Transportation Research Part E 47 (2011) 573–592

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Bargaining framework for competitive green supply chains under governmental financial intervention

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ARTICLE INFO

Article history:
Received 5 July 2010
Received in revised form 12 September 2010
Accepted 27 December 2010

Keywords:
Green supply chain cooperation
Bilateral negotiation
Nash bargaining game
Government's financial instruments

ABSTRACT

This work investigates the problem of negotiations between producers and reverse-logistics (RL) suppliers for cooperative agreements under government intervention. Utilizing the asymmetrical Nash bargaining game with uncertainties, this work seeks equilibrium negotiation solutions to player agendas. Analytical results indicate that financial intervention by a government generates a significant effect on the relative bargaining power of green supply chain members in negotiations. Over intervention by a government may result in adverse effects on chain members' profits and social welfare. Furthermore, a bargaining framework underlying the duopoly–oligopoly context may contribute to a negotiation outcome most profitable for green supply chain members.

1. Introduction

As global environmental issues emerge along with the involvement of governments via green legislation and financial instruments (e.g., green taxation and subsidies), interaction between a producer[1] and reverse-logistics (RL) suppliers[2] is unavoidable in a green supply chain before the condition of cooperative synergism is attained. For example, the impact of the European Waste Electrical and Electronic Equipment (WEEE) and Restriction on Hazardous Substances (RoHS) directives increased costs by 3% for branded firms and 5–10% for manufacturers of consumer electronics (Ho and Kretz, 2005). Such WEEE-induced extra expenses and responsibilities have increased producer awareness of the need to cooperate with RL-suppliers. A producer selling consumer electronics products to the European Union (EU) is required to collect and recycle used-products to comply with WEEE directives. One can then postulate an interaction process in which the producer negotiates with its RL-supplier before achieving a cooperative supply chain relationship for WEEE compliance. When a government's financial instruments are involved, the relative power of producers and RL suppliers is likely to be altered, which may complicate the interaction among chain members and solutions for green supply chain coordination. A typical example is green taxation, where governments levy green taxes on producers and subsidize the recycling industry using the money raised to promote ecologically sustainable activities (Luk, 2005). Additionally, numerous practical cases have indicated that producers used to be defined as powerful supply chain members need help from RL-suppliers to comply with take-back directives; otherwise, producers may take on considerable risk of violating WEEE directives and losing EU markets (Deffree, 2007). Accordingly, adopting a bargaining theory that addresses issues of vertical integration in green supply chains is indispensable, particularly in global operation contexts.

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[1] "Producers" refers to manufacturers and firms that sell products under their own brands.

[2] An RL-supplier is defined as a member that provides RL-related services, including used-product collection and recycling, to the producer in a green supply chain.

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doi:10.1016/j.tre.2010.12.006

Despite the importance of understanding how green supply chain members interact through the bargaining process to move toward green supply chain coordination, previous studies of such member interactions are limited in the field of green supply chain management (GSCM) and related areas. Nagarajan and Bassok (2008) noted that research modeling relationships between agents in a supply chain using economic bargaining theory is limited in operations management literature (van Mieghem, 1999; Gurnani and Shi, 2006; Plambeck and Taylor, 2007a,b; Taylor, 2007). van Mieghem (1999) applied a two-stage stochastic game to address issues associated with outsourcing between a producer and its subcontractor, which build capacity before realizing demand. The role of bargaining power was introduced to analyze the scenario with incomplete contracts. Gurnani and Shi (2006) utilized a Nash bargaining (NB) game to compute optimal contract price and quantity of trade in a supplier–buyer distribution channel under asymmetrical beliefs held by dyadic channel members of supply reliability. Plambeck and Taylor (2007a,b) recently investigated several issues such as investments in innovation and capacity allocation in supply chains, and renegotiation effects on supply contract design. Taylor (2007) addressed the impact of repeated interactions on capacity investment and procurement in a supplier–buyer supply chain, where repeated game theory is applied to generate an optimal relational contract for a long-term supply chain relationship. Nagarajan and Bassok (2008) developed a sequential bargaining framework to address the assembly problem in a decentralized supply chain, where a single assembler buys complementary components from multiple suppliers that form coalitions to negotiate with the assembler on profit allocations in the supply chain. Relative to existing literature, this work focuses on negotiation between producers and RL-suppliers in competitive green supply chains under oligopoly competition and governmental green strategies. Thus, the negotiation issue addressed is extended in this work, where intra-chain cooperation and inter-chain competition in green supply chains are driven by governmental take-back legislation and financial instruments.

Additionally, a vast amount of supply chain contract literature focuses on design of coordinating mechanisms that are generally tied to specific structures of supply chains by assuming asymmetrical bargaining power between supply chain members. The supply chain coordination problems are then solved by allocating the first-best profit among chain members using cooperative game theory. Typical among these are buy-back contracts (Pasternack, 1985), quantity–flexibility contracts (Tsay, 1999), price–discount contracts (Bernstein and Federgruen, 2005), and revenue-sharing contracts (Cachon and Lariviere, 2005; Koulamas, 2006). For instance, Cachon and Lariviere (2005) discussed in-depth the strengths and limitations of revenue-sharing contracts. They demonstrated that revenue-sharing mechanisms are very promising in coordinating dyadic members of supplier–retailer supply chains. A comprehensive review can also be found in Cachon (2003). Furthermore, some efforts have focused on other coordination mechanisms such as two-part tariffs and vender-managed inventory (VMI) when retailers are dominant (Mishra and Raghunathan, 2004; Raju and Zhang, 2005; Kurata, 2006).

Although notable advances in cooperative contracts have been made by scholars, literature is generally limited to the scope of typical supply chain coordination, and does not discuss the influence of bargaining power in green supply chains or address the issue of interaction between forward and reverse supply chain members under governmental green legislation and financial intervention. These shortcomings provide a research opportunity. In reality, evidence from practical cases spanning diverse industries has indicated that negotiation is the antecedent of cooperative contracts in which the relative power of chain members underlies the negotiation process for green supply chains. Conversely, according to Wilson (2006), global recycling industries are attempting to increase awareness of the effects green legislation will have on producers, leaving room to increase benefits when negotiating with producers. Issues such as bargaining power and its influence on green supply chain coordination (e.g., coordination between producers and RL-suppliers) warrant further investigation.

Rooted in the conceptual framework proposed by Sheu et al. (2005), this work focuses on the negotiations between producers and RL-suppliers in competitive green supply chains under the influence of governmental take-back legislation and financial intervention. Specifically, this work addresses the following research questions.

1. How do producers and RL-suppliers interact in bilateral negotiations for cooperative agreements?
2. What are the major concerns of producers and RL-suppliers in bilateral negotiations under governmental intervention, and how do they adapt to these influences while moving toward equilibrium bargaining solutions?
3. How does bargaining power influence the negotiation decisions of dyadic players for a cooperative agreement in a green supply chain contingent on governmental financial intervention?
4. If governmental financial intervention via green taxation and subsidies is indispensable to holding producers responsible for environmental impact, what are the equilibrium solutions of a unit green tax and subsidy? Additionally, how do financial instruments influence the decisions of producers and RL-suppliers in negotiations for green supply chain cooperation?

Compared with typical problems associated with supply chain cooperation, the issue addressed in this work has the following different features. First, this work aims at the green supply chain cooperation case under governmental intervention by means of take-back legislations and financial measures. Although economic incentives (e.g., cost minimization and profit maximization) remain important in any supply chain, cooperation between a producer and RL-supplier in a green supply chain is based on the need for extended producer responsibility (EPR). Therefore, it is logically agreed that a producer needs to seek for an appropriate RL-supplier to form a cooperative green supply chain for take-back legislation compliance in advance of making production decisions. For example, regardless of the reliability and efficiency of virgin-complements (VC) supply provided by VC suppliers in the high-tech industry, producers often require collaboration from RL-suppliers to collect and recycle products in the EU to comply with WEEE directives. Global benchmark branded firms, such as IBM, Hewlett-

Packard, Xerox, Sony, and ASUS are increasingly focusing on their core competencies while contracting out their EPR via sophisticated negotiation mechanisms to gain sustainable competitive advantage (Ho and Kretz, 2005; Lee, 2008; Weber, 2008). Second, under governmental influence and strategic threats from competitors, negotiation between a producer and RL-supplier is indispensable before reaching cooperative green supply and take-back agreements. This is followed by determination of green production for competition. Therein, a producer must consider the response of an RL supplier in negotiation and the bidding effect of its competitors, which may provide alternatives (called outside options in Muthoo, 2002) to the RL-supplier, on the negotiated decision of the RL-supplier and *vice versa*. Additionally, government involvement via green legislation and financial intervention (e.g., green taxes and subsidies) is increasingly recognized as a major coercive influence promoting EPR (Hammond and Beullens, 2007; Atasu et al., 2009). Consequently, the relative bargaining power of producers and RL-suppliers may change, increasing the complexity of interactions between producers and RL suppliers. This is also why this work accounts for relative bargaining power and formulates this power as a function dependent on governmental financial instruments in the proposed producer-RL-supplier bargaining framework. Incorporating bargaining power into a producer and RL supplier bargaining framework to characterize the factors influencing player solutions in negotiations differs from existing models that focused on closed-loop supply chain network equilibrium (Nagurney and Toyasaki, 2005; Hammond and Beullens, 2007).

From a methodological perspective, the proposed model has the following features. First, this model incorporates the influences of governmental take-back directives and financial intervention into the bargaining framework of competing green supply chains to approximate the equilibrium bargaining solutions of producers and RL-suppliers for used-product collection, recycling, and final product production. To the best of our knowledge, such a bargaining framework characterizing the problem of negotiations between producers and RL-suppliers under the influence of governmental green strategies is limited in previous GSCM studies. Second, this work formulates the aforementioned problem of negotiation between a producer and RL-supplier using a novel asymmetrical NB game model. Thus, several uncertainty issues existing in reservation prices of dyadic negotiators, expected profits and breakdown risks from outside options (i.e., cooperating with other partners) are considered in model formulation. Some bargaining theories have recently been proposed to deal with uncertainty issues such as random disagreement points in NB solutions (Chun and Thompson, 1990; Smorodinsky, 2005) and bargaining over alternatives with Markov processes (Merlo and Wilson, 1995; Herings and Predtetchinski, 2009). Unlike those theoretical works, model development in this work is focused on problem solving for green supply chain cooperation. Nevertheless, the proposed treatments in dealing with the aforementioned uncertainty issues are novel applications of NB game theory. Moreover, we assume the relative bargaining power of producers and RL-suppliers is affected by governmental green tax and subsidy policies rather than a given value, as did in literature using asymmetrical NB solutions (Muthoo, 2002). Therefore, the proposed model specifies the respective bargaining-power functions to characterize the effect of governmental financial intervention on bargaining solutions of producers and RL suppliers during negotiations.

Notably, in this work, take-back legislation is treated as a prerequisite to model formulation and analysis, even though this legislation is one of the government's primary instruments to keep production green and manage product lifecycles. Furthermore, the issue of efficient take-back legislation was addressed by Atasu et al. (2009), and may provide insights in the government's use of legislation as a coercive strategy complementing this work. Drawing from the work by Atasu et al. (2009), we assume target collection and recycling rates are adjustable on a case-by-case basis and are given. Nevertheless, differing from Atasu et al. (2009), who considered the potential of subsidizing producers for recycling, this work considers another taxation subsidy scenario in which governments levy green taxes on producers and subsidize RL-suppliers (Luk, 2005). Furthermore, the aim and scope of this work are not limited to the interaction between government and producers. Rather, the main purpose is to develop a bargaining framework that considers the potential problems and solutions in interactions between producers and RL suppliers moving toward green supply chain coordination under governmental take-back legislation and the financial instruments mentioned.

The remainder of this paper is organized as follows. Section 2 defines the producer and RL-supplier negotiation problem through a bargaining framework characterizing problem scope, assumptions, and bargaining structure. In Section 3, a three-stage game-based model is formulated and solved using the asymmetrical NB game and backward induction approaches. Based on the derived equilibrium solutions, Section 4 presents qualitative and quantitative analyses to gain insight into the influence of governmental financial intervention in the specified bargaining framework for a producer and RL-supplier. Section 5 gives conclusions and recommendations.

2. Bargaining framework

This section describes a bargaining framework for negotiation problems for producers and RL-suppliers in competitive green supply chains under the influence of governmental take-back legislation and financial instruments. This work proposes a bargaining framework based on NB game theory (Muthoo, 2002; Brams, 2003) (Fig. 1). This work characterizes the aforementioned negotiation problem in terms of (1) problem scope, (2) assumptions, and (3) bargaining structure.

