Managing Capacity Investment Financing Uncertainty under Supply Chain Competition

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Abstract

In this paper, we study the asymmetric duopoly models of competing supply chains with financing uncertainty. The financing uncertainty of the green supply chain's capacity investment could be available as complete or incomplete information to the traditional supply chain. By analyzing and comparing the optimal quantities, optimal prices, and optimal profits of both cases, we find that the financing uncertainty of capacity investment does not affect either chain's choices of equilibrium quantities and prices in the complete information case. If this information is incomplete for the traditional supply chain, financing uncertainty plays an important role in determining optimal quantities and optimal prices, together with the lending interest rate. To encourage the use of environmentally friendly technologies, government should use per-unit subsidies if the green supply chain suffers the cost disadvantage, and should encourage financial institutions to provide preferential loans to the green supply chain that suffers manufacturing or retailing capacity restrictions.

Keywords: Green supply chain; Asymmetric Cournot competition; Industry policy; Capacity restriction; Financing uncertainty.

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1. Introduction

In recent years, the development of green (or sustainable) supply chains has gained considerable attention from practitioners, researchers, and policy makers. In practice, a green supply chain may exhibit a relatively high production cost, because of its adoption of new and cleaner technology; however, manufacturing or retailing capacity restrictions impede the realization of the scale effect. As a result, green supply chains may disappear in intensely competitive markets, and chains may be left with no incentive to adopt environmentally friendly technologies. Hence, which kinds of policy measures would encourage the development of green supply chains when there are cost disadvantages or capacity restrictions? To answer this question, we analyze the asymmetric model of competing supply chains, based on previous literatures.

Green (sustainable) supply chain management literature indicates that significant research has been done in the areas of operations and environmental science. Beamon (1999) introduces the concepts of green supply chain design. The overviews of green supply chain management literature can be found in Srivastava (2007), Carter and Rogers (2008), and Seuring and Müller (2008). Furthermore, Sarkis, et al. (2011) and Seuring (2013) review the organizational theorey and modeling research on green supply chain management, respectively. Eskandarpour et al. (2015) reviews the design of sustainable supply chain networks. Other interesting research cover the relationship between green supply chain management and the circular economy (Genovese et al., 2017), the performance evaluation of green supply chain management in practice (et al., 2005; Zhu et al., 2008; Varsei and Polyakovskiy, 2017), and the connection between green supply chain management and sustainable regional economic development (Zhang et al., 2015; Zhang and Xie, 2015; Zhang et al., 2016; Zhang et al., 2017; Wu et al., 2017).

However, only a few of researchers study green supply chain management by using mathematical models, while these could help us to clearly identify the optimal strategy for green supply chain development and the effects of government policies (see the review of Badole et al., 2012). Among those literatures, McGuire and Staelin (1983) describe the pioneering study of the market with two competing supply chains in a game model. Bertrand competition (i.e., two supply chains that compete on price) between two supply chains is analyzed, and it is found that both manufacturers prefer a decentralized equilibrium if products are highly substitutable. Moorthy (1988), and Bonanno and Vickers (1988) find similar results in the extended Bertrand competition model and provide more explanations.

Some work focus on enterprise risk management for competing supply chains. Wu et al. (2009) includes demand uncertainty in the Cournot competition (i.e., two supply chains compete on quantity) of supply chains. They consider the symmetric competition of supply chains under three possible strategies: Vertical Integration, Manufacturer's Stackelberg, and Bargaining on the Wholesale price, and show that the first two strategies are two special cases of the last one. On the other hand, Fang and Shou (2015) discuss the Cournot competition model between two supply chains that are subject to supply uncertainty. Besides demand and supply uncertainties, there are still many possible enterprise risks in supply chain competition (Olson and Wu, 2010, 2017; Heckmann,et al., 2015). Among these potential risks that an enterprise may faces, some researchers notice the capacity-related enterprise risk (Chopra and Sodhi, 2004; Cucchiella and Gastaldi, 2006; Wu et al., 2006; Blackhurst et al., 2008, etc.). However, neither of the above-mentioned studies uses the Cournot competition model to analyze the impact of capacity investment and its related risk in supply chain competition.

This paper's main contribution is to link and extend the above works by considering the financing uncertainty of green supply chains in a Cournot competition model. This stylistic setting allows us to gain insight into the differences between various supply chain strategies when some chain needs financing aid for capacity investment. In this paper, we first introduce the asymmetric duopoly model of competing supply chains as benchmark, and discuss the effect of a per-unit subsidy policy to deal with the problem of asymmetric costs between traditional and green supply chains. Based on the benchmark model, we study supply chain competition with asymmetric financing uncertainty. The financing uncertainty of one chain's capacity investment could be available as complete or incomplete information for the other chain. By analyzing and comparing the optimal quantities, optimal prices, and optimal profits in both cases, we find the effects of asymmetric capacity restriction and asymmetric information of financing uncertainty on the competition equilibria.

The paper is organized as follows. Section 2 presents the benchmark model. Section 3 analyzes the Cournot competition model of supply chains with asymmetric financing uncertainty, in the cases of complete and incomplete information on financing uncertainty of the manufacturing and retailing capacity investment. Finally, Section 4 concludes.

2. Supply chain competition model

2.1. Benchmark model

In this section, we consider the Cournot model of competing supply chains in which each chain is composed of a manufacturer servicing a single retailer. The timing of the game is as follows:

1. The manufacturers and the retailers in two supply chains bargain simultaneously on the wholesale price, $w_i, \mathrm{i} = 1,2$.
2. The manufacturers and the retailers in the two supply chains agree simultaneously on the desired retailer's order quantity, $q_i, \mathrm{i} = 1,2$. Thereafter, the quantities of q_i are fully produced and delivered by the manufacturer.

