters such as k,c_m,c_r and p. This is a fundamental feature of two-chain competition.

5. Two-chain competition under bargaining

5.1. A single chain under bargaining

In the previous analysis, we suppose that the wholesale price w is made by the supplier to maximize her own profit, who is regarded as the Stackelberg leader in this non-cooperative game. From the perspective of cooperative game, this reflexes the full bargaining power of the supplier. In reality, the upstream manufacturer usually also has some power. In this section, we utilize Nash bargaining theory and extend the previous model into the scenario in which both the supplier and manufacturer have some bargaining power.

Nash bargaining model is one of the basic conceptions in cooperative Game theory. Its solution, usually so-called Nash bargaining solution, maximizes the product of the power functions of the utilities of two players (Nash 1950). Taking this sustainable supply chain as an example, if the supplier's bargaining power is $a \in [0,1]$ and the manufacturer's is $1 - a$, and each party gains 0 if she does not bargain, then the consequence of the bargaining game is seek to maximize $\pi_S^a \cdot \pi_M^{1-a}$.

Specifically, the sequence of event within a single chain is as follows: first the supplier and manufacturer determine wholesale price w according to the bargaining power of each party, and the manufacturer responsively chooses sustainability degree s to maximize his own profit. Hence, the wholesale price can be expressed as.

$$\mathrm{argmax}_w\left\{\pi_S^a \cdot \pi_M^{1-a}\right\} = \mathrm{argmax}_w\left\{q(w)(w-c_s)^a (p-w-c_m-ks(w))^{1-a}\right\} \tag{24}$$

where $s(w)$ is the optimal sustainability degree chosen from the manufacturer to maximize his profit, and $q(w)$ is the corresponding demand.

It can be seen that a decentralized chain corresponds to the case of $a = 1$, in which the supplier chooses the optimal wholesale price regardless of the manufacturer's interest. On the other hand, the profit of the entire chain is equal to π_M when $a = 0$. In other words, the decentralized and integrated chain correspond to the special cases of $a = 1$ and $a = 0$, respectively. 。

5.2. Two-chain system under bargaining

Now we consider the two-chain system under bargaining, in which each chain maximizes their own profits. The sequence of events is as follows.

First, each chain i determines the bargaining power of their own supplier a_i to maximize the profit of the entire chain i, $i = 1,2$, respectively. Second, each chain i determines the wholesale price w_i according to the bargaining power a_i and criteria (32). Finally, the manufacturers choose the sustainability degrees s_i, $i = 1,2$, respectively, facing the sustainability competition (1). The above decisions are made simultaneously across this two-chain system, which is called $a_1 - a_2$ system under bargaining.

Under this situation, the manufacturers still determine sustainability degrees to maximize their profits, respectively, so Equations (2)–(4) still apply. Substituting them into (24), we have the optimal wholesale price.

$$\mathrm{argmax}_{w_i}\left\{\pi_{Si}^{a_i}\cdot\pi_{Mi}^{1-a_i}\right\} = \mathrm{argmax}_{w_i}\left[\frac{\left(2-\theta-\theta^2\right)\left(p-c_m\right)+\left(2+\theta\right)k-\left(2-\theta^2\right)w_i+\theta w_j}{4-\theta^2}\right]^{2-a_i}\frac{[w_i-c_s]^{a_i}}{k} \tag{25}$$

Taking the first-order derivative of (25) yields.

$$w_i = \frac{Aa_i+\left(2-\theta^2\right)\left(2-a_i\right)c_s+\theta a_i w_j}{2\left(2-\theta^2\right)}, \tag{26}$$

where $A = (2+\theta)[(1-\theta)(p-c_m)+k]$.

Solving the joint Equation (26) for $i = 1,2$ $j = 3-i$ yields.

$$w_i = \frac{2\left(2-\theta^2\right)D+\left[2B\left(2-\theta^2\right)+D\theta\right]a_i+B\theta a_i a_j}{4\left(2-\theta^2\right)^2-\theta^2 a_i a_j} \tag{27}$$

where $B = A-(2-\theta^2)c_s$ and $D = 2(2-\theta^2)c_s$.

Substituting it into (3) and (4) yields.