The problem scope is negotiations between producers and RL-suppliers in competitive green supply chains under governmental influence via take-back legislation and financial instruments. The problem background is such that "*I*" producers with their respective brands compete while selling their products in a demand market subject to governmental take-back directives and financial intervention. Motivated by Luk (2005), we further assume the government levies green taxes (de-

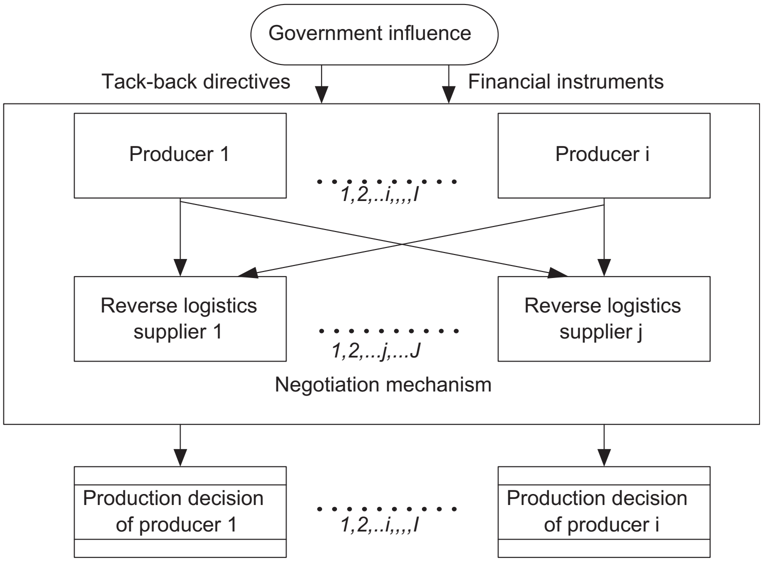

Fig. 1. Bargaining framework for competitive green supply chains.

noted by f for producing each product unit) on producers and provides subsidies (denoted by s for recycling each end-of-life (EOL) product unit) to those in charge of recycling EOL-products (i.e., RL suppliers in this work). Furthermore, drawing from Atasu et al. (2009), we assume unit collection and recycling rates (denoted by c and r) are given and predetermined by the government. Under governmental involvement via the aforementioned green strategies, producers may contract out EOL-product collection and recycling responsibilities with "J" RL providers that are also in competition. Notably, the problem scope is limited to the case in which each given producer cooperates with only one RL-supplier to form a green supply chain. Based on these prerequisites, one can speculate that a producer may negotiate with any given RL-supplier before reaching a cooperative contract, thus leading to a bargaining situation in which both a producer and RL-supplier have a common interest to cooperate (e.g., forming a green supply chain to increase mutual benefits) but have conflicting interests (e.g., the price a producer will pay and that an RL-supplier will sell recycled components to the producer over how to cooperate during negotiations.

It is noteworthy that in most practical cases, a cooperative agreement/contract is needed between green supply chain members (especially for the producer and (green) supplier), such that the original isolated members can be cooperative members collectively working as a team for a green supply chain. According to our preliminary analysis using interview survey data collected from industries including notebook computers, textiles, iron and steel, such cooperative agreements are indispensable, especially to make sure that a producer can obtain reliable recycled materials/components at appropriate prices without concerns of material shortage and unusual variability of procurement prices. Under such a cooperative agreement, both the producer and RL-supplier then go for their profits contingent on the signed contract agenda such as the price and supply of recycled components. Moreover, according to Chen and Sheu (2009), more and more producers take into account the factor of recyclability in product design (Chen and Sheu, 2009), and thus it is inferred that a green producer usually intends to obtain the recycled components processed from its own products for quality and cost control of recycling. Accordingly, it is reasonably agreed that a cooperative RL-supplier sells the corresponding recycled components/materials to the cooperative producer under a green supply chain cooperative agreement, which is also the case primarily investigated in this study.

Compared with a typical bilateral negotiation framework, which involves only two-players in a bargaining process, the proposed negotiation framework for a producer and RL-supplier can be more intricate in the following two perspectives. First, involvement of government via green legislation and financial intervention likely alters the relative power of producers and RL-suppliers while bargaining. This point is drawn from evidence of several practical cases in Europe, indicating that a recycler influences producer market share and costs for WEEE compliance (Clean Production Action, 2003; Stevels and Huisman, 2005). Thereby, we further assume that the relative bargaining power of producers and RL suppliers are functions of f and s, denoted by $\alpha(f,s)$ and $\beta(f,s)$, respectively, where $0 \leqslant \alpha(f,s) \leqslant 1$, $0 \leqslant \beta(f,s) \leqslant 1$, and, moreover, the conditions $\alpha(f,s) + \beta(f,s) = 1, \frac{\partial\alpha(f,s)}{\partial f} < 0, \frac{\partial\alpha(f,s)}{\partial s} < 0, \frac{\partial\beta(f,s)}{\partial f} > 0$, and $\frac{\partial\beta(f,s)}{\partial s} > 0$ must hold. Second, under competition, any producer i must consider the negotiations with RL-suppliers and the bargaining strategies of competing producers $i'(\forall\, i', i' \neq i)$ that seek cooperation with RL suppliers before constructing a green supply chain. Therefore, if a producer fails to reach a negotiated agreement with an RL-supplier, the producer will incur transaction costs spent during negotiation and risk of counterattack from competing green supply chains formed by competing producers and the RL-supplier. Similar phenomena also apply to RL suppliers.

To facilitate problem formulation, we make the following six assumptions.

Assumption 1. Market competition environments in which both producers and RL-suppliers exist are oligopoly competition, where "I" competing producers proceed with Cournot oligopoly competition in production. Furthermore, we assume each producer sources out its take-back responsibility to one of "J" competing RL providers, which also exist in the oligopoly competition contexts.

Assumption 2. The unit cost of final product manufacturing (c_m) is the same for all producers; similarly, the unit cost for recycled component procurement (c_y) is assumed the same for all RL-suppliers.

Assumption 3. All competing green supply chains fully comply with green legislation, and have the capability of producing a homogeneous product, where production of a unit product requires τ_x and τ_y quantities of virgin and recycled components (denoted by x and y, respectively), which are complementary.

Assumption 4. For sake of analytical tractability, the final product price ($P(Q)$) is assumed to be a simple Cournot inverse demand (Q) function in which the final product demand market density is normalized to 1. Therefore, $P(Q) = 1 - Q$, where $Q = \sum_{i=1}^{I} q_i$, where q_i is the amount of product sold by producer *i*.

Assumption 5. All producers have the same bargaining power $\alpha(f,s)$ relative to the bargaining power $\beta(f,s)$ of RL-suppliers, which is also identically for all RL-suppliers.

Assumption 6. Governmental financial instruments are subject to the balanced budget condition (i.e., the total amount of green taxes equals that of green subsidies), meaning that the government would not benefit financially.

Based on the problem scope and assumptions, this work specifies a three-tier bargaining structure (Fig. 1). Drawing from Ulph (1996), this work treats the government as the primary source of coercive power holding producers responsible for collecting and recycling the EOL products they produce. Thus, the first tier deals with the government's financial influence strategies, including green taxation levied on producers and subsidies offered to RL supplies, where *f* and *s* are treated as the two primary governmental decision variables. The second tier specifies the main bargaining structure that contains *I* competing producers negotiating with *J* competing RL-suppliers for cooperative contracts. The unit price ($p_{y_{j,i}}$) and guaranteed quantities ($y_{j,i}$) of recycled components ordered by producer *i* ($\forall\ i \in I$) and supplied by RL-supplier *j* ($\forall\ j \in J$) are considered the two primary agendas during negotiation. If the cooperative agreement is achieved by a given pair of producer *i* and RL-supplier *j*, a green supply chain will be formed, where the cooperative RL-supplier *j* must collect and recycle EOL-products consistent with the amounts requested by take-back directives for cooperative producer *i*. Meanwhile, cooperative producer *i* must purchase these recycled components with $p_{y_{j,i}}$. Conversely, if the cooperative agreement is not achieved, producer *i* and RL supplier *j* incur costs associated with negotiation breakdown (termed breakdown costs); moreover, producer *i* must search for another RL supplier for negotiation until a cooperative agreement is achieved. The third tier determines producers' production (q_i, $\forall\ i \in\ I$) based on governmental strategies and output of negotiations in the first and second tiers.

3. Model

A three-stage game-based model is constructed in this section to formulate the aforementioned bargaining problem in competitive green supply chains. Stage 1 conceptualizes the government's objective by maximizing social welfare (*SW*) to derive the equilibrium solutions for *f* and *s*. In Stage 2, this work applies the asymmetrical NB game with uncertain reservation prices, expected profits and breakdown risks to seek negotiation solutions (i.e., $p_{y_{j,i}}$ and $y_{j,i}$) for cooperative agreements between producers and RL suppliers given *f* and *s*. Based on the government's influence via *f* and *s* as well as the output of cooperative agreements, producer production quantities are determined in Stage 3. To approximate equilibrium solutions of the three-stage game-based model, this work adopts backward induction (Kreps, 1990) starting from Stage 3 under the goal of producer profit maximization, ending with Stage 1 for the solutions of the government's financial intervention. The details of model formulation associated with these three-stages are presented in the following subsections.

3.1. Production solutions of competing producers (Stage 3)

In this stage (Stage 3), this work formulates the problem of producer competition in final product production given governmental influential strategies and agreements with cooperative RL-suppliers. To facilitate model formulation, we assume unit price (p_x) for virgin-components (x) is the same for all producers. By Assumptions 1–4, we infer that any given producer *i* that has a cooperative agreement with a given RL-supplier*j* is likely to maximize its profits (π_i) as

$$\underset{q_i}{Max} \quad \pi_i = \left[1 - \sum_{i'=1}^{I} q_{i'})\right] q_i - p_x\tau_x q_i - p_{y_{j,i}}\tau_y q_i - c_m q_i - f q_i, \quad \forall\ i \tag{1}$$

where c_m is the marginal cost for producing a final product unit. Notably, in Eq. (1), q_i represents the decision of producer i for production quantities, which must be determined at this stage; $p_{y_{j,i}}$ is a negotiation agenda determined in Stage 2; and f is the unit green tax associated with a final product unit, and is determined by the government in Stage 1. The derivations of $p_{y_{j,i}}$ and f are shown in the following subsections.

To ensure the existence of equilibrium solutions of q_i ($\forall\ i$), the first-order condition in Eq. (1) with respect to q_i ($\forall i$) must be satisfied as

$$1 - \sum_{i'=1}^{I} q_{i'} - q_i - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f = 0, \quad \forall\ i \tag{2}$$

Based on Eq. (2), one can further prove that the objective function of producer i, as represented by Eq. (1), is concave on q_i as the corresponding second-order condition is satisfied (i.e., $\frac{\partial^2 \pi_i}{\partial^2 q_i} = -2 < 0, \forall\ i$). Since all competitive producers involved in the oligopoly competing context adopt Cournot competition, as stated in Assumption 1, one can derive the reaction function ($\hat{q}_i$) of producer i with respect to q_i as

$$\hat{q}_i = \frac{1 - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f}{I + 1}, \quad \forall\ i \tag{3}$$

Notably, $\hat{q}_i$ can be regarded as antecedent of the equilibrium solution of q_i as this work must backwardly input such a function in to Stages 2 and 1 to approximate the equilibrium solutions of $p_{y_{j,i}}$ and $y_{j,i}$ (i.e., the negotiation agendas defined in Stage 2) as well as those of f and s (i.e., the governmental financial instruments defined in Stage 1), such that the equilibrium solution of q_i can then be derived.

3.2. Negotiation between a producer and RL-supplier (Stage 2)

This stage deals with the negotiation problem between I competing producers and J competing RL-suppliers using the asymmetrical NB solutions, where the uncertainties of reservation prices with respect to $p_{y_{j,i}}$ associated with producers and RL-suppliers as well as expected profits and breakdown risks from outside options are considered. According to Muthoo (2002), a generalized form of a two-player (A and B) asymmetrical NB game can be expressed as $Max_{(u_A,u_B)\in\Theta}(u_A - d_A)^{\eta}$ $(u_B - d_B)^{1-\eta}$, where u_A and u_B represent the utilities of players A and B, respectively, from obtaining possible shares of a common interest Θ (e.g., a pie) under the achievement of an agreement subject to $u_A + u_B \leqslant \Theta$; d_A and d_B represent the utilities of players A and B, respectively, when they fail to reach an agreement subject to $d_A \leqslant u_A$ and $d_B \leqslant u_B$; and η represents the bargaining power of player A relative to that of player B subject to $0 < \eta < 1$. The asymmetrical NB solutions (u_A^* and u_B^*) can then be derived to characterize the equilibrium solutions of players A and B in the bargaining game.

Utilizing the above NB game concept, this work formulates the green supply chain cooperation problem as an asymmetrical NB game in which uncertainties of reservation prices of $p_{y_{j,i}}$, breakdown risks and expected profits obtained from outside options (i.e., cooperating with other partners) are considered. The proposed asymmetrical NB product is given by

$$\underset{(\pi_A,\pi_j)\in\Theta}{Max} \left[\hat{\pi}_i - \hat{d}_i\right]^{\alpha(f,s)} \left[\hat{\pi}_j - \hat{d}_j\right]^{\beta(f,s)}, \quad \forall\ (i,j) \tag{4}$$

where $\hat{\pi}_i$ and $\hat{\pi}_j$ represent the profits of producer i and RL-supplier j, respectively, obtained under a cooperative agreement obtained during a given negotiation event; $\hat{d}_i$ and $\hat{d}_j$ represent the expected value of net profit associated with producer i and RL-supplier j, respectively, when they cannot reach agreement, but rather cooperate with other players in any the subsequent negotiation events. Moreover, conditions $\hat{d}_i \leqslant \hat{\pi}_i$ and $\hat{d}_j \leqslant \hat{\pi}_j$ must hold.

Consider the probabilities under both agreement and disagreement conditions for both producer i and RL-supplier j in any given negotiation event. Therein, this work introduces the concept of reservation price for $p_{y_{j,i}}$ to characterize the potential outcome of negotiation and breakdown probabilities in a given negotiation event. This work defines $\bar{p}_{y_{j,i}}$ and $\underline{p}_{y_{j,i}}$ as the reservation prices of producer i and RL-supplier j, respectively, to represent the maximum price producer i is willing to pay and the minimum price RL-supplier j is willing to sell a unit of recycled components, respectively. We assume both producer i and RL-supplier j do not know the other's reservation price; furthermore, $\bar{p}_{y_{j,i}}$ and $\underline{p}_{y_{j,i}}$ are drawn from a uniform distribution bounded by the range $[p_0, p_{top}]$, where p_0 and p_{top} are lower and upper bounds specified for the random variables of the uniform distribution. Accordingly, $\bar{p}_{y_{j,i}}$ and $\underline{p}_{y_{j,i}}$ are independent and identically distributed (IID) random variables.

