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Abstract. We consider an infinitely-lived duopoly with asymmetric costs and study the incentives of the firms to collude or compete in supply functions under the possibility of technology licensing. Simulating the subgame-perfect Nash equilibria of alternative industry organizations, we show that licensing makes collusion harder; but it always has a positive effect on the welfares of consumers and the less efficient firm in the duopoly.

Keywords: Duopoly; collusion; supply function equilibrium; licensing.

JEL Codes: D43; L13; O30.

1 Introduction

As we know from the work of Lin (1996a), in an asymmetric duopoly under Bertrand (price) competition tacit collusion is more likely to occur if the (cost) efficient firm licenses its cost-reducing technology to the inefficient firm in return for a fixed fee. The reason is that licensing, or thereof the equalization of the production costs, could act for the licensor as a self-disciplining mechanism, increasing the likelihood of its competitor's retaliation in case

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the licensor cheats on the collusive outcome. A similar result was earlier found by Eswaran (1993) in the context of cross-licensing and by Kesteloot and Veugelers in the context of R&D cooperation with spillovers, as well as by Benoit and Krishna (1987) and Davidson and Deneckere (1990) in models where firms can create excess capacity to prevent deviations from collusive agreements. However, there are also environments where licensing does not always enhance collusion. For example, Lin (1996b) shows that licensing makes tacit collusion harder if the strategies used by the duopolists are restricted to quantities instead of prices. In this paper, we investigate whether the results of Lin (1996a) or Lin (1996b), linking the likelihood of collusion to the presence of licensing positively or negatively, remain to hold when the asymmetric duopolists compete in supply functions, instead of prices as in Lin (1996a) or quantities as in Lin (1996b).

Supply function competition was introduced by Grossman (1981) and developed by Klemperer and Meyer (1989) to analyze oligopolistic games with uncertainties. Since then, this new form of competition has been extensively used to model the strategic games played by generator companies in electricity industries (see, for example, Green and Newbery, 1992; Rudkevich and Duckworth, 1998; Newbery and Greve, 2017; and Escrihuela-Villar et al., 2020). A recent literature pioneered by Ciarreta and Gutiérrez-Hita (2012) studies how collusive agreements arise in industries like electricity generation that are under supply function competition. Using an infinitely-lived duopoly with asymmetric production costs, Ciarreta and Gutiérrez-Hita (2012) theoretically show that an increase in cost differences reduces in such industries the likelihood of cartel formation and collusion sustainability. A related study by Saglam (2020) studies the effect of several profit-sharing rules on the incentives to join a single-period duopolistic cartel that colludes in supply functions under cost asymmetry and demand uncertainty. The integration of supply function competition with technology licensing is due to a recent work of Saglam (2021), who studies the welfare effects of fixed-fee licensing and royalty licensing in a duopoly where one of the firms has a cost-reducing innovation available to be licensed to the inefficient firm.

To the best of our knowledge, our paper is the first one that studies supply function collusion in the presence of technology licensing. Like Ciarreta and Gutiérrez-Hita (2012), we consider an infinitely-lived duopoly with asymmetric production costs. We assume an exogenous and additive demand shock as in Laussel (1992) and Ciarreta and Gutiérrez-Hita (2012) and a linear marginal cost function (or a quadratic cost function) as in Ciarreta and Gutiérrez-Hita (2012) to ensure that each stage game of the repeated game has always a unique non-cooperative equilibrium in supply functions. Besides the possibility of licensing, our model differs from that of Ciarreta and Gutiérrez-Hita (2012) in the sharing of collusive output. While their model allocates the industry output in a ratio that equalizes the firms' marginal costs, we assume that the efficient firm can offer, to the inefficient firm, a take-it-or-leave-it contract specifying the division of collusive output. Our model also differs from those of Lin (1996a,b). This difference is not only in the form of strategies used by the firms when they compete or collude but also concerning the sustainability of licensing in case collusion breaks down. Both Lin (1996a) and (1996b) assume that if in any period one of the firms cheats on the collusive outcome under licensing, then in subsequent periods the other firm reverts, for punishment, to a non-cooperative equilibrium without any licensing, whereas we assume that any deviation from the collusive outcome does not affect the firms' prior agreement on licensing. In our model, the retaliating firm, if it faces any deviant act, (i) reverts to a non-cooperative equilibrium with licensing if collusion involves licensing and (ii) reverts to a non-cooperative equilibrium without licensing if collusion involves no licensing.

Given the above assumptions, we characterize conditions under which collusion in the absence or presence of licensing can occur as a sustainable industrial organization and conduct simulations (numerical computations) to analyze how these conditions and the welfare distribution in the duopolistic industry are affected by the size of the cost asymmetry, the discount factors of the firms, and the presence of licensing. Our simulations show that collusion both in the absence and presence of technology licensing can be supported as a subgame-perfect supply-function Nash equilibrium if the firms are sufficiently patient. This finding is in line with the predictions of folk theorems in infinitely repeated games with discounting (see, for example, Friedman, 1971; and Fudenberg and Maskin, 1986). Our simulations also show that licensing makes tacit collusion in supply functions harder like in the work of Lin (1996b) where the firms' strategies are fixed quantities, and unlike in the work of Lin (1996a) where the firms' strategies are fixed prices. Moreover, conditional on collusion the presence of licensing always has a positive effect on the welfares of consumers and the less efficient firm in the duopoly.

The rest of our paper is organized as follows: Section 2 presents the model, Sections 3 and 4 introduce theoretical and numeric (computational) results respectively, and finally Section 5 concludes.

2 Model

We consider an infinitely-lived duopolistic industry where the two firms produce a homogeneous product under demand uncertainty in each discrete time period $t \in \{0, 1, \ldots, \infty\}$. The firms face a stochastic demand curve in period t, given by

$$D_t(p_t) = \alpha_t - p_t, \tag{1}$$

where p_t denotes the period-t price of their products and α_t denotes an independently and idiosyncratically distributed scalar random variable with full support $[0, \infty)$, a constant mean, μ, and a constant variance, σ^2.

Firm $i \in \{1, 2\}$ faces a quadratic cost function in period t, given by

$$C_{it}(q_{it}) = c_{it} q_{it}^2/2, \tag{2}$$

where $q_{it} \geq 0$ is the quantity of output produced by firm i in period t and $c_{it} \geq 0$ is a parameter denoting the marginal cost of a unit output. We assume that $c_{1t} = c_1$ for all t and also $c_{2t} = c_2$ for $t = 0$ with $c_2 > c_1$, meaning that initially firm 1 is cost-efficient and firm 2 is cost-inefficient. However, we allow for the possibility of technology transfer under which this initial cost difference can disappear. That is, at the beginning of period 0, firm 1 can license its cost-efficient production technology to firm 2 indefinitely. If licensing occurs, then $c_{2t} = c_1$ for all $t \geq 0$, otherwise $c_{2t} = c_2$ for all $t \geq 0$. The forms of the demand and cost functions, the parameters μ and σ^2 as well as the parameters c_{1t} and c_{2t} for all t are common knowledge. The only uncertainty in the industry is about the realization of α_t, which is unknown to any firm until the end of period t.