$$s_i=\left\{4\left(2-\theta^2\right)\left(\Delta-k\right)-2\left(2-\theta^2\right)\left[\left(1-\theta\right)\Delta+k\right]\left(2a_i+\theta a_j\right)-\theta\left[\left(2-\theta^2\right)\Delta+2k\right]a_ia_j\right\}\Big/\left\{\left(2-\theta^2\right)\left[4\left(2-\theta^2\right)^2-\theta^2a_ia_j\right]k\right\} \tag{28}$$

$$q_i = \frac{\left[\left(1-\theta\right)\Delta+k\right]\left(2-\theta^2\right)\left(2-a_i\right)\left(2\left(2-\theta^2\right)+\theta a_j\right)}{(2-\theta)\left[4\left(2-\theta^2\right)^2-\theta^2 a_i a_j\right]k} \tag{29}$$

and further

$$\pi_{Si}=\frac{\left(2+\theta\right)\left(2-\theta^2\right)a_i\left(2-a_i\right)\left[2\left(2-\theta^2\right)+\theta a_j\right]^2[(1-\theta)\Delta+k]^2}{(2-\theta)\left[4\left(2-\theta^2\right)^2-\theta^2a_ia_j\right]^2k} \tag{30}$$

$$\pi_{Mi}=\frac{\left(2-\theta^2\right)^2(2-a_i)^2\left[2\left(2-\theta^2\right)+\theta a_j\right]^2[(1-\theta)\Delta+k]^2}{(2-\theta)^2\left[4\left(2-\theta^2\right)^2-\theta^2a_ia_j\right]^2k} \tag{31}$$

$$\pi_i=\frac{2\left(2-\theta^2\right)\left(2-a_i\right)\left(2-\theta^2+a_i\right)\left[2\left(2-\theta^2\right)+\theta a_j\right]^2[(1-\theta)\Delta+k]^2}{(2-\theta)^2\left[4\left(2-\theta^2\right)^2-\theta^2a_ia_j\right]^2k} \tag{32}$$

It is easy to verify that D–D, I–I, and hybrid structures correspond with 1–1, 0–0, and 1–0 systems under bargaining, respectively. This shows again that the two-chain competition system established in Section 2 is a special case of two-chain system under bargaining. In fact, the bargaining model extends the two-chain system from {0,1} × {0,1} (3 structures) into any two-dimensional real vector[0,1]×[0,1] structures.

Furthermore, we obtain the influences of bargaining power of the supplier to the whole system as follows.

(1) π_{Si} is increasing witha_i while π_{Mi} is decreasing with a_i; both π_{Si} and π_{Mi} are increasing with a_j. That is, a larger bargaining power for the supplier will benefit the supplier and weaken the manufacturer, which is an intuitive result. In addition, both the supplier and manufacturer will benefit from a larger bargaining power for their opponent supplier.

(2) q_i is decreasing with a_i and increasing with a_j, and s_i is decreasing with a_i and a_j. That is, the demand is decreasing with the bargaining power of the supplier of its own chain and increasing with that of the opponent chain. From the perspective of social welfare, a smaller bargaining power of the supplier is more beneficial to the society since it will incur a greater sustainability for the product.

Finally, we provide the Nash equilibrium for the two-chain system under bargaining, which is one of the core results of this paper.

Theorem. The two-chain system under bargaining has unique Nash equilibrium.

$$\begin{cases} I-I, & \text{when } \theta=0 \\ a(\theta)-a(\theta), & \text{when } 0<\theta<0.9661 \\ D-D, & \text{when } 0.9661\leq\theta\leq 1 \end{cases} \tag{33}$$

in which

$$a(\theta)=\frac{2\left(\theta^2-2\right)}{\theta^4}(3\theta^2-4-(\theta^2-4)\sqrt{1-\theta^2}) \tag{34}$$

Proof. For each chain i, the bargaining power of supplier i, a_i, should maximize Equation (30). Taking the first-order derivative yields.

$$a_i^*(\theta)=\frac{4\theta^2\left(2-\theta^2\right)\left(a_j-\theta^2+2\right)}{8\left(\theta^2-2\right)^2-\theta^4 a_j}. \tag{35}$$

We have $a_i=0$ when $\theta=0$. When $\theta>0$, it follows that $a_1=a_2$ according to the symmetry of Equation (35), and substituting it into Equation (35) yields.

$$a_i(\theta)=\frac{4\theta^2\left(2-\theta^2\right)\left(a_i-\theta^2+2\right)}{8\left(\theta^2-2\right)^2-\theta^4 a_i} \tag{36}$$

We can obtain two solutions from Equation (36) but the one greater than 1 should be discarded. The other one can be expressed by $a(\theta)$ in Equation (34). Note that $a(\theta)$ is increasing in θ. Solving $a(\theta)=1$ leads to $\theta=0.9661$. In consequence, when $\theta<0.9661$, $a(\theta)<1$ and thus $a(\theta)-a(\theta)$ system is Nash equilibrium. Furthermore, note that $a_i^*(\theta)$ in Equation (35) is increasing with a_j. Hence, when $\theta\geq 0.9661$ we have $a(\theta)=1$ and $a(\theta)-a(\theta)$ system, i.e., D–D structure is Nash equilibrium.