Theorem 3.1. *Under asymmetrical information conditions for reservation price of $p_{y_{j,i}}$, any given pair of negotiators composed of a producer and an RL-supplier has a 1/6 probability of achieving a cooperative agreement, and a 5/6 probability of negotiation breakdown in any given negotiation event.*

The proof of Theorem 3.1 is straightforward. Notably, the equilibrium solution of $p_{y_{j,i}}$ (denoted by $p^*_{y_{j,i}}$) exists only when $\underline{p}_{y_{j,i}} \leqslant p^*_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}}$. By order statistics (Ross, 1993), the probability $\Phi(\underline{p}_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}})$ can be derived by $\Phi(\underline{p}_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}}) = \int_{p_0}^{p_{top}} \int_{p_0}^{\bar{y}} \phi(\underline{y}, \bar{y}) d\underline{y} d\bar{y} = \int_{p_0}^{p_{top}} \int_{p_0}^{\bar{y}} \phi(\underline{y})\phi(\bar{y}) d\underline{y} d\bar{y} = \frac{1}{2}$, where $\phi\ (\underline{y})$ and $\phi(\bar{y})$ are the probability density functions of $\underline{p}_{y_{j,i}}$ and $\bar{p}_{y_{j,i}}$, respectively. Furthermore, $\Phi(\underline{p}_{y_{j,i}} \leqslant p^*_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}}) = \Phi(p^*_{y_{j,i}} \leqslant \underline{p}_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}}) = \Phi(\underline{p}_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}} \leqslant p^*_{y_{j,i}}) = \frac{1}{3}$ under the condition $\Phi(\underline{p}_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}})$. We then infer the probability for the achievement of a cooperative agreement by $\Phi\Big((\underline{p}_{y_{j,i}} \leqslant p^*_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}}) \cap (\underline{p}_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}})\Big) = \Phi(\underline{p}_{y_{j,i}} \leqslant \bar{p}_{y_{j,i}}) \times \frac{1}{3} = \frac{1}{6}$, and the probability of negotiation breakdown is $\frac{5}{6}$.

The next step is to specify $\hat{\pi}_i, \hat{\pi}_j, \hat{d}_i$ and $\hat{d}_j$ embedded in Eq. (4). As mentioned, $\hat{\pi}_i$ and $\hat{\pi}_j$ are the profits of producer *i* and RL-supplier *j* obtained under cooperative agreement in the present negotiation event. By combining Eqs. (1) and (3), we infer $\hat{\pi}_i$ and $\hat{\pi}_j$ given by

$$\hat{\pi}_i = \left\{\left[1 - \sum_{i'=1}^{I}(\hat{q}_{i'})\right] - c_m\right\}\hat{q}_i - [p_x\tau_x\hat{q}_i + p_{y_{j,i}}\tau_y\hat{q}_i] - f\hat{q}_i, \quad \forall\, i \tag{5}$$

$$\hat{\pi}_j = [p_{y_{j,i}}\tau_y\hat{q}_i - c_y(\tau_y - cr)\hat{q}_i] - c_{col}(c\hat{q}_i) - c_{pro}(crq_i) + s(cr\hat{q}_i), \quad \forall\, j \tag{6}$$

where $\hat{q}_i = \frac{1-p_x\tau_x-p_{y_{j,i}}\tau_y-c_m-f}{I+1}$ which is approximated previously (Stage 3); c_{col} and c_{pro} represent unit costs of collecting and processing EOL-products for recycling, respectively. In terms of $\hat{\pi}_i$ (Eq. (5)), this work mainly accounts for revenues of selling final products, production costs, and component procurement and green taxes charged by the government. In terms of $\hat{\pi}_j$ (Eq. (6)), this work considers the revenues obtained by the RL-supplier from selling recycled components to producers and the costs in recycled component replenishment, EOL product collection and processing for recycling as well as green subsidies from the government. However, $\hat{q}_i = \frac{y_{j,i}}{\tau_y}$ (Assumption 3); thus, under equilibrium conditions one can determine that $y_{j,i}$ is a function of $p_{y_{j,i}}$ and is given by

$$y_{j,i} = \frac{\tau_y(1 - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f)}{I+1}, \quad \forall\, i,j \tag{7}$$

Furthermore, using Eqs. (3), (5) and (6) can be rewritten as

$$\hat{\pi}_i = \frac{(1 - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f)^2}{(I+1)^2}, \quad \forall\, i \tag{8}$$

$$\hat{\pi}_j = \frac{(p_{y_{j,i}}\tau_y + (s + c_y - c_{pro})cr - c_y\tau_y - c_{col}c)(1 - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f)}{I+1}, \quad \forall\, j \tag{9}$$

To formulate $\hat{d}_i$ and $\hat{d}_j$, this work mainly considers: (1) the expected profits ($E_i(\hat{\pi}_{i|j'})$ and $E_j(\hat{\pi}_{j|i'})$) earned by producer *i* and RL supplier *j* when cooperating with other players, and (2) the expected values ($E_i(c_{bre})$ and $E_j(c_{bre})$) of breakdown cost (c_{bre}) associated with producer *i* and RL-supplier *j* in any given negotiation event. Consider the case in which producer *i* fails to achieve an agreement with RL-supplier *j* in the present negotiation event, but searches for another RL-supplier from the $J-1$ RL-supplier pool until a cooperative agreement is obtained. Therein, $E_i(\hat{\pi}_{i|j'})$ is defined as the expected value of profit associated with producer *i* when cooperating with RL supplier j' ($j' \neq j$) in another negotiation event. According to Theorem 3.1, the probability of negotiation breakdown is $\frac{5}{6}$ in a given negotiation event, and thus, $E_i(\hat{\pi}_{i|j'})$ can be computed by

$$E_i(\hat{\pi}_{i|j'}) = \frac{1}{6}\hat{\pi}_{i|j'}\sum_{\varepsilon=1}^{J-1}\left(\frac{5}{6}\right)^{\varepsilon-1}, \quad \forall\, i \tag{10}$$

where $\hat{\pi}_{i|j'} = \frac{(1-p_x\tau_x-p_{y_{j',i}}\tau_y-c_m-f)^2}{(I+1)^2}$ ($j' \neq j$). Similarly, let $E_j(\hat{\pi}_{j|i'})$ be the expected value of profit associated with RL-supplier *j* when cooperating with producer *i* ($i' \neq i$) in another negotiation event. Then, $E_j(\hat{\pi}_{j|i'})$ can be derived as

$$E_j(\hat{\pi}_{j|i'}) = \frac{1}{6}\hat{\pi}_{j|i'}\sum_{\varepsilon=1}^{I-1}\left(\frac{5}{6}\right)^{\varepsilon-1}, \quad \forall\, j \tag{11}$$

where $\hat{\pi}_{j|i'} = [p_{y_{j,i'}}\tau_y + (s + c_y - c_{pro})cr - c_y\tau_y - c_{col}c]\frac{1-p_x\tau_x-p_{y_{j,i'}}\tau_y-c_m-f}{I+1}$ ($i' \neq i$). By contrast, breakdown cost (c_{bre}) is the additional cost dyadic negotiators pay when a negotiation event breaks down in disagreement, and is assumed a constant to facilitate analysis. Therefore, this work introduces expected values ($E_i(c_{bre})$ and $E_j(c_{bre})$) of breakdown costs to characterize potential risks of breakdown associated with producer *i* and RL-supplier *j* and, thus, approximate E_i (c_{bre}) and $E_j(c_{bre})$ by

$$E_i(c_{bre}) = c_{bre}\left[\sum_{\varepsilon=1}^{J-1}\left(\frac{5}{6}\right)^{\varepsilon-1}\right], \quad \forall\, i \tag{12}$$

$$E_j(c_{bre}) = c_{bre}\left[\sum_{\varepsilon=1}^{I-1}\left(\frac{5}{6}\right)^{\varepsilon-1}\right], \quad \forall\, j \tag{13}$$

Using Eqs. (10)–(13), one can approximate $\hat{d}_i$ and $\hat{d}_j$ by

$$\hat{d}_i = E_i(\hat{\pi}_{i|j'}) - E_i(c_{bre}), \qquad \forall\, i \quad \text{and} \quad j' \neq j \tag{14}$$

$$\hat{d}_j = E_j(\hat{\pi}_{j|i'}) - E_j(c_{bre}), \qquad \forall\, j \quad \text{and} \quad i' \neq i \tag{15}$$

By combining Eqs. (8), (9), (14), and (15) with Eq. (4), the proposed asymmetrical NB product can then be reformulated as

$$\underset{(\pi_A,\pi_j)\in\Theta}{Max}\left[\hat{\pi}_i-\left(E_i(\hat{\pi}_{i|j'})-E_i(c_{bre})\right)\right]^{\alpha(f,s)}\left[\hat{\pi}_j-\left(E_j(\hat{\pi}_{j|i'})-E_j(c_{bre})\right)\right]^{\beta(f,s)},\quad\forall\ (i,j)\tag{16}$$

Theorem 3.2. *Under equilibrium conditions, the profit earned by any given player (either a producer or an RL-supplier) from a cooperative agreement at a given negotiation event is always greater than the expected value of net profit earned by cooperating with any other players at any following negotiation event.*

The proof of Theorem 3.2 is shown in Appendix B.1. In addition to supporting the existence of NB solutions by proving $\hat{d}_i \leqslant \hat{\pi}_i$ and $\hat{d}_j \leqslant \hat{\pi}_j(\forall\ i,j)$, the generalization of Theorem 3.2 also indicates that for any given player (either a producer or an RL-supplier) in the specified bargaining framework, profit obtained under a cooperative agreement is always greater than that obtained under disagreement even though the player is likely to reach agreement with another player in a subsequent negotiation event. Drawing from Theorem 3.2, each player should devote their effort to achieving a cooperative agreement at the present negotiation event; waiting for a second chance to reach an agreement is never a good negotiation strategy in the specified bargaining framework.

Using Theorem 3.2 and Eq. (16) one can then derive the equilibrium solution of $p_{y_{j,i}}$ (denoted by $p^*_{y_{j,i}}$) by utilizing NB solutions of $\hat{\pi}_i$ and $\hat{\pi}_j$. Therefore,

$$\begin{aligned}&p^*_{y_{j,i}}=\frac{\beta(f,s)(1-N_i)\frac{G^2}{(I+1)^2}-6[N_j\alpha(f,s)-N_i\beta(f,s)]c_{bre}-\alpha(f,s)(1-N_j)\frac{GH}{I+1}}{[2\beta(f,s)(1-N_i)\tau_y]\frac{G}{(I+1)^2}+[\alpha(f,s)(1-N_j)\tau_y]\frac{G-H}{I+1}},\quad\forall\ (i,j)\\&s.t.\quad\beta(f,s)(1-N_i)G^2\geqslant 6(I+1)^2[N_j\alpha(f,s)-N_i\beta(f,s)]c_{bre}+\alpha(f,s)(1-N_j)(I+1)GH\end{aligned}\tag{17}$$

where $G=1-p_x\tau_x-c_m-f; H=(s+c_y-c_{pro})cr-c_y\tau_y-c_{col}c; N_i=1-\left(\frac{5}{6}\right)^{J-1}(\forall\ i)$ and $N_j=1-\left(\frac{5}{6}\right)^{I-1}(\forall\ j)$. Note that G, H, N_i and N_j are unnamed parameters specified only for model simplification. The proof of $p^*_{y_{j,i}}$ is given in Appendix A.1.

By inputting Eq. (17) into Eqs. (8) and (9), the profits ($\hat{\pi}^*_i$ and $\hat{\pi}^*_j$) of producer *i* and RL-supplier *j* obtained from cooperative agreement under equilibrium conditions can then be approximated. Furthermore, using Eqs. (7) and (17) one can also derive the equilibrium solution of $y_{j,i}$ ($y^*_{j,i}$) as

$$y^*_{j,i}=\frac{\tau_y\left(G-\tau_y p^*_{y_{j,i}}\right)}{I+1},\quad\forall\ (i,j)\tag{18}$$

Theorem 3.3. *The specified $I \times J$ producer and RL-supplier bargaining framework has NB solutions for any given pair of a producer and RL-supplier at a bilateral negotiation event. Under NB equilibrium conditions, the following is true:*

$$\beta(f,s)(1-N_i)\hat{\pi}^*_i=\alpha(f,s)(1-N_j)\hat{\pi}^*_j+6(\alpha(f,s)N_j-\beta(f,s)N_i)c_{bre},\quad\forall\ (i,j)\tag{19}$$

where $\hat{\pi}^*_i$ and $\hat{\pi}^*_j$ represent the profits earned by producer *i* and RL-supplier *j* under NB equilibrium conditions. The proof of Theorem 3.3 is given in Appendix B.2. Theorem 3.3 indicates that $\hat{\pi}^*_i$ and $\hat{\pi}^*_j$ are contingent upon the dyadic players' relative bargaining power and number of competitors under NB equilibrium conditions. Notably, $\beta(f,s) = 1 - \alpha(f,s)$, $N_i=1-\left(\frac{5}{6}\right)^{J-1}$ $(\forall\ i)$, and $N_j=1-\left(\frac{5}{6}\right)^{I-1}(\forall\ j)$. Generally, the bargaining power of a producer exceeds that of an RL-supplier (i.e., $\alpha(f,s) > \beta(f,s)$) during negotiations as EOL product collection and recycling technology is not unique in the RL market. Moreover, the number of producers is smaller than the number of RL suppliers (i.e., $I < J$) in the specified bargaining framework, indicating that $N_i > N_j$. Therefore, Theorem 3.3 implies that producer profit is greater than RL-supplier profit (i.e., $\hat{\pi}^*_i > \hat{\pi}^*_j$) under NB equilibrium conditions.