The firms can either compete or collude in supply functions. Let $S_{it}(.)$ denote the supply function of firm i in period t such that $S_{it}(p_t) = s_{it}p_t$, where $s_{it} \geq 0$. We assume that in the pre-production stage of period t, the firms cooperatively or non-cooperatively select their supply functions. Without knowing the realization of the demand variable α_t, the firms can calculate, for each possible value of α_t, the market-clearing price p_t^* by solving

$$D_t(p_t^*) = S_{1t}(p_t^*) + S_{2t}(p_t^*) \tag{3}$$

or

$$\alpha_t - p_t^* = s_{1t}p_t^* + s_{2t}p_t^*, \tag{4}$$

which yields

$$p_t^* = \frac{\alpha_t}{1 + s_{1t} + s_{2t}}. \tag{5}$$

At this price, the output and profit of firm i in period t would become $q_{it}^* = S_{it}(p_t^*) = s_{it}p_t^*$ and

$$\begin{aligned} \pi_{it}(s_{it}, s_{jt}) &= p_t^* q_{it}^* - c_{it}(q_{it}^*)^2/2 \\ &= s_{it}\left(1 - \frac{c_{it}s_{it}}{2}\right)\left(\frac{\alpha_t}{1 + s_{it} + s_{jt}}\right)^2 \end{aligned} \tag{6}$$

respectively. Given equation (6) and the commonly known moments of the probability distribution for α_t, both firms can calculate the expected profit of firm $i \in \{1, 2\}$ as

$$
\begin{aligned}
E[\pi_{it}(s_{it}, s_{jt})] &= s_{it}\left(1 - \frac{c_{it}s_{it}}{2}\right)\frac{E[\alpha_t]^2}{(1 + s_{it} + s_{jt})^2} \\
&= s_{it}\left(1 - \frac{c_{it}s_{it}}{2}\right)\frac{\mu^2 + \sigma^2}{(1 + s_{it} + s_{jt})^2} \qquad (7)
\end{aligned}
$$

using the fact that $\sigma^2 = E[\alpha_t^2] - \mu^2$.

3 Theoretical Results

We assume that the firms in the duopoly can either compete or collude in supply functions with or without technology licensing. This assumption leads to four distinct market structures, of which we are particularly interested, as the main topic of this research, in the one where the firms collude in all periods in supply functions with technology licensing. The conditions under which we observe this particular market structure will depend on the size of the expected (discounted) lifetime profit streams of the duopolistic firms in comparison to what they would get under alternative forms of equilibrium and disequilibrium structures. To calculate these profits and make the required welfare comparisons, we will first calculate the single-period profits in each market structure we have mentioned above.

3.1 Supply Function Competition in Period t

We will first analyze a stage game where the two firms engage in supply function competition as in Klemperer and Meyer (1989). So, consider period t where the cost parameters of the firms are c_{1t} and c_{2t}. Suppose that each firm i selects for this period a supply function, or more specifically the slope parameter s_{it} of such a function, to maximize its expected profit $E[\pi_{it}(s_{it}, s_{jt})]$

given its conjecture about the choice s_{jt} made by firm $j \neq i$. When the conjecture of each firm is consistent with the choice of its opponent, the choices of the two firms are said to form a supply-function Nash equilibrium (SFNE). Formally, a pair of supply functions, $\langle S_{1t}^N(p_t^*), S_{2t}^N(p_t^*)\rangle$ with $S_{1t}^N(p_t^*) = s_{1t}^N p_t^*$ and $S_{2t}^N(p_t^*) = s_{2t}^N p_t^*$, form a SFNE if

$$s_{it}^N = \underset{s_{it} \geq 0}{\operatorname{argmax}} \ E[\pi_{it}(s_{it}, s_{jt}^N)] \tag{8}$$

for each $i, j \in \{1, 2\}$ with $i \neq j$.

Proposition 1. *A period-t game where the firms compete in supply functions has a unique SFNE involving* $S_{1t}^N(p_t^*) = s_1^N(c_{1t}, c_{2t})p_t^*$ *and* $S_{2t}^N(p_t^*) = s_2^N(c_{1t}, c_{2t})p_t^*$ *such that for each* $i = 1, 2$

$$s_i^N(c_{1t}, c_{2t}) = \frac{\beta_t - c_{1t}c_{2t} - 2c_{it}}{2(c_{1t}c_{2t} + c_{1t} + c_{2t})} \tag{9}$$

with

$$\beta_t = \sqrt{(c_{1t} + 2)(c_{2t} + 2)(c_{1t}c_{2t} + 2c_{1t} + 2c_{2t})}. \tag{10}$$

Proof. Differentiating $E[\pi_{it}(s_{it}, s_{jt})]$ with respect to s_{it} and equating to zero, we obtain

$$0 = -\frac{(\mu^2 + \sigma^2)(c_{it}s_{it}s_{jt} + c_{it}s_{it} + s_{it} - s_{jt} - 1)}{(s_{it} + s_{jt} + 1)^3}, \tag{11}$$

implying the best-response function for firm i given by

$$s_{it}^B(s_{jt}) = \frac{s_{jt} + 1}{c_{it}s_{jt} + c_{it} + 1}. \tag{12}$$

Since the two firms' problems only differ in their cost parameters c_{1t} and c_{2t}, we can directly write the best-response function of firm j as

$$s_{jt}^B(s_{it}) = \frac{s_{it} + 1}{c_{jt}s_{it} + c_{jt} + 1}. \tag{13}$$

If the supply functions $S_{1t}^N(p_t^*) = s_{1t}^N p_t^*$ and $S_{2t}^N(p_t^*) = s_{2t}^N p_t^*$ form a SFNE, then we must have $s_{1t}^N = s_{1t}^B(s_{2t}^N)$ and $s_{2t}^N = s_{2t}^B(s_{1t}^N)$. These conditions imply that we should solve (12) and (13) together, yielding

$$(c_{it} + c_{it}c_{jt} + c_{jt})(s_{it}^N)^2 + (2c_{it} + c_{it}c_{jt})s_{it}^N - (c_{jt} + 2) = 0, \tag{14}$$

which has the unique solution $s_{it}^N = s_i^N(c_{1t}, c_{2t})$ satisfying (9) and (10). ■

We should note that the equilibrium of a non-cooperative stage game without technology licensing was already characterized by Ciarreta and Gutiérrez-Hita (2012). However, we cannot directly borrow their result because their industry structure is, in some aspects, slightly more restrictive than ours. For example, they assume for mathematical simplicity a 'symmetric' version of cost asymmetry by setting $c_1 = 1 - c$ and $c_2 = 1 + c$ where $c \in (0, 1)$ and a simpler version of demand shock where the random variable α_t can take values $\alpha + \mu$ and $\alpha - \mu$ with equal probability for some values of μ. One can easily check that under these restrictions, Proposition 1 boils down to the earlier result of Ciarreta and Gutiérrez-Hita (2012).