3. The retailing prices $p_i, \mathrm{i} = 1,2$, are determined by market demand, and sales take place.

We denote the first supply chain as the traditional chain and the second one as the green supply chain, which could be a new entrant in the industry. Compared to the traditional supply chain, the manufacturing or transportation technology in the green supply chain is more environmentally friendly and produces fewer emissions. Normally, the new entrant in the market may suffer the cost disadvantage, because its manufacturing or retailing capacity restrictions may impede the scale effect from taking place. We assume that the per-unit production cost for the manufacturer in the green supply chain is higher, i.e., $0 < c_1 < c_2$. Let π_i^{SC}, π_i^M, and π_i^R denote the profit of the supply chain as a whole, the manufacturer's profit, and the retailer's profit, respectively. We can write these profit functions as follows:

$$\pi_i^{SC} = q_i(p_i - c_i),\ i = 1,2; \tag{1}$$

$$\pi_i^M = q_i(p_i - w_i),\ i = 1,2; \tag{2}$$

$$\pi_i^R = q_i(w_i - c_i),\ i = 1,2. \tag{3}$$

One can find that $\pi_i^{SC} = \pi_i^M + \pi_i^R, i = 1,2$, which implies that the supply chain profit is the sum of the manufacturer's and retailer's profit.

The manufacturers and retailers in the two supply chains bargain on the wholesale price, $w_i, i = 1,2$, to determine their respective profit shares. Following Wu et al. (2009), we formulate the bargaining process on the wholesale price between the manufacturer and the retailer as a Nash Bargaining game, which is firstly presented by Nash (1950) and extended by Kalai and Smordinsky (1975), and Binmore et al. (1986). In the bargaining stage, we let $\alpha \in [0,1]$ be the bargaining power, and $\Phi_i(w)$ denote the Nash bargaining product. Then, the Nash Bargaining Product model for a manufacturer and a retailer choosing a wholesale price $w_i, i = 1,2$ is:

$$Max_w\{\Phi_i(w_i)\} = Max_w\{(\pi_i^M)^\alpha(\pi_i^R)^{1-\alpha}\}, i = 1,2. \tag{4}$$

Note that we allow the bargaining power parameter $\alpha \in [0,1]$, where α is given exogenously.[1] We first assume that $\alpha = 0.5$, which reflects a balance of bargaining power between the manufacturer and the retailer.[2] Given that $\alpha = 0.5$, we can derive that $w_i = \frac{p_i - c_i}{2}$, $\pi_i^M = \pi_i^R = \frac{\pi_i^{SC}}{2}, i = 1,2$, i.e., the manufacturer and the retailer share the chain profit equally because their bargaining powers are balanced.

To keep things simple and tractable, we consider the additive inverse demand function where the ith retailer's price, p_i, depends on two elements: its own quantity of product, q_i, and the competitor's quantity of product, q_j $(j \neq i)$, through a substituting coefficient $b_i \in$

[1] Note that Wu et al. (2009) has shown that the cases of $\alpha = 0$ and $\alpha = 1$ are equivalent to two special supply chain models, namely, Vertical Integration (VI) and Manufacturer's Stackelberg (MS), respectively.

[2] The assumption will be relaxed in Section 3.4, and a general model with $\alpha \in (0,1)$ will be discussed.

(0,1):[3]

$$p_i = a_i - q_i - b_i q_j, i = 1,2;\ j = 3 - i. \tag{5}$$

As reflected in (5), $b_i = 0$ implies that the chains are independent of each other, while $b_i = 1$ implies that the products are identical. We assume that $a_1 = a_2 \equiv a$, which implies that the highest possible quantity of demand of the two supply chains are identical; we also assume that $b_1 = b_2 \equiv b$, which implies that the substitution effects between the two supply chains are symmetric. By making these two assumptions, we can emphasize the effect of asymmetric costs ($0 < c_1 < c_2 < a$) on the competition between the traditional supply chain and the green supply chain.

We denote $\mathrm{k_i}, \mathrm{i} = 1,2$, as the manufacturing capacities of two supply chains. If the production capacity of each manufacturer k_i is large enough to meet the demand $d_i, i = 1,2$, it faced, then $k_i \geq d_i = q_i$; otherwise, when the production capacity is less than demand, i.e., $k_i < d_i$, each manufacturer can only supply to its capacity, then $q_i = k_i < d_i$.

In this benchmark model, we assume that manufacturers have sufficient capacity, we can ensure that $d_i = q_i$, and we therefore rewrite the profit functions of supply chains as follows:

$$\pi_i^{SC} = q_i(a_i - q_i - bq_j - c_i), i = 1,2;\ j = 3 - i. \tag{6}$$

By taking the first order derivatives with respect to q_i, we have the First Order Conditions (FOC):

$$\frac{\partial \pi_i^{SC}}{\partial q_i} = a - 2q_i - bq_j - c_i = 0, i = 1,2;\ j = 3 - i. \tag{7}$$

By solving two equations in (7), we have the best reaction functions:

$$q_i^* = \frac{a - c_i - bq_j}{2}, i = 1,2;\ j = 3 - i. \tag{8}$$

Rearranging the best reaction functions above, the optimal quantities of two chains are:

$$q_i^* = \frac{(2-b)a - 2c_i + bc_j}{4 - b^2}, i = 1,2;\ j = 3 - i. \tag{9}$$

Substituting the optimal quantities of (9) into (5), the optimal prices are solved as:

$$p_i^* = \frac{(2-b)a + (2-b^2)c_i + bc_j}{4 - b^2}, i = 1,2;\ j = 3 - i. \tag{10}$$