Additionally, the generalization of Theorem 3.3 suggests the effects of bargaining power and number of competitors on player profits in negotiations. In this case, as the bargaining power of the RL-supplier ($\beta(f,s)$) decreases, the bargaining power of the producer ($\alpha(f,s)$) increases, and thus, producer profit ($\hat{\pi}^*_i$) increases based on Eq. (19). From a producer perspective, that many competitors (i.e., competing producers) exist in competing contexts suggests a great number of negotiation opportunities for RL-suppliers, thereby increasing the value of N_j and decreasing producer profit $\left(\hat{\pi}^*_i\right)$ according to Eq. (19). A similar inference also applies to the case of RL-suppliers. Briefly, bargaining power and the number of competitors adversely affect player profits in the producer and RL-supplier bargaining framework. Such a generalization supports the rationalization of the form of coalitions observed in some negotiation cases, e.g., an assembler negotiating with supplier coalitions (Nagarajan and Bassok, 2008).

Proposition 3.1. *Under NB equilibrium conditions of the specified $I \times J$ producer and RL-supplier bargaining framework, the profit of the producer is the same as that of the RL-supplier (i.e., $\hat{\pi}^*_i=\hat{\pi}^*_j, \forall\ i,j$) if $I = J$ and $\alpha(f,s)=\frac{N_i}{N_i+N_j}$.*

The proof of Proposition 3.1 is straightforward. Let $I = J$ and $\alpha(f,s)=\frac{N_i}{N_i+N_j}$; thus, $N_i=N_j=N_*\Rightarrow\alpha(f,s)=\beta(f,s)=\frac{1}{2}$. Inputting the above prerequisites into Eq. (19) (Theorem 3.3) yields

$$\begin{aligned}&\beta(f,s)(1-N_i)\hat{\pi}_i^* = \alpha(f,s)(1-N_j)\hat{\pi}_j^* + 6(\alpha(f,s)N_j - \beta(f,s)N_i)c_{bre}\\ &\quad\Rightarrow \tfrac{1}{2}(1-N_*)\hat{\pi}_i^* = \tfrac{1}{2}(1-N_*)\hat{\pi}_j^* + 6\left(\tfrac{1}{2}N_* - \tfrac{1}{2}N_*\right)c_{bre} \qquad ,\forall\ (i,j)\\ &\quad\Rightarrow \hat{\pi}_i^* = \hat{\pi}_j^*\end{aligned} \tag{20}$$

Thus, Proposition 3.1 is proved. Proposition 3.1 is a special case of green supply chain cooperation, in which the producer and RL-supplier obtain the same profit from a cooperative agreement under NB equilibrium conditions.

3.3. Government financial instruments (Stage 1)

This stage investigates the effect of green taxes (*f*) and subsidies (*s*) on cooperative agreements (i.e., $p^*_{y_{j,i}}$ and $y^*_{j,i}$) and players profits in the specified bargaining framework. Drawing from the concept of social welfare (*SW*) maximization, which is extensively used in literature for green policy determination (Dobbs, 1991; Walls and Palmer, 2001), this work proposes an objective function for the government that has the following four key elements: (1) consumer surplus (*CS*); (2) chain-based producer surplus (*PS*); (3) production-induced environmental costs (*ECs*); and, (4) recycling-induced environmental benefits (*EBs*). Therefore, the objective function of the government is given by

$$\underset{f,s}{Max}\quad SW = CS + PS - ECs + EBs = \frac{1}{2}\left(\sum_{i=1}^{I}\hat{q}_i^*\right)^2 + \left(\sum_{i=1}^{I}\hat{\pi}_i^* + \hat{\pi}_{j|i}^*\right) - D\times\sum_{i=1}^{I}\hat{q}_i^* + V\times\sum_{i=1}^{I}cr\hat{q}_i^* \tag{21}$$

where *D* and *V* represent unit green cost and benefit induced by producing a unit product and recycling a unit EOL product, respectively. Determining the values of *D* and *V* requires sophisticated economic approaches (Bovenberg and Goulder, 1996; Kalimo, 2006). This work sets the ratio of *D* to *V* at 1:20 in Eq. (21) to facilitate further analysis (Stern, 2006). Therefore, Eq. (21) can be rewritten as

$$\underset{f,s}{Max}\quad SW = \frac{1}{2}\left(\sum_{i=1}^{I}\hat{q}_i^*\right)^2 + \left(\sum_{i=1}^{I}\hat{\pi}_i^* + \hat{\pi}_{j|i}^*\right) + (20cr-1)D\sum_{i=1}^{I}\hat{q}_i^* \tag{22}$$

However, by Assumption 6, we speculate that the government may attempt to balance induced budget items, i.e., green taxes and subsidies, to avoid additional financial loading. Thus, the above objective function should be subject to the specified balanced budget condition given by

$$s\times\sum_{i=1}^{I}cr\hat{q}_i^* = f\times\sum_{i=1}^{I}\hat{q}_i^*,\quad f,s \geqslant 0 \tag{23}$$

Notably, the involvement of *ECs* and *EBs* in the above objective function of the government is rooted in the concept of Green Gross Domestic Product (Green GDP), which was developed by the World Commission on Environment and Development in 1987. The basic idea underlying the Green GDP is that domestic ecological and environmental damage should be regarded as a gross domestic cost and, thus, should be integrated into net GDP estimations. Furthermore, a growing number of environmental economists have argued for the importance of both environmental costs and savings when assessing the environmental protection system performance (Bovenberg and Goulder, 1996; Mayers et al., 2005; Ruedenauer et al., 2005). Accordingly, this work considers both *ECs* and *EBs* in characterizing the objective function of the government with respect to environmental profits obtained from intervention in the specified producer and RL-supplier bargaining framework.

Moreover, estimating the values of parameters *D* and *V* is theoretically feasible but beyond the scope and purpose of this work. Furthermore, some studies have suggested that the environmental impact of a product is from two main sources—(1) hazardous wastes generated by the manufacturing process (Sheu, 2007), and (2) hazardous components in a product (Huisman et al., 2007; Mayers et al., 2005). Therefore, approximating the value of *D* based on official report by the governmental environmental protection administration (EPA) with respect to aggregate external costs of hazardous wastes associated with the target product seems promising. Then, the value of *V* is estimated using the aforementioned *V*/*D* ratio.

To derive equilibrium solutions of *f* and *s* (f^* and s^*), the effects of *f* and *s* on bargaining power should be specified in advance. Thus, we assume that a linear form (Eq. (24)) characterizes the effects of *f* and *s* on the relative bargaining power of a producer ($\alpha(f,s)$).

$$\alpha(f,s) = a_0 - (af + bs) \tag{24}$$

where a_0 is the initial bargaining power of a producer relative to the that of the RL-supplier without governmental financial intervention, and $0 \leqslant a_0 \leqslant 1$; *a* and *b* represent the incremental effects of *f* and *s* on $\alpha(f,s)$, respectively, subject to $a > 0$, $b > 0$ and $0 \leqslant a_0 - (af + bs) \leqslant 1$.

Using Eqs. (22)–(24), one can then derive the equilibrium solutions of *f* and *s* (denoted by f^* and s^*, respectively) given by

$$f^* = \frac{[(20cr-1)D + L](a_0K + 2K - 3a_0L) + (1-a_0)K^2 - 3a_0KL}{[(20cr-1)D + L](4a_0 - 3\rho L + \rho K + 2) - \rho K(3L + K)} \tag{25}$$

$$s^* = \frac{f^*}{cr} \tag{26}$$

where $K = 1 - p_x\tau_x - c_m$; $L = (c_y - c_{pro})cr - c_y\tau_y - c_{col}\,c$; and $\rho = \frac{acr+b}{cr}$. Note that K, L, and ρ are unnamed parameters specified for model simplification. The proof of f^* and s^* is given in Appendix A.2.

Proposition 3.2. *Under the goal of SW maximization, the optimal solutions of the government for green taxes and subsidies are* $f^* = s^* = 0$ *when the following conditions hold: (1)* $cr = 0.05$, *(2)* $a_0 = 0.5$, *and (3)* $K = L$.

Proposition 3.2 can be proved easily using Eqs. (25) and (26) subject to the aforementioned conditions. This proposition suggests that the phenomenon in that without the aid of financial instruments the government can achieve the goal of *SW* maximization only when (1) the product of collection and recycling rates equals 0.05, (2) the initial bargaining power of producers and RL-suppliers is the same, and (3) the ante-contract comparative profits of a producer and RL-supplier are the same (i.e., $1 - p_x\tau_x - c_m = (c_y - c_{pro})cr - c_y\tau_y - c_{col}\,c$).

Once f^* and s^* are determined, one can feed their values back to Stage 2 to determine the values of $p^*_{y_{j,i}}$ and $y^*_{j,i}$, and then to Stage 3 to determine the value of $\hat{q}_i$ as well as the profits obtained by producers and RL suppliers in the proposed bargaining framework.

4. Analysis

Based on the derived equilibrium solutions, qualitative and quantitative analyses are conducted as follows to provide additional insights into the correlations among government, producer, and RL-supplier decision variables in the specified producer and RL-supplier bargaining framework.

4.1. Qualitative analysis

Proposition 4.1. Financial instruments vs. bargaining power). *For government use of financial instruments,* f^* *and* s^* *determine the relative bargaining power of dyadic players by*

$$\alpha(f^*, s^*) \gtreqless \beta(f^*, s^*), \quad \text{if } f^* \gtreqless \frac{2a_0 - 1}{2\rho}\left(\text{i.e.}, s^* \gtreqless \frac{2a_0 - 1}{2(acr + b)}\right).$$

The above proposition characterizes the relationship between government instruments and the relative bargaining power of players in the specified producer and RL-supplier bargaining framework. To maximize *SW*, the government may adopt f^* and s^* as financial instruments, thereby changing the bargaining power of a producer from a_0 to $a_0 - \rho f^*$, and that of the RL supplier from $1 - a_0$ to $1 - a_0 + \rho f^*$. Consequently, government intervention using financial instruments decreases producer bargaining power and increases that of the RL-supplier in negotiations. The rule provided by this proposition can then be used to analyze the trade-off in relative bargaining power between producers and RL suppliers under government financial intervention. The proof of Proposition 4.1 is given in Appendix B.3.

Remark 4.1 (*Financial instruments vs. negotiation agendas*). Increases in green tax (f) or green subsidy (s) increases $p_{y_{j,i}}$ and decreases $y_{j,i}$; conversely, a decrease to f or s decreases $p_{y_{j,i}}$ and increases $y_{j,i}$. This remark is based on the derivatives shown in Eqs. (27)–(30). Under governmental intervention with financial instruments, RL-suppliers are stimulated to bid up the unit price ($p_{y_{j,i}}$) of recycled components sold to producers due to the increased bargaining power ($\beta(f,s)$). Conversely, green taxation increases producer production cost and weakens their bargaining power in negotiations with RL-suppliers, thus discouraging producer from obtaining additional recycled components (i.e., reduction of $y_{j,i}$) in negotiations with RL-suppliers that move toward cooperative agreements.

$$\frac{\partial p_{y_{j,i}}}{\partial f} = \frac{\left\{6\rho(N_j+N_i)c_{bre}+(1-N_j)\frac{\rho GH-(a_0-\rho f)(G-H)}{I+1}+(1-N_i)\frac{\rho G^2-2(1-a_0+\rho f)G}{(I+1)^2}\right\}}{\Delta} - \frac{\xi\times\left\{[2(1-N_i)\tau_y]\frac{\rho G-(1-a_0+\rho f)}{(I+1)^2}-[(1-N_j)\tau_y]\frac{\rho(G-H)+2(a_0-\rho f)}{I+1}\right\}}{\Delta^2} > 0 \tag{27}$$

where $\xi = (1 - a_0 + \rho f)(1 - N_i)\frac{G^2}{(I+1)^2} - 6[(a_0 - \rho f)N_j - (1 - a_0 + \rho f)N_i]c_{bre} - (a_0 - \rho f)(1 - N_j)\frac{GH}{I+1}$; $\Delta = [2(1 - a_0 + \rho f)(1 - N_i)\tau_y]\frac{G}{(I+1)^2} + [(a_0 - \rho f)(1 - N_j)\tau_y]\frac{G-H}{I+1}$; both ξ and Δ are unnamed parameters specified only for model simplification.

$$\frac{\partial p_{y_{j,i}}}{\partial s} = \frac{\partial p_{y_{j,i}}}{\partial\left(\frac{f}{cr}\right)} = cr\frac{\partial p_{y_{j,i}}}{\partial f} > 0 \tag{28}$$

$$\frac{\partial y_{j,i}}{\partial f} = \frac{-\tau_y\left(1 + \tau_y\frac{\partial p_{y_{j,i}}}{\partial f}\right)}{I+1} < 0 \tag{29}$$

$$\frac{\partial y_{j,i}}{\partial s} = \frac{-cr\tau_y\left(1 + \tau_y\frac{\partial p_{y_{j,i}}}{\partial f}\right)}{I+1} < 0 \tag{30}$$