Given the equilibrium supply functions satisfying (9)-(10), the market-clearing price, p_t^N, and the equilibrium output, $q_{it}^N = s_i^N(c_{1t}, c_{2t})p_t^N$, of firm i become

$$p_t^N(c_{1t}, c_{2t}) = \frac{\alpha_t}{\beta}(c_{1t} + c_{2t} + c_{1t}c_{2t}) \tag{15}$$

and

$$q_{it}^N(c_{1t}, c_{2t}) = \frac{\alpha_t}{2\beta_t}(\beta_t - 2c_{it} - c_{1t}c_{2t}), \tag{16}$$

leading to the equilibrium industry output

$$Q_t^N(c_{1t}, c_{2t}) = \frac{\alpha_t}{\beta_t}(\beta_t - c_{1t} - c_{2t} - c_{1t}c_{2t}). \tag{17}$$

For convenience, we shall introduce the following notation. For any variable X that is a function of $s_1^N(c_{1t}, c_{2t})$ and $s_2^N(c_{1t}, c_{2t})$, let $X(c_{1t}, c_{2t}) \equiv$

$X(s_1^N(c_{1t}, c_{2t}), s_2^N(c_{1t}, c_{2t}))$. Using our findings above, we can now calculate the expected period-t profit of firm i in the supply function equilibrium as

$$\begin{aligned} E[\pi_i^N(c_{1t}, c_{2t})] &= \frac{\mu^2+\sigma^2}{2\beta_t^2}(\beta_t - 2c_{it} - c_{1t}c_{2t})(c_{1t} + c_{2t} + c_{1t}c_{2t}) \\ &\quad - \frac{\mu^2+\sigma^2}{2\beta_t^2}(\beta_t - 2c_{it} - c_{1t}c_{2t})\frac{c_{it}(\beta_t - 2c_{it} - c_{1t}c_{2t})}{4}, \quad (18) \end{aligned}$$

and the expected period-t industry profit, $E[\Pi^N(c_{1t}, c_{2t})] \equiv \sum_{i=1}^2 E[\pi_{it}^N(c_{1t}, c_{2t})]$, as

$$E[\Pi^N(c_{1t}, c_{2t})] = \frac{\mu^2+\sigma^2}{4}(c_{1t} + c_{2t})\left(\frac{\sqrt{(c_{1t}+2)(c_{2t}+2)}}{\sqrt{2c_{1t} + 2c_{2t} + c_{1t}c_{2t}}} - 1\right). \quad (19)$$

(Note that we have been able to get rid of the subscript t in the profit equations above since the only dependence on time is caused by the arguments c_{1t} and c_{2t}.) Also, we can calculate in period t the expected consumer surplus, $E[CS^N(c_{1t}, c_{2t})]$, and the expected social welfare, $E[SW^N(c_{1t}, c_{2t})] \equiv E[\Pi^N(c_{1t}, c_{2t})] + E[CS_t^N(c_{1t}, c_{2t})]$, as

$$E[CS^N(c_{1t}, c_{2t})] = \frac{\mu^2+\sigma^2}{2}\left(1 - \frac{c_{1t} + c_{2t} + c_{1t}c_{2t}}{\beta_t}\right)^2 \quad (20)$$

and

$$\begin{aligned} E[SW^N(c_{1t}, c_{2t})] &= \left(\frac{\mu^2+\sigma^2}{2}\right)\left(1 - \frac{c_{1t} + c_{2t} + c_{1t}c_{2t}}{\beta_t}\right)^2 \\ &\quad + \left(\frac{\mu^2+\sigma^2}{2}\right)\left(\frac{c_{1t}+c_{2t}}{2}\right)\left(\frac{\sqrt{(c_{1t}+2)(c_{2t}+2)}}{\sqrt{2c_{1t} + 2c_{2t} + c_{1t}c_{2t}}} - 1\right). \quad (21) \end{aligned}$$

3.2 Supply Function Collusion in Period t

Now, we will consider a stage game where the two firms collude in supply functions. Again, consider period t where the cost parameters of the firms are c_{1t} and c_{2t}. We assume that the two firms can collude if they can agree on a plan specifying the division of the collusive supply, between themselves, at any possible price. Let the shares of the firm 1 and firm 2 in such a plan be denoted by r_{1t} and r_{2t} with $r_{1t} + r_{2t} = 1$. Let $S_t(p_t) = s_t p_t$ denote the industry supply function which is the sum of individual supply curves of the colluding firms, i.e., $S_t(p_t) \equiv S_{1t}(p_t) + S_{2t}(p_t)$ for each $p_t \geq 0$. Given the market-share parameters r_{1t} and r_{2t}, the supply functions of the two firms can be written as $S_{1t}(p) = r_{1t}S_t(p) = r_{1t}s_t p_t$ and $S_{2t}(p) = r_{2t}S_t(p) = r_{2t}s_t p_t$.

Equating the industry demand and supply curves, the market-clearing price p_t^* can be calculated for each realization of the demand parameter α_t, as given by

$$p_t^* = \frac{\alpha_t}{1 + s_t}. \tag{22}$$

Given (22) and the supply functions $S_{1t}(p_t)$ and $S_{2t}(p_t)$, the profit obtained by firm i from the described collusive agreement would be

$$\pi_{it}(s_t) = s_t \left(\frac{\alpha_t}{1 + s_t}\right)^2 \left(r_{it} - \frac{c_{it} r_{it}^2 s_t}{2}\right). \tag{23}$$

The cartel consisting of the colluding firms chooses the industry supply function $S_t = s_t p_t$ to maximize the expected industry profits $E[\pi_{1t}(s_t) + \pi_{2t}(s_t)]$. Formally, an industry supply function $S_t^C(p_t^*) = s_t^C p_t^*$ ensures collusion in period t if

$$s_t^C = \underset{s_t \geq 0}{\operatorname{argmax}} \; \frac{s_t(\mu^2 + \sigma^2)}{(1 + s_t)^2} \left(1 - \frac{(c_{1t}r_{1t}^2 + c_{2t}r_{2t}^2)\, s_t}{2}\right). \tag{24}$$

Proposition 2. *If firm 1 and firm 2 engage, in period t, to collude in supply functions, then they should select the industry supply function as $S_t^C(p_t^*) = s^C(c_{1t}, c_{2t}, r_{1t})p_t^*$ with*

$$s^C(c_{1t}, c_{2t}, r_{1t}) = \frac{1}{c_{1t}r_{1t}^2 + c_{2t}(1 - r_{1t})^2 + 1}. \tag{25}$$

Proof. The first-order necessary condition associated with the above maximization implies

$$0 = -\frac{(\mu^2+\sigma^2)(s_t^C(c_{1t}r_{1t}^2 + c_{2t}(1-r_{1t})^2+1)-1)}{(s_t^C+1)^3}, \tag{26}$$

which has the unique solution given by (25). ■

We should note that the result in Proposition 2 is entirely different from the respective result in Ciarreta and Gutiérrez-Hita (2012) for stage-game collusion. The difference mainly stems from the fact that they allocate the industry output in a ratio that equalizes the firms' marginal costs, whereas we assume that the efficient firm can offer, to the inefficient firm, a take-it-or-leave-it contract specifying, using the pair of parameters (r_{1t}, r_{2t}), the division of collusive output at each possible price.

Using Proposition 2, we can calculate the market-clearing price and the equilibrium industry output as

$$p_t^C(c_{1t}, c_{2t}, r_{1t}) = \alpha_t \frac{c_{1t}r_{1t}^2 + c_{2t}(1-r_{1t})^2+1}{c_{1t}r_{1t}^2 + c_{2t}(1-r_{1t})^2+2} \tag{27}$$

and

$$Q_t^C(c_{1t}, c_{2t}, r_{1t}) = \alpha_t \frac{1}{c_{1t}r_{1t}^2 + c_{2t}(1-r_{1t})^2+2} \tag{28}$$

respectively. Noting that the output of firms 1 and 2 are $q_{1t}^C = r_{1t}Q_t^C$ and $q_{2t}^C = (1-r_{1t})Q_t^C$ respectively, we can calculate their expected period-t profits under collusion as

$$E[\pi_{1t}(c_{1t}, c_{2t}, r_{1t})] = \left(\frac{\mu^2+\sigma^2}{2}\right) \frac{r_{1t}\left(c_{1t}r_{1t}(2r_{1t}-1) + 2(c_{2t}(1-r_{1t})^2+1)\right)}{\left(c_{1t}r_{1t}^2 + c_{2t}(1-r_{1t})^2+2\right)^2}, \tag{29}$$