By calculating the optimal profits of the two supply chains, we can derive the following proposition of the benchmark model:

Proposition 1. *In the Sub-game Perfect Equilibrium (SPE) of the asymmetric Cournot competition model of supply chains, the optimal profits of chains, manufacturers, and retailers are:*

[3] Instead of the demand function, we adopt the inverse demand function in our paper because we will be discussing the effects of capacity restrictions on the green supply chain, which can directly restrict the choice of optimal quantity.

$$\pi_i^{SC^*} = [\frac{(2-b)a-2c_i+bc_j}{4-b^2}]^2, i = 1; j = 3-i. \quad (11)$$

$$\pi_i^{M^*} = \pi_i^{R^*} = \frac{1}{2} \cdot [\frac{(2-b)a-2c_i+bc_j}{4-b^2}]^2, i = 1; j = 3-i. \quad (12)$$

It is clear that the optimal profit of the traditional supply chain is higher than that of the green supply chain, i.e., $\pi_1^{SC^*} > \pi_2^{SC^*} > 0$, because the cost of the latter chain is higher, $c_1 < c_2$. We denote the cost difference as $\Delta c \equiv c_2 - c_1$ and the profit difference as $\Delta\pi^{SC^*} \equiv \pi_1^{SC^*} - \pi_2^{SC^*}$. Similarly, we can define the price difference and the quantity difference in the equilibrium as $\Delta p^* \equiv p_2^* - p_1^*$ and $\Delta q^* \equiv q_1^* - q_2^*$, respectively. Some properties related to those differences can be summarized in the following lemma:

Lemma 1. *In the SPE of the asymmetric Cournot competition model of supply chains, as the cost difference between supply chains, Δc, increases, the price difference, Δp^*, the quantity difference, Δq^*, and the profit difference, $\Delta\pi^{SC^*}$, increases.*

Proof: Employing the equations in (10), (9) and (11), we can derive the expressions of three difference functions, respectively:

$$\Delta p^* = \frac{(2-b-b^2)\Delta c}{4-b^2},$$

$$\Delta q^* = \frac{(2-b)\Delta c}{4-b^2},$$

$$\Delta\pi^{SC^*} = \frac{2(2-b)a-(2-b)\Delta c}{4-b^2} \cdot \frac{(2+b)\Delta c}{4-b^2}.$$

Taking the first order derivatives of Δp^*, Δq^*, and $\Delta\pi^{SC^*}$ with respect to Δc, respectively, we have:

$$\frac{\partial\Delta p^*}{\partial\Delta c} = \frac{2-b-b^2}{4-b^2} > 0,$$

$$\frac{\partial\Delta q^*}{\partial\Delta c} = \frac{2-b}{4-b^2} > 0,$$

$$\frac{\partial\Delta\pi^{SC^*}}{\partial\Delta c} = \frac{2(2-b)a-(2-b)\Delta c}{4-b^2} \cdot \frac{(2+b)\Delta c}{4-b^2} = \frac{2(a-\Delta c)}{4-b^2} > 0$$

because $b \in (0,1)$ and $0 < c_1 < c_2 < a$.

From Lemma 1, we notice that—regardless of a decrease in c_1 or an increase in c_2, which result in an increase in Δc—as the production costs become more asymmetric, the green supply chain will suffer the lower optimal price, lower optimal quantity, and lower optimal profit. To encourage the development of the green supply chain, government may need to consider some policy measures to reduce this cost difference.

2.2. The asymmetric competing supply chains with government subsidy

In this section, government policy is introduced into our model. To encourage the use of environmentally friendly technology, the government issues a subsidy policy, s, to every product that the green supply chain sells to consumers. We can rewrite the profit functions of the green supply chain:

$$\pi_2^{SC} = q_2(a - q_2 - bq_1 - c_2 + s), \tag{13}$$

while the profit function of the traditional supply chain remains the same as (7). Taking the first order derivatives of (7) and (13) with respect to $p_i, i = 1,2$, we have the FOCs:

$$\frac{\partial \pi_1^{SC}}{\partial q_1} = a - 2q_1 - bq_2 - c_1 = 0, \tag{14}$$

$$\frac{\partial \pi_2^{SC}}{\partial p_2} = a - 2q_2 - bq_1 - c_2 + s = 0, \tag{15}$$

Solving equations (14) and (15), we can derive the best reaction functions:

$$q_1^* = \frac{a-c_1-bq_2}{2},\ q_2^* = \frac{a-c_2+s-bq_1}{2} \tag{16}$$

Solving the two equations above, the optimal quantities of the two chains are:

$$q_1^* = \frac{(2-b)a-2c_1+b(c_2-s)}{4-b^2}, q_2^* = \frac{(2-b)a-2(c_2-s)+bc_1}{4-b^2} \tag{17}$$

Substituting the optimal quantities of (17) into (5), the optimal prices are solved as:

$$p_1^* = \frac{(2-b)a+(2-b^2)c_1+b(c_2-s)}{4-b^2}, p_1^* = \frac{(2-b)a+(2-b^2)(c_2-s)+bc_1}{4-b^2}. \tag{18}$$

By calculating the optimal profits of the two supply chains, we can derive the following proposition of the benchmark model:

Proposition 2. *In the SPE of the asymmetric Cournot competition model of supply chains with government subsidy, the optimal profits of the chains are:*

$$\pi_1^{SC^*} = [\frac{(2-b)a - 2c_1 + b(c_2 - s)}{4 - b^2}]^2,$$

$$\pi_2^{SC^*} = [\frac{(2-b)a - 2(c_2 - s) + bc_1}{4 - b^2}]^2.$$

Note that the manufacturer and the retailer in each chain still share the chain profit equally, because they have balanced bargaining powers. By comparing the results of Proposition 2 with that of the benchmark model, we find that $\pi_1^{SC^*}$ decreases and $\pi_2^{SC^*}$ increases, hence the profit difference $\Delta\pi^{\mathrm{SC}^*}$ decreases as a result of imposing a subsidy on the green supply chain. Some properties related to the government's subsidy policy could be summarized in the following lemma:

Lemma 2. *In the SPE of the asymmetric Cournot competition model of supply chains with government subsidy, as the government subsidy of the green supply chain, s, increases, the price difference Δp^*, the quantity difference, Δq^*, and the profit difference, $\Delta\pi^{SC^*}$, decrease.*

Proof: Adopt similar procedures as for the proof of Lemma 1.