Remark 4.2 (*Bargaining power vs. negotiation agendas*). Under governmental financial intervention, the decrease in producer bargaining power ($\alpha(f,s)$) corresponding to the increase in RL-supplier bargaining power ($\beta(f,s)$) increases $p_{y_{j,i}}$ and decreases $y_{j,i}$. This remark is developed by taking the partial derivatives of $p_{y_{j,i}}$ and $y_{j,i}$ based on the bargaining power $\alpha(f,s)$ and $\beta(f,s)$, as in Eqs. (31)–(34). In reality, Remark 4.2 reasons how the relative bargaining power of players influences negotiation agendas $p_{y_{j,i}}$ and $y_{j,i}$ under governmental financial intervention. As mentioned, governmental financial intervention via green taxes and subsidies decreases in producer bargaining power and increase that of the RL-supplier. Therefore, an RL-supplier is prone to bid up the unit price of recycled components ($p_{y_{j,i}}$) during negotiation with a producer toward a cooperative agreement. Additionally, producer bargaining power is adversely affected by green taxation in this case, such that a producer may compromise with an RL-supplier on a higher value of $p_{y_{j,i}}$, leading to a lower demand for recycled components ($y_{j,i}$) specified in the negotiation agenda, compared with the case without government intervention.

$$\frac{\partial p_{y_{j,i}}}{\partial \alpha} = \frac{-\left[(1-N_i)\frac{G^2}{(I+1)^2} + 6(N_j+N_i)c_{bre} + (1-N_j)\frac{GH}{I+1}\right]}{\Delta} - \frac{\xi\left\{[-2(1-N_i)\tau_y]\frac{G}{(I+1)^2} + [(1-N_j)\tau_y]\frac{G-H}{I+1}\right\}}{\Delta^2} < 0 \tag{31}$$

$$\frac{\partial p_{y_{j,i}}}{\partial \beta} = -\frac{\partial p_{y_{j,i}}}{\partial \alpha} > 0 \quad (\because \beta = 1-\alpha \Rightarrow \partial\beta = -\partial\alpha) \tag{32}$$

$$\frac{\partial y_{j,i}}{\partial \alpha} = \frac{\partial p_{j,i}}{\partial \alpha} \times \frac{\partial y_{j,i}}{\partial p_{y_{j,i}}} = \frac{\partial p_{j,i}}{\partial \alpha} \times \frac{-(\tau_y)^2}{I+1} > 0 \tag{33}$$

$$\frac{\partial y_{y_{j,i}}}{\partial \beta} = -\frac{\partial y_{y_{j,i}}}{\partial \alpha} < 0 \quad (\because \beta = 1-\alpha \Rightarrow \partial\beta = -\partial\alpha) \tag{34}$$

Remark 4.3 (*Negotiation agendas vs. production quantities*). Under governmental financial intervention, the increase of recycled component unit price ($p_{y_{j,i}}$) decreases the guaranteed quantities of recycled components ($y_{j,i}$) specified in a negotiation agenda, thus decreasing the producer production ($\hat{q}_i$). This remark is based on derived results by Eqs. (35) and (36), which indicate how $p_{y_{j,i}}$ and $y_{j,i}$ specified in negotiation agendas affect the amount ($\hat{q}_i$) of products produced. Under governmental financial intervention, an RL-supplier is likely to raise $p_{y_{j,i}}$ during negotiation with a producer. This may weaken producer intention to develop a contract with an RL-supplier to acquire recycled components for production, thereby reducing $y_{j,i}$ in negotiation agendas. Consequently, the amount of final products produced $\hat{q}_i$ is decreased.

$$\frac{\partial \hat{q}_i}{\partial p_{y_{j,i}}} = \frac{-\tau_y}{I+1} < 0, \quad \forall\, i \tag{35}$$

$$\frac{\partial \hat{q}_i}{\partial y_{j,i}} = \frac{-\tau_y\left(\frac{\partial p_{y_{j,i}}}{\partial y_{j,i}}\right)}{I+1} = \frac{1}{\tau_y} > 0, \quad \forall\, i \tag{36}$$

4.2. Numerical illustration

In the subsequent quantitative analysis, the notebook computer manufacturing industry is utilized to demonstrate the effects of governmental financial intervention on the specified green supply chain bargaining framework. Particularly, this work presets cost-related parameters needed in the proposed model using data obtained from interview surveys of managers of global logistics sectors of notebook computer producers and recyclers. Table 1 summarizes the key preset parameters

Table 1
Preset values of parameters for quantitative analysis.

1. Government-related parameters			2. Number of competitors	
Collection rate (%)	Recycling rate r (%)	Unit green cost D	Number of competitive producers I	Number of competitive RL-suppliers J
80	80	0.8	2	2

3. Producer-related parameters						
Initial bargaining power a_0	Incremental effect of f on producer's bargaining power (a)	Incremental effect of s on producer's bargaining power (b)	Unit price of virgin-components p_x	*Quantities of virgin-components for unit product production*τ_x	*Quantities of recycled components for unit product production*τ_y	Unit cost of manufacturing c_m
0.9	0.5	0.5	0.005	0.5	0.5	0.03

4. RL-supplier related parameters			Others
Unit cost for recycled component procurement c_y	Unit cost for EOL-product collectionc_{col}	Unit cost for processing EOL product c_{pro}	Breakdown cost in each negotiation event c_{bre}
0.003	0.0006	0.0005	0.02

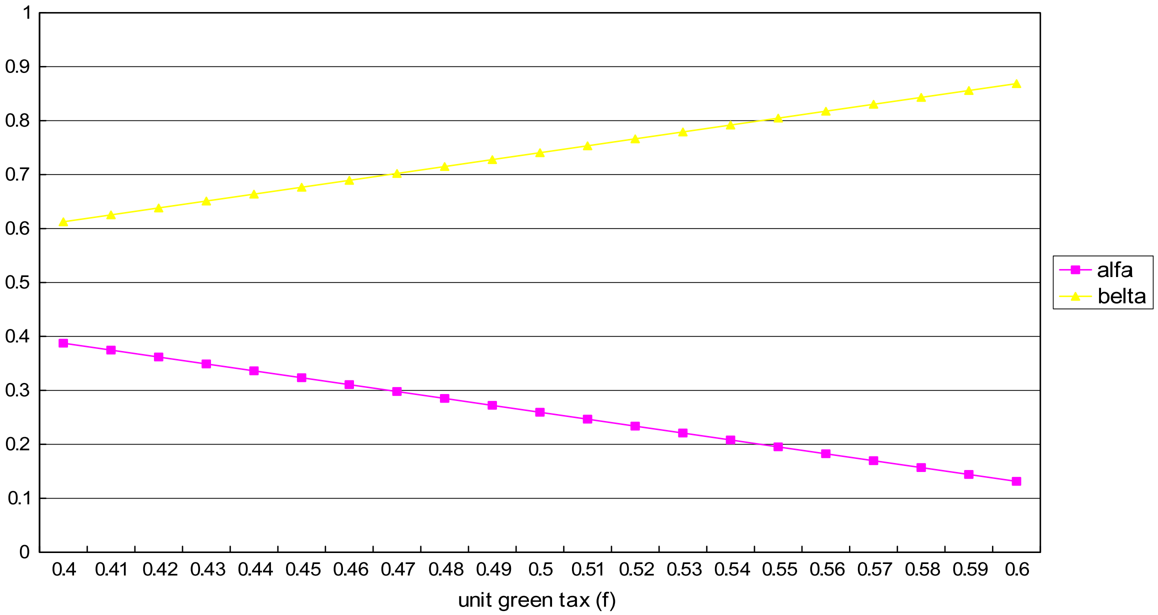

Fig. 2. Quantitative analysis (I): unit green tax vs. bargaining power.

in this study case. Sensitivity analysis was then conducted for unit green tax (f) starting from the value of 0.4–0.6 with an increment 0.01 to characterize changes to player bargaining power, negotiation decisions, and acquired profits in the proposed bargaining framework. According to preliminary analysis, the aforementioned range of f values covers all feasible domains of equilibrium solutions of decision variables, including f^*, which equals 0.42, approximated using the preset parameters (Table 1). Thus, this work subjects the corresponding quantitative results to further analysis. Figs. 2–4 present analytical results.

Fig. 2 indicates that the bargaining power ($\alpha(f,s)$) of a producer decreases as the unit green tax (f) increases, and that of the RL-supplier increases as f increases within the feasible domain of 0.4–0.6. Such a generalization is consistent with the expectation of the trade-off relationship in bargaining power of a producer and RL supplier in the specified bargaining framework. Furthermore, under the influence of green taxation, producer bargaining power is less than that of an RL-supplier. Compared with 0.9 (i.e., the initial value of a_0 (Table 1)), such a decline in bargaining power is significant and coincides with the predicament global producer face in the EU market. This finding is also consistent with that obtained by Wilson (2006), who identified the increase in the influence of recyclers under green legislation.

An increase in unit green tax (f) increases $p_{y_{j,i}}$ and decreases y_i in negotiation agendas, thereby decreasing production quantities (q_i) (Fig. 3). This finding is consistent with Remark 4.3 in qualitative analysis, suggesting that governmental financial intervention has a negative effect on negotiation agendas from a producer perspective. Furthermore, given the preset parameters (Table 1), the equilibrium solution of f is 0.42, which contributes to $p^*_{y_{j,i}}$ equaling 0.0026, which is the lowest feasible solution of $p_{y_{j,i}}$ compared with other solutions (Fig. 3). Therefore, we reason that under equilibrium conditions, unit price of the recycled component supply ($p^*_{y_{j,i}}$) obtained through negotiations is less than that of any other feasible solutions in this work. Furthermore, we infer that a producer always intends to achieve a cooperative agreement under a low $p_{y_{j,i}}$ value regardless of whether governmental financial instruments (f and s) intervene in the bargaining framework. Conversely, the bargaining power of an RL supplier is enhanced by governmental green subsidies and, thus, an RL supplier can adopt strategies such as increasing $p_{y_{j,i}}$ and limiting $y_{j,i}$ to a guaranteed profit value when entering into a cooperative agreement with a producer.

Fig. 4 provides the following three generalizations. First, under governmental financial intervention, the profit $\left(\hat{\pi}^*_j\right)$ of an RL-supplier is greater than that of a producer $(\hat{\pi}^*_i)$ in any scenario within the feasible domain. Such a generalization is consistent with the fundamentals of the asymmetrical NB solutions (Muthoo, 2002), revealing that the player with relatively greater bargaining power yields more remaining utility which refers to net aggregated profits, i.e., $(\hat{\pi}_i + \hat{\pi}_j) - \left(E_i(\hat{\pi}_{i|j'}) - E_i(c_{bre}) + E_j(\hat{\pi}_{j|i'}) - E_j(c_{bre})\right)$, in this work. Second, under equilibrium conditions in which $f^* = 0.42$, the obtained sum of player profits is greater than that of others obtained within the feasible domain. Notably, the summed profits obtained at $f = 0.4$ and $f = 0.41$ are beyond the feasible domain (Fig. 3), even though they are greater than the summed profits obtained at $f^* = 0.42$. Additionally, increasing the unit green tax (f) will likely increase producer production costs and weaken producer bargaining power when negotiating with RL-suppliers (Fig. 2). Therefore, the overall effect on $\hat{\pi}_i$ is straightforward and negative, as characterized by the $\hat{\pi}_i$ curve (Fig. 4). Conversely, the effect of raising either f or s on RL-supplier profits ($\hat{\pi}_j$) is arguable. The value of $\hat{\pi}_j$ increases as f increases initially, and then declines when $f > 0.45$, implying the existence of a counter-effect due excess governmental intervention on both $\hat{\pi}_i$ and $\hat{\pi}_j$ (Fig. 4).

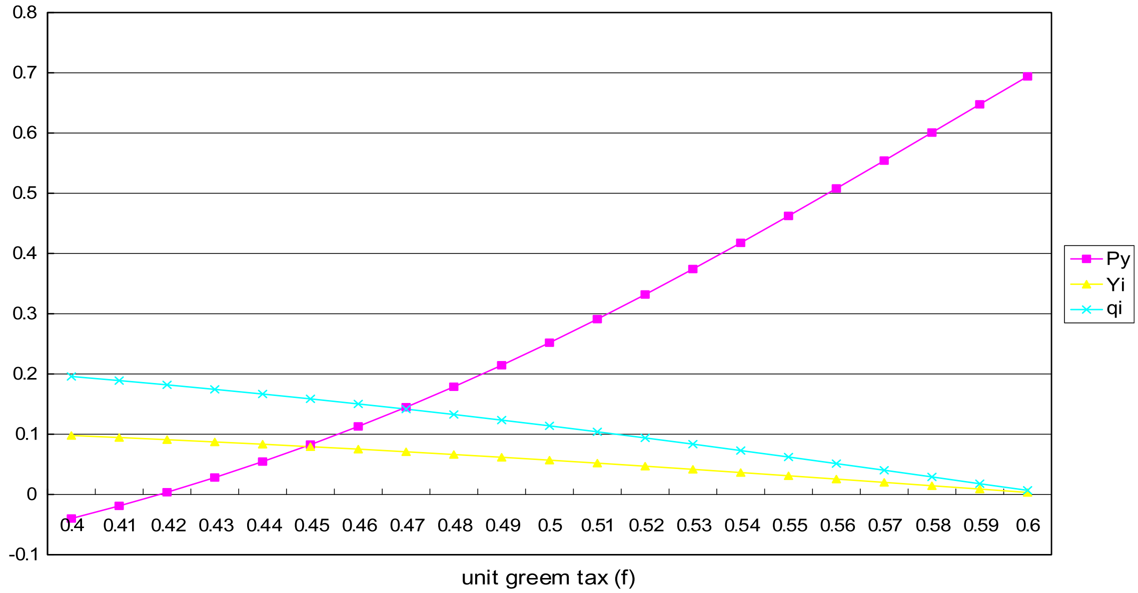

Fig. 3. Quantitative analysis (II): unit green tax vs. negotiation agendas and production.