and

$$E[\pi_{2t}(c_{1t}, c_{2t}, r_{1t})] = \left(\frac{\mu^2+\sigma^2}{2}\right) \frac{(1-r_{1t})\left(2c_{1t}r_{1t}^2 - c_{2t}(1-r_{1t}) + 2(c_{2t}(1-r_{1t})^2+1)\right)}{\left(c_{1t}r_{1t}^2 + c_{2t}(1-r_{1t})^2+2\right)^2}, \tag{30}$$

implying an expected industry profit, $E[\Pi^C(c_{1t}, c_{2t}, r_{1t})] \equiv \sum_{i=1}^{2} E[\pi_i^C(c_{1t}, c_{2t}, r_{1t})]$, of amount

$$E[\Pi^C(c_{1t}, c_{2t}, r_{1t})] = \left(\frac{\mu^2 + \sigma^2}{2}\right) \frac{1}{(c_{1t}r_{1t}^2 + c_{2t}(1 - r_{1t})^2 + 2)}. \tag{31}$$

We can also calculate in period t the expected consumer surplus

$$E[CS^C(c_{1t}, c_{2t}, r_{1t})] = \left(\frac{\mu^2 + \sigma^2}{2}\right) \frac{1}{(c_{1t}r_{1t}^2 + c_{2t}(1 - r_{1t})^2 + 2)^2} \tag{32}$$

and the expected social welfare, $E[SW^C(c_{1t}, c_{2t}, r_{1t})] \equiv E[\Pi^C(c_{1t}, c_{2t}, r_{1t})] + E[CS^C(c_{1t}, c_{2t}, r_{1t})]$, given by

$$E[SW^C(c_{1t}, c_{2t}, r_{1t})] = \left(\frac{\mu^2 + \sigma^2}{2}\right) \frac{c_{1t}r_{1t}^2 + c_{2t}(1 - r_{1t})^2 + 3}{(c_{1t}r_{1t}^2 + c_{2t}(1 - r_{1t})^2 + 2)^2}. \tag{33}$$

Now, we are ready to consider the infinitely repeated games.

3.3 Infinitely Repeated Games of Competition and Collusion

Using the stage games examined in Sections 3.1 and 3.2, we will now study infinitely repeated games where the duopolistic firms have to decide whether to compete or collude in supply functions in an infinite horizon and also whether to make a licensing agreement for technology transfer. We assume that the firms discount future payoffs. Let $\delta \in (0, 1)$ denote the common discount factor for the firms. Because of discounting, the firms, to avoid any potential welfare loss due to delayed decisions, will prepare their infinite-horizon plans right at the beginning of period 0, taking into account the expected value of their discounted lifetime profits. Here, we assume that licensing agreements are in the form of a take-it-or-leave-it contract offered by the efficient firm (the licensor) to the inefficient firm (the licensee), which designates a fixed fee the licensee must pay to the licensor to use its cost-reducing technology.

Given the above assumptions, the firms have the following four alternative strategy plans at the beginning of period zero.

Plan 1. In each period, engage in supply-function competition without technology transfer.

Plan 1 is a subgame-perfect supply-function Nash equilibrium (hereafter an SPNE), since this plan induces a Nash equilibrium in every period as we already know from Proposition 1. When firms 1 and 2 follow Plan 1, their cost parameters respectively become c_1 and c_2 in all periods, and their expected discounted lifetime profits become $E[\pi_1^N(c_1, c_2)]/(1-\delta)$ and $E[\pi_2^N(c_1, c_2)]/(1-\delta)$.

Plan 2. In each period, engage in supply-function competition with technology transfer under the contract that requires firm 2 to pay, in the first period this plan comes into effect, a fixed-fee F to firm 1.

If firms 1 and 2 follow Plan 2, their cost parameters become the same and equal to c_1 after they sign the licensing contract; and their expected discounted lifetime profits become $E[\pi_1^N(c_1, c_1)]/(1-\delta)+F$ and $E[\pi_2^N(c_1, c_1)]/(1-\delta)-F$. For Plan 2 to be an SPNE, competing under licensing must be bilaterally more beneficial for the two firms, in comparison to competing under no licensing which is prescribed by Plan 1. Thus, Plan 2 can arise as an equilibrium plan if and only if

$$\frac{1}{1-\delta} E\left[\pi_i^N(c_1, c_1)\right] + (-1)^{i+1} F \geq \frac{1}{1-\delta} E\left[\pi_i^N(c_1, c_2)\right] \tag{34}$$

for each $i \in \{1, 2\}$. If the incentive conditions of the two firms in (34) are satisfied at multiple values of F, then firm 1 should always pick, among them, the one with the highest value. We will denote this particular value by $\hat{F}$.

Plan 3. In each period, (i) engage in supply function collusion without technology licensing under the contract that firm 1 will produce the fraction r_1^{NL} of the total supply at any possible price (where the superscript NL stands for 'no licensing'), and (ii) threaten to retaliate to any non-collusive action in any period by reverting to Plan 1 from the next period onwards.

The punishment strategy in Plan 3, known as grim trigger strategy, was first introduced by Friedman (1971), and also used by Ciarreta and Gutiérrez-Hita (2012) in characterizing supply function collusion without technology licensing. If both firms follow Plan 3, then the cost parameters of firm 1 and firm 2 will be c_1 and c_2 in all periods; moreover, if no deviation ever occurs, then the expected discounted lifetime profit of firms 1 and 2 will be $E[\pi_1^C(c_1, c_2, r_1^{NL})]/(1-\delta)$ and $E[\pi_2^C(c_1, c_2, r_1^{NL})]/(1-\delta)$, respectively.

For Plan 3 to be an SPNE, neither firm 1 nor firm 2 should have any incentive to deviate from this plan in any period. Let us characterize when this condition holds. Suppose that in period t firm $i \in \{1, 2\}$ deviates from Plan 3 while $j \in \{1, 2\} \setminus \{i\}$ sticks to it. As Plan 3 involves no licensing (NL), we know that firm j should select the slope of its collusive supply function as $s_j^{C,NL} \equiv s_j^C(c_1, c_2, r_1^{NL})$. Also, the proof of Proposition 1 implies that the best-response of firm i to the collusive supply function of firm j must be a (deviation) supply function with a slope coefficient $s_i^{D,NL}$ such that $s_i^{D,NL} = s_i^B(s_j^{C,NL}) = (s_j^{C,NL}+1)/(c_i s_j^{C,NL}+c_i+1)$. Given this deviation, the market-clearing price in period t would become $p_t^{D,NL} = \alpha_t/(1 + s_i^{D,NL} + s_j^{C,NL})$ and firm i would supply $q_{it}^{D,NL} = s_i^{D,NL} p_t^{D,NL}$ in accordance with its supply function. Consequently, firm i could enjoy in period t an expected profit given by

$$E[\pi_i^D(c_1, c_2, r_1^{NL})] = \frac{\mu^2+\sigma^2}{(1+s_i^{D,NL}+s_j^{C,NL})^2}\left(s_i^{D,NL} - \frac{c_i(s_i^{D,NL})^2}{2}\right). \quad (35)$$