As shown in Lemma 2, the green supply chain enjoys a higher optimal price, higher optimal quantity, and higher optimal profit, as government increases its per-unit subsidy on the production of Chain 2. However, the green supply may face a manufacturing or retailing capacity restriction, which implies that Chain 2 is not able to produce sufficient quantity to satisfy consumer demand. This problem cannot be solved by the per-unit subsidy, and the green supply chain should seek funding from banks for investment in capacity. In the following section, we add the choice of corporate finance into our model and analyze the effects of the related financial uncertainty on capacity investment.

3. The model with financing uncertainty

3.1. Financing uncertainty on the investment of manufacturing capacity

In this section, we consider the case where only the green supply chain faces the manufacturing capacity restriction and needs to borrow from the financial institution to invest in capacity. To simplify the expressions, we assume that $c_1 = c_2 \equiv c$, given that chains are still asymmetric in the sense of capacity restrictions. To meet the demand of consumers, Manufacturer 2 needs to increase its capacity by Δk_2, and ask the financial institution for a loan $l(\Delta k_2)$, where l is an increasing function of Δk_2, i.e., $l'(\Delta k_2) > 0$. The financial institution agrees to lend the loan $l(\Delta k_2)$ with an exogenous probability $u \in (0,1)$, and uses $r \in (0,1)$ as the interest rate. Hence, in this Cournot competition model of supply chains with asymmetric financing uncertainty in manufacturing capacity investment, the timing of the game becomes:

1. Manufacturer 2 in the green supply chain, who faces a capacity restriction, asks the financial institution for a loan, $l(\Delta k_2)$, to increase its capacity. The financial institution approves the loan application with probability $u \in (0,1)$. If the loan is approved, Manufacturer 2 will receive the full loan amount with an interest rate $r \in (0,1)$.
2. The manufacturers and retailers in the two supply chains bargain simultaneously on the wholesale price, $w_i, \mathrm{i} = 1,2$.
3. The manufacturers and the retailers in the two supply chains simultaneously agree on the desired retailer order quantity, $q_i, \mathrm{i} = 1,2$. Thereafter, the quantities of q_i are fully produced and delivered by the manufacturer.
4. The retailing prices $p_i, \mathrm{i} = 1,2$, are determined by market demand, and sales take place. After retailing, Manufacturer 2 pays interest, $rl(\Delta k_2)$, to the financial institution and every player receives its payoff.

Because of the financing uncertainty, there are two possible situations in this model. If Manufacturer 2 has received the loan and makes an investment, its capacity increases; we denote the quantity and the price as q_i^h and p_i^h, respectively; similarly, let q_i^l and p_i^l denote the quantity and price if the loan application has been rejected and the capacity of Manufacturer 2 remains low. The expected profit functions of the green supply chain are the following:

$$\pi_2^{SC} = u[q_2^h(p_2^h - c) - rl(\Delta k_2)] + (1-u)q_2^l(p_2^l - c),$$
$$\pi_2^{M} = u[q_2^h(w_2^h - c) - rl(\Delta k_2)] + (1-u)q_2^l(w_2^l - c),$$
$$\pi_2^{R} = uq_2^h(p_2^h - w_2^h) + (1-u)q_2^l(p_2^l - w_2^l),$$

where $q_2^h = k_2 + \Delta k_2$, $q_2^l = k_2$. In this section, financing behavior constitutes complete information and every player in the game observes the outcome of the loan application. The financing uncertainty is resolved before a retail price p_i is chosen.

Before analyzing the optimal choices of the chains, we need to add a new assumption here to guarantee that the capacity restriction of Manufacturer 2 truly holds. By taking $c_1 = c_2 \equiv c$ into (9) and (11), we can derive the optimal quantity and optimal profit of symmetric chains without financing uncertainty as follows:

$$q_i^* = \frac{a-c}{2+b},\ i = 1,2. \tag{19}$$

$$\pi_i^{SC^*} = (\frac{a-c}{2+b})^2,\ i = 1,2. \tag{20}$$

Note that if there is no financing, the green supply chain faces the capacity restriction which implies that q_2^* should be strictly larger than the capacity k_2, otherwise the capacity of Manufacturer 2 is not a restriction. Hence, we assume that $\frac{a-c}{4+b} > k_2$. However, Manufacturer 1 does not face any capacity restriction, and can produce its optimal quantity. The expected profit functions of the traditional supply chain are the following:

$$\pi_1^{SC} = uq_1^h(p_1^h - c) + (1-u)q_1^l(p_1^l - c),$$
$$\pi_1^{M} = uq_1^h(w_1^h - c) + (1-u)q_1^l(w_1^l - c),$$
$$\pi_1^{R} = uq_1^h(p_1^h - w_1^h) + (1-u)q_1^l(p_1^l - w_1^l).$$