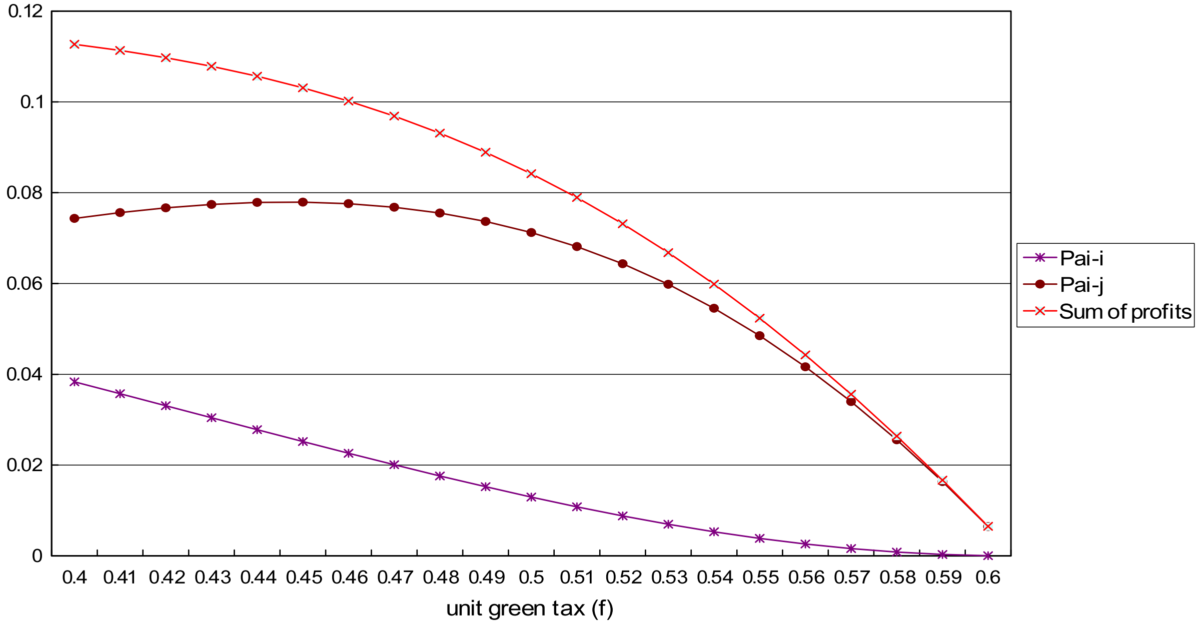

Fig. 4. Quantitative analysis (III): unit green tax vs. player profits.

Briefly, under governmental financial intervention, the bargaining power of a producer declines, whereas that of an RL-supplier increases. Such a trade-off effect further benefits an RL-supplier when negotiating with a producer, thus leading to an increased unit price for recycled components an RL-supplier is willing to offer a producer, which in turn weakens producer demand for recycled components. Consequently, the outcome of the aforementioned negotiation agendas is unfavorable for producer profits, and favorable for RL-supplier profits under equilibrium conditions. Fig. 5 presents the relationships among governmental financial intervention, bargaining power, negotiation agendas, and resulting profits of players.

4.3. Number of competitors and its impact in bargaining decisions

The following numerical study examines the impact of the number of competitors on bargaining solutions in the producer and RL-supplier bargaining framework. In addition to the basic scenario ($I = J = 4$), this work considers the following two dif-

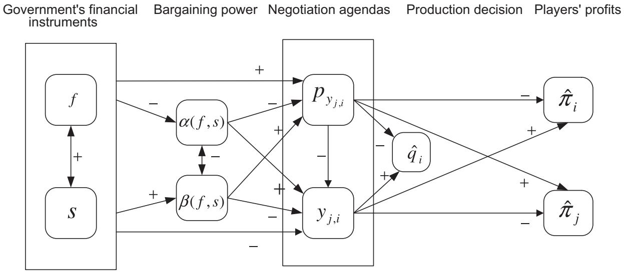

Fig. 5. Relationships between key variables in the specified bargaining framework.

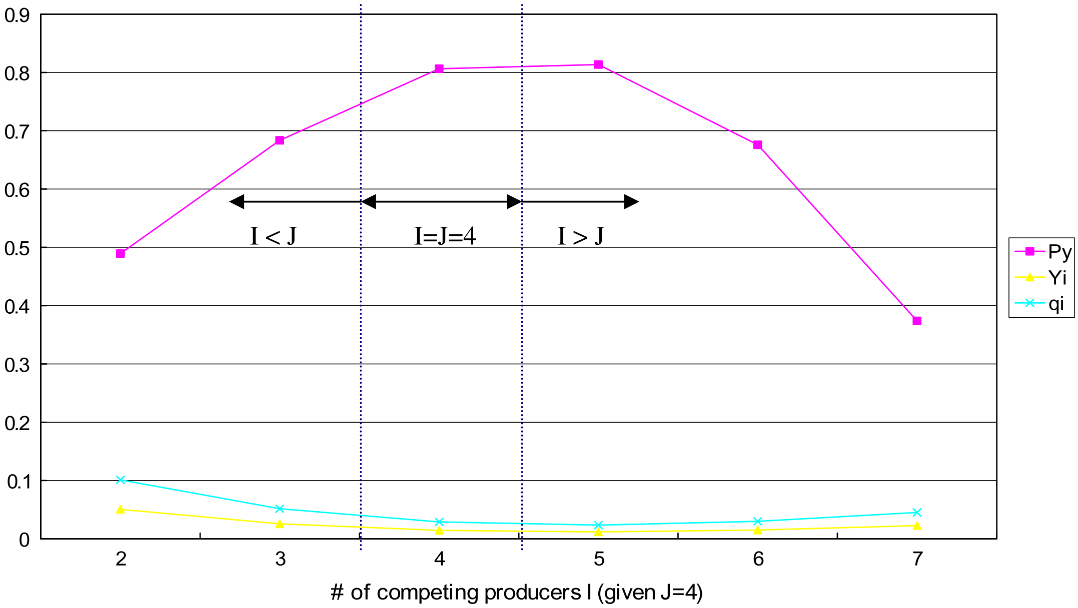

Fig. 6. Number of competing players vs. negotiation decisions.

ferent scenarios: (1) the number of producers is greater than the number of RL-suppliers (i.e., $I > J$); and (2) the number of producers is less than that of RL suppliers (i.e., $I < J$). All preset parameters (Table 1) remain the same except for the number of competitors (I and J). Figs. 6 and 7 summarize analytical results for $p^*_{y_{j,i}}$, $y^*_{j,i}$, q^*_i, and player profits.

Fig. 6 indicates that the asymmetry in the number of producers and RL suppliers favors producers when bargaining in negotiations. Given the number of RL-suppliers (J), few producers (i.e., $I < J$) existing in the bargaining framework represents few outside options to RL-suppliers, implying a reduced likelihood of achieving a agreement with another producer when current negotiations fail. Therefore, an RL supplier is likely to decrease $p_{y_{j,i}}$ in the case $I < J$ to facilitate achieving a cooperative agreement with a producer. The case $I > J$ implies that many competing producers exist and share a given product demand market, where each competing producer is prone to increase its production amount q_i under Cournot competition. This may lead to RL-supplier expectation of an increase in overall recycled component demand, and thus, an RL-supplier is willing to reduce $p_{y_{j,i}}$ when negotiating with a producer toward a cooperative agreement. Consequently, the amount of recycled components ($y_{j,i}$) and final product production (q_i) increase, as compared with those for the case in which $I = J$.

In contrast with Fig. 6, the analytical results of Fig. 7 further indicate that asymmetry in the number of producers and RL-suppliers is profitable to dyadic players in negotiations. Such a positive effect is particularly significant as the number of competing producers decreases to 2 (i.e., duopoly competition) given that RL-suppliers compete in an oligopoly context, where $J = 4$ in this case. If one further compares the analytical results for two extreme cases—$I = 2$ and $I = 7$ (Figs. 6 and 7), one can determine that the value of $p_{y_{j,i}}$ in the case when $I = 2$ is higher than that when $I = 7$. Nevertheless, the induced promotional effect on q_i when $I = 2$ is more significant than that when $I = 7$.

Accordingly, we infer that a bargaining framework underlying the duopoly–oligopoly context where only two competing producers exist and negotiate with a few competing RL-suppliers may contribute to a negotiation outcome that is most profitable to dyadic players in bilateral negotiations.

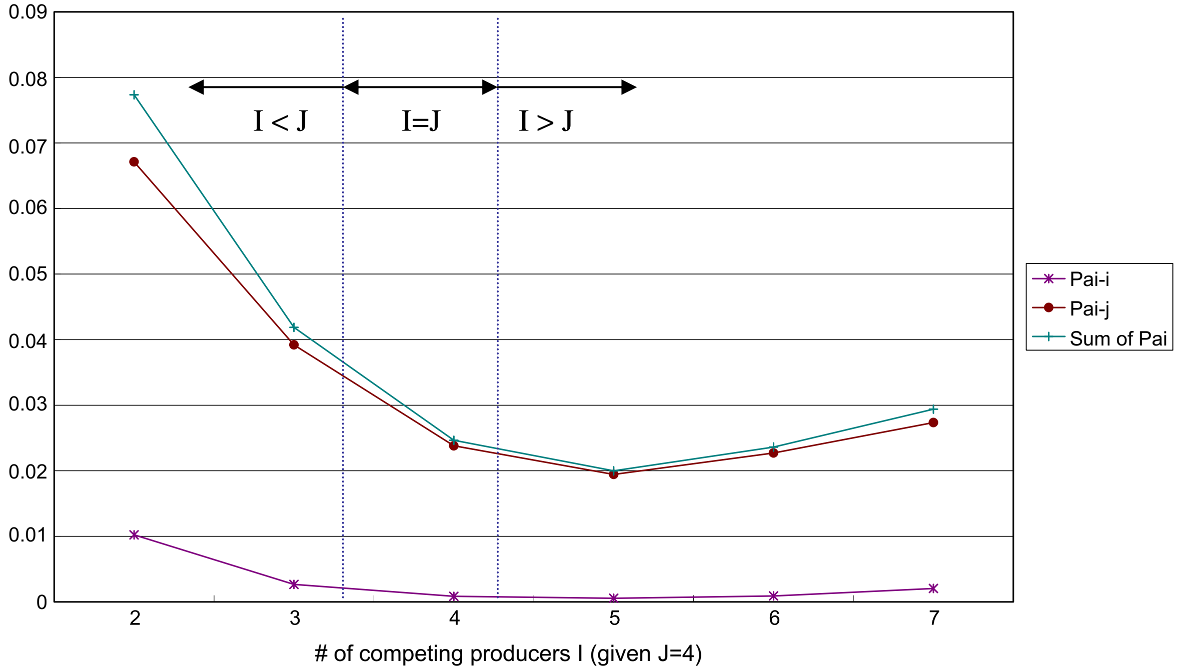

Fig. 7. Number of competing players vs. profits.

5. Conclusions and recommendations

5.1. Conclusions

This work utilized a bargaining framework to analyze negotiations between producers and RL-suppliers toward cooperative agreements under governmental financial intervention with the goal of *SW* maximization. With the proposed 3-stage game-based model, this work formulates governmental objective functions to approximate equilibrium solutions for green taxation and subsidization, followed by the use of the asymmetrical NB game with uncertainties to determine negotiation agendas and decisions of players in the specified bargaining framework.

Drawing from the proposed model and analytical results, the following summarizes several conclusions that help address the four research questions.

In the specified bargaining framework, each producer seeks a cooperative RL-supplier via sequential bilateral negotiations. During the negotiation process, dyadic players interact on the unit price of recycled component supply ($p_{y_{j,i}}$) and guaranteed supply ($y_{j,i}$) toward a cooperative agreement. A cooperative agreement is achieved only when the equilibrium solutions $p^*_{y_{j,i}}$ and $y^*_{j,i}$ exist, which can be derived by Eqs. (17) and (18), respectively. If negotiation fails, dyadic players seek another player for negotiation.

In the aforementioned bilateral negotiation under governmental intervention, each player is concerned about (1) governmental financial instruments, (2) potential threats from outside competitors (e.g., bidding and competing strategies), and (3) the reactions of dyadic players in negotiation. For instance, a producer will account for the unit green tax (f^*) levied by the government and RL-supplier's decisions in negotiation agendas (i.e., $p_{y_{j,i}}$ and $y_{j,i}$) to evaluate potential costs, and the potential risks due to negotiation breakdown and potential benefits from outside options (i.e., cooperating with another RL-supplier). Thus, this work formulates the aforementioned producer and RL-supplier bargaining problem as an asymmetrical NB problem with uncertainties (Eq. (16)). The equilibrium solutions of $p^*_{y_{j,i}}$ and $y^*_{j,i}$ are approximated based on asymmetrical NB solutions.

In the work, we assume the relative bargaining power $\alpha(f,s)$ of a producer is a linear function of unit green tax and subsidies (Eq. (24)), and embed such a function into the proposed asymmetrical NB product. Accordingly, the derived asymmetrical NB solutions, i.e., profits shared by dyadic players through a cooperative agreement rely on equilibrium solutions of unit green tax and subsidies (f^* and s^*) mediated by the effect of relative bargaining power.