Thus, we can calculate the expected period-t profit gain of firm i from deviating from Plan 3 as $E\left[\pi_i^D(c_1, c_2, r_1^{NL})\right] - E\left[\pi_i^C\left(c_1, c_2, r_1^{NL}\right)\right]$. However, Plan 3 requires, after the deviation in period t was observed, the firms to supply their outputs in accordance with Plan 1 starting from period $t+1$ onwards. This would yield to firm i an expected continuation profit of amount $\delta E[\pi_i^N(c_1, c_2)]/(1-\delta)$, when discounted to period t. Thus, we can calculate the expected (discounted) future profit loss of firm i as $\delta \left(E\left[\pi_i^C(c_1, c_2, r_1^{NL})\right] - E\left[\pi_i^N(c_1, c_2)\right]\right)/(1-\delta)$. Taking into consideration the expected period-t profit gain and the expected (discounted) future profit loss of firm i, we can observe that firm i would have no (strict) incentive to unilaterally deviate from Plan 3 if and only if

$$\begin{aligned} &E[\pi_i^D\big(c_1, c_2, r_1^{NL}\big)] - E[\pi_i^C\big(c_1, c_2, r_1^{NL}\big)] \leq \\ &\frac{\delta}{1-\delta}\big(E[\pi_i^C\big(c_1, c_2, r_1^{NL}\big)] - E[\pi_i^N(c_1, c_2)]\big). \end{aligned} \tag{36}$$

So far, we have established that Plan 3 can be an equilibrium plan only if there exists some $r_1^{NL} \in [0,1]$ that satisfies the incentive condition in equation (36) for each i. However, we should also notice that if the incentive conditions of the two firms are satisfied at multiple values of r_1^{NL}, then firm 1 should always pick, among them, the value that maximizes $E[\pi_1^C\left(c_1, c_2, r_1^{NL}\right)]/(1-\delta)$. We will denote this particular value by $\hat{r}_1^{NL}$.

Plan 4. In each period, (i) engage in supply function collusion with technology licensing under the contract that firm 1 will produce the fraction r_1^L of the total supply at any possible price (where the superscript L stands for 'licensing'), and (ii) threaten to retaliate to any non-collusive action in any period by reverting to Plan 2 from the next period onwards.

Plan 4 also uses the grim trigger strategy of Friedman (1971), taking into account the possibility of licensing too, unlike Plan 3. Here, we should note that the works of Lin (1996a,b) also use grim trigger strategies to characterize the sustainability of collusion under licensing. But, their punishment strategies do not respect the firms' initial agreement on licensing. That is, Lin (1996a) and (1996b) assume that if in any period any firm cheats on the collusive outcome under licensing, then in subsequent periods the punishing firm reverts to a non-cooperative equilibrium without any licensing. This implicitly assumes that if the licensee were to cheat on the collusive outcome, the licensor would be able to legally or practically prevent the licensee from using the licensed technology in subsequent periods, which one can argue, however, may not be always possible. Thus, we design our grim trigger strategies in this paper in such a way that any deviation from the collusive outcome does not affect the firms' prior agreement on licensing. Thus, the retaliating firm facing any deviant act and pulling the trigger (i) reverts to a non-cooperative equilibrium without licensing (Plan 1) if collusion involves no licensing (Plan 3), and (ii) reverts to a non-cooperative equilibrium with licensing (Plan 2) if collusion involves licensing (Plan 4).

Note that if the two firms follow Plan 4, they must sign not only the contract for sharing the collusive output under technology transfer (specifying the value of the market-share parameter r_1^L) but also, as a contingency, the licensing contract (which specifies the value of the fixed fee F) mentioned in Plan 2. The cost parameters of firms 1 and 2 will be the same under Plan 4 and equal to c_1 in all periods; moreover, if no deviation ever occurs, the expected discounted lifetime profits of firms 1 and 2 will be $E[\pi_1^C(c_1, c_1, r_1^L)]/(1-\delta)$ and $E[\pi_2^C(c_1, c_1, r_1^L)]/(1-\delta)$, respectively.

For Plan 4 to be an SPNE, (i) neither firm 1 nor firm 2 should have any incentive to use any non-collusive supply function in any period and (ii) licensing must be bilaterally more beneficial for the two firms than no licensing. Let us first characterize when condition (i) holds. Suppose that firm $i \in \{1, 2\}$ unilaterally deviates from Plan 4 by using in period t a supply function different from its collusive function $S_{ti}^C(.)$. Since firm $j \neq i$ has not deviated from Plan 4, it should select the slope of its supply function as $s_j^{C,L} \equiv s_j^C(c_1, c_1, r_1^L)$. Then, we know by the proof of Proposition 1 that the best-response of firm i to the collusive supply function of firm j must be a (deviation) supply function with a slope coefficient $s_i^{D,L} = s_i^B(s_j^{C,L}) =$

$(s_j^{C,L}+1)/(c_1 s_j^{C,L}+c_1+1)$. Given this deviation, the market-clearing price in period t would become $p_t^{D,L} = \alpha_t/(1+s_i^{D,L}+s_j^{C,L})$ and firm i would supply $q_{it}^{D,L} = s_i^{D,L} p_t^{D,L}$ in accordance with its supply function. Consequently, firm i could enjoy in period t an expected profit given by

$$E[\pi_i^D(c_1, c_1, r_1^L)] = \frac{\mu^2+\sigma^2}{(1+s_i^{D,L}+s_j^{C,L})^2}\left(s_i^{D,L} - \frac{c_1\left(s_i^{D,L}\right)^2}{2}\right). \tag{37}$$

Thus, we can calculate the expected period-t profit gain of firm i from deviating from Plan 4 as $E\left[\pi_i^D(c_1, c_1, r_1^L)\right] - E\left[\pi_i^C(c_1, c_1, r_1^L)\right]$. Notice that Plan 4 requires, after the deviation in period t was observed, the firms to supply their outputs in accordance with Plan 2 starting from period $t+1$ onwards. Hence, Plan 4 can be an SPNE only if Plan 2, whenever it is played under Plan 4, is an equilibrium of the continuation game following the deviation of firm i. This implies that the fixed fee F in Plan 2 must satisfy the incentive conditions in (34) for the two firms. If these conditions hold, firm i obtains an expected continuation profit of size $\delta E[\pi_i^N(c_1, c_1)]/(1-\delta) + (-1)^{i+1}F$, when discounted to period t. Thus, we can calculate the expected (discounted) future profit loss of firm i as $\delta\left(E\left[\pi_i^C(c_1, c_1, r_1^L)\right] - E\left[\pi_i^N(c_1, c_1)\right]\right)/(1-\delta) - (-1)^{i+1}F$. Taking into consideration the expected period-t profit gain and the expected (discounted) future profit loss of firm i from deviation, we can observe that firm i would have no (strict) incentive to unilaterally deviate from using the collusive supply function $S_{it}^C(.)$ only if the fixed F in Plan 2 satisfies the incentive conditions in (34) and

$$\begin{aligned} E\left[\pi_i^D(c_1, c_1, r_1^L)\right] - E\left[\pi_i^C(c_1, c_1, r_1^L)\right] \leq \\ \frac{\delta}{1-\delta}\left(E\left[\pi_i^C(c_1, c_1, r_1^L)\right] - E\left[\pi_i^N(c_1, c_1)\right]\right) - (-1)^{i+1}F. \end{aligned} \tag{38}$$

So far, we have established that Plan 4 can be an equilibrium plan only if there exists some $r_1^L \in [0,1]$ and $F \geq 0$ that satisfy the incentive conditions in (34) and (38). Now, let us consider our second equilibrium condition, which requires that given the market sharing rule implied by r_1^L, licensing (and producing under the same costs) must be bilaterally more beneficial for the two firms than no licensing (and producing under different costs). Evidently, this condition holds if and only if

$$E\left[\pi_i^C\big(c_1, c_1, r_1^L\big)\right] \geq E\left[\pi_i^C\big(c_1, c_2, r_1^L\big)\right] \tag{39}$$

for each $i \in \{1, 2\}$. We should be cautious that the above condition does not require that Plan 4 should be superior to Plan 3 for the two firms, as these two plans involve, in general, different contracts to share the market supply. The left-hand side of (39) is the expected profit of firm i under Plan 4 involving the supply-sharing contract associated with r_1^L, whereas the right-hand side of (39) merely denotes the expected profit obtained by firm i under Plan 3 if it were to face the same contract (associated with the parameter r_1^L) as in Plan 4. We know that Plan 3, whenever arises as an SPNE, involves the use of a supply sharing contract associated with $\hat{r}_1^{NL}$, which is not necessarily equal to any arbitrary r_1^L, nor to the optimal value of r_1^L from the viewpoint of firm 1. Thus, the right-hand side of (39) is in general different from the expected profit obtained by firm i under Plan 3.