Given that Manufacturer 2 faces the capacity restriction if it has not received the loan, $q_2^l = k_2$, we can rewrite the following expected profit functions of the supply chains:

$$\pi_1^{SC} = uq_1^h(a - q_1^h - bq_2^h - c) + (1-u)q_1^l(a - q_1^l - bk_2 - c), \tag{19}$$

$$\pi_2^{SC} = u\left[q_2\left(a - q_2^h - bq_1^h - c\right) - rl\left(q_2^h - k_2\right)\right] + (1-u)k_2\left(a - k_2 - bq_1^l - c\right). \tag{20}$$

Taking the first order derivatives with respect to q_1^l, q_1^h, and q_2^h, we have three FOCs:

$$\frac{\partial \pi_1^{SC}}{\partial q_1^l} = a - 2q_1^l - bk_2 - c = 0, \tag{21}$$

$$\frac{\partial \pi_1^{SC}}{\partial q_1^h} = a - 2q_1^h - bq_2^h - c = 0, \tag{22}$$

$$\frac{\partial \pi_2^{SC}}{\partial q_2^h} = u[a - 2q_2^h - bq_1^h - c) - rl'(\Delta k_2)] = 0. \tag{23}$$

Rearranging equations (21)–(23), we can derive the following best reaction functions:

$$q_1^{l^*} = \frac{a-c-bk_2}{2}, \tag{24}$$

$$q_1^{h^*} = \frac{a-c-bq_2^h}{2}, \tag{25}$$

$$q_2^{h^*} = \frac{a-c-rl\prime(\Delta k_2)-bq_1^l}{2}. \tag{26}$$

Note that the optimal choice of $q_1^{l^*}$ has been derived in (24), given that $q_2^{l^*} = k_2$. Solving equations (25) and (26), the optimal quantities of two chains when Manufacturer 2 has increased its capacity are:

$$q_1^{h^*} = \frac{(2-b)(a-c)+brl\prime(\Delta k_2)}{4-b^2}, \tag{27}$$

$$q_2^{h^*} = \frac{(2-b)(a-c)-2rl\prime(\Delta k_2)}{4-b^2}. \tag{28}$$

Note that $q_1^{h^*} > \frac{a-c}{2+b} > q_2^{h^*}$, where $\frac{a-c}{2+b}$ is the optimal quantity of two symmetric chains without capacity restriction. Due to the capacity restriction of Manufacturer 2, Chain 1 can supply more output compared to the benchmark model, while Chain 2 supplies less. We need the inequality condition $q_2^{h^*} > k_2$ to hold, otherwise Manufacturer 2 will lack the incentive to invest in capacity. By deriving $q_2^{h^*} > k_2$, we get

$$r < \bar{r} \equiv \frac{(2-b)(a-c)-(4-b^2)k_2}{2l'(\Delta k_2)}, \tag{29}$$

which implies that the affordable interest rate range for Manufacturer 2, $r \in [0, \bar{r}]$. Note that the inequality (29) is not affected by the financing uncertainty coefficient u. Substituting (24), (27), (28), and $q_2^l = k_2$ into (5), we can derive the optimal prices of two chains in two possible situations:

$$p_1^{l^*} = \frac{a+c-bk_2}{2}, \tag{30}$$

$$p_2^{l^*} = \frac{(2-b)a+bc-(1-b^2)k_2}{2}, \tag{31}$$

$$p_1^{h^*} = a - \frac{(2+b-b^2)(a-c)-brl\prime(\Delta k_2)}{4-b^2}, \tag{32}$$

$$p_2^{h^*} = a - \frac{(2+b-b^2)(a-c)-(2-b^2)rl'(\Delta k_2)}{4-b^2}. \tag{33}$$

Note that the financing uncertainty u is not included in all expressions of optimal quantities (24), (28) and (29), or in all expressions of optimal prices (30)–(33). This follows because in this complete information case, each player observes the outcome of the loan application before the optimal quantities and prices are determined. The game can be reduced into two sub-games of complete information, with the results remaining the same. By calculating the optimal profits of the two supply chains, we can derive the following proposition of the model:

Proposition 3. *In the SPE of the Cournot competition model of supply chains with asymmetric financing uncertainty in manufacturing capacity, the optimal profits are:*

$$\pi_1^{SC^*} = u[\frac{(2-b)(a-c)+brl'(\Delta k_2)}{4-b^2}]^2 + \frac{(1-u)(a-c-bk_2)^2}{4}, \quad (34)$$

$$\pi_2^{SC^*} = u\left[\frac{(2-b)(a-c)-2rl'(\Delta k_2)}{4-b^2} \cdot \frac{(2-b)(a-c)+(2-b^2)rl'(\Delta k_2)}{4-b^2} - rl(\Delta k_2)\right] + (1-u)k_2 \frac{(2-b)(a-c)-(1-b^2)k_2}{2}. \quad (35)$$

Recalling that the optimal profit of symmetric chains without financing uncertainty (20), $\pi_i^{SC^*} = (\frac{a-c}{2+b})^2,\ i = 1, 2$, we can derive that the optimal profit of the traditional supply chain (34) is higher than $(\frac{a-c}{2+b})^2$, and the optimal profit of the green supply chain (35) is lower than $(\frac{a-c}{2+b})^2$, i.e., $\pi_1^{SC^*} > (\frac{a-c}{2+b})^2 > \pi_2^{SC^*}$. Some properties related to this inequality can be summarized in the following lemma:

Lemma 3. *In the SPE of the Cournot competition model of supply chains with asymmetric financing uncertainty in terms of manufacturing capacity, as the financing uncertainty of the green supply chain, u, increases, the optimal profit of the traditional supply chain decreases and the optimal profit of the green supply chain increases.*
Proof: See the Appendix A.