If governmental financial intervention is indispensable to holding producers responsible for environmental impact, the equilibrium solutions f^* and s^* are recommended to governments as they help maximize *SW* and chain member profits, compared with other feasible solutions. Notably, the method used to derive f^* and s^* is a game-based approach and, thus, f^* and s^* are equilibrium solutions rather than optimal solutions. Therein, governments should account for the factors influencing *SW*, profit and reaction functions of chain members to determine f^* and s^*. Proposition 4.1 and Remarks 4.1 and 4.2 further clarify how governmental financial instruments influence the relative bargaining power and negotiation outcome of dyadic players in the specified bargaining framework. Nevertheless, analytical results obtained from numerical studies reveal the disadvantageous effect of governmental intervention on chain-based profits and *SW* in the case of excessive governmental intervention (e.g., levying a high unit green tax on producers). Additionally, the duopoly–oligopoly competing context in which only two competing producers and a few competing RL suppliers exist may contribute to negotiation outcomes that are most profitable to dyadic players in bilateral negotiations.

5.2. Recommendations

Although some findings and generalizations have been made to advance knowledge of negotiations among green supply chain members moving toward cooperative agreements under governmental intervention, several other directions are suggested for future research.

First, the characterization of bargaining power and corresponding power sources remain important to addressing negotiation issues of green supply chain members. To the best of our knowledge, the relative bargaining power of dyadic players in bilateral negotiations is typically treated as a parameter predetermined for simplicity in the bargaining game. Conversely, this work conceptualized the effect of green taxation and subsidization into a simplified linear function to characterize the influence of governmental financial intervention in the green supply chain bargaining framework. Nevertheless, we ague that additional power sources should be considered to rationalize such bargaining-power functions. For instance, in the field of channel relationship management (CRM) and related areas, diverse power sources, including coercive (e.g., legitimate power) and non-coercive power sources (e.g., rewards power and information power), and their derivatives, such as trust and relationship commitment, have been extensively analyzed (Raven and Kruglanski, 1970; Frazier and Rody, 1991; Sheu and Hu, 2009), but lack rationalization in quantitative approaches. Future research can focus on either methodological development or quantitative analysis to bridge the gap between CRM and green supply chain cooperation.

Model extension to incorporate different bargaining frameworks and negotiation mechanisms in green supply chains are also noteworthy. For instance, issues associated with producer collusion to form an alliance with increased bargaining power for negotiating with RL-suppliers may need sophisticated bargaining game models, and *vice versa*. This can increase the flexibility of extended models for analyzing practical cases. Additionally, issues of information asymmetry in negotiations among players may complicate the aforementioned bargaining problems, and thus warrant further investigation. Theoretically, repeated games with uncertainties combined with Markov-based approaches seem promising for a bargaining framework in which dyadic players are pursuing long-term cooperative contracts through multiple negotiations.

Furthermore, diverse influential strategies adopted by a government and their influences on green supply chain cooperation and competition warrant further investigation. Therein, different governmental financial instruments aimed at different chain members (e.g., retailers, virgin-component suppliers, and even end-customers) and product categories may generate different effects on the performance of green supply chains. Strategically, green supply chain members may take different negotiation mechanisms and cooperative strategies into account in response to governmental intervention, which may raise additional critical issues that must be addressed.

In summary, this work made an incremental contribution to literature on green supply chain management by integrating governmental financial intervention into the producer and RL-supplier bargaining framework to gain insights into the negotiation process and decisions of dyadic members moving toward green supply chain cooperation. We recommend that on the path leading to sustainable green supply chains, government involvement as a mediator is indispensable to facilitate integration of supply and reverse supply chain members. Therein, these three parties should reach consensus on collectively addressing environmental impact issues, appropriate use of economic incentives and legislation as strategies that may generate certain effects that facilitate GSCM and enrich *SW*.

Acknowledgements

This research was supported by Grant NSC 99-2410-H-009-031-MY3 from the National Science Council of Taiwan. The author also wishes to thank the referees for their helpful comments. The valuable suggestions of Professor Wayne K. Talley to improve this paper are also gratefully acknowledged. Any errors or omissions remain the sole responsibility of the authors.

Appendix A

A.1. Proof of equilibrium solution $p^*_{y_{j,i}}$ (Stage 2)

Using the proposed asymmetric Nash bargaining product (Eq. (16)), let $\Psi = \hat{\pi}_i + \hat{\pi}_j$ be the aggregate profits of a given green supply chain composed on producer *i* and RL-supplier *j* when a cooperative agreement is achieved between them. Additionally, let $\hat{d}_i = E_i(\hat{\pi}_{i|j'}) - E_i(c_{bre})$ and $\hat{d}_j = E_j(\hat{\pi}_{j|i'}) - E_j(c_{bre})$ be the expected values of net profits associated with producer *i* and RL-supplier *j* under the condition of disagreement. As $\hat{\pi}_i > \hat{d}_i$ and $\hat{\pi}_j > \hat{d}_j$ (by Theorem 3.2), and the proposed producer-RL-supplier bargaining model (Eq. (16)) follows the properties of asymmetric Nash bargaining product (Muthoo, 2002), then we can readily derive the asymmetric Nash bargaining solutions $\hat{\pi}_i^*$ and $\hat{\pi}_j^*$ associated with producer i and RL-supplier j, respectively, such that

$$\pi_i^* = \hat{d}_i + \alpha(f,s)(\Psi - \hat{d}_i - \hat{d}_j), \qquad \forall\ i \tag{A1}$$

$$\pi_j^* = \hat{d}_j + \beta(f,s)(\Psi - \hat{d}_i - \hat{d}_j), \quad \forall\ j \tag{A2}$$

Using Eqs. (8)–(15), we have the specifications of $\hat{\pi}_i, \hat{\pi}_j, E_i(\hat{\pi}_{i|j'}), E_j(\hat{\pi}_{j|i'}), E_i(c_{bre})$ and $E_j(c_{bre})$, and input them into Eq. (A1). Then, we have

$$\begin{aligned}
&\hat{\pi}_i = (E_i(\hat{\pi}_{i|j'}) - E_i(c_{bre})) + \alpha(f,s)\Big[(\hat{\pi}_i + \hat{\pi}_j) - \Big(E_i(\hat{\pi}_{i|j'}) - E_i(c_{bre}) + E_j(\hat{\pi}_{j|i'}) - E_j(c_{bre})\Big)\Big] \\
&\quad \Rightarrow \hat{\pi}_i = N_i\Big(\hat{\pi}_{i|j'} - 6c_{bre}\Big) + \alpha(f,s)\Big[(\hat{\pi}_i + \hat{\pi}_j) - N_i\Big(\hat{\pi}_{i|j'} - 6c_{bre}\Big) - N_j(\hat{\pi}_{j|i'} - 6c_{bre})\Big] \\
&\quad \Rightarrow \beta(f,s)\hat{\pi}_i - N_i\beta(f,s)\hat{\pi}_{i|j'} - \alpha(f,s)\hat{\pi}_j + \alpha(f,s)N_j\hat{\pi}_{j|i'} = 6(N_j\alpha(f,s) - N_i\beta(f,s))c_{bre} \qquad , \quad \forall\ i \\
&\quad \Rightarrow \beta(f,s)(1-N_i)\tfrac{(1-p_x\tau_x-p_{y_{j,i}}\tau_y-c_m-f)^2}{(I+1)^2} \\
&\qquad -\alpha(f,s)(1-N_j)[p_{y_{j,i}}\tau_y + (s+c_y-c_{pro})cr - c_y\tau_y - c_{col}c]\tfrac{1-p_x\tau_x-p_{y_{j,i}}\tau_y-c_m-f}{I+1} = 6[N_j\alpha(f,s) - N_i\beta(f,s)]c_{bre}
\end{aligned} \tag{A3}$$

where $N_i = 1 - \left(\frac{5}{6}\right)^{J-1}(\forall\ i)$ and $N_j = 1 - \left(\frac{5}{6}\right)^{I-1}(\forall\ j)$. By taking the Taylor's series of the left-hand side of Eq. (A3) extended to the 1^{st}-order derivative with respect to $p_{y_{j,i}}$, we have

$$\begin{aligned}
&\beta(f,s)(1-N_i)\frac{(1-p_x\tau_x-c_m-f)^2}{(I+1)^2} - \alpha(f,s)(1-N_j)[(s+c_y-c_{pro})cr - c_y\tau_y - c_{col}c]\frac{1-p_x\tau_x-c_m-f}{I+1} \\
&\quad - 2\beta(f,s)(1-N_i)\tau_y\frac{(1-p_x\tau_x-c_m-f)}{(I+1)^2}p_{y_{j,i}} - \alpha(f,s)(1-N_j)\tau_y\frac{1-p_x\tau_x-c_m-f}{I+1}p_{y_{j,i}} \\
&\quad + \alpha(f,s)(1-N_j)\tau_y\frac{(s+c_y-c_{pro})cr - c_y\tau_y - c_{col}c}{I+1}p_{y_{j,i}} = 6[N_j\alpha(f,s) - N_i\beta(f,s)]c_{bre} \\
&\Rightarrow p_{y_{j,i}}\left\{[\alpha(f,s)(1-N_j)\tau_y]\frac{[(s+c_y-c_{pro})cr - c_y\tau_y - c_{col}c] - (1-p_x\tau_x-c_m-f)}{I+1} - 2\beta(f,s)(1-N_i)\tau_y\frac{(1-p_x\tau_x-c_m-f)}{(I+1)^2}\right\} \\
&= 6[N_j\alpha(f,s) - N_i\beta(f,s)]c_{bre} + \alpha(f,s)(1-N_j)[(s+c_y-c_{pro})cr - c_y\tau_y - c_{col}c]\frac{1-p_x\tau_x-c_m-f}{I+1} \\
&\quad - \beta(f,s)(1-N_i)\frac{(1-p_x\tau_x-c_m-f)^2}{(I+1)^2} \\
&\Rightarrow p^*_{y_{j,i}} = \frac{\beta(f,s)(1-N_i)\frac{G^2}{(I+1)^2} - 6\big[N_j\alpha(f,s) - N_i\beta(f,s)\big]c_{bre} - \alpha(f,s)(1-N_j)\frac{GH}{I+1}}{[2\beta(f,s)(1-N_i)\tau_y]\frac{G}{(I+1)^2} + [\alpha(f,s)(1-N_j)\tau_y]\frac{G-H}{I+1}}
\end{aligned} \tag{A4}$$

where $G = 1 - p_x\tau_x - c_m - f; H = (s + c_y - c_{pro})cr - c_y\tau_y - c_{col}\ c$. As $p^*_{y_{j,i}}$ must be non-negative to ensure its existence, therefore, the following condition should hold.

$$\begin{aligned}
&\beta(f,s)(1-N_i)\tfrac{G^2}{(I+1)^2} \geqslant 6[N_j\alpha(f,s) - N_i\beta(f,s)]c_{bre} + \alpha(f,s)(1-N_j)\tfrac{GH}{I+1} \\
&\quad \Rightarrow \beta(f,s)(1-N_i)G^2 \geqslant 6(I+1)^2[N_j\alpha(f,s) - N_i\beta(f,s)]c_{bre} + \alpha(f,s)(1-N_j)(I+1)GH
\end{aligned} \tag{A5}$$

Thus, $p^*_{y_{j,i}}$ is proved.

$$\begin{aligned}
\frac{\partial p^*_{y_{j,i}}}{\partial f} &= \frac{\left\{6[-\rho(N_j+N_i)]c_{bre} + (1-N_j)\frac{(a_0-\rho f)(G-H)-\rho GH}{I+1} + (1-N_i)\frac{2(1-a_0+\rho f)G-\rho G^2}{(I+1)^2}\right\} \times \Delta}{\left\{[(a_0-\rho f)(1-N_j)\tau_y]\frac{H-G}{I+1} - [2(1-a_0+\rho f)(1-N_i)\tau_y]\frac{G}{(I+1)^2}\right\}^2} \\
&\quad - \frac{\nabla \times \left\{(1-N_j)\tau_y\frac{\rho(G-H)+2(a_0-\rho f)}{I+1} - [2(1-N_i)\tau_y]\frac{(1-a_0+\rho f)-\rho G}{(I+1)^2}\right\}}{\left\{[(a_0-\rho f)(1-N_j)\tau_y]\frac{H-G}{I+1} - [2(1-a_0+\rho f)(1-N_i)\tau_y]\frac{G}{(I+1)^2}\right\}^2}
\end{aligned}$$

A.2. Proof of equilibrium solutions f^* and s^* (Stage 1)

To obtain f^*, the 1st-order derivative of Eq. (22) with respect to f must satisfy the condition $\frac{\partial SW}{\partial f} = 0$, thus we have

$$\begin{aligned}
\frac{\partial SW}{\partial f} &= \hat{q}_i^* \frac{\partial \hat{q}_i^*}{\partial p^*_{y_{j,i}}} + \left(\frac{\partial \hat{\pi}_i^*}{\partial p^*_{y_{j,i}}} + \frac{\partial \hat{\pi}_{j|i}^*}{\partial p^*_{y_{j,i}}} \right) + (20cr-1)D \frac{\partial \hat{q}_i^*}{\partial p^*_{y_{j,i}}} = 0 \\
&\Rightarrow \frac{G - p^*_{y_{j,i}}\tau_y}{I+1} \times \frac{-\tau_y}{I+1} + \left(\frac{2(G - p^*_{y_{j,i}}\tau_y)(-\tau_y)}{(I+1)^2} + \frac{\tau_y(G - H - 2p^*_{y_{j,i}}\tau_y)}{I+1} \right) + (20cr-1)D \times \frac{-\tau_y}{I+1} = 0 \qquad \text{(A5)} \\
&\Rightarrow 3(G - p^*_{y_{j,i}}\tau_y) - (G - H - 2p^*_{y_{j,i}}\tau_y)(I+1) + (20cr-1)(I+1)D = 0 \\
&\Rightarrow (I-2)G^* = (I+1)H^* + (2I-1)p^*_{y_{j,i}}\tau_y + (20cr-1)(I+1)D
\end{aligned}$$