Combining all of our findings, we conclude that Plan 4 can be an equilibrium plan if and only if there exists some $r_1^L \in [0, 1]$ and $F \geq 0$ that satisfy the incentive conditions in (34), (38), and (39) for both $i = 1$ and $i = 2$. If these conditions are satisfied at multiple (r_1^L, F) pairs, then firm 1 should always pick, among them, the pair that yields, for itself, the highest expected profit at all contingencies. We will denote this particular pair by $(\hat{r}_1^L, \hat{F}^L)$.

In the next section, we will show that some of the strategy plans we have described above start or stop to become an SPNE as the parameters of our model are varied over their domains. As we are unable to make this analysis analytically due to the mathematical complexity of some equilibria plans involving multiple inequalities in many variables and parameters, we will make numerical computations.

4 Computational Results

We have performed all numerical computations in this paper with the help of MATLAB, Release 2021a. The source code of the computation program and the resulting data are available from the corresponding author upon request.

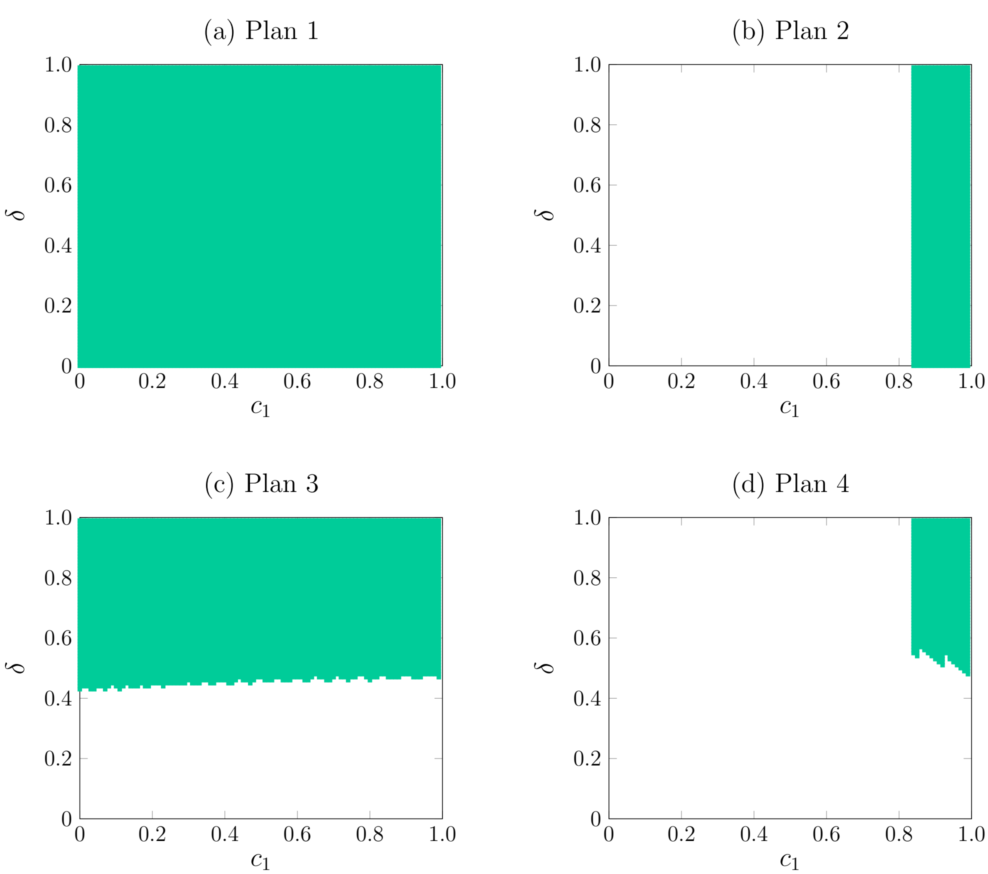
For all computations, we have set the initial cost parameter c_2 of firm 2 at 1, and varied the cost parameter c_1 of firm 1 as well as the common discount factor δ in the interval $[0, 1)$ with increments of 0.01. Also, for all computations, we have set $\mu = 3$ and $\sigma = 1$. Recall that in each of Plans 1-4, the profits of the firms depend linearly on μ^2 and σ^2; thus, we know theoretically that an increase in any of these two parameters would only increase the profits of the firms (as well as the consumer surplus). Therefore, we have kept μ^2 and σ^2 unchanged in our computations. Given the described setting for our model parameters, we have considered 10^4 distinct pairs of (δ, c_1) values for each analysis of interest.

As we already know theoretically, supply function competition without licensing (by Plan 1) can always be supported as an SPNE. Below, we investigate whether/when any of the other three plans we described in Section 3.3 can arise as an SPNE. Our simulations illustrated in Figure 1 suggest the following findings.

Result 1. *Supply function competition without licensing can always be supported (by Plan 1) as an SPNE, as we already know theoretically. On the other hand, (i) supply function competition with licensing can be supported (by Plan 2) as an SPNE at any δ only if c_1 is sufficiently high; (ii) supply function collusion without licensing can be supported (by Plan 3) as an SPNE at any c_1 only if δ is sufficiently high; (ii) supply function collusion with licensing can be supported (by Plan 4) as an SPNE if both c_1 are δ are sufficiently high.*

Result 1 reveals that firm 1 benefits from licensing under supply function competition, according to Plan 2, if and only if its cost advantage, $1-c_1$, is sufficiently small, which occurs when $c_1 \geq 0.84$. On the other hand, a collusion plan with or without licensing can be an equilibrium only if the discount factor of the firms is sufficiently high. In particular, collusion without licensing (according to Plan 3) can be an SPNE at any simulation level of c_1 if and only if δ is sufficiently high (approximately not less than 0.43), whereas collusion with licensing (according to Plan 4) can be an SPNE if and only if the cost advantage, $1-c_1$, of firm 1 is sufficiently small (not higher than 0.16) and δ is sufficiently high (approximately not less than 0.54).