Lemma 3 shows that a preferential policy to provide more financing opportunities to the green supply chain will encourage its development. By increasing the probability of getting the loan, the green supply chain will be better off if its corporate finance risk reduces. However, does this result still hold when the financing uncertainty represents incomplete information to the traditional supply chain?

3.2. The asymmetric information of financing uncertainty

If the financing uncertainty represents incomplete information to the traditional supply chain, we can rewrite the following expected profit functions of the two chains:

$$\pi_1^{SC} = uq_1(a - q_1 - bq_2^h - c) + (1-u)q_1(a - q_1 - bq_2^l - c),$$

$$\pi_2^{SC} = u[q_2^h(a - q_2^h - bq_1 - c) - rl(q_2^h - k_2)] + (1-u)q_2^l(a - q_2^l - bq_1 - c),$$

where $q_2^l = k_2 < q_2^h = k_2 + \Delta k_2$. Note that there is only a single quantity choice q_1 for the traditional supply chain because it cannot observe the result of the loan application. The traditional supply chain has to decide the optimal quantity choice q_1 in dealing with two possible situations, but it is not able to distinguish which situation the chain faces. Taking the first order derivatives with respect to q_1 and q_2^h, we have the following FOCs:

$$\frac{\partial \pi_1^{SC}}{\partial q_1} = u\left(a - 2q_1 - bq_2^h - c\right) + (1-u)(a - 2q_1 - bk_2 - c) = 0, \quad (36)$$

$$\frac{\partial \pi_2^{SC}}{\partial q_2^h} = u[a - 2q_2^h - bq_1 - c - rl'(\Delta k_2)] = 0. \quad (37)$$

We can then solve the best reaction functions:

$$q_1^* = \frac{a-c-(1-u)bk_2-ubq_2^h}{2}, \quad (38)$$

$$q_2^{h^*} = \frac{a-c-rl\prime(\Delta k_2)-bq_1}{2}. \quad (39)$$

Solving the two equations above, the optimal quantities of the two chains are:

$$q_1^* = \frac{(2-ub)(a-c)+ubrl'(\Delta k_2)-2(1-u)bk_2}{4-ub^2}, \quad (40)$$

$$q_2^{h^*} = \frac{(2-b)(a-c)-2rl'(\Delta k_2)+(1-u)b^2k_2}{4-ub^2}. \quad (41)$$

Note that we still need the inequality condition $q_2^{h^*} > k_2$ to hold, otherwise Manufacturer 2 will lack the incentive to invest in its capacity. By deriving $q_2^{h^*} > k_2$, we still get

$$r < \frac{(2-b)(a-c)-(4-b^2)k_2}{2l'(\Delta k_2)},$$

which is the same inequality as (29); this inequality is not affected by the financing uncertainty coefficient u. By taking the first order derivative of $q_2^{h^*}$ with respect to r, we have:

$$\frac{\partial q_1^*}{\partial u} = \frac{2b[2rl'(\Delta k_2)-(2-b)(a-c)+(4-b^2)k_2]}{(4-ub^2)^2}. \quad (42)$$

We can derive that $\frac{\partial q_1^*}{\partial u} < 0$ if and only if inequality (29) holds. If $u = 0$, $q_1^* = q_1^{l^*} = \frac{a-c-bk_2}{2}$, which is the optimal quantity of Chain 1 given that it receives the information that Manufacturer 2 has not obtained the loan from the financial institution in (24); If $u = 1$, $q_1^* = q_1^{h^*} = \frac{(2-b)(a-c)+brl\prime(\Delta k_2)}{4-b^2}$, which is the optimal quantity of Chain 1 given that it receives the information that Manufacturer 2 has obtained the loan and increased the capacity successfully in (27). We can derive that

$$q_1^* = uq_1^{h^*} + (1-u)q_1^{l^*}, \quad (43)$$

which implies that the optimal quantity choice of Chain 1 in the incomplete information model is a weighted average of two optimal quantities in the complete information case, by using the financing uncertainty of Chain 2, u, as the weight. Compared to the complete information model, Chain 2 will face less intense competition if it has not obtained the loan, since Chain 1 will choose a quantity $q_1^* < q_1^{l^*}$; otherwise, if Chain 2 has obtained the loan, it will face more intense competition, since Chain 1 will choose a quantity $q_1^* > q_1^{h^*}$.

Similarly, we can derive that

$$\frac{\partial q_2^{h^*}}{\partial u} = \frac{b^2[(2-b)(a-c)-2rl'(\Delta k_2)-(4-b^2)k_2]}{(4-ub^2)^2}. \quad (44)$$

We find that $\frac{\partial q_2^{h^*}}{\partial u} > 0$ if and only if inequality (29) holds. Compared to the optimal quantity of Manufacturer 2, who successfully increases its capacity in the case of complete information in (28), we can find that $q_2^{h^*}$ in the incomplete information model is lower. This follows because Manufacturer 1 can only choose a quantity q_1^* to produce in two possible situations and $q_1^* > q_1^{h^*}$. We can calculate the difference by considering (44) minus (28),

$$\Delta q_2^{h^*} = \frac{(u-1)b^2[(2-b)(a-c)-2rl'(\Delta k_2)-(4-b^2)k_2]}{(4-b^2)(4-ub^2)}.$$

Because $u \in (0,1)$ and inequality (29) holds, we can derive that $\Delta q_2^{h^*} < 0$.