For simplicity, let $I = J = 2$, $c_{bre} \approx 0$, and $\alpha\,(f,s) = a_0 - (af + bs)$, Eq. (A5) can then be rewritten as

$$\begin{aligned}
&[3(a_0 - \rho f)(2f + L - K) - 2(1 - a_0 + \rho f)(K - f)]f + [3(a_0 - \rho f)(K - f)(L + f) - (1 - a_0 + \rho f)(K - f)^2] \\
&\quad + [(20cr-1)D + L][3(a_0 - \rho f)(2f + L - K) - 2(1 - a_0 + \rho f)(K - f)] = 0
\end{aligned} \qquad \text{(A6)}$$

where $K = 1 - p_x\tau_x - c_m; L = (c_y - c_{pro})cr - c_y\tau_y - c_{col}c;\ \rho = \frac{acr+b}{cr}$. Take the Taylor's series of the left-hand side of Eq. (A6) extended to the 1^{st}-order derivative with respect to f, we then have

$$\begin{aligned}
&3a_0KL - (1 - a_0)K^2 + [(20cr-1)D + L](3a_0L - a_0K - 2K) \\
&\quad + \left\{ -3\rho KL - \rho K^2 + [(20cr-1)D + L](4a_0 - 3\rho L + \rho K + 2) \right\} f = 0 \qquad \text{(A7)} \\
&\Rightarrow f^* = \frac{[(20cr-1)D+L](a_0K+2K-3a_0L)+(1-a_0)K^2-3a_0KL}{[(20cr-1)D+L](4a_0-3\rho L+\rho K+2)-\rho K(3L+K)}
\end{aligned}$$

Using Eqs. (A7) and (23) shown in the text, we can further approximate $s^* = \frac{f^*}{cr}$.

To prove that f^* and s^* exist, the conditions $\frac{\partial^2 SW}{\partial^2 f} < 0$ and $\frac{\partial^2 SW}{\partial^2 s} < 0$ must also hold. Taking advantage of the result of Eq. (A5), we have

$$\begin{aligned}
\frac{\partial^2 SW}{\partial^2 f} &= \frac{\partial \left\{ \left[\hat{q}_i^* \frac{\partial \hat{q}_i^*}{\partial p^*_{y_{j,i}}} + \left(\frac{\partial \hat{\pi}_i^*}{\partial p^*_{y_{j,i}}} + \frac{\partial \hat{\pi}_{j|i}^*}{\partial p^*_{y_{j,i}}} \right) + (20cr-1)D \frac{\partial \hat{q}_i^*}{\partial p^*_{y_{j,i}}} \right] \frac{\partial p^*_{y_{j,i}}}{\partial f} \right\}}{\partial f} \\
&= \frac{\partial \left\{ \left(\frac{-3\tau_y(G - p^*_{y_{j,i}}\tau_y)}{(I+1)^2} + \frac{\tau_y(G - H - 2p^*_{y_{j,i}}\tau_y)}{I+1} + (20cr-1)D \times \frac{-\tau_y}{I+1} \right) \frac{\partial p^*_{y_{j,i}}}{\partial f} \right\}}{\partial f} \\
&= \frac{(\tau_y)^2(1-2I)}{(I+1)^2} \times \left(\frac{\partial p^*_{y_{j,i}}}{\partial f} \right)^2 \qquad \text{(A8)} \\
&\quad + \left\{ \left(\frac{-3\tau_y(G - p^*_{y_{j,i}}\tau_y)}{(I+1)^2} + \frac{\tau_y(G - H - 2p^*_{y_{j,i}}\tau_y)}{I+1} \right) + (20cr-1)D \times \frac{-\tau_y}{I+1} \right\} \times \frac{\partial^2 p^*_{y_{j,i}}}{\partial^2 f} \\
&\Rightarrow \frac{\partial^2 SW}{\partial^2 f} < 0 \quad \left(\because \frac{\partial^2 p^*_{y_{j,i}}}{\partial^2 f} > 0 \right)
\end{aligned}$$

$$\begin{aligned}
\frac{\partial^2 SW}{\partial^2 s} &= \frac{\partial \left\{ \left[\hat{q}_i^* \frac{\partial \hat{q}_i^*}{\partial p^*_{y_{j,i}}} + \left(\frac{\partial \hat{\pi}_i^*}{\partial p^*_{y_{j,i}}} + \frac{\partial \hat{\pi}_{j|i}^*}{\partial p^*_{y_{j,i}}} \right) + (20cr-1)D \frac{\partial \hat{q}_i^*}{\partial p^*_{y_{j,i}}} \right] \frac{\partial p^*_{y_{j,i}}}{\partial s} \right\}}{\partial s} \\
&= \frac{\partial \left\{ \left(\frac{-3\tau_y(G - p^*_{y_{j,i}}\tau_y)}{(I+1)^2} + \frac{\tau_y(G - H - 2p^*_{y_{j,i}}\tau_y)}{I+1} + (20cr-1)D \times \frac{-\tau_y}{I+1} \right) \frac{\partial p^*_{y_{j,i}}}{\partial s} \right\}}{\partial s} \\
&= \frac{(\tau_y)^2(1-2I)}{(I+1)^2} \times \left(\frac{\partial p^*_{y_{j,i}}}{\partial s} \right)^2 \qquad \text{(A9)} \\
&\quad + \left\{ \left(\frac{-3\tau_y(G - p^*_{y_{j,i}}\tau_y)}{(I+1)^2} + \frac{\tau_y(G - H - 2p^*_{y_{j,i}}\tau_y)}{I+1} \right) + (20cr-1)D \times \frac{-\tau_y}{I+1} \right\} \times \frac{\partial^2 p^*_{y_{j,i}}}{\partial^2 s} \\
&\Rightarrow \frac{\partial^2 SW}{\partial^2 s} < 0 \quad \left(\because \frac{\partial p^*_{y_{j,i}}}{\partial s} < 0 \text{ and } \frac{\partial^2 p^*_{y_{j,i}}}{\partial^2 s} > 0 \right)
\end{aligned}$$

Based on Eqs. (A8) and (A9), we can conclude that f^* and s^* exist, and thus f^* and s^* are proved.

$$p^*_{y_{j,i}} = \frac{6[N_j\alpha(f,s) - N_i\beta(f,s)]c_{bre} + \alpha(f,s)(1-N_j)\frac{GH}{I+1} - \beta(f,s)(1-N_i)\frac{G^2}{(I+1)^2}}{[\alpha(f,s)(1-N_j)\tau_y]\frac{H-G}{I+1} - [2\beta(f,s)(1-N_i)\tau_y]\frac{G}{(I+1)^2}}, \quad \forall\ (i,j) \tag{17}$$

$$p^*_{y_{j,i}} = \frac{(a_0 - \rho f)GH - (1 - a_0 + \rho f)\frac{G^2}{(I+1)}}{(a_0 - \rho f)(H - G) - 2[1 - a_0 + \rho f]\frac{G}{(I+1)}}$$

$$G = 1 - p_x\tau_x - c_m - f; \quad H = (s + c_y - c_{pro})cr - c_y\tau_y - c_{col}c$$

$$\hat{\pi}_i = \frac{(1 - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f)^2}{(I+1)^2}, \quad \forall\ i \tag{8}$$

$$\hat{\pi}_j = [p_{y_{j,i}}\tau_y + (s + c_y - c_{pro})cr - c_y\tau_y - c_{col}c]\frac{1 - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f}{I+1}, \quad \forall\ j \tag{9}$$

$$\hat{q}_i = \frac{1 - p_x\tau_x - p_{y_{j,i}}\tau_y - c_m - f}{I+1}, \quad \forall\ i \tag{3}$$

Appendix B

B.1. Proof of Theorem 3.2

Theorem 3.2 can be proved straightforwardly by $\hat{\pi}_i - \hat{d}_i$ and $\hat{\pi}_j - \hat{d}_j$. Using Eqs. (10)–(13), we can prove the following conditions $\hat{\pi}_i > \hat{d}_i, \forall\ i$ (Eq. (B1)) and $\hat{\pi}_j > \hat{d}_j, \forall\ j$ (Eq. (B2)) always hold true, and thus Theorem 3.2 is proved.

$$\begin{aligned} \hat{\pi}_i - \hat{d}_i &= \hat{\pi}_i - (E_i(\hat{\pi}_{i|j'}) - E_i(c_{bre})) \\ &= \hat{\pi}_i - \left[1 - \left(\tfrac{5}{6}\right)^{J-1}\right]\hat{\pi}_{i|j'} + 6\left[1 - \left(\tfrac{5}{6}\right)^{J-1}\right]c_{bre} \\ &= \left(\tfrac{5}{6}\right)^{J-1}\hat{\pi}_i + 6\left[1 - \left(\tfrac{5}{6}\right)^{J-1}\right]c_{bre} > 0 \\ &\Rightarrow \hat{\pi}_i > \hat{d}_i \end{aligned} \tag{B1}$$

$$\begin{aligned} \hat{\pi}_j - \hat{d}_j &= \hat{\pi}_j - (E_j(\hat{\pi}_{j|i'}) - E_j(c_{bre})) \\ &= \hat{\pi}_j - \left[1 - \left(\tfrac{5}{6}\right)^{I-1}\right]\hat{\pi}_{j|i'} + 6\left[1 - \left(\tfrac{5}{6}\right)^{I-1}\right]c_{bre} \\ &= \left(\tfrac{5}{6}\right)^{I-1}\hat{\pi}_j + 6\left[1 - \left(\tfrac{5}{6}\right)^{I-1}\right]c_{bre} > 0 \quad (\because \hat{\pi}_j = \hat{\pi}_{j|i'} \text{ under equilibrium conditions}) \\ &\Rightarrow \hat{\pi}_j > \hat{d}_j \end{aligned} \tag{B2}$$

B.2. Proof of Theorem 3.3

According to asymmetric Nash bargaining solutions (Eqs. (A1) and (A2)), under equilibrium conditions we have

$$\begin{aligned} &\hat{\pi}^*_i = \hat{d}^*_i + \alpha(f,s)\left(\hat{\pi}^*_i + \hat{\pi}^*_j - \hat{d}^*_i - \hat{d}^*_j\right) \\ &\Rightarrow \hat{\pi}^*_i = \left(E_i(\hat{\pi}^*_{i|j'}) - E_i(c_{bre})\right) + \alpha(f,s)\left[\left(\hat{\pi}^*_i + \hat{\pi}^*_j\right) - \left(E_i(\hat{\pi}^*_{i|j'}) - E_i(c_{bre}) + E_j(\hat{\pi}^*_{j|i'}) - E_j(c_{bre})\right)\right] \\ &\Rightarrow \hat{\pi}^*_i = N_i(\hat{\pi}^*_i - 6c_{bre}) + \alpha(f,s)\left[\left(\hat{\pi}^*_i + \hat{\pi}^*_j\right) - N_i(\hat{\pi}^*_i - 6c_{bre}) - N_j\left(\hat{\pi}^*_j - 6c_{bre}\right)\right] \qquad , \quad \forall\ (i,j) \\ &\Rightarrow \beta(f,s)\hat{\pi}^*_i - N_i\beta(f,s)\hat{\pi}^*_i = \alpha(f,s)\hat{\pi}^*_j - \alpha(f,s)N_j\hat{\pi}^*_j + 6\left(N_j\alpha(f,s) - N_i\beta(f,s)\right)c_{bre} \\ &\Rightarrow \beta(f,s)(1 - N_i)\hat{\pi}^*_i = \alpha(f,s)(1 - N_j)\hat{\pi}^*_j + 6(\alpha(f,s)N_j - \beta(f,s)N_i)c_{bre} \end{aligned} \tag{B3}$$

Thus, Theorem 3.3 is proved.

B.3. Proof of Proposition 4.1

By Eq. (24), let $\alpha(f^*,s^*) = a_0 - (af^* + bs^*)$, and $\beta(f^*,s^*) = 1 - \alpha(f^*,s^*) = 1 - a_0 + (af^* + bs^*)$. Now, consider the following case:

$$\begin{aligned} &\alpha(f^*,s^*) > \beta(f^*,s^*) \\ &\qquad \Rightarrow a_0 - (af^* + bs^*) > 1 - a_0 + (af^* + bs^*) \\ &\qquad \Rightarrow a_0 - \rho f^* > 1 - a_0 + \rho f^* \quad \left(\because f^* = s^*cr, \rho = \tfrac{acr+b}{cr}\right) \\ &\qquad \Rightarrow f^* < \tfrac{2a_0-1}{2\rho} \quad \left(i.e., s^* < \tfrac{2a_0-1}{2acr+b}\right) \end{aligned} \tag{B4}$$

Similarly, we can easily derive $\alpha(f^*,s^*) < \beta\ (f^*,s^*)$ if $f^* > \frac{2a_0-1}{2\rho}$ $\left(i.e.,\ s^* > \frac{2a_0-1}{2acr+b}\right)$, and $\alpha\ (f^*,s^*) = \beta(f^*,s^*)$, if $f^* = \frac{2a_0-1}{2\rho}$ $\left(i.e.,\ s^* = \frac{2a_0-1}{2acr+b}\right)$. Thus, Proposition 4.1 is proved.

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