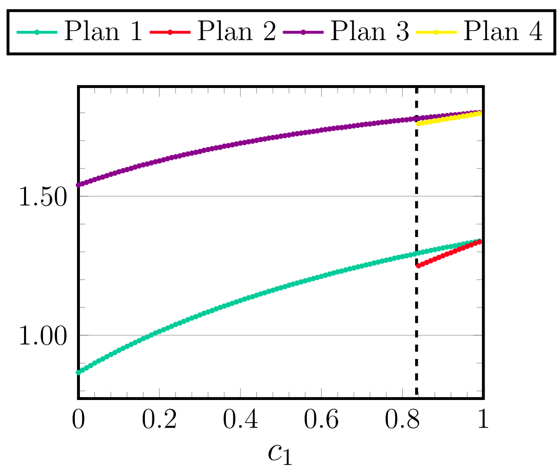
Figure 1. The Set of (c_1, δ) Pairs Supporting Equilibrium Plans



We can compare our findings reported above to those of Ciarreta and Gutiérrez-Hita (2012), who show that in the absence of licensing collusion becomes sustainable if the cost asymmetry is sufficiently small and the discount factors of the firms are sufficiently high. We find a similar result only in the presence of licensing (according to Plan 4), which was not studied by Ciarreta and Gutiérrez-Hita (2012). In the absence of licensing, our results are partially different. As in Ciarreta and Gutiérrez-Hita (2012), we find that collusion becomes sustainable (according to Plan 3) only if the discount factors of the firms are sufficiently high. But, unlike their findings, we do not need the cost asymmetry (the difference $c_2 - c_1 = 1 - c_1$ in our model) to be sufficiently small. Comparing our results for Plan 3 and Plan 4, we also observe that technology licensing makes tacit collusion in supply functions harder like in the work of Lin (1996b) where the firms' strategies are fixed quantities, and unlike in the work of Lin (1996a) where the firms' strategies are fixed prices. We should recall that the cooperative equilibrium in Plan 4 (collusion with licensing) requires the firms to play the non-cooperative equilibrium strategies according to Plan 2 (competition with licensing) in case one of the firms cheats on the collusive outcome. Therefore, Plan 4 may arise as an SPNE only if the parameters supporting Plan 4 can also support Plan 2. On the other hand, the cooperative equilibrium in Plan 3 (collusion without licensing) requires the firms to play the non-cooperative equilibrium strategies according to Plan 1 (competition without licensing) in case one of the firms cheats on the collusive outcome. Thus, Plan 3 may arise as an SPNE only if the parameters supporting Plan 3 can also support Plan 1. But, we know that Plan 1 is supported by all cost parameters and therefore it has no bite for Plan 3, whereas Plan 2 can be supported by a thin set of cost parameters (requiring c_1 to be not less than 0.84) rendering Plan 4 less likely than Plan 3 to arise as an equilibrium. One can observe from Figure 1 that the set of (c_1, δ) parameters supporting Plan 4 is nearly the intersection of the set of parameters supporting Plan 3 and the set of parameters supporting Plan 2.

Our next goal is to examine how our model variables, the product price, the output of firms, and the welfare distribution change when c_1 is varied. To this aim, we will compute for any model variable X a total of 10^4 simulated values, denoted by $X(c_1, \delta)$, by varying both c_1 and δ inside the set $\{0.00, 0.01, \ldots, 0.99\}$. Next, we will report for each c_1 the average value of X, denoted by $\bar{X}(c_1) = \sum_{\delta=0.00}^{0.99} X(c_1, \delta)/100$. Following this procedure, we first calculate for each equilibrium plan the expected product price, as illustrated in Figure 2.

Figure 2. The Price of the Product Under Alternative Equilibrium Plans



Our findings in Figure 2 are summarized as follows.

Result 2. *The product price is always increasing in c_1 and always higher under collusion than under competition. Moreover, licensing has always a negative effect on the product price both under competition and collusion.*

Because the industry demand curve is always negatively sloped, Result 2 implies that the industry output is always decreasing in c_1 and it is always lower under collusion than under competition. Moreover, licensing always increases the industry output under both competition and collusion. Our simulations illustrated in Figure 3 investigate whether these findings can also be observed for the output of each firm.

Figure 3. The Outputs of the Firms Under Alternative Equilibrium Plans

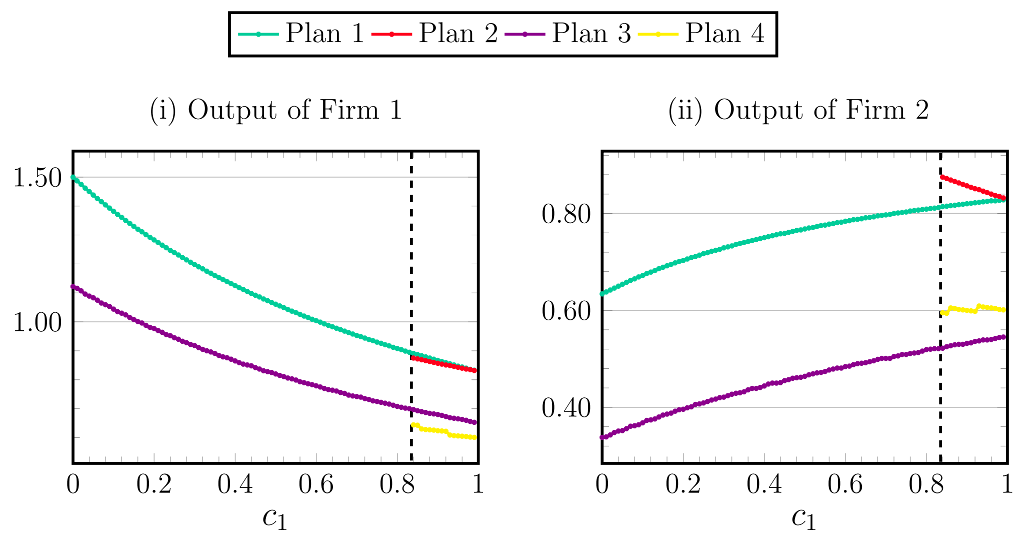
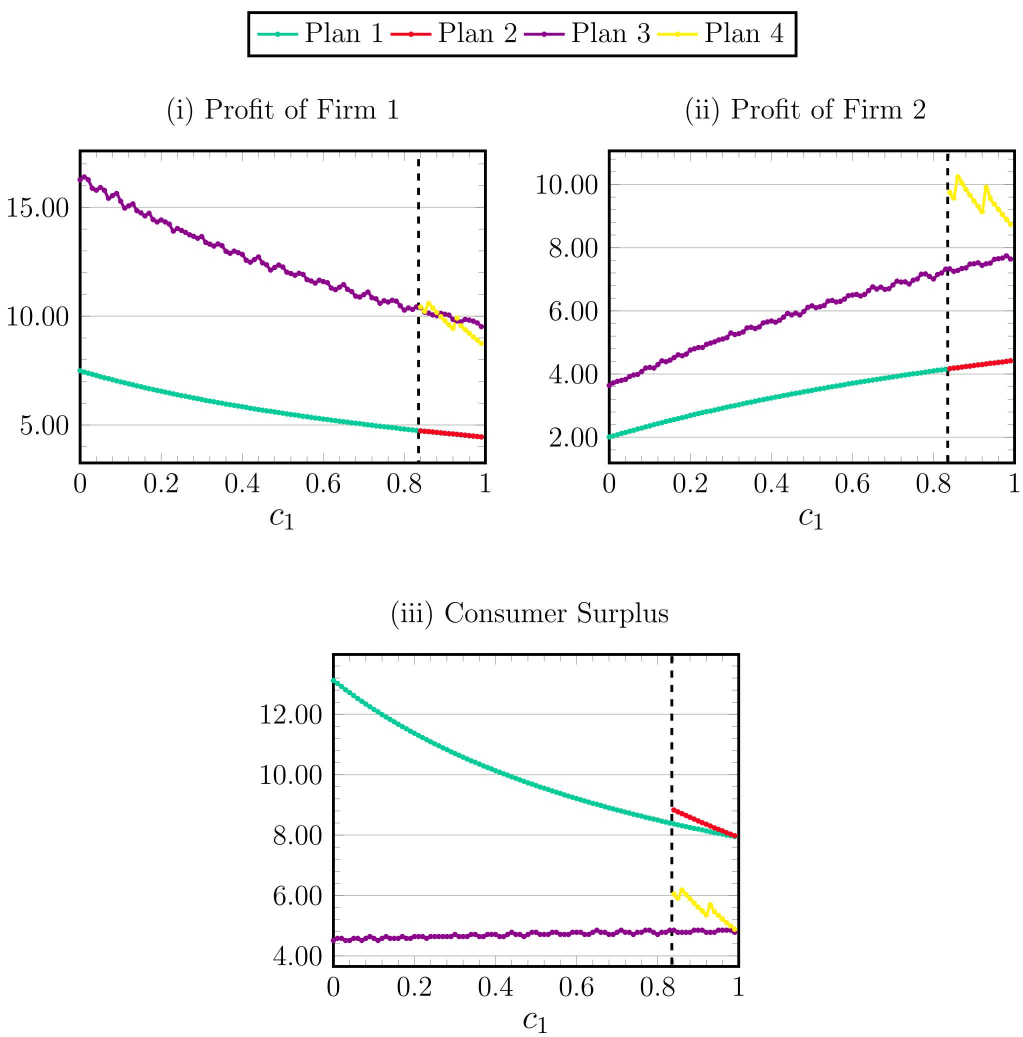