We can then calculate the optimal prices of the two chains:

$$p_1^{l^*} = a - \frac{(2-ub)(a-c)+ubrl'(\Delta k_2)+(2+2u-ub^2)bk_2}{4-ub^2}, \tag{46}$$

$$p_2^{l^*} = a - \frac{(2-ub)b(a-c)+ub^2rl'(\Delta k_2)-(4-2b^2)k_2}{4-ub^2}, \tag{47}$$

$$p_1^{h^*} = a - \frac{(2+2b-ub-b^2)(a-c)-(2-u)brl'(\Delta k_2)-(1-u)(2-b^2)bk_2}{4-ub^2}, \tag{48}$$

$$p_2^{h^*} = a - \frac{(2+b-ub^2)(a-c)-(2-ub^2)rl'(\Delta k_2)-(1-u)bk_2}{4-ub^2}. \tag{49}$$

Summarizing the results above, we can get the following proposition about the optimal quantities and optimal prices in the incomplete information model:

Proposition 4. *In the Perfect Bayesian Equilibrium (PBE) of the Cournot competition model of supply chains with asymmetric financing uncertainty of manufacturing capacity, for the optimal quantities,* $q_1^* = uq_1^{h^*} + (1-u)q_1^{l^*}$, *and* $q_1^{h^*} < q_1^* < q_1^{l^*}$; $q_2^{l^*} \equiv k_2$, $q_2^{h^*}$ *is lower in comparison with the complete information case. For the optimal prices,* $p_1^{l^*}$, $p_2^{l^*}$ *are higher in comparison with the complete information case. The effects on* $p_1^{h^*}$ *and* $p_2^{h^*}$ *depend on the value of* $r \in (0, \bar{r}]$; *if* $r \in (0, r^*)$, $p_1^{h^*}$ *and* $p_2^{h^*}$ *are higher; if* $r \in (r^*, r^{**})$, $p_1^{h^*}$ *is lower and* $p_2^{h^*}$ *is higher; if* $r \in (r^{**}, \bar{r}]$, $p_1^{h^*}$ *and* $p_2^{h^*}$ *are lower, in comparison with the complete information case.*[4]

Proof: The first part of the proposition, which comprises the discussions of optimal quantities, has been shown above; for the second part of the proposition, which comprises the discussions of optimal prices, see the Appendix B.

We have discussed the complete and incomplete information models of the effect of financing uncertainty on manufacturing capacity. What would happen if Retailer 2, instead of Manufacturer 2, faces the capacity restriction?

4 We could still discuss the properties of optimal profits in the incomplete information model as Proposition 3. However, the expected profit functions in this section become much more complicated, and we cannot derive many explicit results. Hence, we omit the discussion of optimal profits from this section.

3.3. Financing uncertainty on the investment of retailing networks

In this section, we consider the case that only the green supply chain needs to receive financing from banks to invest in its retailing capacity to meet market demand. In this model, Retailer 2 needs to increase its capacity by Δk_2, and ask the financial institution for the loan $l(\Delta k_2)$ with an interest rate r. Similarly, we can write the expected profit functions of the green supply chain when it faces a retailing capacity constraint, and can receive the loan $l(\Delta k_2)$ with probability u:

$$\pi_2^{SC} = u[q_2^h(p_2^h - c) - rl(\Delta k_2)] + (1-u)q_2^l(p_2^l - c),$$
$$\pi_2^M = uq_2^h(w_2^h - c) + (1-u)q_2^l(w_2^l - c),$$
$$\pi_2^R = uq_2^h[p_2^h - w_2^h - rl(\Delta k_2)] + (1-u)q_2^l(p_2^l - w_2^l),$$

where $q_2^h = k_2 + \Delta k_2, q_2^l = k_2$. One can find that the chain profit of π_2^{SC} is exactly the same as for the model of manufacturing capacity, while the chain profit of π_1^{SC} remains unchanged as in the previous model. Hence, we can derive the following proposition:

Proposition 5. *In the Cournot competition model of supply chains with asymmetric financing uncertainty, the optimal quantities, optimal prices, and optimal profits are the same for both the manufacturing capacity restriction case and the retailing capacity restriction case, regardless of whether the financing uncertainty represents complete or incomplete information.*

The main results of our analysis remain the same in the case of a retailing capacity restriction, because the bargaining powers of the manufacturer and retailer in both supply chains are balanced, i.e., $\alpha = 0.5$. The manufacturing and retailing capacity restrictions cause similar effects on chain profit, which is shared equally by the manufacturer and the retailer. However, do the results in the previous analysis still hold if the bargaining powers of the manufacturer and retailer are unbalanced?

3.4. The unbalanced bargaining powers

In the previous analysis, we assumed that the bargaining power parameter between a manufacturer and a retailer in any supply chain, $\alpha = 0.5$, to derive the explicit functions of equilibrium quantities, prices, and profits. However, α could be any value within the interval $[0,1]$. Recall that the Nash Bargaining Product model of choosing a wholesale price w_i is:

$$\text{Max}_{w_i}\{\Phi_i(w_i)\} = \text{Max}_{w_i}\{(\pi_i^M)^\alpha(\pi_i^R)^{1-\alpha}\}, \qquad i = 1,2.$$

By taking the first order derivative with respect to α, we can derive the F.O.C. condition,

$$\alpha q_i^\alpha (w_i - c)^{\alpha-1} - (1-\alpha)q_i^{1-\alpha}(p_i - w_i)^{-\alpha} = 0. \qquad (51)$$

Rearranging equation (51), we can derive

$$\frac{(p_i - w_i^*)^{\alpha}}{(w_i^* - c)^{1-\alpha}} = \frac{(1-\alpha)}{\alpha} q_i^{1-2\alpha}. \quad (52)$$

Note that as α increases, w_i^* must increase for the equation to hold. Hence, w_i^* is increasing in α. An increase in the bargaining parameter α will result in an increase in the wholesale price and an increase in the manufacturer's share of chain profit. Given any $\alpha \in (0,1)$, we can still derive consistent properties of market equilibria as in our previous analysis, except that the shares of profit distribution between manufacturer and retailer are different. Although the explicit functions of optimal quantities, optimal prices, and optimal profits in competing equilibria for the general bargaining power parameter α cannot be solved, we can use some values of $\alpha \in [0,1]$, other than 0.5, to repeat the previous analysis. The simplest cases should be $\alpha = 0$ and $\alpha = 1$, which are equivalent to the cases of Vertical Integration (VI) and Manufacturer's Stackelberg (MS) in [25]. By assuming $\alpha = 0$ or $\alpha = 1$, we can derive the same propositions and lemmas as in the previous analysis, except for the wholesale prices and the shares of chain profit between manufacturers and retailers. This follows because in two extreme cases, only the retailers or the manufacturers in the supply chain receive all the chain profit.