As to the uniqueness of Nash equilibrium, it will suffice to verify $\left|\frac{\mathrm{d}a_i^*(\theta)}{\mathrm{d}a_j}\right|<1$ for $i=1,2$, $j=3-i$, $\forall\theta\in[0,1)$, $a_j\in[0,1]$, according to Cachon and Netessine (2004). When $\theta\geq 0.9661$, this condition is obviously satisfied since $a_i(\theta)=1$. When $\theta<0.9661$, it follows.

$$\frac{\mathrm{d}^2a_i^*\left(\theta\right)}{\mathrm{d}\left(a_j\right)^2}=\frac{8\theta^6\left(2-\theta^2\right)^2\left(4-\theta^2\right)^2}{\left(32-32\theta^2+8\theta^4-\theta^4a_j\right)^3}\geq 0, \quad \text{and}$$

$$\frac{\mathrm{d}^2a_i^*\left(\theta\right)}{\mathrm{d}\left(a_j\right)^2}=8\theta\left\{a_j\left[(2-\theta^2)(\theta^6+2\theta^4-16\theta^2+32)+2\theta^4a_j\right]\right.$$
$$\left.+8\left(2-\theta^2\right)^4\right\}\Big/\left(32-32\theta^2+8\theta^4-\theta^4a_j\right)^2\geq 0.$$

Hence, $\frac{\mathrm{d}a_i^*(\theta)}{\mathrm{d}a_j}$ is increasing with θ and a_j. It will suffice to prove $\frac{\mathrm{d}a_i^*(\theta)}{\mathrm{d}a_j}\Big|_{a_j=1,\theta=1}<1$, which is true since

$$\frac{\mathrm{d}a_i^*(\theta)}{\mathrm{d}a_j}\Big|_{a_j=1,\theta=1}=\frac{4\theta^2\left(2-\theta^2\right)^2\left(4-\theta^2\right)^2}{\left(32-32\theta^2+8\theta^4-\theta^4a_j\right)^2}\Big|_{a_j=1,\theta=1}$$
$$=36/49.$$

It is shown that the equilibrium structure of the two-chain system under bargaining is only related to the competition degree θ and has no relation with other parameters, which is similar to the case of no bargaining. The difference from the case of no bargaining is that the equilibrium structure is unique. More importantly, D–D system will occur only if the sustainability competition is extremely fierce, and I–I system will occur only if the two chains are independent. For a more general parameter setting, the equilibrium structure is a bargaining two-chain system related to the competition degree. This result is very different with the case of no bargaining. For example, I–I is always a Nash equilibrium in the case of no bargaining, but now I–I is never an equilibrium as long as the competition exists. Hence, the structure of two-chain system with bargaining has fundamental difference with the "common sense" of a two-chain competition system, and the concept of supply chain coordination should be redefined: the purpose of coordination is no longer to make the supply chain as an integrated operating one. The coordination scheme proposed in the single-chain scenario, e.g., in Swami and Shah (2013) and Zhang and Liu (2013), for sustainable supply chain is also no longer effective under this situation.

6. Conclusion

This paper considers a two-chain system under competition between product sustainability. Each chain consists of a supplier providing raw material and a manufacturer produces sustainable product. First, we investigate the scenario in which the supplier and manufacturer acts in an uncooperative way, and thus three two-chain structures are formulated. The main results include:

(1) The equilibrium structure of the two-chain system is only related to the competition degree of product sustainability and irrelevant to other parameters.
(2) Counterintuitively, the vertical integration is only beneficial to a supply chain when the competition degree is relatively low; when the competition is fierce, the system can fall into a prisoner dilemma or even two decentralized chains can be a more preferable structure.
(3) The society should always expect vertical integration instead of decentralization which incurs a higher sustainability degree for the manufacturer. On the other hand, the hybrid structure leads to the largest demand although it is never an equilibrium structure.

Furthermore, we consider the scenario in which the manufacturer and supplier can cooperate to determine the wholesale price according to the bargaining power, which maximizes the total profit of the supply chain. The following results are generated.

(1) The bargaining model generalizes the previous two-chain system without bargaining from 3 structures into a continuum of structures with bargaining powers defined in two-dimensional real vector [0,1] × [0,1].
(2) The bargaining powers within two chains significantly affect the product sustainability degrees, the demands and the member profits of the two chains. For example, the increase in the supplier's bargaining power will increase not only the

profit of the supplier in its own chain but also benefit the supplier and manufacturer in the opponent chain; it also decreases the sustainability degrees of two competing products.

(3) If the two chains can coordinate with the bargaining power to achieve profit maximization of its own chain, then the equilibrium result is a two-chain system with the bargaining power related to the competition degree. Vertical integration only occurs when two chains are independent.

Our paper is among the first efforts to investigate the chain-to-chain competition on product sustainability. There are several possible extensions for the future research. First, in this paper, we assume that the market prices are exogenous. Taking the price competition into the model will make the problem more complicated and interesting. Second, we assume the manufacturing cost is linear with the product sustainability for mathematical tractability. Other forms of the manufacturing cost can be considered in future study. Finally, we assume a deterministic demand in our model, while incorporating random factors is an important future direction.

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