Figure 3 shows that both the presence of licensing and changes in the cost parameter of firm 1 affect the outputs of the two firms in opposite directions.

Result 3. *The output of firm 1 is always decreasing in* c_1 *regardless of the presence of licensing, whereas the output of firm 2 is always increasing in* c_1 *if there is no licensing (Plans 1 and 3). If there is licensing, the output of firm 2 is decreasing in* c_1 *if the firms compete (Plan 2) and slightly fluctuating in* c_1 *if the firms collude (Plan 4). Besides, the output of both firms are always lower when they collude (Plans 3 and 4) than when they compete (Plans 1 and 2). Moreover, licensing has always a negative effect on the output of firm 1 and a positive effect on the output of firm 2 both under competition* *and collusion.*

In Figure 4, we consider the effects of cost changes and the presence of licensing on the welfare distribution.

Figure 4. The Profits of the Firms Under Alternative Equilibrium Plans



Result 4. *The profit of firm 1 is almost always decreasing in c_1 whereas the profit of firm 2 is almost always increasing in c_1 except under Plan 4 where it is slightly fluctuating. Besides, the profit of each firm is always higher under collusion than under competition and licensing has negligible effects on the profits of the two firms under competition. We also find that the consumer surplus is always decreasing in c_1 under competition and slightly increasing under collusion. Moreover, licensing has always a positive effect on the consumer surplus.*

Ciarreta and Gutiérrez-Hita (2012) show that the efficient firm always benefits from supply function collusion whereas the inefficient firm benefits from it only if the cost asymmetry is sufficiently small. Figure 4 shows that in our model even the inefficient firm always benefits from collusion irrespective of the presence of licensing. The difference between our result and that of Ciarreta and Gutiérrez-Hita (2012) is caused by the difference in our assumptions as to the division of collusive output. Ciarreta and Gutiérrez-Hita (2012) assume that the collusive output is allocated between the firms in a ratio that equalizes their marginal costs whereas we assume that the efficient firm can offer to the inefficient firm any individually rational (admissible) contract specifying the division of the collusive output. It seems that the contract proposed by the efficient firm to maximize its self-interest not only prevents the two firms from cheating on the collusive outcome but also ensures that they both have an incentive to join a collusive agreement regardless of whether licensing occurs or not.

Comparing the findings for Plan 3 and Plan 4 in Figure 4, we also observe that firm 2 always prefers Plan 4 (collusion with licensing) to Plan 3 (collusion without licensing), while the same is true for firm 1 only for a thin range of the cost parameter c_1 (requiring it to lie between 0.84 and 0.89). On the other hand, for consumers Plan 4 is always preferred to Plan 3. Therefore, collusion with licensing is Pareto superior to collusion without licensing if c_1 is in $\{0.84, \ldots, 0.89\}$.

5 Conclusion

In this paper we have considered an infinitely-lived duopoly with asymmetric costs and studied the incentives of the firms to collude in supply functions under the possibility of technology licensing. We have shown that licensing makes tacit collusion in supply functions harder like in the work of Lin (1996b) where the firms' strategies are fixed quantities, and unlike in the work of Lin (1996a) where the firms' strategies are fixed prices. We have also found that conditional on collusion, the presence of licensing always has a positive effect on the welfares of consumers and the less efficient firm in the duopoly, whereas it may have a positive effect on the welfare of the more efficient firm only for a thin range of cost parameters.

Our welfare results hinge on several assumptions in our model. For example, we have assumed that all contracts are made by the more efficient firm in the duopoly. As for the licensing contract, we have also assumed that side payments are possible, allowing the licensee to pay a fixed fee to the licensor to use its cost-reducing innovation. Besides, we have enabled the licensor, the more efficient firm in the duopoly, to choose this fixed fee to maximize its welfare. One could alternatively consider, of course, licensing contracts that are determined jointly by the licensor and the licensee using some cooperative bargaining rule. As for the collusion contracts in our model, side payments are not required, since these contracts only specify how the firms should share the industry supply, not the industry profits. However, one could alternatively model the collusion contracts as in Ciarreta and Gutiérrez-Hita (2012), which divides the supply, according to the proposal of Patinkin (1947), in a ratio that equalizes the marginal costs of the firms. We should note that the alternative contracts for licensing and collusion might change the equilibrium welfares of the firms, possibly in favor of the less efficient firm, both under competition plans and collusion plans. Moreover, under these contracts the likelihood of collusion would be smaller than implied by our model. The reason is that even though in our model the more efficient firm has the complete power to choose the best licensing and collusion contracts for itself, it makes these choices under the constraint that both contracts should satisfy the incentive constraint of the less efficient firm, as well. This flexibility is lost when the licensing contract determines the fixed fee according to a predetermined bargaining rule or when the collusion contract divides the output to a prespecified rule such as the one used in Ciarreta and Gutiérrez-Hita (2012). Thus, we can argue that our results on the likelihood of collusion may be an upper limit that may provide a benchmark to compare the implications of possible variations of our model.

Given the relevance of supply function competition to power industries, our results may have some practical implications, as well. Power industries usually have an oligopolistic structure due to several factors including demand elasticity, the number of potential generators, transmission constraints and congestion, transmission losses, and entry barriers in the form of capital investment (David and Wen, 2001; Aliabadi et al., 2016). It is well known that the lack of perfect competition makes electricity industries susceptible to explicit or implicit (tacit) collusion. Fabra and Toro (2005), Sweeting (2007), and Cabacungan et al. (2013) report that in the past power generators might have been engaged in implicit collusion in electricity markets of Spain, the UK, and the Philippines, respectively. Implicit collusion cannot be held unlawful by competition laws, but regulators may nevertheless implement preventive measures to reduce its likelihood, provided they can detect, or at least credibly suspect, its existence. Our results show how collusion in supply functions, both in the presence and absence of technology sharing, could affect the market-clearing price and the industry output, offering to regulators some helpful guidance to detect collusion.

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