4. Conclusions

In this paper, we introduced the Cournot competition model of asymmetric supply chains as the benchmark, and discussed the effect of a per-unit subsidy policy to deal with the problem of asymmetric costs between traditional and green supply chains. We then added the financing uncertainty about capacity investment into the benchmark model. The financing uncertainty of the green supply chain's capacity investment could be available as complete or incomplete information to the traditional supply chain. We find that, in the complete information case, the financing uncertainty of capacity investment does not affect the choices of optimal quantities and optimal prices, because both chains can observe the outcome of the loan application. If this information is incomplete for the traditional supply chain, the financing uncertainty plays an important role in the determination of optimal quantities and optimal prices, together with the interest rate of the loan. In either case, the green supply chain benefits from the preferential loan, which could increase its probability of getting the loan for capacity investment.

Some policy implications can be derived from the model results. To encourage the development of green supply chains, government should use per-unit subsidy if the green supply chain suffers the cost disadvantage, and should encourage financial institutions to provide preferential loans to a green supply chain if it faces capacity restrictions. Specifically, if government wants the manufacturer in a supply chain with retailing capacity restrictions to adopt environmentally friendly technology, it may be useful to encourage financial institutions to provide loans to increase the retailer's capacity, which could in turn increase the total chain profit.

A limitation of our model is that the financial institution's decision is not endogenous, due to the model's complexity. It could be an interesting approach for government to motivate financial intuitions to provide more preferential loans for the development of green supply chains. The model framework could be richer if the optimal loan decisions of financial intuitions, or perhaps competition among financial intuitions, were added. Another possible direction for further research is the empirical verification of model results. By collecting the data of some traditional and green supply chains, an empirical analysis may assist with the deduction of more detailed policy and practical implications for green supply chain development.

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Appendix A

The proof of Lemma 3

Proof: Taking the first order derivatives of $\pi_1^{SC^*}$ with respect to u, respectively, we have:

$$\frac{\partial \pi_1^{SC^*}}{\partial u} = \left[\frac{(2-b)(a-c)+brl'(\Delta k_2)}{4-b^2} + \frac{a-c}{2}\right] \cdot \frac{brl'(\Delta k_2)-(2-b)(a-c)}{4-b^2}. \quad \text{(A.1)}$$

Because $r < \bar{r} \equiv \frac{(2-b)(a-c)-(4-b^2)k_2}{2l'(\Delta k_2)}$ as shown in (29), we can derive that $brl'(\Delta k_2) - (2-b)(a-c) < 0$, while other parts of (A.1) are positive. Hence, we can derive that $\frac{\partial \pi_1^{SC^*}}{\partial u} < 0$.

Using the similar procedure and apply the inequality (29), we can also derive that $\frac{\partial \pi_2^{SC^*}}{\partial u} > 0$.

Appendix B

The proof of Proposition 4 (second part)

Proof: For the changes of optimal prices, $q_1^* < q_1^{l^*}$, and $q_2^{l^*} \equiv k_2$, recall the inverse demand function in (5),

$$p_i = a_i - q_i - b_i q_j, i = 1,2; \; j = 3-i.$$

We can derive that $p_1^{l^*}$, $p_2^{l^*}$ are higher in comparison with the complete information case.

To analyze the effects on $p_1^{h^*}$, we calculate (48) minus (32) derive:

$$\Delta p_1^{h^*} = \frac{(1-u)(2-b^2)}{(4-b^2)(4-ub^2)}[b(2-b)(a-c) - 2rl'(\Delta k_2) - (4-b^2)k_2]. \tag{B.1}$$

Let denote $r^* \equiv \frac{b(2-b)(a-c)-(4-b^2)k_2}{2l'(\Delta k_2)}$. Because the substituting coefficient $b \in (0,1)$, $r^* < \bar{r}$, where $\bar{r}$ is the highest affordable interest rate for Manufacturer 2.

Similarly, by using (49) minus (33), we can derive:

$$\Delta p_2^{h^*} = \frac{b^2(1-u)}{(4-b^2)(4-ub^2)}[(2-b)(a-c) - 2rl'(\Delta k_2) - \frac{(4-b^2)}{b}k_2]. \tag{B.2}$$

Let denote $r^{**} \equiv \frac{b(2-b)(a-c)-(4-b^2)k_2}{2bl'(\Delta k_2)}$. Because the substituting coefficient $b \in (0,1)$, $r^* < r^{**} < \bar{r}$, where $\bar{r}$ is the highest affordable interest rate for Manufacturer 2.

Hence, if $r \in (0, r^*)$, $p_1^{h^*}$ and $p_2^{h^*}$ are higher; if $r \in (r^*, r^{**})$, $p_1^{h^*}$ is lower and $p_2^{h^*}$ is higher; if $r \in (r^{**}, \bar{r}]$, $p_1^{h^*}$ and $p_2^{h^*}$ are lower, in comparison with the complete information case.

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